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RADIOACTIVE AND MIXED WASTE—RISK AS A BASIS FOR WASTE CLASSIFICATION

Symposium Proceedings No. 2

National Council on Radiation Protection and Measurements

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Radioactive and Mixed Waste—Risk as a Basis for Waste Classification

Symposium Proceedings No. 2

Held November 9,1994
Las Vegas, Nevada

Issued June 21, 1995

National Council on Radiation Protection
and Measurements
7910 Woodmont Avenue
Bethesda, Maryland 20814-3095

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Preface

The National Council on Radiation Protection and Measurements (NCRP) was asked by the U. S. Environmental Protection Agency (EPA) to initiate a series of public symposia on topics of current mutual interest. This Proceedings covers the first of this series of symposia and is the second proceedings of a public symposium conducted by NCRP, the first being *The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack* published in 1982.

The Symposium presented here was organized by a Program Committee consisting of:

Donald G. Jacobs, *Chairman*
Roy F. Weston, Inc.
Oak Ridge, Tennessee

Members

Allen G. Croft
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Dade W. Moeller
Dade Moeller & Associates, Inc.
New Bern, North Carolina

Paul Slovic
Decision Research
Eugene, Oregon

In addition to serving on the Program Committee, Dade Moeller, participating as a Consultant to the NCRP, played a major staff role in connection with the work of organizing and promoting the Symposium and, subsequently, served as rapporteur for the meeting, and editor of these Proceedings.

Participating from the NCRP Secretariat were:

William M. Beckner, *Senior Staff Scientist*
Cindy L. O'Brien, *Editorial Assistant*
Laura Atwell, *Staff*
Stephanie Dawley, *Staff*

The Council wishes to express its appreciation to all of these individuals for the time and effort devoted to conducting the Symposium and the preparation of these Proceedings.

Charles B. Meinhold
President, NCRP

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Opening Remarks

Charles B. Meinhold
President, NCRP

First, let me thank you all for coming to this Symposium. It is certainly a privilege to welcome you to this NCRP Public Symposium on "Radioactive and Mixed Waste—Risk as a Basis for Waste Classification." As many of you know, the NCRP began its existence in 1929 as the Advisory Committee on X-Ray and Radium Protection. Shortly after the second World War, it became the National Committee on Radiation Protection in recognition of its new concerns with all aspects of ionizing radiation.

Today, it is the National Council on Radiation Protection and Measurements, having received a congressional charter in 1964 as a nongovernment, public service organization. The primary objective in that charter is that we should "collect, analyze, develop and disseminate in the public interest, information and recommendations about radiation protection and radiation measurements."

We have traditionally depended upon the distribution of our scientific reports as a primary source of informing the public and disseminating information. And also we depend upon our annual open meeting which is held each April in the Washington, D.C. area.

We are delighted that the Environmental Protection Agency's Office of Indoor Air and Radiation is able to provide the support required for what, I hope, will be the first in a long series of NCRP symposia on radiation protection concerns which can be held throughout the United States, in the lingo of the people in Washington, "outside the Beltway."

Although the NCRP has issued a number of reports on selected topics related to waste management over its long history, in 1990 our Board of Directors recognized the unique issues associated with waste management and established a standing committee, NCRP Scientific Committee 87 on Radioactive and Mixed Waste, under the chairmanship of Dr. Donald Jacobs. Based on the Committee's recommendation, the

Council appointed a new Scientific Committee 87-2 on Waste Classification Based on Risk under the chairmanship of Dr. Allen Croff. Scientific Committee 87-2 is tasked with the preparation of an NCRP report on a risk-based system for classifying radioactive and mixed waste, an activity supported by the Department of Energy. I know that Dr. Croff and his Committee members, many of whom are speaking today, are looking forward to the insights that today's discussions can bring to this topic. And I am just as hopeful that the discussions will be useful to all of you.

It is now my privilege to introduce Dr. Donald Jacobs, chairman of Scientific Committee 87, a long time Council member, a member of the NCRP's Board of Directors, Vice President of Roy F. Weston, Inc.; and of most importance to this meeting, the Program Chairman for our Symposium. Dr. Jacobs . . .

Introductory Remarks

Donald G. Jacobs
Roy F. Weston, Inc.

The management of risks from radioactive and chemical materials has been a major environmental concern in the United States for the past two or three decades. Risk management of these materials encompasses the remediation of past disposal practices as well as development of appropriate strategies and controls for current and future operations. This Symposium is concerned primarily with low-level radioactive and mixed waste.

The development of successful risk management strategies for low-level radioactive and mixed waste requires that we understand both the nature and the level of the risks involved. In attempting to assure proper disposal of low-level radioactive waste, the U.S. Nuclear Regulatory Commission promulgated regulations some years ago that require such waste be designated as Class A, B or C based on the halflives and concentration of the radionuclides they contain. Although this classification scheme was based, to a large extent, on the associated risks and the persistence of the radionuclides, today we realize that several other factors may need to be considered. Some waste contains both radioactive and hazardous materials and we recognize that if the mixed waste is to be properly managed and disposed, we need to develop a system that can be used to express the nature and level of risks from the radioactive and chemically hazardous constituents in a comparable manner.

The purpose of this Symposium is to help identify the key issues that are relevant to the development of such a risk-based system. In planning the program, the NCRP has invited a group of outstanding speakers to address, in as systematic manner as possible, the range of subjects that must be considered. We have scheduled discussions following each of the presentations to provide an opportunity for each of you to comment, and perhaps expand upon what the speakers have presented. To the extent practical, we are also asking for your input in ranking the various issues according to their importance.

I will introduce each of the speakers prior to his or her presentation, but I believe it may be helpful for me to offer a broad preview of the program.

In order to develop a risk-based system as a basis for management, it is necessary to understand the nature and characteristics of the risks imposed by the waste that must be disposed—this will be covered by our lead-off speaker.

A second major consideration is "How do radioactive materials and hazardous chemicals affect the health of people and environmental quality?"—this will be covered by our second speaker.

Once the issues relevant to these topics have been identified, we need to estimate quantitatively how and under what conditions the contaminants can be released from the waste, move through the environment, and become accessible to people—this exercise, "risk assessment," will be covered by our third speaker.

The final presentation this morning will be a review of the concepts of risk management, and will include a comparison of the differences in the strategies currently being used to control the risks from radioactive versus chemically hazardous waste.

After a break for lunch, our fifth speaker will review some of the social and political considerations that must be taken into account in selecting strategies for the management and disposal of any type of waste. Certainly all of you know that the issues surrounding the subject of waste disposal are not all technical in nature—equity and fairness are among a number of other social and political factors that need to be considered.

The last formal presentation will be to outline the application of the principles of risk to the classification of radioactive waste, as practiced in one of our states. This presentation will demonstrate one possible approach to the subject. One of the benefits from this discussion will be to highlight some of the issues that will be faced in the "real-world" application of a risk-based system.

We have deliberately limited the number of presentations to allow opportunities for discussion and input by you, the participants in this Symposium. I want to emphasize that we are not here to tell you what the key issues are, or to decide for you which of them are the most important—the purpose of the formal presentations is to stimulate discussion, We want your input and we have tried to design the Symposium to provide opportunities for you to participate in the discussion. Because of the number in the audience, it is obvious that not everyone will have an opportunity to express his or her views orally. For this reason, we have included in your packet of handouts a card on which we would like for you to write down your views on the subject. We hope that each of you will take the opportunity to provide us with your input. Dr. Moeller and I promise that each and every card will be carefully read and your expressed views taken into account in summarizing the conclusions of the Symposium.

The final presentation of the day will be a summarization of the major conclusions of the Symposium. One objective of this recap will be to highlight areas of consensus and areas of disagreement; we will cite any recommendations on which there appears to be general agreement. This summary presentation will be followed by comments from the individual speakers, and the Symposium will conclude with a final period of discussion in which you, the participants, will have an opportunity to express any conclusions and recommendations that you may have developed as a result of the day's discussions.

We are pleased that you are attending this Symposium and hope you enjoy the presentations. Most of all we hope the discussions stimulate your interest in this topic and we encourage you to let us have the benefit of your views.

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Radioactive and Mixed Waste—Risk as a Basis for Waste Classification

Definition of the Problem

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Abstract

Definition of the problem requires a general understanding of the current regulatory situation. "Mixed waste" is generally defined as waste that contains both radioactive materials subject to the Atomic Energy Act and hazardous waste subject to the Resource Conservation and Recovery Act.

Atomic Energy Act materials derive from, or are related to, fission, and do not include radioactive materials produced in accelerators or occurring naturally (with the exception of uranium and thorium). Mixed waste is subject to dual regulation by federal and state agencies under programs established under these separate laws. The objective of a risk-based framework for classifying mixed waste could be: (1) to enable determinations that waste is no longer "mixed" and can be managed as either radioactive or hazardous and (2) to provide the means for estimating total risk to provide a technical basis for optimizing management decisions.

Other background information provided includes summary information on the various types of commercial and U.S. Department of Energy (DOE) managed radioactive and mixed waste, discussion of the key parameters needed to assess risks and the availability of input needed to use risk to classify mixed waste. The radiological, physical and chemical properties of mixed waste span a

[1]The information provided and views expressed are those of the author and cited references and do not necessarily reflect those of her employer.

wide range. Decommissioning and remedial action waste is difficult to project. The waste classification established in 10 CFR Part 61 for disposal of commercial low-level radioactivity provides an example of a risk-based classification and illustrates the type of information needed. Key categories of parameters and tools needed include biological information on hazards, waste properties and other components of the management system, performance assessment and technology. Many of the parameters and tools needed to perform traditional risk assessment are not available or fully developed.

Ideally, the scope of the method or framework for classifying waste should be sufficiently comprehensive and flexible to be applied to all aspects of waste management and all types of mixed waste, but practicality suggests that efforts be focused on disposal of mixed low-level waste.

A major challenge is to find practical ways to deal with the complexities, uncertainties and developing technologies. A risk-based classification system could provide a means of determining the significance of missing information and help in assigning priorities to develop the information. Another challenge is to devise a framework that deals with the interaction of the components of the disposal system, how they collectively work together and how the framework should accommodate site-specific considerations.

Definition of the problem requires a general understanding of the current regulatory situation and some of the legal and waste terms that have evolved over the years. Other background information to be addressed in this paper includes summary information on the various types of radioactive and mixed waste, discussion of the key parameters needed to assess risks, and the availability of input needed to use risk to classify mixed waste.

The current situation developed over decades, but the details of development are not important to risk classification for mixed waste. What is important is that mixed waste is currently subject to dual regulation under multiple laws and regulations. Although there are exceptions, such as the Bevill exemptions for certain mining and milling waste and those noted below, radioactive waste containing or exhibiting hazardous properties are now subject to regulation under programs established by the Environmental Protection Agency (EPA) for hazardous waste. Separately developed requirements apply to the radioactive component of the waste. Some key terms used in this background paper are discussed below. The discussion paraphrases the legal definitions for simplicity and indicates generally how the type of material and waste are regulated. Exceptions to full dual regulation are noted.

"Mixed waste" is generally defined as waste that contains both radioactive materials subject to the Atomic Energy Act and hazardous waste subject to the Resource Conservation and Recovery Act.

Atomic Energy Act materials are radioactive materials that derive from or are related to the fission process and do not include radioactive materials produced in accelerators or occurring naturally (with the exception of uranium and thorium). They are designated as by-product, source and special nuclear material. (Uranium and thorium mill tailings are legally defined as a type of by-product material, but they are a special case in that both the radioactive and hazardous components are regulated under a single authority and are not part of the "mixed waste" problem.) "By-product materials" are radioactive materials resulting from the use of special nuclear material. "Source material" contains uranium and thorium and includes ores containing these elements. "Special nuclear materials" are the fissionable isotopes of uranium, uranium with the fissionable isotopes at concentrations greater than those in nature, and plutonium. Atomic Energy Act materials used in the civilian or commercial sector are regulated by the Nuclear Regulatory Commission (NRC) or Agreement States. The DOE controls Atomic Energy Act materials in the defense sector, although the NRC regulates disposal of high-level waste and greater than Class C waste.

"Solid waste" is virtually anything (solids, liquids and gases) that is a waste. Garbage, refuse, sludge, filters, treatment residues and industrial operational waste are included. Management of solid waste is subject to the Resource Conservation and Recovery Act. This Act excludes source, special nuclear and by-product materials. Management of solid waste is regulated by the EPA or states.

"Hazardous waste" is defined as solid waste that poses a substantial present or potential hazard to human health or the environment if improperly managed. Waste may be hazardous because it exhibits a hazardous characteristic or may be specifically identified as being hazardous based on the process generating the waste. Characteristics include being ignitable, corrosive, reactive or toxic. Hazardous waste is regulated by the EPA and delegated states. (States need specific approval from the EPA to regulate the hazardous component of mixed waste.) Because the definitions of solid waste and hazardous waste are so powerful in their reach, the EPA is looking at ways to focus the regulatory programs on the significant hazards through its hazardous waste identification efforts.

"Debris" is solid waste that is discarded material larger than 60 mm (about two inches). It can be a mixture of materials, including soils and liquids, provided more than half the waste by volume is of the specified size. It can be hazardous or mixed, depending on its properties and is regulated according to its properties.

Waste is considered non-Atomic Energy Act radioactive waste if it contains naturally occurring radionuclides other than uranium or thorium or accelerator produced radionuclides. States regulate these radioactive materials under general state authority (radioactivity is not currently a hazardous characteristic). Hazardous waste containing these radionuclides is currently regulated as hazardous, but it may be subject to additional requirements imposed by the states related to its radioactivity content.

What do we mean by "waste classification"? One meaning could be a method for sorting waste for developing and applying appropriate management options and requirements. Waste management includes storage, shipment, testing, treatment and disposal. Different classification criteria might apply to each management activity since the potential risks are different. For example, when shipping radioactive waste, the external gamma dose rates from packages are much more important to controlling risk during handling and transport than after disposal in a fixed, shielded facility.

What is the problem that prompted this Symposium? The multitude of laws, regulations and implementation philosophies that apply to management of an incredible variety of waste are potentially inconsistent and clearly overlap. There may also be gaps. Although there may be risk considerations in establishing individual requirements and even a risk-based classification for disposal of commercial low-level radioactive waste, there is currently no risk-based method for addressing the full array of waste or mixed waste in particular. Many existing classifications for radioactive or hazardous waste is largely by source (*e.g.,* high-level waste or household waste) or presence of any amount of hazardous material, not risk (*e.g.,* hazard or concentration) based.

What is the objective of a risk-based classification for mixed waste? The objective of a risk-based framework for classifying waste containing both hazardous and radioactive components could be twofold:
(1) enable determinations that waste is no longer "mixed" and can be managed as either radioactive or hazardous and (2) provide the means for estimating total risk from radiological and nonradiological properties combined to provide a technical basis for establishing reasonable and appropriate requirements when both properties must be considered in management decisions.

An overview of the characteristics of radioactive and mixed waste provides additional background. Topics addressed in the following discussion include the radioactive characteristics of both commercial and DOE waste, the nonradiological properties of the waste, and summary information on the relative volume and type.

The radioactive characteristics and associated categories established in law for commercial waste cover a wide range in radioactive content and characteristics. Figures 1 and 2 reproduced from a 1989 brochure published by the NRC conceptually display the generation of waste in the commercial sector and provide a quick reference to the spectrum of waste and the generators and regulators (NRC, 1989). High-level waste and spent fuel generally contain sufficient radioactivity to require cooling to dissipate the energy from decay and require significant shielding. High-level waste and spent fuel contain large quantities of by-product material and special nuclear materials; high-level waste is the very radioactive waste from chemical processing of spent fuel. Because recycle of power reactor fuel was practiced only briefly and is not currently practiced in the United States, most of the commercial waste in storage and to be disposed of as high-level waste is spent fuel. Waste that contains Atomic Energy Act materials and is not high-level waste, spent fuel, transuranic waste or mill tailings is termed low-level waste. Low-level waste includes waste from decommissioning and cleanup of sites. Its radioactive content ranges from small quantities of a single radionuclide to significant quantities of many radionuclides. Commercial low-level waste has been classified for disposal based on increasing radioactive content in 10 CFR Part 61 into Classes A, B and C and greater than Class C. This classification scheme will be discussed in more detail later. The states are responsible for providing disposal capacity for Classes A, B and C. The DOE is legally responsible for disposal of greater than Class C waste; 10 CFR Part 61 currently provides that waste be disposed of in a high-level waste repository unless specifically approved otherwise.

DOE generated waste is categorized as high-level waste, transuranic waste, low-level waste, and waste from environmental restoration activities. High-level waste is generally the same as for the commercial sector; the DOE processes spent fuel and irradiated targets and does not typically have significant quantities of the fuel or targets on hand. The DOE is responsible for disposal of high-level waste and spent fuel from both sectors. Geologic disposal is the preferred and planned disposal method. Transuranic waste contains more than 100 nanocuries per gram of long-lived alpha emitting radionuclides with atomic numbers greater than uranium's. Most transuranic waste contains mainly plutonium and little by-product material; consequently cooling and shielding are not routinely required. Disposal of transuranic waste, including mixed transuranic waste, is expected in the Waste Isolation Pilot Plant, which is a deep geologic repository. Low-level waste contains mostly by-product materials and the contents vary over a wide range; shielding may be required for some.

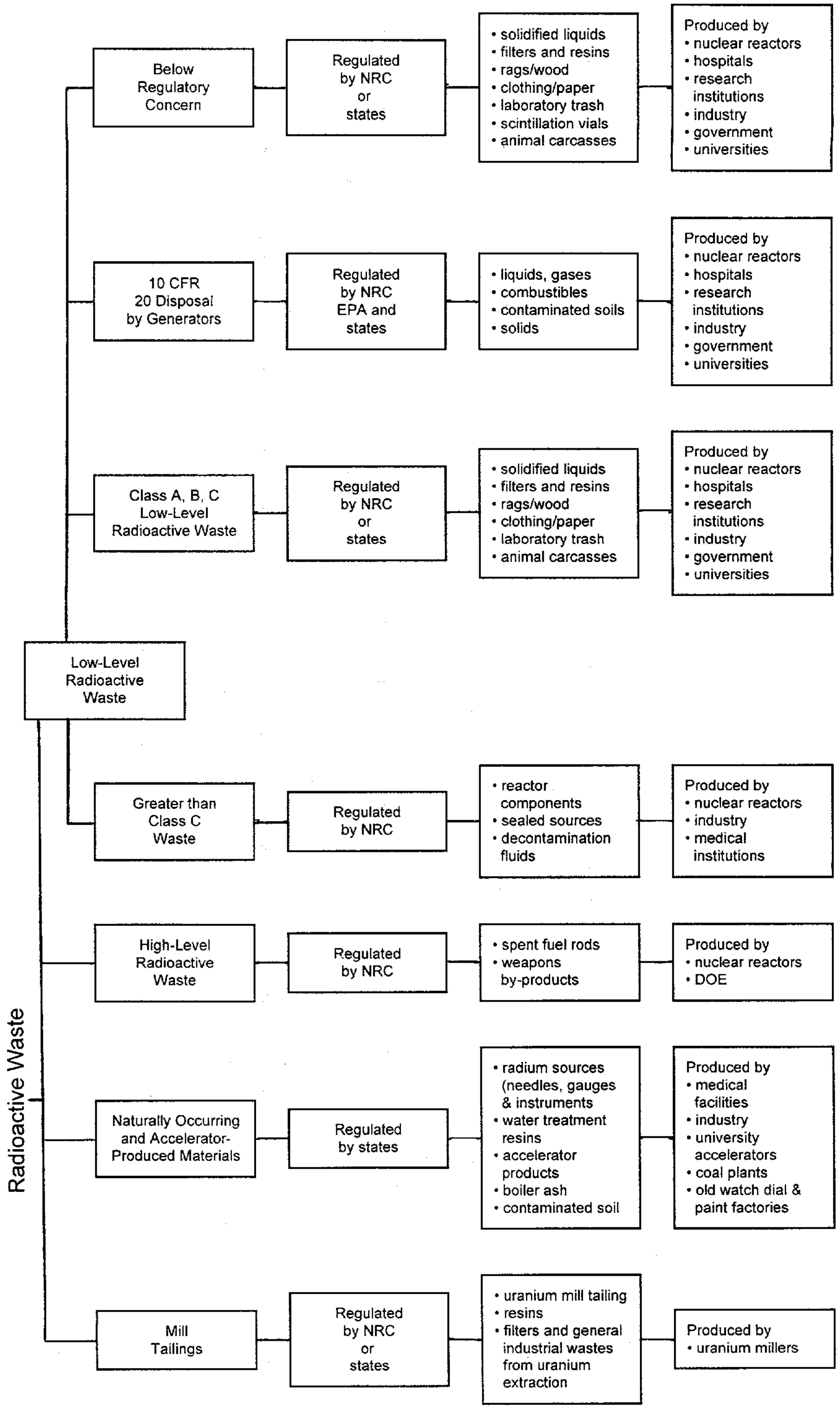

Fig. 1. Commercial waste generation.

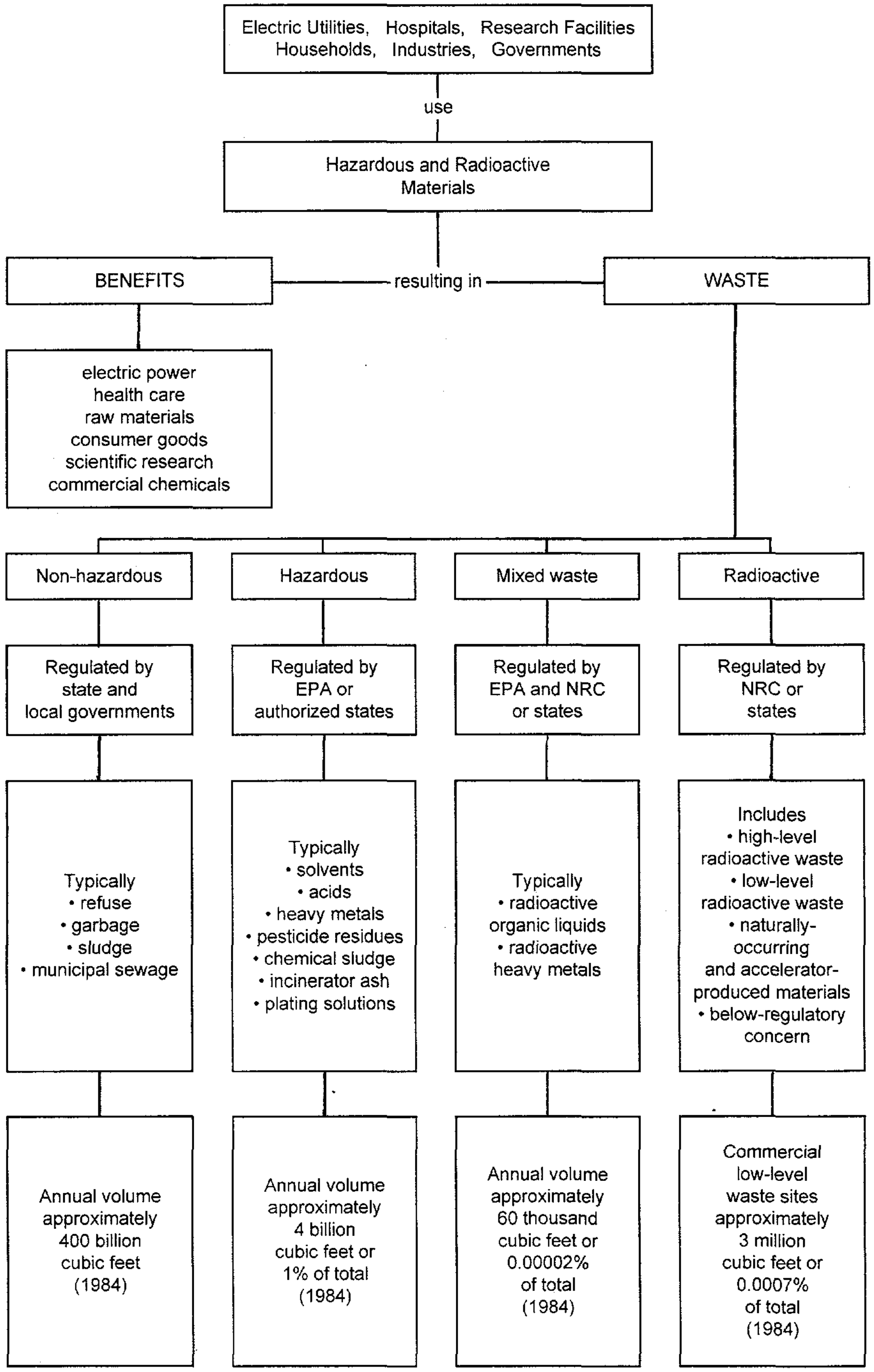

Fig. 2. Radioactive waste.

Non-Atomic Energy Act waste also contains a wide range of activity. In attempting to address the disposal of these materials, the EPA has generally categorized them as discrete and diffuse. Discrete waste includes sealed ^{226}Ra sources and materials where the natural concentrations have been significantly enhanced. Water treatment resins or oil field waste contaminated with ^{226}Ra are examples of potential discrete waste, depending on the final dividing line or definitions adopted. Diffuse sources include materials such as coal fly ash or phosphate fertilizer tailings. Accelerator waste typically contains concentrated but short-lived radionuclides.

The nonradiological properties of commercial and defense mixed waste reflect the diverse activities generating them. The physical and chemical forms are also influenced by mandatory and voluntary treatment. The EPA has been issuing statutorily mandated treatment standards for hazardous waste. Under the Hazardous and Solid Waste Amendments of 1984, untreated hazardous waste may not be disposed of in a land disposal facility, except under limited conditions such as demonstrating that there will be no migration of the waste from the disposal unit. Land disposal includes landfills, surface impoundments, waste piles, injection wells, land treatment facilities, salt formations, underground mines or caves, or disposal vaults or bunkers. The treatment standards prescribe either a concentration of a constituent in the waste or treatment residue or use of the best demonstrated available technology. Existing standards specifically developed for mixed waste include: vitrification (making into glass) for high-level waste, macroencapsulation (coating or covering) for pieces of lead, amalgamation (form a solid alloy as in dental fillings) for elemental mercury, and incineration for hydraulic oil contaminated with mercury. Treatability for mixed waste requires consideration of the radioactive characteristics, the hazardous characteristics, and the physical/ chemical matrix of the waste. Methods or standards to cover the full gamut of mixed waste are needed. The DOE has a major program underway for waste it manages.

High-level waste is mixed waste, unless proven otherwise, due to its corrosive nature (*e.g.,* highly acidic), the organic solvents present, or the hazardous metals present. Liquid high-level waste has been converted to a variety of physical/chemical forms such as salts, calcines, glass and sealed sources. Spent fuel is the uranium fuel and metal components holding the fuel in the fuel rods and bundles; its status as a potential mixed waste is still under consideration and it has not been generically determined to be mixed waste. However, EPA staff have made a preliminary finding that spent fuel from naval reactors is not mixed waste.

In 1992, the NRC and the EPA published the results of the National Profile on Commercially Generated Low-Level Radioactive Mixed Waste

(NRC, 1992). This project was intended to help reduce the uncertainties in the volume and characteristics of low-level mixed waste which had been one of the principal barriers to commercial development of treatment and disposal facilities for mixed waste (Orlando and Weber, 1993).

Figure 3 presents a summary of the commercial mixed waste streams and types of generating facilities in 1990 from the National Profile. Seventy-one percent by volume was liquid scintillation fluids used in counting samples in various research and testing activities. Organic solvents such as chlorofluorocarbons, corrosive organics and waste oil made up 18 percent, toxic metals made up three percent, and "other" made up eight percent. "Other" means too complex to consider as a waste stream. Figure 3 also shows the relative volumes from each major generating category. The industrial category generated 35 percent of the mixed waste. This category includes radiopharmaceutical, chemical, nuclear fuel and sealed source manufacturers; research and development and consulting firms, and analytical laboratories. The predominant waste stream reported was liquid scintillation fluids (68 percent). The predominant waste streams for the utility category were waste oil (35 percent) and chlorofluorocarbons (27 percent). Academic and medical generators produced mainly liquid scintillation fluids (92 and 93 percent, respectively). The government category is the licensed agencies, who produced mainly liquid scintillation fluids (77 percent) and other organics (13 percent). The estimated 1990 volume of generated mixed waste in the Profile was 140,000 ft^3 (3,900 m^3) which can be compared to the 1.1 million ft^3 (about 31,000 m^3) of disposed low-level waste. The predominant radionuclides were ^{14}C, ^{3}H, ^{32}P, ^{35}S, ^{51}Cr, ^{60}Co, ^{125}I, ^{137}Cs, ^{134}Cs and ^{238}U. The Profile data represents a snapshot with the associated uncertainties of surveys. Further, although the Profile included one decommissioning or cleanup waste (sewer sludge containing cadmium and uranium), it did not attempt to categorize this source by waste stream or volumes. Potentially large volumes may be generated, but "accurate projections of these mixed waste will be difficult" (Orlando and Weber, 1993).

The states, who are responsible for providing disposal capacity for commercial low-level waste generated in their state, including mixed low-level waste, have approached the DOE about potential acceptance. The states support the idea of DOE acceptance "because: (a) there is very little commercial mixed waste generated in relation to that generated at DOE facilities (DOE generates 26,300 m^3 annually while commercial industries generate only 3,900 m^3), (b) costs for commercial disposal are estimated to be very expensive because of the economy of scale, (c) once treatment capability becomes available, at least 70 percent of commercial mixed waste will be eliminated (not have to be disposed

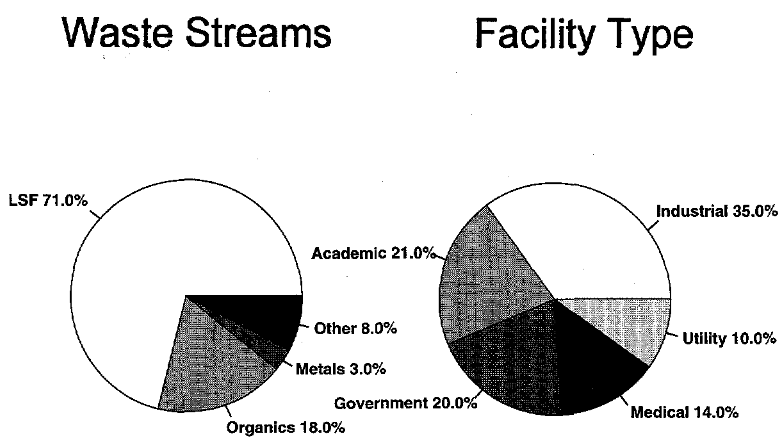

Fig. 3. National profile on commercial mixed waste (low-level radioactive waste only).

of in a dually regulated facility), . . . and (f) no states are developing mixed waste disposal facilities" (Owens, 1993). The Department studied the feasibility and concluded that "..the potential role of DOE would be limited to disposal of commercially treated residues" (Owens, 1993). The DOE evaluation concluded that there are many commercial waste streams similar to DOE's (89 percent for generated waste and 96 percent for stored waste) but some that are significantly different or problematic, in the medical and research areas and certain uranium fuel cycle waste, and that DOE's treatment technologies under development would not address these significantly different or problematic waste. Examples of treated waste that presents problems include waste solidified with cement and compacted waste. Most liquid scintillation fluids are being treated for fuel reclamation (*i.e.,* burned for fuel) with minimal residues remaining as mixed waste; this practice might be seriously curtailed if the EPA implements more stringent regulatory requirements for use of the fluids for fuel in cement kilns. Mixed waste presents a catch-22 situation. Under the technology forcing Resource Conservation and Recovery Act and related requirements, waste cannot be legally stored or disposed without treatment and sufficient treatment and disposal capacity does not exist for all waste. In addition, generators do not take advantage of available treatment capacity for a number of reasons, including liability concerns, confusion over requirements, and lack of data on the waste, and they continue to store some waste (Orlando and Weber, 1993). In 1990, there were 75,000 ft^3 (2,100 m^3) in storage. The catch-22 is a practical side of the problem for both sectors and has required some accommodation in law and enforcement programs. The EPA has extended to 1996 its conditional lower enforcement priority policy for the commercial sector.

The Federal Facility Compliance Act of 1992 amended the Resource Conservation and Recovery Act primarily addressing DOE managed mixed waste issues. The Act included a requirement for the DOE to prepare an inventory and to project generation of mixed waste over the next 5 y (DOE, 1993). The report states that there are 50 sites (note that since this report was published, the DOE has revised the number of sites to 48) that store, generate or are expected to generate DOE managed mixed waste in 22 states. The primary programs that generate or manage mixed waste are the Defense Program, the Energy Research Program, the Nuclear Energy Program, the Environmental Restoration and Waste Management Program, and the Naval Nuclear Propulsion Program. Most of the current inventory comes from routine operations and the environmental restoration activities. Total mixed waste in storage on January 1, 1993 was about 590,000 m^3 and the volume projected for 1993 to 1997 was for an additional 300,000 m^3. These volumes include high-level waste, transuranic waste and low-level waste. The report also states that about 44 percent of the inventory has been characterized as hazardous through sampling and the rest by process knowledge. This 5 y projection does not include environmental restoration waste because of the uncertainties, but the total volume of environmental restoration waste estimated to be on hand January 1, 1993 was approximately 27,000 m^3 and the total of this type of waste expected to be on hand at the end of 1997 was estimated to be 620,000 m^3.

Figure 4 shows the DOE estimates of mixed waste inventories on hand as of the first of January 1993 by radioactive category. The categories shown are mixed high-level waste, mixed transuranic waste, mixed low-level waste, and mixed environmental restoration waste. All high-level waste was assumed to be mixed. All transuranic waste was assumed to be mixed, unless they had been determined not to be and managed separately. Low-level waste is only those that have components regulated under federal or state hazardous waste laws. Figure 4 also shows the estimated generation for the 5 y of 1993 to 1997, with similar assumptions. [All values in Figures 4 to 7 were derived from DOE (1993) using two significant figures.]

Figures 5 to 7 show a simplified breakdown by volume of the 1,400 plus waste streams identified for mixed high-level waste, transuranic waste and low-level waste, respectively. For high-level mixed waste (Figure 5),

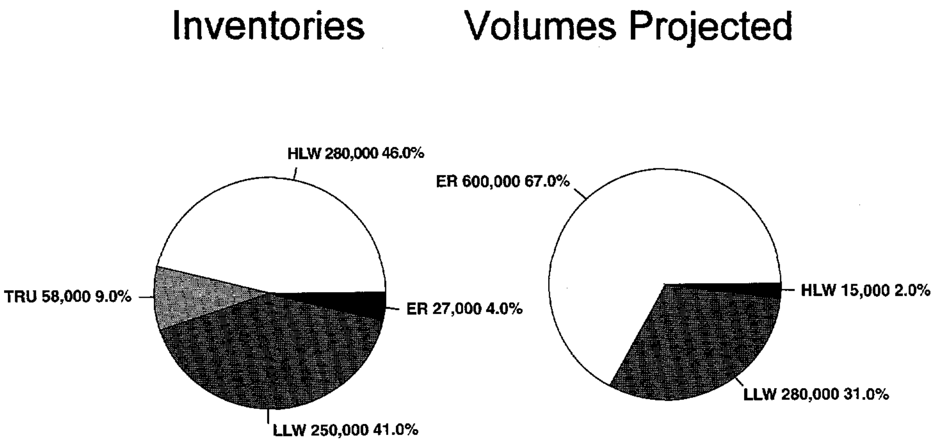

Fig. 4. DOE mixed waste by radioactive category (volumes in cubic meters). Left: inventories for January 1, 1993. Right: volumes projected 1993 to 1997.

the January 1, 1993 inventory was about half aqueous liquids and half inorganic sludge and particulates. The 5 y projections are only about five percent by volume of the current inventory and are expected to be only aqueous liquids and calcine solids. For transuranic mixed waste (Figure 6), the predominant waste forms for the January 1, 1993 inventory were organic, inorganic and heterogeneous debris; organic and inorganic sludge were next. The reference to "TBD" means "to be determined." The remainder includes forms such as metals, batteries and materials with multiple components. The estimated 5 y additional accumulation was also only about five percent. Aqueous liquids were the most common low-level mixed waste in inventory (48 percent) and projected (87 percent) (Figure 7). Debris, organic liquids (primarily solvents), and sludge were the next most significant volumes. The inventory and 5 y projections were about equal in volume (250,000 and 280,000 m^3, respectively) [see (DOE, 1993) for additional detail].

Environmental restoration waste is expected to include materials such as decontamination residuals, contaminated equipment and structural debris, and soils contaminated with asbestos, diesel fuel, polychlorinated biphenyls (PCBs), paints and solvents, where the radioactive contamination is only incidental. Most (99.9 percent) are expected to be

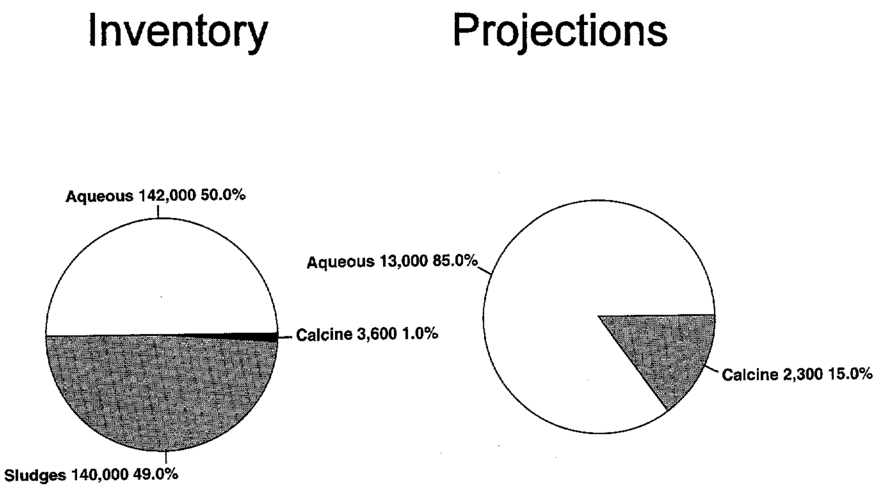

Fig. 5. DOE high-level mixed waste streams (volumes in cubic meters). Left: inventory as of January 1, 1993. Right: 1993 to 1997 projections.

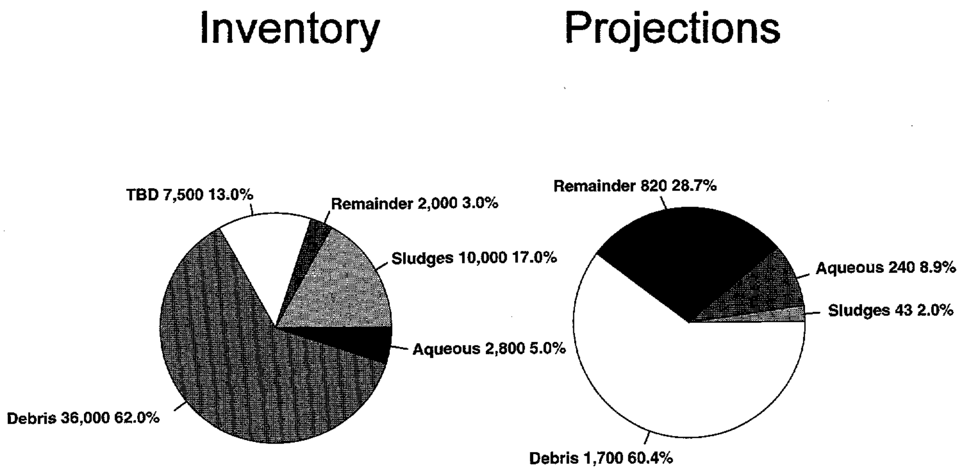

Fig. 6. DOE transuranic mixed waste streams (volumes in cubic meters). Left: inventory as of January 1, 1993. Right: 1993 to 1997 projections

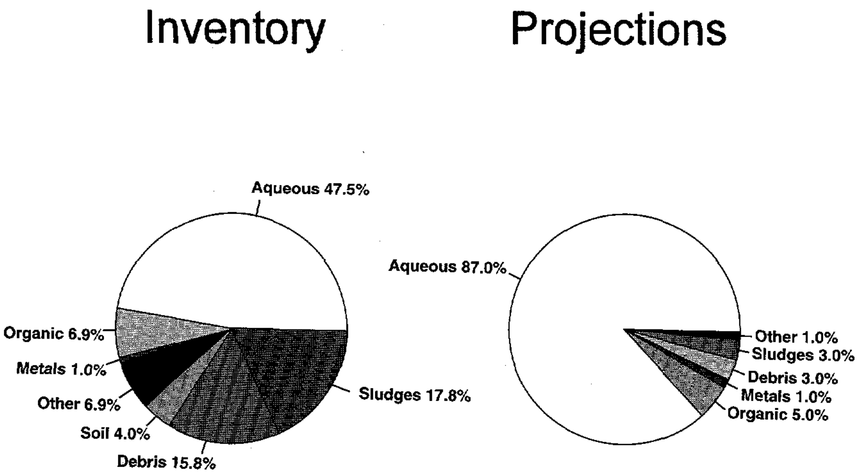

Fig. 7. DOE low-level mixed waste streams. Left: inventory as of January 1, 1993. Right: 1993 to 1997 projections.

low-level mixed waste; the remainder will be transuranic mixed waste. Three sites account for 80 percent of the volumes expected to be generated during 1993 to 1997: the Nevada Test Site, the Fernald Environmental Management Project, and the Rocky Flats Plant in Colorado.

In a recent risk assessment on naturally occurring radioactive contamination of oil production waste in Louisiana (Rogers *et al.*, 1993), the authors estimated annual generation of about 350,000 ft^3 (10,000 m^3) of sludge and scales. This risk assessment compared the risks from downhole disposal with various surface disposal methods and concluded that downhole represented a significant reduction in risk from the radioactivity present. The pathways considered included ground water, food production and radon inhalation; intrusion scenarios were also evaluated. Individual lifetime risks and population risks were estimated. This waste is not currently considered mixed, but the analysis illustrates a potential use of risk to make decisions on appropriate management options.

What are the key parameters needed to assess the associated risks from mixed waste? Classical risk assessment requires knowledge or estimates of the hazard, dose response and exposure assessment. Information needed can be grouped into four categories: biological, waste system components, calculational tools and technology. In the case of the oil field scales and sludge assessment in Rogers *et al.* (1993), the authors projected the volumes and physical types of waste and radionuclide content (total quantity and average concentrations), developed fourteen scenarios for potential human exposure from down-hole disposal options, and estimated potential exposures from six potential alternative near-surface disposal alternatives. Four EPA computer codes were used for evaluating potential doses from ^{226}Ra and resulting risks for each disposal scenario.

In the case of ^{226}Ra, the risk is due to internal and external exposure to ionizing radiation. For mixed waste, the risk is due to both radiological and nonradiological hazards. Biological information on the nature of the hazard or adverse effect (*e.g.,* cancer induction, genetic effects on offspring of exposed individuals, burns from corrosive materials) is needed for each hazard. Information on the relationship between the dose or exposure and incidence of the effect is needed to quantify dose response. If thresholds for effects on humans and the environment exist, that information needs to be considered. The chemical components and mixtures in mixed waste can involve many adverse effects and complex interactions among the agents. Sheer numbers of chemicals compound the problem, because there are some six million known chemicals of which 60,000 were in commerce in 1984 (NCRP, 1989). Only about 400 chemicals have been officially listed as hazardous in environmental protection regulations. There is good evidence that some contaminants can cause multiple effects (*e.g.,* arsenic is a poison and carcinogen). The challenge is to provide a method or methods to quantify risks from the multiple components so they can be normalized or added together.

Assessment of exposure requires information on all components of the waste management systems sufficient to make reasonable estimates of releases and exposures. Consider the Class A, B and C waste classification scheme for near surface disposal of commercial low-level radioactive waste in 10 CFR Part 61 as an example of classifying waste based on risk from disposal (NRC, 1982). The classification was based on the projected properties of commercial waste for the next 20 y, assuming no reprocessing of spent fuel in the commercial sector and incidental quantities of source material waste. The performance objectives for releases at the site boundary and intruder protection were the decision criteria used. The philosophy was to place more restrictive conditions on the more hazardous waste. Combinations of requirements were tried to achieve the objectives in a manner that minimized the burden on small waste generators. The classification was a systems approach to control the potential dose to humans from the disposed waste. The components of the system included the site characteristics, design and operations; institutional controls; waste form; and intruder barrier.

The quantity and type of radioactivity permitted in each waste class depends on the combination of components used for disposal. Figure 8 shows these concepts in a matrix. *Class A* waste must meet the minimum nonradiological waste form requirements and is segregated from the other waste; *Class B* waste must meet both the minimum and stability waste form requirements; *Class C* waste must meet the minimum and stability waste form requirements and be protected from inadvertent intrusion by deeper burial or other barrier. The classification tables separately address the short-lived and long-lived radionuclides. In order to minimize analytical burdens on generators, the concept of key indicator radionuclides was used. For example, ^{134}Cs was dropped from the proposed rule because ^{137}Cs provided sufficient indication of hazard from the two radionuclides in the projected waste. The stability requirements on waste form were intended to provide long-term stability of the waste under the assumed disposal conditions so that degradation of the waste would not lead to cover failure and water infiltration. Stability can be provided by the waste itself, the treatment matrix, packaging or disposal method. The minimum requirements include minimizing liquids; absorbing liquids; treatment to reduce biological, pathogenic or infectious hazards; and exclusion of reactive materials.

The determination of estimated concentrations required performance assessment tools (models) to estimate releases of radionuclides over time and the resulting potential exposures from all pathways to man and to estimate the potential doses to intruders. Extensive pathway analyses were performed. Intrusion was generally the limiting scenario. Based on balancing institutional burdens against potential exposures, licensed

	Site, Design and Operations	Institutional Controls	Waste Form	Intruder Barrier
Class A	X	X		
Class B	X	X	X	
Class C	X	X	X	X

Fig. 8. Matrix approach for classifying low-level radioactive waste.

institutional controls were relied on to prevent intrusion and residency for 100 y. After 100 y, the analyses assumed that an intruder would build a home, live there, grow and consume food, and drink local water and that Class A waste would be indistinguishable from soil. Based on the projected inventories of waste and radioactive decay, stability for 300 y was optimum; the recognizable form of Class B waste, potentially assessable to an intruder, was assumed to limit intruder exposures to short periods in discovery and construction scenarios. The intruder would stop and investigate what previous activities had occurred. During discovery, the intruder exposure was primarily through inhalation and direct exposure to gamma radiation. The stable waste was assumed to gradually fail 300 to 500 y after site closure. Intruder protected Class C waste was evaluated for intrusion after 500 y for scenarios similar to Class A, assuming all waste is indistinguishable from soil and that Class C waste was mixed with and diluted by the waste disposed on top of it and by soil covers. Regional sites were modeled to cover a wide range of potential site characteristics. This scheme was recently reaffirmed in the denial of a petition for rule making (NRC, 1994). Challenges to the classification scheme included the 5 mSv annual dose limit used for inadvertent intruders, lack of assessment of intentional intrusion, and the need to update cost estimates.

The waste disposal classes in 10 CFR Part 61 provide a generic classification scheme for waste. The amount of waste and radioactivity acceptable at a site must still be determined on a site-specific basis. Inventory limits may need to be set for certain radionuclides. All three classes may not be acceptable at a site if the design does not provide sufficient intruder protection. Nevertheless, it represents a risk-based approach to determining acceptable, reasonable requirements on the components of the waste disposal system.

The calculational tools needed have continued to evolve since the 1982 publication of 10 CFR Part 61. Federal agencies, states and consultants have been fine tuning these performance assessment tools to address generic issues and site-specific analyses. There is a wide range in purpose, complexity and flexibility of the codes. The degree of sophistication needed depends on the objective. Simpler codes can be used for optimization studies comparing alternatives, whereas more sophisticated codes are needed for site-specific evaluations.

State-of-the-art technology is a practical aspect to consider for all components of the disposal system. Ideally, all decisions, particularly treatment decisions, should be based on risk using a systems approach and optimization process. This is not generally the case in view of statutory requirements, but there is evidence of some consideration of risk. The EPA's debris approach uses technology to classify waste as mixed or radioactive, based on performance of prescriptive treatment requirements. This approach is an example of technology classification and indirect application of risk considerations (EPA, 1992; Vetter *et al.*, 1993). The debris rule requires that mixed waste debris be treated with methods selected from the prescribed treatment standards, but flexibility to address the diverse nature of the waste and contaminants is provided. Seventeen best demonstrated available technologies are reflected in the standards (see Table 1, "Alternative Treatment Standards for Hazardous Debris," of 40 CFR 268.45) (EPA, 1992). These technologies either extract, destroy or immobilize the constituents. Extraction may be either physical, chemical or thermal; destruction technologies include biodegradation and chemical processes. Except for immobilization, the treatment methods are presumed to destroy or extract all the constituents if the prescribed methods are followed for the category of constituents, thus eliminating the hazardous risk; the treated mixed waste debris may be classified as radioactive waste only and would not be subject to further Resource Conservation and Recovery Act regulation. Another advantage of this approach is that it would reduce the need for extensive sampling to confirm the presence and to assess the quantities of all constituents in the waste, before and after treatment. It would also result in reduced risks to workers.

Environmental restoration waste and commercial sector decommissioning and cleanup waste will likely include debris. Typical examples of mixed waste debris include air filters, concrete, piping and laboratory equipment. As noted earlier, however, actual amounts are difficult to estimate. A few percent of the 1990 commercially generated and stored mixed waste may qualify as debris, but no survey has been conducted. The DOE data in Figures 5 to 7 reflect the debris definition in the 1992 regulations.

Availability of the required data for establishing a risk-based classification system is difficult to assess. Other speakers will address the biological data needs and performance assessment (computer codes); however, the following discussion touches briefly on these. NCRP Report No. 96 (NCRP, 1989) was prepared to evaluate "... the extent to which the principles and methods that have been developed for use in assessing the carcinogenic risks of ionizing radiation are applicable in assessing the carcinogenic risks of chemicals." The scope included surveys of parameters such as how radionuclides and chemicals enter and distribute in the body, biological effects, dosimetry and dose-response. It examined extrapolation from laboratory models to humans and found mixed results. For some chemicals, the parallel to radiological effects and methods was found to be sufficient to enable useful projections, particularly when human data is limited or lacking. The report illustrates that much data and understanding on the chemical side is lacking, particularly in view of the far more complex metabolic considerations and variations. It also demonstrates that expert judgment is required to reach conclusions. Two conclusions on similarities were that the cancers caused were individually indistinguishable meaning that statistics must be used for both types of carcinogens and that projections from high dose to low dose are required. NCRP (1989) addressed cancer as the effect; it did not try to evaluate other effects. It noted that current priorities for testing chemicals is based on qualitative criteria, but as the procedures for more quantitative analysis become available, more precise assignment of priorities should be possible. The biological information needed is not unique to mixed waste; it merely reflects the problems of quantitatively assessing risks from the thousands of chemicals that are potentially hazardous, each with potentially unique features.

Computer codes for calculating exposures are still under development, including codes to combine radiological and nonradiological constituent transport. The degree of detail, documentation and validation needed for various applications involves technical judgments and acceptance of codes will likely remain an issue.

Much information on the components of the waste management system is known and more is being developed. More is known about certain categories of waste, such as high-level waste. The DOE is developing comprehensive treatment technologies for all types of mixed waste. Characterization of the components of disposal systems requires engineering projections over long periods of time and data and tests to make reasonable estimates of performance. There remains much flexibility in the choices for most of the components and much uncertainty in the level of detail needed to adequately assess performance. The economic and worker exposure costs to reduce uncertainties in the knowledge base should be considered if decisions are to be optimized. A decision on whether a classification process or framework is feasible will involve consideration of cost effectiveness.

State-of-the-art technology is being used to compensate for uncertainties and difficulties in waste characterization and in projecting future performance. Analytical methods for full characterization of radiological and nonradiological content are expensive and have detection limitations. Treatment methods that are compatible with the waste or waste matrix and multiple constituents do not cover all mixed waste streams.

In summary, the existing legal and regulatory framework poses challenges. The radiological, physical and chemical properties of mixed waste span a wide range. Decommissioning and remedial action waste are difficult to project. Many of the parameters and tools needed to perform traditional risk assessment are not available or fully developed.

Ideally, the scope of the method or framework for classifying waste should be sufficiently comprehensive and flexible to be applied to all aspects of waste management and all types of mixed waste. Practicality suggests that efforts be focused on disposal and on waste other than high-level and transuranic mixed waste. Focusing on disposal limits the scope and addresses the long-term risks. High-level and transuranic waste should be excluded because the type of disposal method (deep geologic) has already been decided, many decisions have been made on other aspects, and there are only a few sites to be considered. For the remainder (*i.e.,* low-level waste), there are still options for decisions on all components of the waste disposal system, although required treatment and forms have been codified for some types of mixed waste. If a method can be developed for low-level waste, it could provide guidance for the non-Atomic Energy Act radioactive waste as well.

A major challenge is to find practical ways to deal with the uncertainties and developing technologies. A risk-based classification system could provide a means of determining the significance of missing information and help in assigning priorities to efforts to develop the information. Another challenge is to devise a framework that deals with the interaction of the components of the disposal system and how they collectively work together. A final challenge is whether and how the framework should accommodate site specific considerations.

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Discussion

MR. LESLIE: My name is Bret Leslie, and I am with the Institute for Energy and Environmental Research. My question is this: If the current classification scheme for radioactive waste is not entirely risk-based, what does that say about our efforts here today to try to define a risk-based classification scheme that covers both radioactive and toxic chemical waste? For instance, if the risk is not known or quantified, how will we incorporate it into the classification scheme for radioactive waste?

MS. DRAGONETTE: I am not sure I can answer that. Perhaps one example is pipe scale that is contaminated with radium. There was a paper in Waste Management '93 where they evaluated different disposal methods, down hole versus land surface disposal and several others, and showed that if you properly characterize the waste, you can then evaluate the risk levels represented by each disposal option. This can, in turn, provide guidance on the optimum method for disposal.

One reason why I emphasized the 10 CFR, Part 61, classification scheme was because it represents a thought process that can be expanded to cover all categories of waste. It represents, in essence, a systems approach, a risk-based approach, an optimization.

That's about the best I can answer you on that.

MR. BROWN: I am Steve Brown. R2C2. Kitty, is there anything in the legislation, particularly with respect to radioactive waste management, that constrains you to what categorizations you can use, or is that mainly a regulatory decision that you can make in the executive branch?

MS. DRAGONETTE: Well, high-level waste and spent fuel are defined in the law. Even the Low-Level Waste Policy Act references Part 61 and Class A, B and C. It also assigns certain responsibilities to the states for the management and disposal of low-level radioactive waste, and responsibilities for greater than class C waste to the Department of Energy.

In a way, we are sort of stuck with the legislation, but that does not mean you cannot use a risk-based approach to decide what's the best thing to do with each type of waste. It would take a change in law not to call high-level waste, high-level waste. But if you are developing standards or if you are evaluating a site, you would hopefully be able to use a risk-based approach.

Biology of Risk

Arthur C. Upton

Abstract

Any physical or chemical agent is capable of harming human beings and other living organisms under certain conditions of exposure, but most such agents are harmless in minute amounts. Nevertheless, even at the low levels of exposure encountered under normal living conditions, the possibility that ionizing radiation and certain chemicals—notably those which are genotoxic—may pose some risks of harm through mutagenic and carcinogenic effects cannot be excluded. Such risks, if they exist at all, however, are too small to have been detectable thus far epidemiologically. Hence, they can be assessed only by extrapolation from effects observed at higher levels of exposure, involving assumptions about the relevant exposure-effect relationships, based on what is known about the biology of the effects in question.

While it is possible, in assessing the cancer risks that may be attributable to low-level irradiation, to extrapolate from carcinogenic effects of radiation that have been observed in humans at high-dose levels, comparable data are lacking for most chemicals. Consequently, assessment of the risks that a given chemical may pose must commonly be based on structure-activity analyses or data from nonhuman surrogates, which involve many inherent uncertainties, owing to species differences in pharmacokinetics (*e.g.,* uptake, distribution, metabolism, excretion), toxicokinetics (*e.g.,* activation, inactivation), homeostatic mechanisms (*e.g.,* repair, misrepair, adaptation, regeneration), and other factors affecting susceptibility (*e.g.,* age, sex, genetic background, exposure to other disease-causing agents, etc.). Furthermore, when a combination or mixture of chemical and/or physical agents is involved, which is often the case, the risk assessment is particularly uncertain since it may not be possible from existing knowledge to predict whether the effects of the agents will be mutually additive, synergistic or antagonistic under such conditions. The risk, in any case, will inevitably be a function of the dose(s) to critical biological targets in exposed individuals, adequate evaluation of which is essential to appropriate assessment of the risk.

Although each of the above complexities must be evaluated carefully in assessing the risks that may be posed by a given exposure to radiation- and/or mixed-waste, such evaluation is often fraught with uncertainty in our present state of knowledge. As a consequence, the resulting risk assessment must often be qualified accordingly.

Introduction

All chemical and physical agents, natural and synthetic, are capable of causing injury to human beings and other living organisms under certain conditions of exposure (Amdur *et al.,* 1991). Such exposure conditions vary markedly from one agent to another, however, as do the types of injury that may result. Therefore, to assess the risks that a given agent, or combination of agents, may pose to an exposed population, one must evaluate: (1) the types of adverse effects the agent(s) can produce, (2) the exposure conditions under which such effects may occur, and (3) the extent to which comparable exposure conditions are, or are likely to be, experienced by the population in question.

Mixed-waste sites vary so widely in the numbers, types and amounts of different chemicals and radionuclides they contain that it is beyond the scope of this report to attempt a comprehensive review of the risks they may pose to human health and the environment. This report focuses instead on the biology of the risks in question and on the scientific rationale underlying the choice of dose-effect models to be used in assessing such risks.

Stochastic versus Deterministic Effects

In radiological protection, it is customary to distinguish between those biological effects of radiation which are stochastic in nature and those which are deterministic in nature (ICRP, 1991). Those effects which are classified as stochastic effects include the mutagenic and carcinogenic effects of radiation, which are presumed to increase in frequency in proportion to the dose, without threshold, even at the lowest levels of exposure. Essentially all other adverse effects of radiation are classified as deterministic, since they are known or presumed to occur only when the dose exceeds an appreciable threshold, above which their severity as well as their frequency increases with increasing dose (*e.g.,* Figure 1).

In principle, the toxicological effects of chemicals can be similarly classified. It is noteworthy, however, that the carcinogenicity of some chemicals appears to be mediated through effects that are not stochastic in nature (*e.g.,* Kitchin *et al.,* 1994). One must be cautious, therefore, about evaluating the risks of such effects—or any other effects, for that matter—without knowledge of their dose-response relationships and/or underlying biological mechanisms.

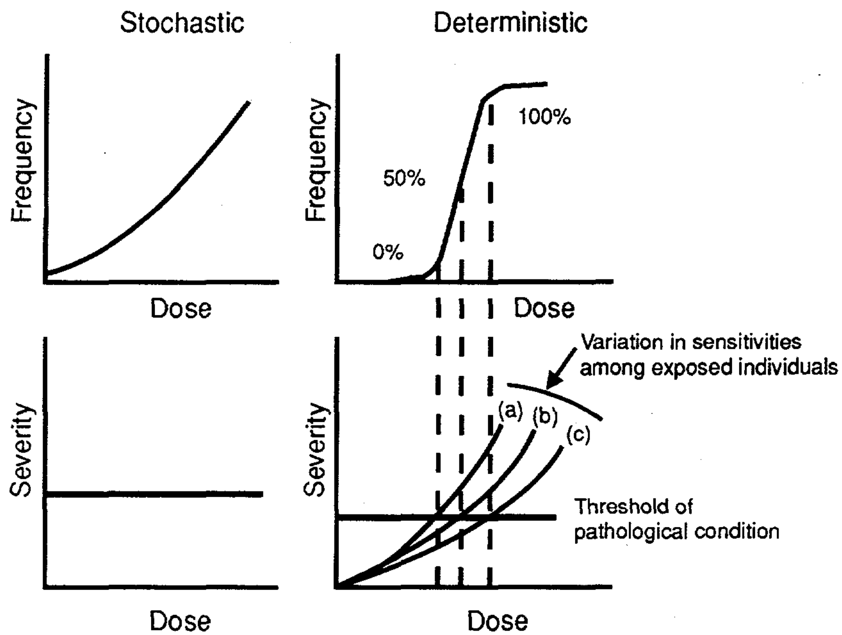

Fig. 1. Characteristic differences in dose-response curves between stochastic and deterministic effects (from ICRP, 1984).

Effects on Genes and Chromosomes

Biological Basis

Ionizing radiation and genotoxic chemicals can cause various molecular changes in DNA that may give rise to mutations and chromosome aberrations (Ward, 1988). The types, frequencies and repairability of the initial lesions in DNA vary markedly, depending on the dose, dose rate and LET of the radiation (Cole *et al.,* 1980; Goodhead, 1988; Ward, 1988; Cornforth and Bedford, 1993) or on the dose and molecular structure of the reactive chemical (Singer and Grunberger, 1983). The majority of such lesions are repairable (Ward, 1988), but damage to a single gene left unrepaired or misrepaired may ultimately be expressed as a mutation.

Empirical Dose-Effect Relationships

Mutations and chromosome aberrations vary in frequency with the dose rate and LET of radiation (*e.g.,* Figure 2), but both appear to increase in frequency as linear-nonthreshold functions of the radiation dose in the

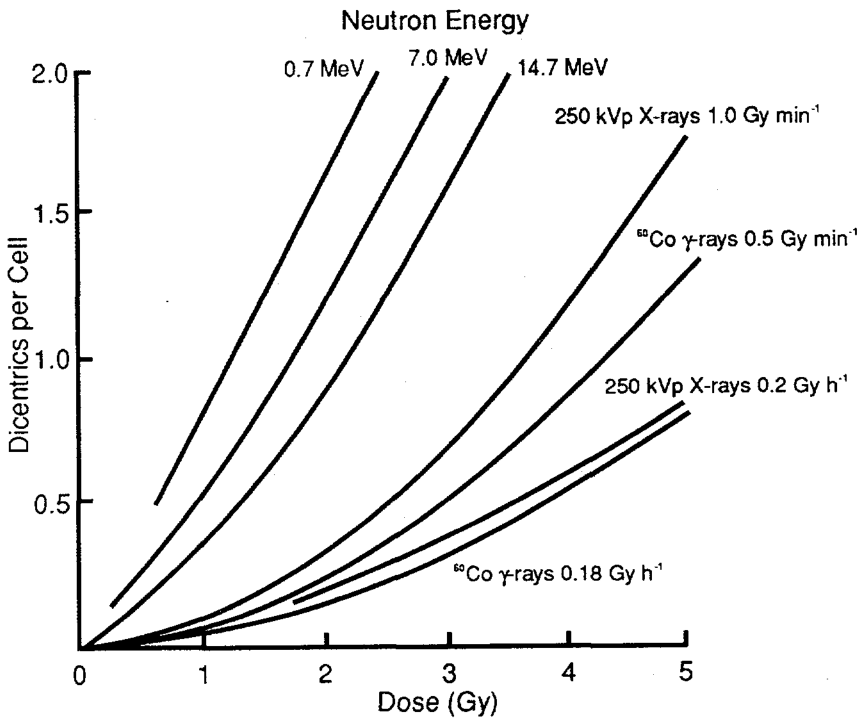

Fig. 2. Dose-response curves for induction of dicentric chromosome aberrations in human lymphocytes irradiated *in vitro*, in relation to the dose, dose rate, and quality of the radiation (from Lloyd and Purrott, 1981).

low-to-intermediate dose range (UNSCEAR, 1986; 1993; NAS/NRC, 1990; ICRP, 1991), implying that such effects may, in principle, result from the interaction of DNA with a single ionizing particle (Cole *et al.*, 1980) or a single electrophilic molecule (Singer and Kusmierek, 1982). In the mammalian cell assay systems investigated to date, the frequency of mutations approximates 10^{-5} to 10^{-6} per locus per Sv , and the frequency of interchange chromosome aberrations 0.1 aberration per cell per Sv (NAS/NRC, 1990; UNSCEAR, 1993).

Chemically-induced mutations and chromosome aberrations vary widely in dose-response relationships, owing to large inter-chemical variations in genotoxic potency, heterogeneity among different subpopulations of cells in susceptibility to chemicals, and the inherent complexity of the toxicological processes that are involved in the production of the effects, which include pharmacokinetic variables (uptake, transport, diffusion, excretion), metabolic activation and inactivation mechanisms, DNA-damaging reactions, homeostatic mechanisms through which DNA lesions may be repaired or misrepaired, and subsequent steps leading to the expression of genetic changes in surviving cells (NCRP, 1989). Although each of the above steps may conceivably be linear at low doses, nonlinear mechanisms also may be involved, and a threshold at any step in the sequence can cause the overall process to have a threshold (Hoel *et al.*, 1983). In view of these complexities, it is not surprising that the dose-response curves for chemically-induced mutations and chromosome aberrations in mammalian cells vary markedly, some even exhibiting real or apparent thresholds (Ehling *et al.,* 1983).

Heritable Abnormalities

Although well documented in other organisms, heritable radiation- or chemically-induced abnormalities have yet to be demonstrated in human beings. The lack of evidence for such effects in humans is noteworthy in view of the failure to detect them in the more than 76,000 children of atomic-bomb survivors studied intensively over four decades for such measures of the effects as untoward pregnancy outcomes, neonatal deaths, malignancies, balanced chromosomal rearrangements, sex- chromosome aneuploids, changes in sex ratio, disturbances in growth and development, and alterations of blood serum and cell types (Neel *et al.,* 1990). While the findings do not exclude the occurrence of heritable radiation-induced genetic abnormalities in this human population or others, they are interpreted to signify that human germ cells are no more radiosensitive than those of the mouse and that the dose required to double the frequency of heritable abnormalities in such cells must be at least 1.0 Sv (Neel *et al.,* 1990; NAS/NRC, 1990). On the basis of the existing evidence, therefore, it is estimated that less than one percent of all genetically determined diseases in the human population is attributable to natural background radiation (see Table 1) and that, weighted for severity, such heritable effects are not likely to exceed one to two percent per Sv in frequency, with relatively few offspring of the first two generations being affected (ICRP, 1991).

At variance with the above estimate is the suggestion, based on a case-control study, that the excess of leukemia and non-Hodgkin's lymphoma in young people residing in the village of Seascale, England, may have been caused by the occupational irradiation of their fathers, who worked at the Sellafield nuclear installation (Gardner *et al.,* 1990). This possibility is generally given little credence, however, in view of the: (1) absence of any comparable excess in larger numbers of children born outside Seascale to fathers who had received similar, or even larger, occupational doses at the same nuclear plant (Wakeford *et al.,* 1994a), (2) lack of similar excesses in French (Hill and LaPlanche, 1990), Canadian (McLaughlin *et al.,* 1993), or Scottish (Kinlen *et al.,* 1993)

TABLE 1—*Estimated frequencies of heritable disorders attributable to natural background ionizing irradiation.*[a]

Type of Disorder	Prevalence (per million live births)	Contribution from Natural Background Radiation[b]	
		First Generation	Equilibrium
	(number)	(number per million live births)[c]	
Autosomal dominant	180,000	20-100	300
X linked	400	<1	<15
Recessive	2,500	<1	very slow increase
Chromosomal	4,400	<20	very slow increase
Congenital defects	20,000 -30,000	30	30-300
Other disorders of complex etiology			
Heart disease	600,000	—[d]	—[d]
Cancer	300,000	—[d]	—[d]
Selected others	300,000	—[d]	—[d]

[a]Based on NAS/NRC, 1990.
[b]Equivalent to ~1 mSv y^{-1} or ~30 mSv per generation (30 y).
[c]Values rounded.
[d]Quantitative risk estimates not estimated because of uncertainty about the mutational component(s) of the disease(s) indicated.

children born to fathers with comparable occupational exposures, (3) lack of excesses in the children of atomic-bomb survivors (Yoshimoto *et al.,* 1990), (4) lack of excesses in United States counties containing nuclear plants (Jablon *et al.,* 1991), (5) fact that the frequency of radiation-induced mutations implied by the interpretation is far higher than established rates (Wakeford *et al.,* 1994b), and (6) evidence that the mutations causing childhood leukemia are of a severity likely to interfere with the viability of affected germ cells (Evans, 1990). It is concluded, therefore, that the weight of evidence argues persuasively against paternal gonadal irradiation as a cause for the cancers in question (Doll *et al.,* 1994).

Carcinogenic Effects

Biology of Carcinogenesis

There is strong evidence that cancer usually arises from a single transformed cell (Fialkow, 1976; Sandberg, 1990), implying that appropriate alteration of one cell alone may increase the probability of cancer in a suitably susceptible individual (Knudson, 1993). At the same time, a single alteration apparently does not generally suffice to transform a normal cell into a cancer cell. Instead, this process typically appears to require multiple changes (*e.g.,* McCormick and Maher, 1994) and to evolve through a succession of stages, three of which, defined operationally, consist of the stages of "initiation," "promotion" and "progression" (Farber and Sarma, 1987; Nicholson, 1987). Although scientific advances have disclosed biochemical differences among neoplasms, depending on the pathogenesis and sites of origin of the growths, no characteristics have yet been identified by which a given neoplasm can be classified conclusively as having resulted from a particular chemical or physical carcinogen, as opposed to some other cause.

While the molecular alterations underlying each of the successive stages remain to be established in detail for most cancers, as noted above, the *activation of oncogenes and/or the inactivation of tumor-suppressor* genes are generally implicated (Knudson, 1993). That tumor initiation itself involves some type of genetic alteration is implied by the evidence that: (1) the initiating step resembles a mutational change in being relatively prompt and irreversible, (2) most initiating agents are mutagenic, (3) the frequency of neoplastic transformation induced by a given agent in cultured cells is usually maximal if exposure to the agent occurs just before or during DNA synthesis, (4) the potency of an initiating chemical is generally correlated with its capacity to bind covalently to DNA and with the nature of the resulting DNA adducts, (5) DNA to which a carcinogen is bound can serve as a template for DNA replication, which, along with subsequent cell division, is necessary to "fix" the potential for neoplastic change, and (6) susceptibility to cancer is increased in individuals who are deficient in DNA repair capacity (NCRP, 1989). Although the activation of a single oncogene or the inactivation of a single tumor-suppressor gene may suffice to initiate the process of neoplasia in a suitably susceptible cell, a minimum of two or more such changes is characteristically required to completely transform a normal cell (Knudson, 1993), as noted above, and as exemplified by the multiplicity of genetic alterations implicated in the pathogenesis of human colon cancer (Figure 3).

In contrast to tumor initiation, which is typically irreversible and can be produced promptly in a normal cell by a single exposure to a genotoxic carcinogen, tumor promotion characteristically requires previously initiated cells to be exposed repeatedly over a prolonged period to an appropriate promoting stimulus (NCRP, 1989). Promoting agents also differ from initiating agents in not binding covalently to DNA (Weinstein, 1991). Furthermore, although promoting agents as a class tend to stimulate cell division, the activity of any one such agent varies markedly

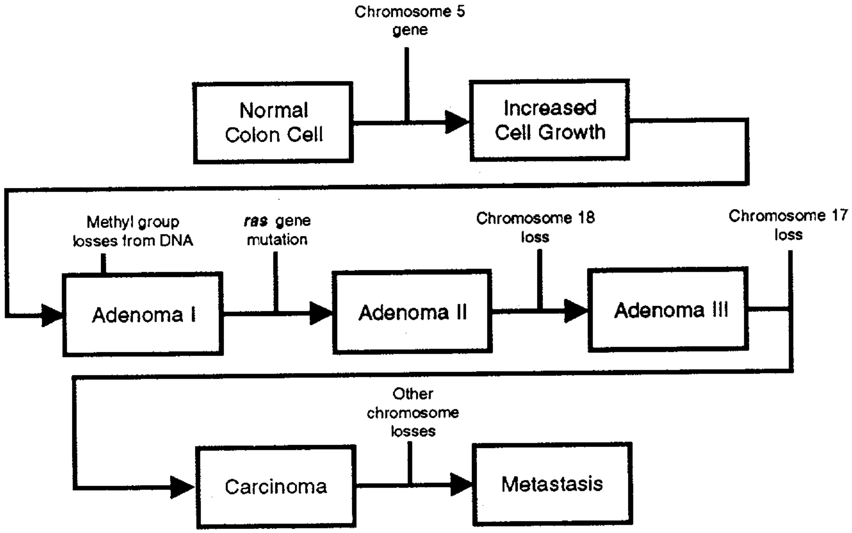

Fig. 3. Sequential genetic alterations involved in the development of cancer in cells of the human colon (from Fearon and Vogelstein, 1990).

with the particular organ and type of cell exposed (IARC, 1991). Although the action of most promoting agents remains to be elucidated in detail at the molecular level, their effects are generally interpreted to be mediated primarily through epigenetic mechanisms, as opposed to genotoxicity (IARC, 1991; Weinstein, 1991). In view of evidence that some promoting agents can damage DNA indirectly, however, the possibility that such damage may contribute to their tumor-promoting effects remains to be excluded (Frenkel, 1993).

Tumor progression, the step-wise process through which successive generations of neoplastic cells produce increasingly malignant clonal derivatives (Foulds, 1969), is attributed primarily to mutations and chromosome aberrations that activate oncogenes, inactivate or delete tumor-suppressor genes, or derange other regulatory elements (Farber, 1984; Nicholson, 1987; Knudson, 1993). Selection pressures that favor the outgrowth of proliferative subpopulations, such as may result from the effects of certain hormones, inflammatory agents, carcinogens, cytokines or other growth-stimulating agents can accelerate the process (Farber, 1984).

Empirical Dose-Effect Relationships

In mammalian cells exposed experimentally *in vitro* to radiation or benzo(a)pyrene under conditions in which the initiating effects of the carcinogen are promoted to full expression, the frequency of the resulting morphological transformation characteristically increases as a linear-nonthreshold function of the dose (*e.g.,* Figure 4) (NCRP, 1989). The initiating effects of exposure *in vivo* to radiation or benzo(a)pyrene under comparable conditions also typically follow a linear-nonthreshold type of dose-response relationship (NCRP, 1989). Although the linear-nonthreshold nature of the observed relationships is consistent with a mutational mechanism for the effects in question, the frequency with which the effects are induced in exposed cells far exceeds the established mutation rate at any given genetic locus, implying that multiple loci in the genome, genomic sites unlikely to be repaired, or genetic damage other than point mutations are likely to be involved (NCRP, 1989).

Dose-response relationships for carcinogenesis *in vivo* vary widely, depending on the carcinogen in question, the conditions of exposure, the age, sex and genetic background of the exposed population, and the anatomical sites and types of neoplasms induced (NCRP, 1989). In a number of instances, dose-response relationships that clearly exhibit thresholds have been observed (*e.g.,* Kitchin *et al.,* 1994). Such variations are not surprising in view of the multicausal, multistage nature of carcinogenesis and the fact that the underlying mechanisms may not be the same for all agents and all cancers (IARC, 1991). To explore the dose-incidence curve for carcinogenesis at low doses, a number of large-scale experiments have been carried out in laboratory animals. In the two largest such experiments to date, one involving the chronic exposure of thousands of BALB/c mice to 2-acetylaminofluorine (Littlefield *et al.*, 1979) and the other involving the chronic exposure of thousands of Colworth rats to N-nitrosodiethylamine or N-nitrosodimethylamine (Peto *et al.,* 1991), the cumulative incidence of liver tumors was observed to increase as a linear-nonthreshold function of the dose, while tumors of other organs showed different dose-response relationships (*e.g.,* Figure 5). The observed differences in dose response may conceivably have resulted from tissue-dependent variations in toxicokinetics and homeostatic mechanisms; however, they are consistent with the results to be expected if the effects of the carcinogen and those of causal factors accounting for the "spontaneous" background incidence of neoplasms were merely additive in their combined effects (*e.g.,* Figure 6), given the relatively high incidence of liver tumors in the unexposed controls.

In human populations, the available epidemiological data do not suffice to define the dose-incidence relationship unambiguously for any form of radiation- or chemically-induced cancer, but they are consistent with the data from laboratory animals in showing the dose-incidence relationship to vary, depending on the type of cancer in question, the age, sex and genetic background of the exposed individuals, the nature of the

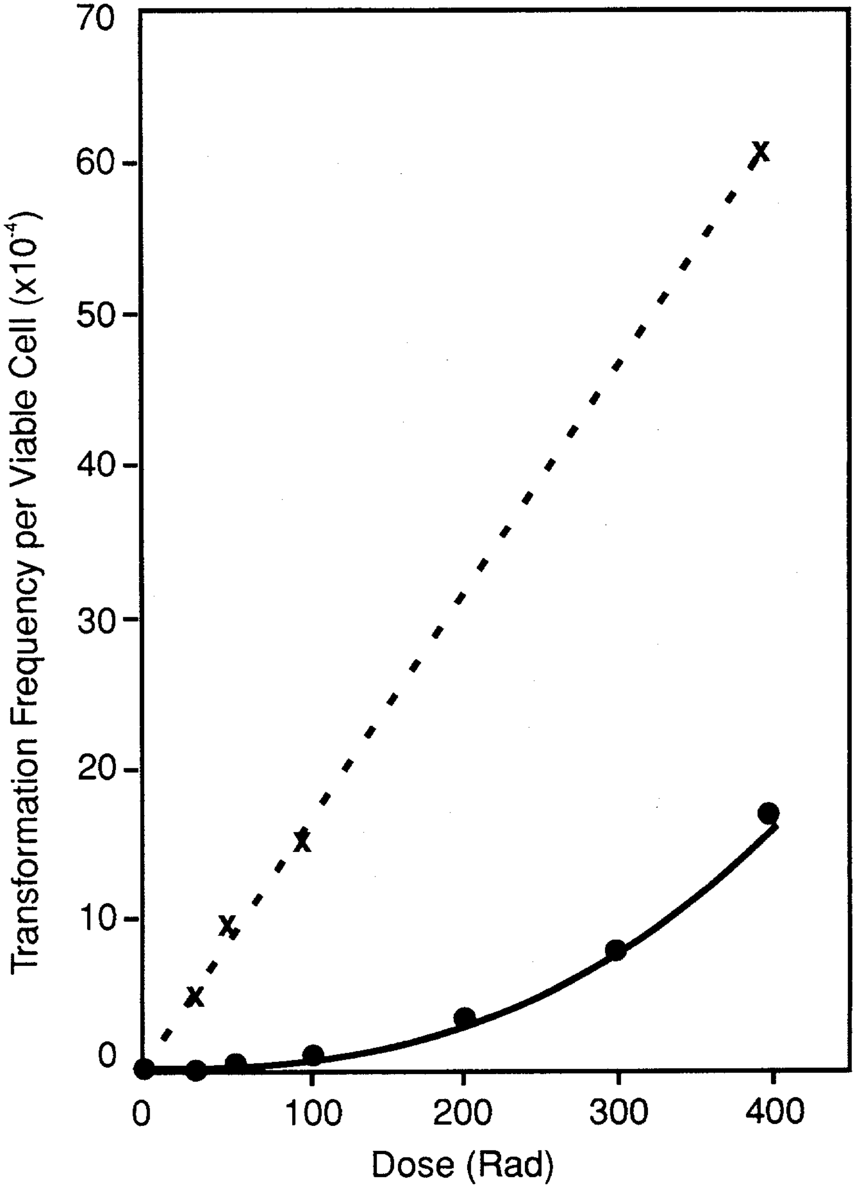

Fig. 4. Dose-response relationship for the neoplastic transformation of mouse 10T1/2 cells by x rays alone (●) or by x rays followed by repeated exposure to phorbol ester (x) (from Little, 1981).

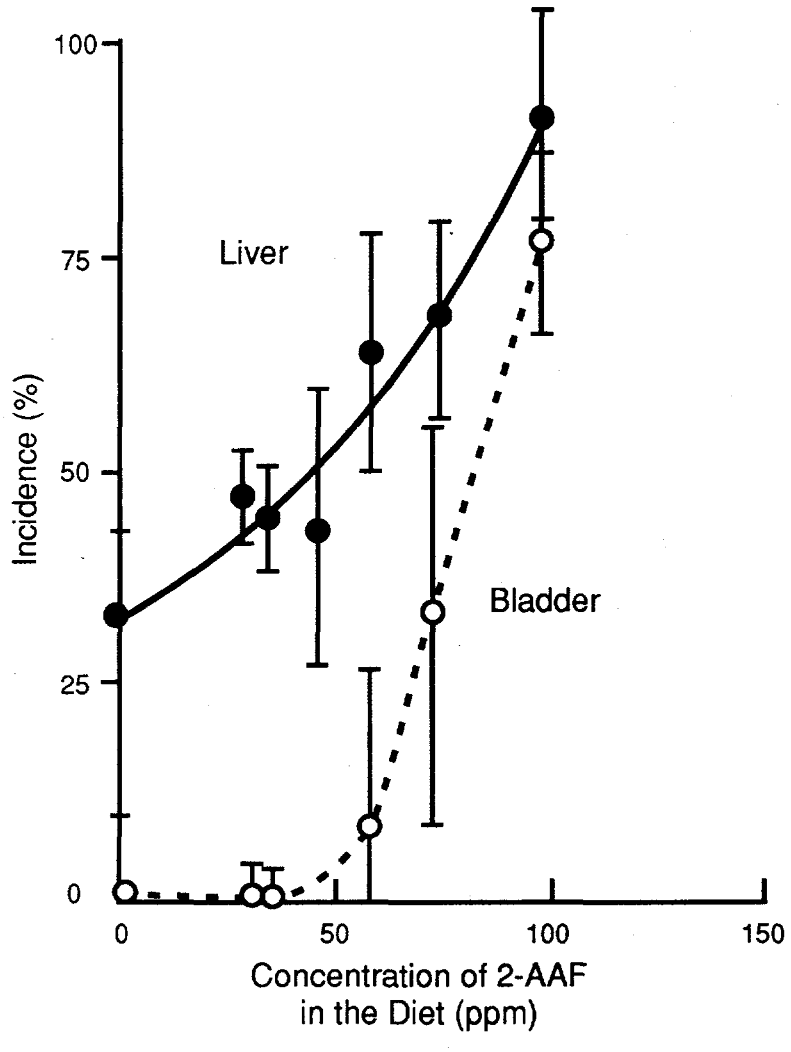

Fig. 5. Dose-response curves for the cumulative incidence of tumors of the liver and urinary bladder in female BALB/c mice exposed chronically to 2-acetylaminofluorine (from Littlefield *et al.*, 1979).

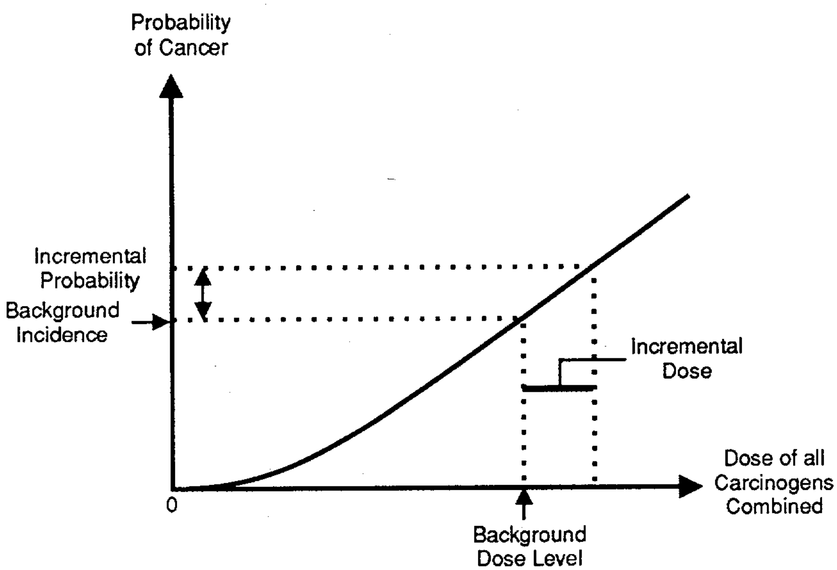

Fig. 6. Diagram illustrating the expected increase in the probability of cancer resulting from an additive interaction between the effects of a low dose of a hypothetical carcinogen and those of other "background" risk factors accounting for the "spontaneous" incidence of the disease (from NCRP, 1989).

carcinogen, the conditions under which exposure to the carcinogen occurs, and the possible modifying influence of other factors affecting susceptibility (UNSCEAR, 1986; 1988; NAS/NRC, 1990). While many of the observed dose-response relationships are clearly nonlinear, some even appearing to have a threshold, a number are compatible with linear- nonthreshold functions: *e.g.,* (1) the data for thyroid tumors in persons who received therapeutic x-irradiation of the neck in infancy for enlargement of the thymus (Figure 7); (2) the data for breast cancer (Figure 8) in women exposed to atomic-bomb radiation, women given therapeutic irradiation of the breast for acute postpartum mastitis, women who received repeated fluoroscopic examinations of the chest in the treatment of pulmonary tuberculosis, and women exposed to external gamma radiation in the painting of luminous clock and instrument dials; (3) the data for mortality from cancer, all types combined, in atomic-bomb survivors (Shimizu *et al.*, 1990; NAS/NRC, 1990); (4) the data for lung cancer in underground hard-rock miners and atomic-bomb survivors (*e.g.,* Figure 9); (5) the data for the cumulative incidence of urinary bladder cancer in distillers of β-naphthylamine and benzidine (Figure 10); and (6) the data for lung cancer and mesothelioma in asbestos workers (HEI-AR, 1991).

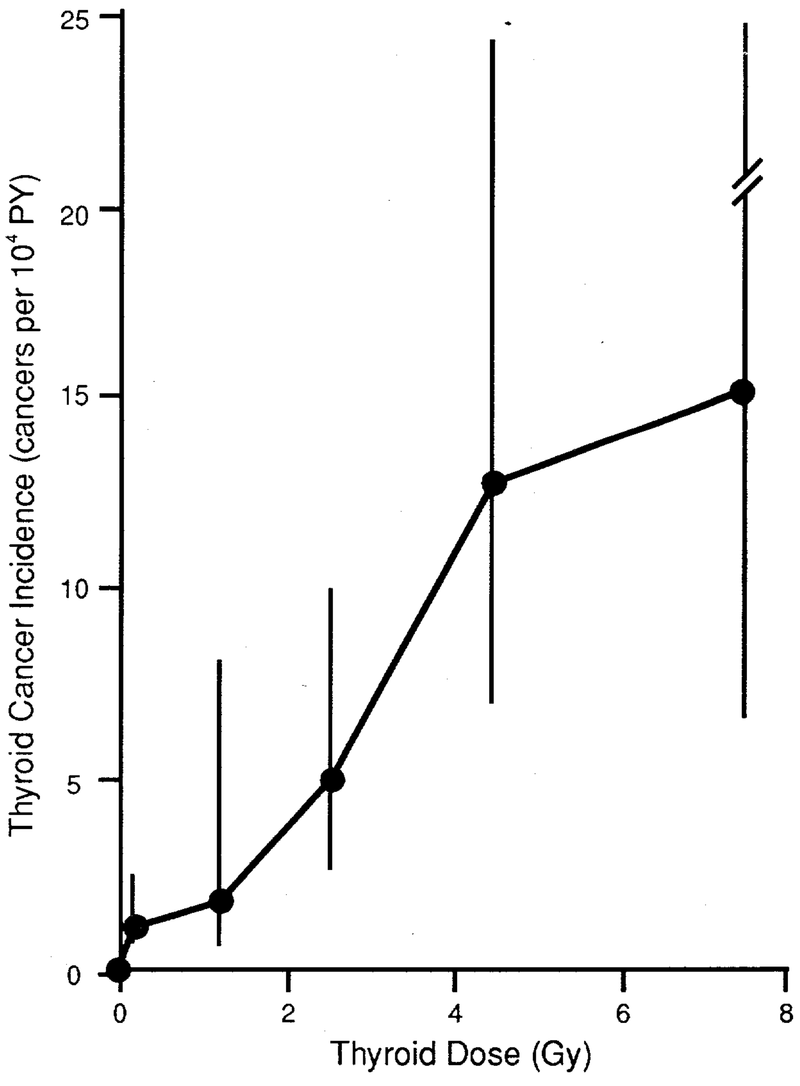

Fig. 7. Dose-incidence relationship for thyroid cancer after irradiation of the neck in childhood for thymic enlargement (from Shore *et al.*, 1985).

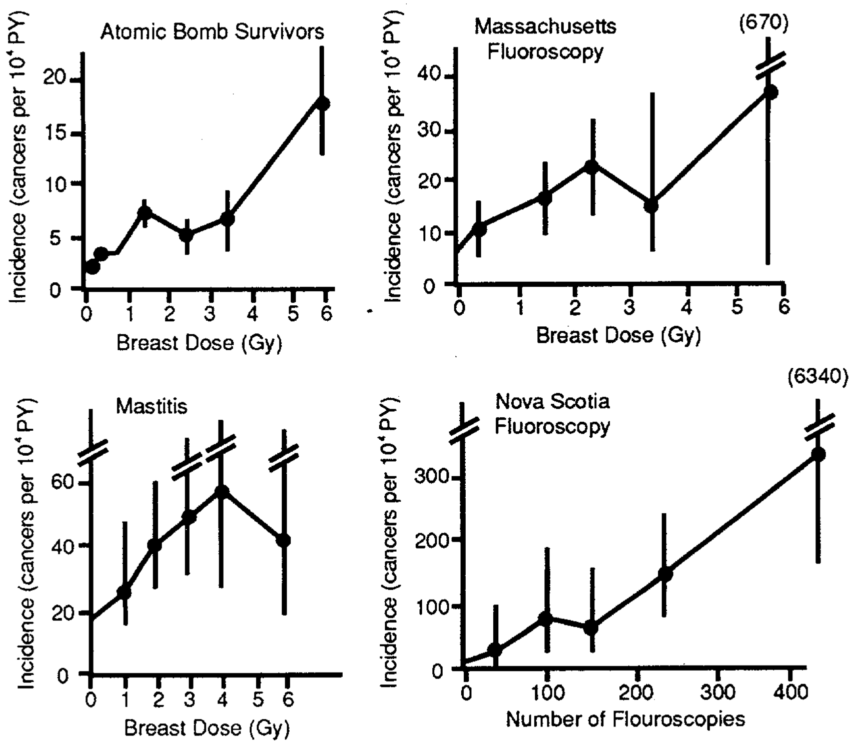

Fig. 8. Dose-incidence relationship for cancer of the female breast in atomic-bomb survivors, mastitis patients, and repeatedly fluoroscoped tuberculosis patients (from Boice *et al.,* 1979).

Because a given carcinogen may influence the probability of cancer through more than one type of effect, at least at high-dose levels, the dose-incidence curve for the carcinogen may reflect differing combinations of initiating effects, promoting effects, and effects on the progression of cancer, depending on the dose, the dose rate, and other circumstances (Upton, 1989; IARC, 1991). It is not unusual, therefore, for experimental dose- response curves to: (1) increase in steepness with increasing dose (presumably as effects on the promotion and progression of cancer are increasingly brought into play), (2) reach a plateau at some intermediate dose, and (3) turn downward at high doses delivered at high-dose rates (presumably because of excessive cytotoxicity) (*e.g.,* Figure 11). By the same token, the combined effects of multiple agents may be additive, synergistic or mutually antagonistic, depending on the nature and doses of the agents in question, as well as the conditions of exposure (UNSCEAR, 1982). In their combined carcinogenic effects on the lung, for example, cigarette smoking and radon appear to interact multiplicatively in asbestos workers (Selikoff, 1981; HEI-AR, 1991) and less than multiplicatively, but more than additively, in underground hard-rock miners (NAS/NRC, 1988a).

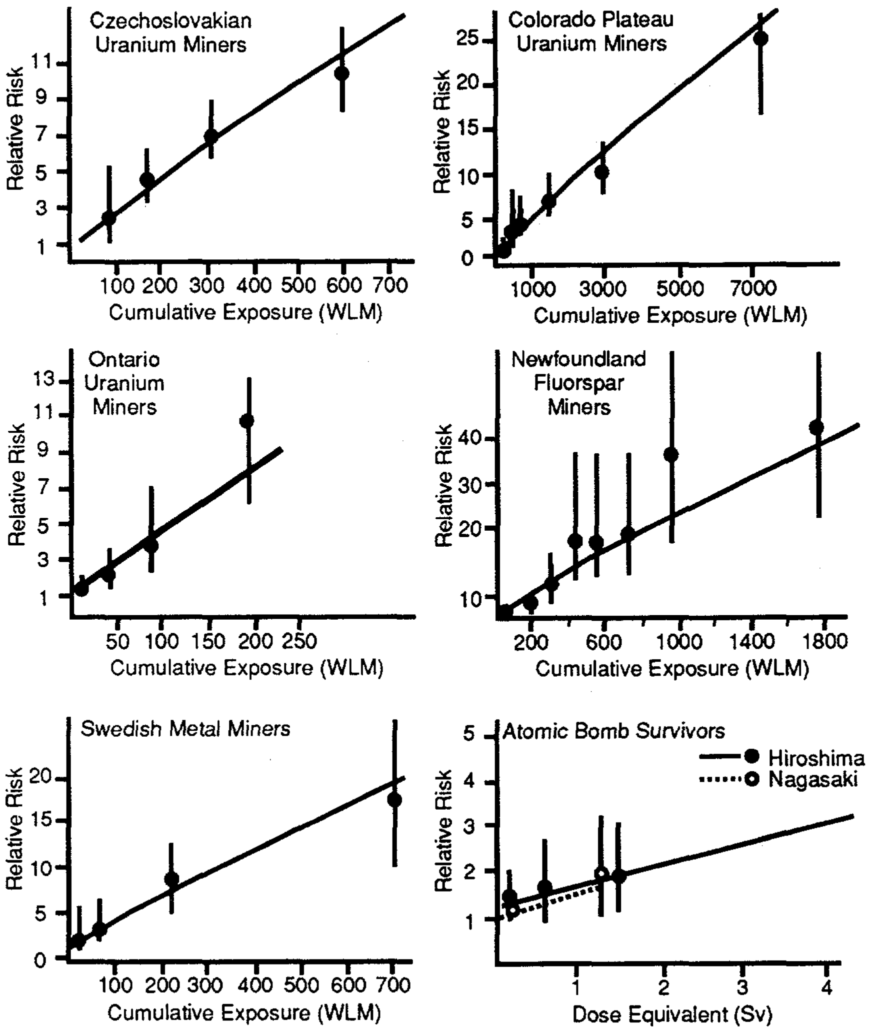

Fig. 9. Dose-response curves for lung cancer risk in five groups of underground miners and atomic-bomb survivors (from Thomas and McNeill, 1982).

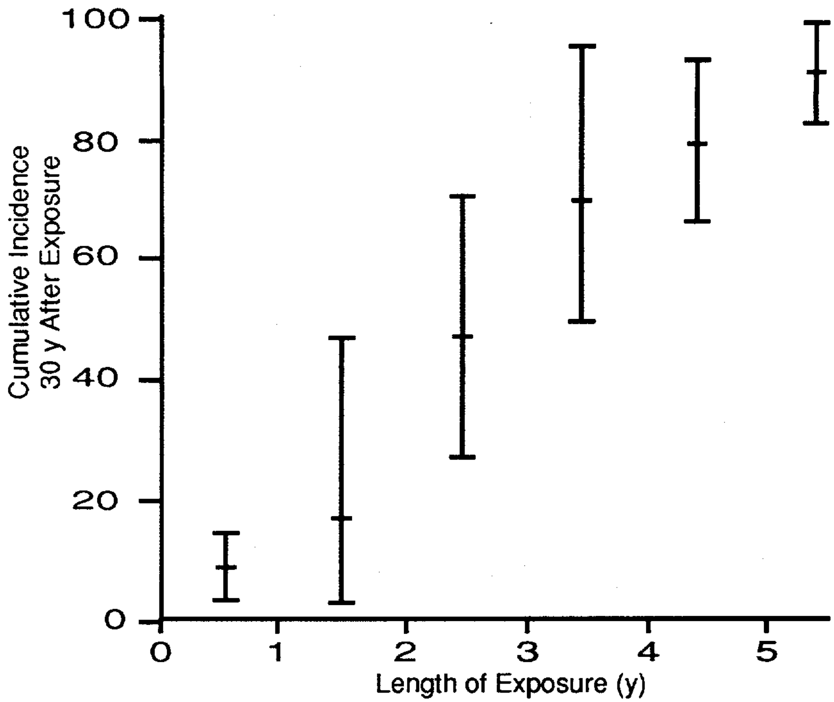

Fig. 10. Cumulative incidence of bladder cancer in 78 distillers of β-naphthylamine and benzidine (from NCRP, 1989, based on the data from Williams, 1958).

Models for Extrapolating to Low Doses

In view of the variations mentioned above, the particular extrapolation model that is appropriate for use in estimating the cancer risks posed by low-level exposure to a given carcinogen or combination of carcinogens will vary, depending on what is known about the action of the carcinogen(s) in question, the characteristics of the exposed population, and the specific conditions under which the population is, has been, or is likely to be exposed. If the carcinogenicity of the agent(s) appears to be mediated through epigenetic mechanisms, a threshold model may be appropriate for use in extrapolating from high doses to low doses (IARC, 1991; Kitchin *et al.,* 1994). Conversely, if the carcinogenic effects of the agent(s) are mediated through genotoxic mechanisms, the use of a nonthreshold model would be more consistent with present scientific knowledge (NCRP, 1989; Upton, 1989). In such instances, moreover, since more than one mutation and/or chromosome aberration is likely to be involved, a linear-multistage model would have less tendency than

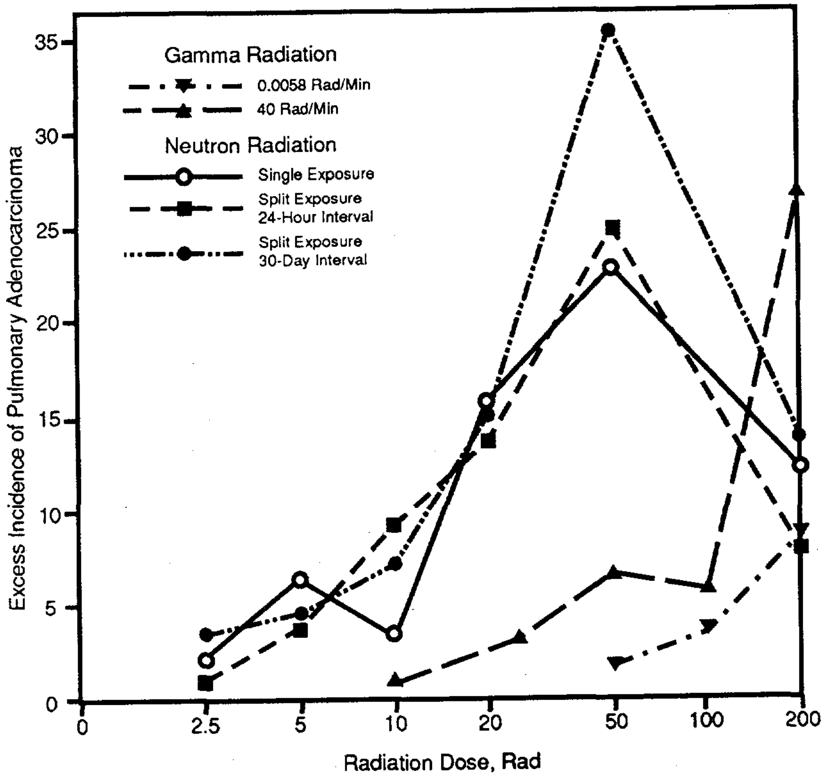

Fig. 11. Dose-response relationship for lung cancer in mice exposed to neutrons or gamma rays (from Ullrich, 1982).

a simple (single-hit) linear model to overestimate risks in the low-dose domain (*e.g.,* Figure 12).

An analogous rationale argues for the use of a linear-quadratic dose-response function, with its inherent dose rate weighting factor (DREF), for modeling the carcinogenic effects of low-LET radiation, especially since such radiation can be up to 10 times less carcinogenic in laboratory animals at low doses and low-dose rates than at high doses and high-dose rates (NCRP, 1980; NAS/NRC, 1990; ICRP, 1991). Conversely, a linear model is generally considered more appropriate for high-LET radiation, since the effectiveness per unit dose of high-LET radiation is generally not reduced at low doses and low-dose rates but may, on the contrary, actually be higher at low-dose rates than at high-dose rates (NCRP, 1990; NAS/NRC, 1990).

In the interpretation of dose-response data and in the fitting of extrapolation models to such data, proper assessment of the dose is of

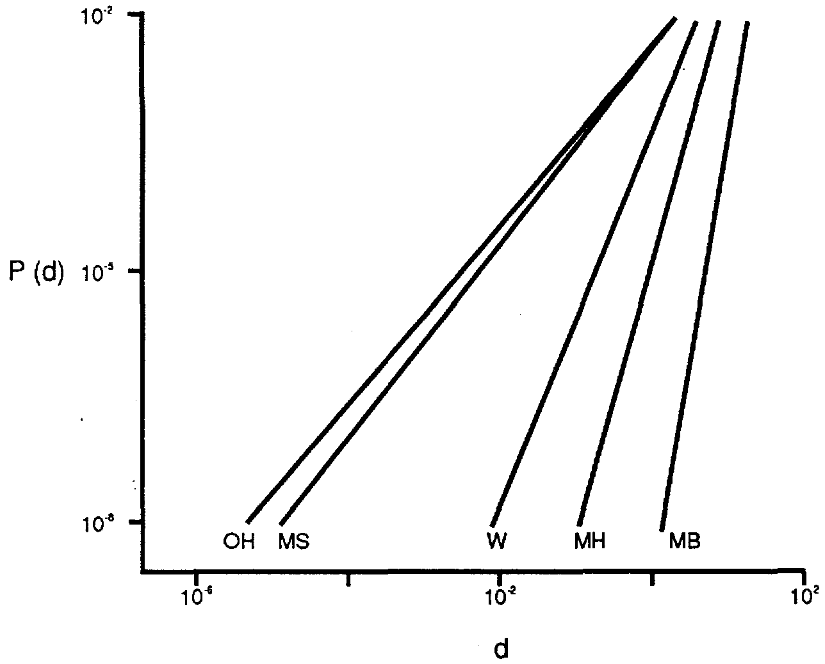

Fig. 12. Risk of liver cancer, $p(d)$, in relation to the dose of aflatoxin, d, as estimated by various extrapolation models; *i.e.*, OH, one-hit model; MS, multistage model; W, Weibull model; MH, multihit model; and MB, Mantel-Bryan model (from Krewski and Van Ryzin, 1981).

paramount importance. Although accurate assessment of the dose can be complicated in situations involving radiation alone, the anatomical distribution of radiation seldom being uniform, it can be especially complicated in situations involving radionuclides, chemical carcinogens or combinations of such agents, since the localization of carcinogen in such cases is influenced by pharmacokinetic and/or toxicokinetic variables (uptake, distribution, excretion, activation, inactivation, etc.). Whenever such variables are involved in determining the target dose of a carcinogen, proper allowance for their effects must be incorporated into the exposure-response model that is used in assessing the associated risks (NAS/NRC, 1993; Medinsky *et al.*, 1994).

Other factors to be incorporated into the model include: (1) the relationship between the excess cancer risk that is projected to be caused by the carcinogen(s) and the "spontaneous" background risk in the exposed individuals (*e.g.,* whether the effects of the carcinogen(s) are additive or multiplicative with those of other causes of cancer in the exposed individuals) and (2) the temporal distribution of the projected excess (*e.g.,* latent period before the onset of the excess and the subsequent duration of the excess) and how the excess may vary, if at all, with the dose of carcinogen(s) and with age of exposed individuals at the time of their exposure (*e.g.,* Figure 13).

Of various dose-effect models that have been used to estimate the risks of *low-level irradiation,* those providing the best fit to the available data have generally been multiplicative (relative risk) models of the form:

$$R(d) = Ro\ [1+ f(d)g(b)] \qquad (1)$$

where $R(d)$ denotes the age-specific cancer risk attributable to dose d, Ro denotes the age-specific background risk of death from a specific type of cancer, d the radiation dose, $f(d)$ a function of dose that is linear-quadratic for leukemia [*i.e.*, $f(d) = \alpha_1 d + \alpha_2 d^2$] and linear for other types of cancer [*i.e.,* $f(d) = \alpha_3 d$], and $g(b)$ is a risk function dependent on other parameters, such as sex, age at exposure, and time after exposure (NAS/NRC, 1990). Comparable models applied to epidemiological data from the atomic-bomb survivors and other irradiated populations have yielded various estimates of the lifetime risks of different forms of radiation-induced cancer (*e.g.,* Table 2). Because of the many uncertainties inherent in the estimates, however, they should not be interpreted without caution. Particular caution should be exercised in using the estimates to predict the risks of cancer attributable to small doses of radiation accumulated over weeks, months or years, since, as noted above, experiments with laboratory animals have shown the carcinogenic potency of x rays and gamma rays to be reduced by as much as an order of magnitude when the exposure is greatly prolonged. As has been emphasized elsewhere (NAS/NRC, 1990), moreover, the available data do not exclude the possibility that there may be a threshold in the mSv dose range, below which radiation does not cause cancer.

For estimating the risks of chemical carcinogens, analogous approaches can be taken when justified by comparable human data. In the absence of such data, the estimates must be based on the results of assays in laboratory animals, short-term *in vitro* tests, and/or structure/activity analyses, evaluated critically for their underlying toxicological mechanisms (Zeise *et al.*, 1987; NAS/NRC, 1993).

When dealing with combinations or mixtures of carcinogens at low levels of exposure, it is considered reasonable to assume that the risks of the individual components of the mixture are additive, in the absence of evidence to the contrary (NAS/NRC, 1988b); however, summing of upper-bound estimates of the risks of the individual components is likely to overestimate the risk of the aggregate mixture. To avoid this pitfall, an

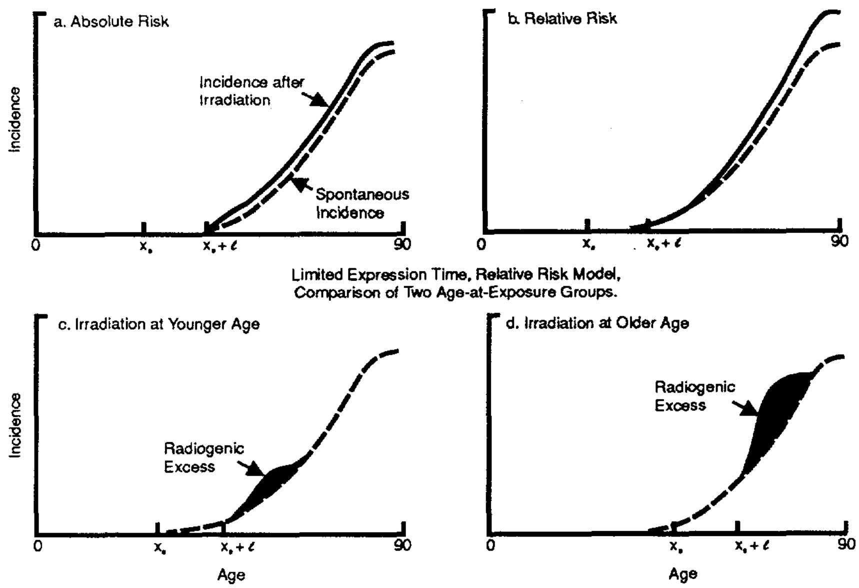

Fig. 13. Diagram contrasting the different ways in which the additive (arithmetic) model and the relative (multiplicative) model project the relationship between a radiation-induced increase in cancer risk and the age-dependent underlying "spontaneous" background risk of cancer (from NAS/NRC, 1980).

TABLE 2—*Estimated lifetime risks of fatal cancer attributable to 0.1 Sv rapid irradiation.*[a]

Type or Site of Cancer	Excess Cancer Deaths per 100,000	
	(number)	(percent)[b]
Stomach	110	18
Lung	85	3
Colon	85	5
Bone marrow (leukemia)	50	10
Urinary bladder	30	5
Esophagus	30	10
Breast	20	1
Liver	15	8
Gonads	10	2
Thyroid	8	8
Bone	5	5
Skin	2	2
Remainder	50	1
Total	500	2

[a]Modified from Table B-20, ICRP, 1991.

[b]Percentage increase in the "natural" lifetime risks of dying from the same types of cancer.

alternative approach employing likelihood and bootstrap computational techniques has been suggested by Kodell and Chen (1994). Finally, the risk posed by a given exposure to a carcinogen, or combination of carcinogens, cannot be assessed adequately merely in terms of the predicted increase in the probability or numbers of neoplasms that will be produced. The projected impacts of such neoplasms on the life expectancy and quality of life in those who are affected also must be considered (UNSCEAR, 1988; ICRP, 1991).

Effects on the Growth and Development of the Embryo

The embryo is highly vulnerable to radiation- and chemically-induced disturbances in growth and development. Most such disturbances appear to be deterministic in nature and are inducible only during relatively short windows of time corresponding to critical periods in the organogenesis of the various developing organ systems (UNSCEAR, 1977; 1986; 1993). The thresholds for such effects appear to be relatively low, however, and the available data do not exclude the possibility that damage to a single cell (the fertilized egg) or only a few of the cells in a primordial anlage at a critical stage in organogenesis may suffice under certain conditions to cause some effects of this type (UNSCEAR, 1977; 1986; 1993).

Unlike mutagenic and carcinogenic effects, which are expressed in only a small percentage of exposed individuals, a disturbance of growth and development may be projected to occur in all who are exposed at a vulnerable stage during prenatal life to a dose that exceeds the relevant threshold. Thus, while only a small percentage of the individuals who were exposed prenatally to atomic-bomb radiation at a critical stage in brain development (*i.e.,* 8 to 15 weeks after conception) exhibited severe mental retardation, a larger percentage exhibited less marked decrements in intelligence and school performance, implying that there was a dose-dependent downward shift in the distribution of intelligence levels within the entire cohort (NAS/NRC, 1990; UNSCEAR, 1993). In view of the broadly similar neurotoxic effects of certain chemical agents (*e.g.,* lead, mercury, alcohol) on the developing brain (Tilson, 1990; NAS/NRC, 1992; Rodier, 1994), it is conceivable that some of the chemical components of mixed waste may pose comparable risks to the embryo.

Deterministic Effects

Apart from the effects discussed above, all other adverse effects of radiation and chemical agents are considered to be deterministic in nature; *i.e.*, not to be produced unless the dose of the causative agent(s) exceeds a threshold, above which the effects may increase in severity as well as frequency with further increase in the dose (ICRP, 1991). Such effects vary widely, however, in causal mechanisms and dose-response relationships, differences which must be considered carefully in evaluating the risks that radioactive and mixed waste may pose to exposed populations.

In general, the thresholds for deterministic effects of radiation are high enough (ICRP, 1984) so that radioactive or mixed waste can generally be expected to pose little risk of such effects to members of the public. With certain chemicals, on the other hand, the thresholds for some such effects—*e.g.*, sensitization to beryllium in susceptible subpopulations (Kreiss *et al.*, 1993)—may be low enough so that the probability of such effects should not be overlooked.

Ecological Effects

On the basis of existing evidence, it is inferred that other living organisms are generally less radiosensitive than humans and that exposure limits which prevent the risks of stochastic effects of radiation from exceeding socially acceptable levels in the human population will suffice to provide adequate protection to other species in the biosphere (*e.g.*, Rice and Baptist, 1974; NCRP, 1991). While not purporting to provide every living organism with complete protection against radiation, the exposure limits are expected to ensure that too few organisms of any species are harmed to disturb the ecosystem significantly.

The same generalization may hold for many of the chemicals in mixed waste; however, species vary widely in susceptibility to chemical injury, owing to variations in their uptake, metabolism, elimination and bioaccumulation of different chemicals (Amdur *et al.*, 1991). DDT, for example, which is degraded slowly in the environment and stored in the fat of animals, accumulates in progressively higher concentrations in organisms at each succeeding step of the food chain, as a result of which it may ultimately threaten the survival of certain species of birds (*e.g.*, Radcliffe, 1967). Such differences must, obviously, therefore receive careful consideration in evaluating the risks of any ecological impacts that radioactive and mixed waste may pose.

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Discussion

UNIDENTIFIED: I am also a former NYU student. I would like to make one comment on your lecture and presentation. I would like to see more attention addressed to the immune system because the immune system plays an important part in the effects of toxicants.

DR. UPTON: I am grateful for that comment. I did not say anything about the immune system, but clearly that is one of the areas of concern.

MR. BROOKS: I am Antone Brooks from the Pacific Northwest Laboratory. I had a couple of questions I would like to ask Art.

First of all, you alluded to the fact that there's individual sensitivity and modern molecular biology is rapidly identifying a lot of genes that are involved in that sensitivity. There are certain genes, for example, that put people in different risk categories. Do you think that we will ever get to the point where we have to do individual risk assessments? That's the first question.

The second area that I am concerned about is that in all of the waste cleanup, we do a tremendous amount of work to do chemical characterization of the waste. As you stated, we do not know much about interactions between different chemicals and radiation. Should we invest some time or some money in biological characterization of areas that we are trying to cleanup?

DR. UPTON: Two excellent questions. I am somewhat at a loss to address them adequately. Clearly, we want to protect sensitive individuals. And we need to watch very closely the evolution of our understanding of genetic differences in susceptibility.

Our laws, thus far, require that the susceptible subpopulations be protected. It is not yet clear how far this will go, but it certainly could be an important development.

MR. BROOKS: Just on a follow-up of that. If you knew there was a sensitive population and could remove them from risk, then the risk to the rest of the population would be greatly reduced.

DR. UPTON: Yes. The point was, if you could identify the sensitive subpopulation and remove it from risk, the residual risk to others would be greatly reduced, and that's certainly true.

We know of some genetic traits now that predispose to radiation. The nevoid basal cell carcinoma syndrome makes the individual very much more susceptible to skin cancer from radiation. We know in the case of UV, that the xeroderma pigmentosum trait, in which there is a DNA repair defect, greatly sensitizes, and so on.

In terms of biological characterization, I think Kitty Dragonette emphasized that there are millions of substances out there, and very few have thus far been adequately characterized toxicologically. We hope to be able to do better using new methods of structure-activity analysis, but I think ultimately we will need better epidemiological data, buttressed with laboratory animal data, to do justice to the problems that face us.

MR. BUSHBURG: Jerrold Bushburg, University of California, Davis. Thank you very much for an excellent review of radiation biology, particularly with regard to the differences between initiators and promoters. Insofar as ionizing radiation acts, both as an initiator and a promoter, we know there is a wide variety of endonucleases that can repair essentially sublethal damage itself. Could you elaborate a little bit more on that distinction?

DR. UPTON: The distinction between initiation and promotion?

MR. BUSHBURG: Insofar as initiators being non-repairable and the promoters being repairable. The damage that they cause?

DR. UPTON: I think these are still largely operational definitions. It has been observed, using the operational context, that the effects of the initiating agents, which have been shown to be genotoxic, are essentially permanent.

The promoting agents appear as a class to stimulate cell turnover. In the case of radiation, if one kills a cell, this elicits regenerative proliferation of the surviving cells. And cell division is essential to fix mutational change and to produce the clone that can expand and express the transformed phenotype.

That is the technical response. However, I am not sure I am answering the question the way you hoped.

MR. BUSHBURG: I think you are. I guess I just wanted you to make the distinction that some forms of initiational cell damage that are DNA-related and are sublethal to the cell, in fact, may very well be repaired. The cells carry enzymes that routinely fix oxidatine damage to DNA as part of normal biochemistry.

DR. UPTON: Good point.

NCRP

Assessment of Risk

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Abstract

The most significant advances in quantitative risk assessment have been made in the nuclear power field. These techniques have been adopted and modified for assessing risk in numerous other fields including nuclear waste management and disposal. Risk-based performance assessment has become the principal analysis activity for assessing the safety of both low-level and high-level nuclear waste disposal facilities. A concept of risk-based performance assessment having considerable appeal is based on the "triplet" definition of risk. The triplet relates to the following three questions: (1) What can go wrong? (2) How likely is it? and (3) What are the consequences? The result is a performance assessment consisting of scenarios, likelihoods, and possible outcomes or consequences of the scenarios. The outcomes or performance measures of interest include time dependent dose rates, cumulative releases of radiation, and numbers and types of health effects. The key element of this type of risk assessment is the quantification of uncertainty in the results. Uncertainty is included in each of the performance measures to convey the analyst's confidence in the results.

Risk-based performance assessment of nuclear waste repositories involves two broad assessments, the undisturbed case and the disturbed case. The disturbed case addresses the impact of such events as meteorites, earthquakes, volcanic eruptions and human intrusions. Although risk-based performance assessment is established, there are continuing questions of its viability. These questions turn out to be more related to specific technical issues than the process of risk assessment. They include concerns about the adequacy of the database for calculating risk, the complexities of the chemistry and physics of radionuclides, the ability to predict the future behavior of engineered barriers and geology and the ability to develop realistic scenarios of radionuclide transport in the geosphere and biosphere. In spite of these issues and concerns, risk-based performance assessment is the emerging methodology in the nuclear waste field for quantifying the safety performance of nuclear waste management and disposal practices. Its greatest contribution is believed to be the enhancement of the decision-making process associated with protecting our environment.

Introduction

One of the most important requirements facing societies, governments, institutions and even individuals is the ability to make rational decisions on matters that affect our lives and our lifestyles. As the alternatives facing societies become more complex and dependent on technology, so do the attributes or performance measures for quantifying the outcome of a decision. A key performance measure in all decisions is that of the health and safety risk attendant to whatever action (or inaction) we are contemplating. Traditionally, however, this attribute has not been quantified as part of our decision analyses. The reason has been, mainly, a lack of clarity in the definition of risk, much less in methods for computing it quantitatively. Risk has traditionally been an "intangible." We have much more experience in calculating such decision outcomes or performance measures as costs and benefits than we do in assessing risks. On the other hand, during the past two decades there has been a focused effort in the development of concepts, definitions, methods and our knowledge base to support meaningful and quantitative risk assessments. In fact, since risk assessment has now become such a high-profile discipline, lessons learned from application of risk assessment methods have provided important feedback to improving the quality of calculating other performance measures such as the costs and benefits of different outcomes of societal decisions.

Many of the advances in risk assessment have been made in connection with facilities and processes involving radioactive materials. It is the purpose of this paper to highlight the risk assessment process and how it can be used to enhance decision making and thereby our general quality of life.

Definition of Quantitative Risk Assessment

Risk assessment as generally practiced on engineered nuclear facilities tends to follow the definition put forth by Kaplan and Garrick (1981). In particular, this definition considers risk assessment to be the answer to three basic questions: (1) What can go wrong? (2) How likely is it? and (3) What are the consequences? This "triplet" definition is completely general and, thus, in principle accommodates any kind of system or situation, engineered or otherwise. The first question is usually answered by developing a set of scenarios that identify various initiators and describe the resulting sequences of events that might occur if the initiating events take place. This is sometimes referred to as the "scenario-based approach to risk assessment." The second question addresses the issue of quantification and the results are usually expressed in the form of a probability curve that conveys the confidence the analysts have in the calculation of a particular outcome. The third question is situation driven and is a matter of what performance measures best indicate the consequences or outcomes of the different scenarios. This definition will become more clear later.

The Form and Structure of a Risk Assessment

It follows from the definition of risk that a risk assessment consists of scenarios and consequences in the form of probability curves. The probability curves, as we shall soon see, represent what is meant by quantification since they display the level of confidence the analyst has in the consequences, that is, in the outcomes of the different scenarios. The goal is to develop a complete set (full range) of scenarios and then to select those that lead to consequences of interest. The starting point of a risk assessment is the development of a set of initiating events or initiating event categories that become the building blocks for developing the scenarios. Structuring the scenario set requires a detailed understanding of the system involved and the physical processes associated with the events that make up the scenario.

As will be illustrated later, if there is great uncertainty in the performance measures, that is, if the probability curves are very broad, the analyst is conveying a poor state of knowledge about the performance measure. On the other hand, if the probability curves are narrow, the implication is that we have a high state of knowledge of the various factors and processes that underlie that particular scenario. Both outcomes represent a quantification of the risk; the only difference is in our states of knowledge. The significance of such calculations is what it tells us that we know, as well as what it tells us that we do not know. We need not fret over the quality of the data, etc, because that is a built-in feature of the uncertainties in the results. The uncertainties, in a sense, are the risk. The analysis characterizes that uncertainty, including its origin, so that how to control it becomes visible—a critically important result of the quantitative risk assessment process.

A Conceptual Approach to Risk Assessment

To illustrate more concretely how risk assessments are actually performed, a conceptual approach is presented. An application of risk assessment that is very important is with respect to nuclear waste. One of the more challenging nuclear waste problems is the management and disposal of the spent fuel that is removed from commercial nuclear power plants and the radioactive waste that is produced as a result of nuclear operations within the military and the defense nuclear weapons complex. In any event, the concept is general enough to be applicable to any nuclear waste facility.

Performance assessments are required by the federal regulations to demonstrate the safety of low- and high-level waste management and disposal facilities. In particular, it is the purpose of performance assessment to integrate the information about a nuclear waste facility into a form that answers basic questions about the safety performance of the facility. Clearly the movement is towards risk-based assessments. Performance assessments are being performed on all low-level waste disposal sites, the Waste Isolation Pilot Plant (WIPP) for transuranic waste, and the Yucca Mountain High Level Waste Repository. The WIPP performance assessment (SNL, 1992) is probably the most advanced in terms of scope and number of iterations.

Rather than present ongoing performance assessments as an example, we have chosen to discuss a concept of performance assessment in relation to a nuclear waste repository that illustrates some of the basic principles of quantitative risk assessment while taking some license on the direction we would like to see the assessments take. That direction is to adopt the risk perspective of the triplet definition of risk which, in fact, has been adopted by the WIPP performance assessment effort.

What are the Questions?

When we ask about a waste repository's performance, we actually have two questions in mind:

- What will the performance be if the repository is undisturbed?
- What will the performance be if various events occur that can impact the performance of the repository?

Risk-Based Definition of Performance Assessment

We adopt the "set of triplets" definition of risk-based performance assessment, P_R:

$$P_R = \{\langle s_i, \ell_i, X_i \rangle\}, \; i = 0, 1, 2, \dots I \qquad (1)$$

where

s_i = the i[th] scenario
ℓ_i = the likelihood of the i[th] scenario
X_i = the "damage vector" consequent to the i[th] scenario

With this schema, we would let s_0 denote the "undisturbed" scenario in which nothing goes wrong, and the remaining s_i's would denote the various "things that go wrong" (that is, the "episodic" scenarios) and would include the impacts of the occurrence of events such as earthquakes, meteorites, volcanic eruptions, human intrusion, etc., and the time at which they take place.

The X_i vectors would have as components the various "performance measures," or "outcomes," X_j. For example, we could let:

$X_1(t)$ = the dose rate in year t to the maximally exposed individual
$X_2(t)$ = the total curie release, C_i, in year t after closure
$X_3(t)$ = the total dose to the human population in year t
$X_4(t)$ = the total number of health effects in year t

and so on. These can be expanded and elaborated to whatever level of detail is of interest; *e.g.,* the radionuclide in question, the type and number of health effects, etc.

The likelihood terms, ℓ, would be best expressed as probabilities; *i.e.,* as measures of the degree of credibility that we can assign to the scenarios based on the total body of relevant evidence available. The probability that nothing will go wrong, ℓ_0, would thus be one minus the sum of the probabilities for occurrence of all of the disturbing types of events, namely:

$$\ell_0 = 1 - \sum_i \ell_i \quad (2)$$

Form of Results

The first results that we should calculate are the outcomes or performance measures for the undisturbed scenario, *i.e.,* $X_1(t)$ for scenario s_0. These should be plotted, for example:

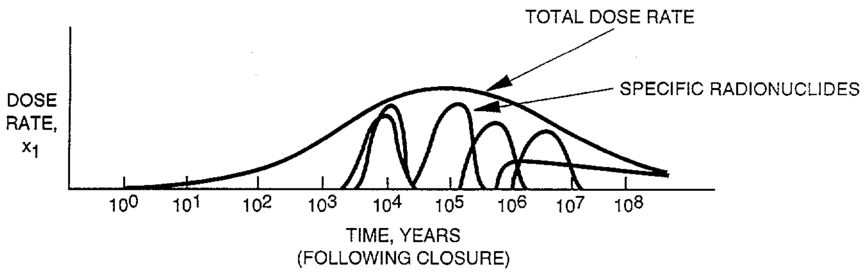

Fig. 1. Damage index X_1 (dose rate) as a function of time.

Since there will be uncertainty in the actual dose rate, it is best to express the results of these types of calculations as a family of curves:

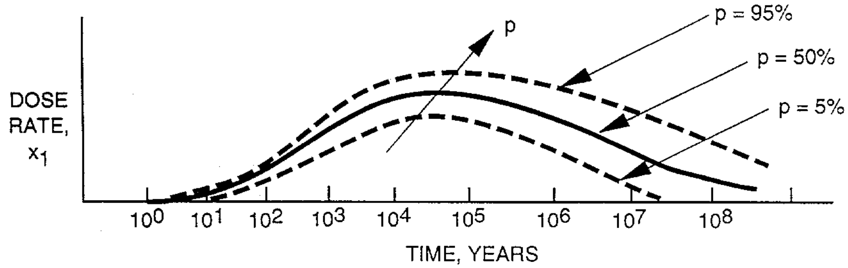

Fig. 2. Uncertainty in $X_i(t)$ expressed in a family of percentile curves with probability p as parameter.

and, similarly, for the other performance measures. We can also plot cumulative curves, for example, for $C_1(t)$ = total curies released up to time t for scenario, i = 1. These would appear as follows:

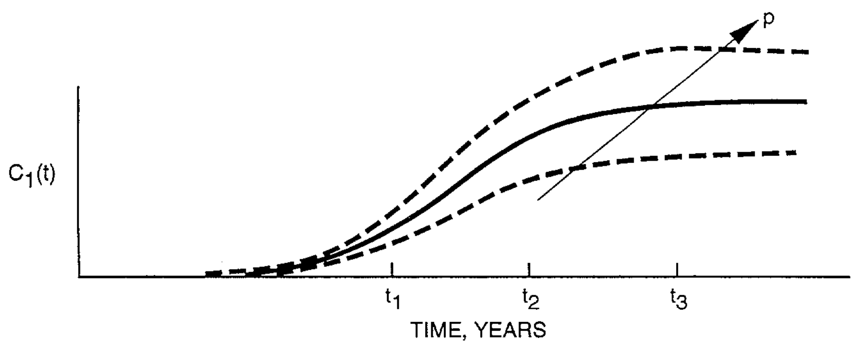

Fig. 3. Cumulative curies released to time *t*.

If desired, we can also cut these curves at particular future times, say, t_1, t_2 and t_3 to obtain probability density curves of the cumulative release of radionuclides up to these different points in time denoted by the subscript. As may be noted in Figure 4, such curves clearly show an increase in the uncertainties of such calculations the farther into the future one attempts to project.

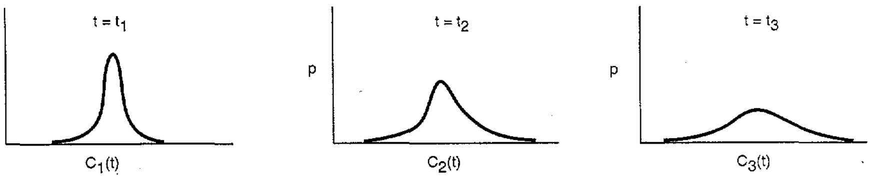

Fig. 4. Probability curves for $C_1(t_1)$.

The above performance measures are quite adequate for displaying the risk for the undisturbed case. If desired, the individual doses could be converted to population doses and the resulting collective doses used to estimate the number of resulting health effects, etc. It is a matter of whether the results warrant further calculations. The important quality of these results is that the uncertainties are clearly displayed, and behind these results is the information on what is contributing to these uncertainties. Thus, if we do not like the results, the information exists to do something about it—engineered barriers, administrative controls, a new site, or an entirely different approach to managing the waste.

For the cases in which the performance of the repository is disturbed, we may want to adopt the frequency of occurrence of events of different levels of severity as the parameter of the model. Of course, there is uncertainty in the frequencies, and this leads us to adopt the "probability of frequency" idea used extensively in nuclear plant risk assessments (Kaplan and Garrick, 1981). This approach allows an ordered grouping of the scenarios by type of consequence (fatalities, injuries, dose, property damage, etc.) and the casting of the results in the form of a risk curve known as the complementary cumulative distribution function (CCDF). The results take the following form:

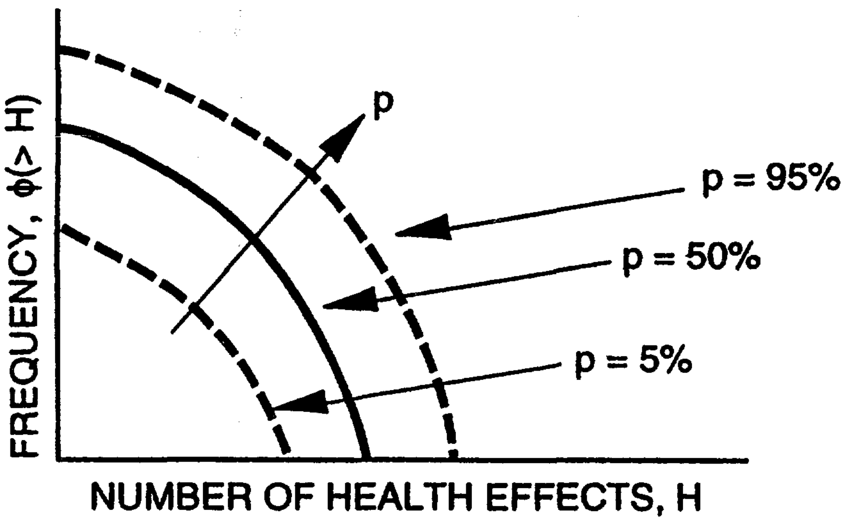

Fig. 5. CCDF curves in probability of frequency format.

These types of risk curves are helpful in that they clearly show that the events having the most damaging consequences have the least probability of occurrence.

The General Structure of Quantitative Performance Assessment

The basic building blocks of scenario-based and risk-based performance assessment are a set of initiating events and an agreed on set of outcomes or performance measures. The assessment process is logically and systematically staged to provide scenario continuity from initiating event to specific performance measure. While the definition of the specific stages is a matter of modeling convenience, conceptually the process takes the following form:

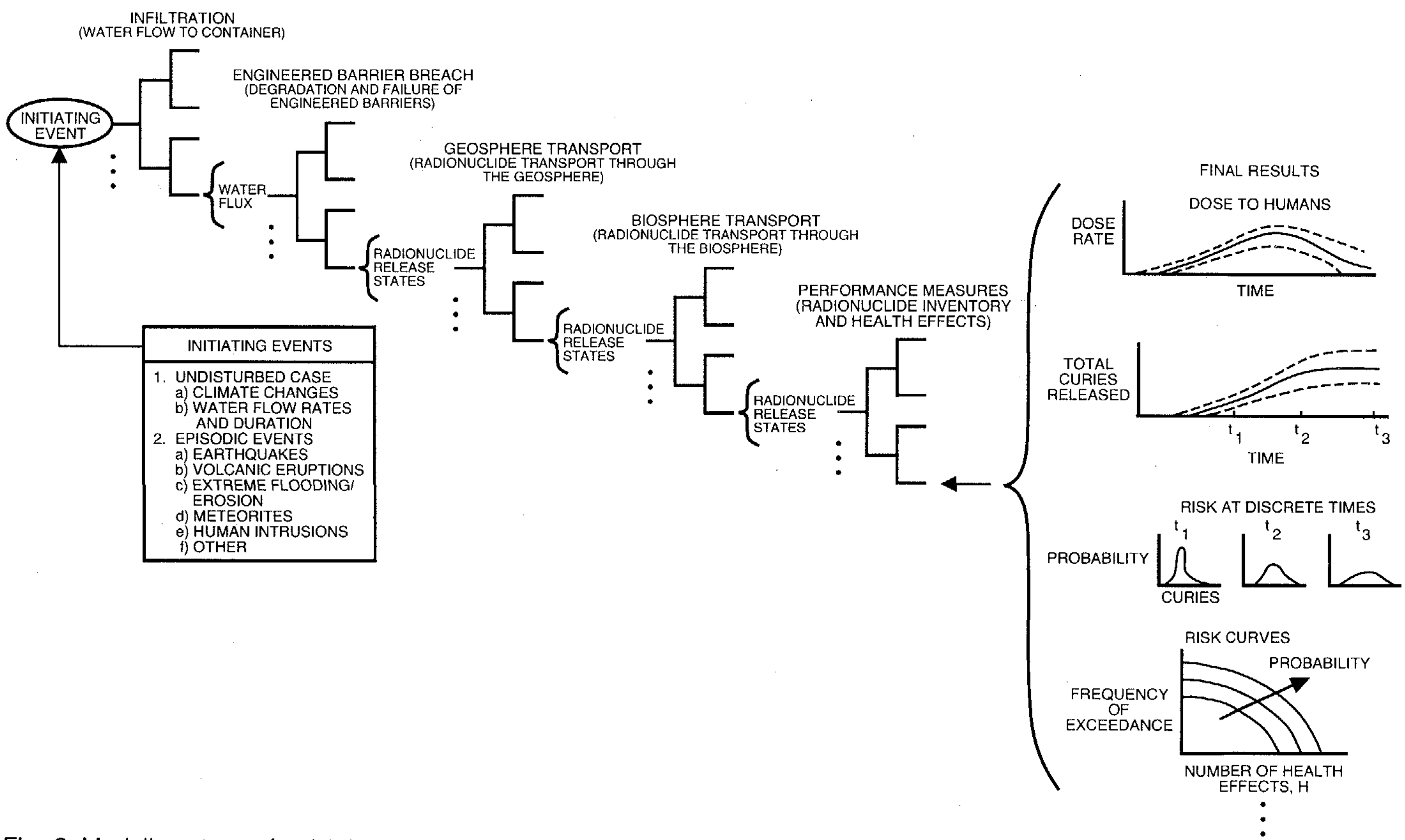

Fig. 6. Modeling stages for risk-based performance assessment of nuclear waste storage.

Which Performance Measure Should We Use?

The question is often asked, "Which performance measure is the right one or the best one to use in characterizing repository performance?" The answer is that we need not limit ourselves to one "best" measure. Each measure characterizes one aspect of the performance, and we are interested in all aspects. Let us then pick out a set of the most important measures, and characterize each by one (or more) graphs, of type Figures 1 through 5 and summarized in Figure 6.

The total set of such output curves can be said to characterize and quantify the performance of the repository. From them, we could decide where to put a repository, how to design canisters, etc., and even, for example, whether we should build a geologic repository at all.

Action Proposal: Sequencing of Analyses and Method of Successive Approximations

As for any complicated engineering problem, the assessment of repository performance should be done by the "method of successive approximations." Under this approach, a "first-pass," quick turnaround simplified analysis is made, using conservative model approximations, so that we can confidently regard the results of this analysis as an "upper bound"; *i.e.,* a pessimistic assessment of the true repository performance. If this upper bound turns out to be of negligible consequence, then no additional analyses are necessary. If not, then the first-pass results can be used to answer the following questions:

1. What aspects of the repository design are yielding poor performance?
2. What aspects are leading to insufficient confidence in satisfactory performance?

For aspects of type 1, we then change the design of the repository to improve the performance. For aspects of type 2, we can change the design to eliminate the uncertainty, or we can attempt to gain sufficient confidence by doing detailed "second-pass" analyses, improving the accuracy of those parts of the first-pass model that relate to the performance aspects in question.

If the results of the second pass are satisfactory, then we can accept the repository as designed. If not, we either redesign, or/and go on to a third pass, etc., until we have sufficient confidence that the repository will perform in a satisfactory way or that there is a more acceptable alternative.

Example

To make this action proposal a little more definite, let us consider Figure 7 (Andrews, 1993). This figure is a concrete example of Figure 1, with the annual dose broken down by individual isotope. This figure can be considered as a first-pass characterization of repository performance under the undisturbed scenario, s_0.

Underlying the calculations leading to this figure is a first-pass mathematical model of the repository. A study of the figure leads us to ask how the individual radionuclides are leaving the repository and

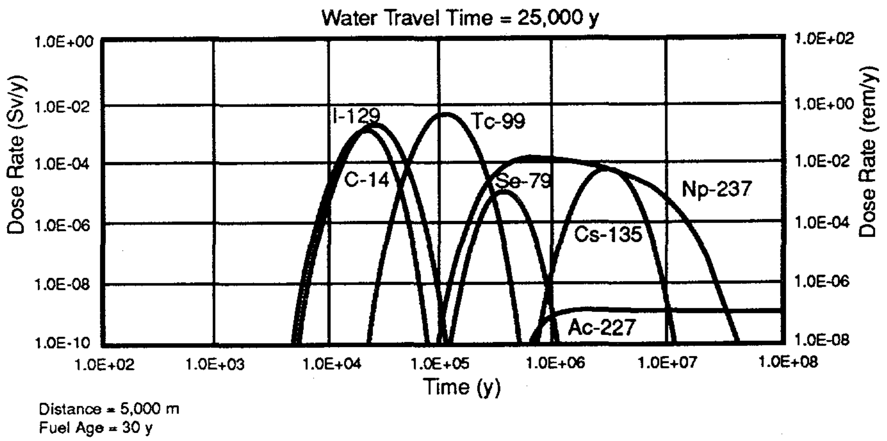

Fig. 7. Dose rate contribution from individual radionuclides (baseline case).

gaining access to the environment. Study of the model answers this question and immediately stimulates our creative engineering thinking towards ways of improving the design of the repository, canister, waste form, etc., in order to improve the performance depicted in Figure 7.

Using the iterative process, we can thus refine the design of the repository until we are satisfied with its performance under scenario s_0. We then must construct similar models for the scenarios s_i (or at least for those s_i's having significant likelihood of occurring). We then use again the iterative design/analysis process until we are satisfied with the performance of the repository under both the s_0 and s_i scenarios.

Acceptability and Decision

An important point to mention here is that, in this iterative process, we should not, and need not, struggle unduly to try to define a so-called "acceptable" level of performance. It really makes no sense to think in terms of a "speed limit" above which we are unacceptable and below which we are OK. This would imply, for example, that so long as a person does not exceed the speed limit, they are totally safe, and that all drivers who exceed the speed limit will inevitably have an accident. Risk is a continuous, not a discontinuous, function.

It makes much more sense to adopt a decision theoretic way of looking at the problem. The smaller the dose delivered to the biosphere from the repository the better. It is only a question of how much we are willing to pay since from an engineering standpoint we have the ability to make the risk as small as we wish. Not zero, of course, since in the real world there are no absolutes, but we can make the risk as close to zero as we like.

The real questions therefore are "How much improved performance can we get for each incremental expenditure of resources?" and "Are there other ways in which we can expend these increments more productively, to yield more benefits, more risk reduction, to our society and our planet?"

The real questions, in other words, and the real decisions that have to be made, are all concerned with the allocation of societal resources.

Analytical, mathematical repository performance models of the type that we have been discussing, including uncertainty calculations, used iteratively with engineering design creativity, can answer these questions and thus allow us to make, defend, support and gain consensus for these decisions. Without the use of such models, and the logic, science and rational treatment of evidence that they comprise, such decisions can only be made on political and emotional bases, in which case they will certainly not be optimal from society's standpoint, and will have very little chance of building the understanding and consensus needed to get them implemented.

Impediments to Effective Risk-Based Radioactive Waste Management

Risk-based performance assessment of the form described above can be extremely effective in aiding the decision making process for effective nuclear waste management. The extensive work going on in the nuclear waste performance assessment field is mainly pointed in the right direction, but has not yet fully responded to the associated needs. The development of the performance assessment models is slow, and they seem to have low visibility in the decisions affecting the design and construction of the waste disposal facilities. There is the further problem of a lack of public participation in the process. As a result, the performance assessments are not playing a major role in building public confidence in the nuclear waste management choices being made. Some of the issues that would advance the use of risk-based performance assessment, and for that matter the achievement of a nuclear waste management program, are the following:

1. Performance assessment efforts need to be given a key role in the decision-making process affecting program directions for the management of radioactive waste.
2. Performance assessments need to be more responsive to program activities. Of particular need are fast feedback simplified performance assessment models that can provide timely first-order approximations to the risks as new information becomes available and design alternatives are considered.
3. Performance assessments need to be more focused on calculating performance measures and outcomes that are important rather than trying to outguess the regulations in terms of what the new standard(s) might be. For example, it is clear that we need to know if the disposal facility can in any way significantly increase the background radiation dose rates within the biosphere. We need to do a good job of making that calculation. In fact, we should not hesitate to calculate as many performance measures as we need to in order to provide assurance of the safety of the storage facility.
4. Performance assessment needs to be made more acceptable to the public through education and much greater involvement in the process.

While the above issues are specific to the use and acceptance of risk-based performance assessment, there are other impediments to the general acceptance of risk assessment. These have to do with poor quality technical information, that is, a poor understanding of the technical processes involved, and poor risk assessment practices. It is important to point out that whether we have good technical information or limited information does not take away our ability to do a competent risk assessment. In fact, the less information we have, the more important it is to do a risk assessment to reveal our level of understanding of the risk issues. We may not like the results, especially the large uncertainties that may be involved, but it is not because of an intrinsic failing of risk assessment. Poor information certainly affects the outcome and acceptance of a risk assessment and usually means there are technical problems, but it is important to distinguish between technical problems and poor risk assessment practices. Of course, there is always the issue of the occasional poor use of risk assessment methods and the resulting negative impact. Whether it be poor technical information or risk assessment practices, it is appropriate to note some of the more general issues impeding the acceptance of a risk-based approach to assessing the safety of nuclear waste disposal systems.

1. **The detailed nature, including the physical and chemical characteristics, of nuclear waste.** The complex chemical and physical characteristics of nuclear waste leads to difficulties in fully understanding the processes associated with their interaction with different media. While there are issues of basic science, the greater uncertainties are in our ability to adequately define the form and quantities of the materials involved, which brings us to point number two.
2. **The ability to develop an adequate database through site characterization to support high confidence risk assessments.** The challenge is to develop sufficient understanding of the site characteristics to enable detailed modeling of radionuclide changes of state and transport behavior. A competent performance assessment program should serve as an indicator of the adequacy of the site characterization program.
3. **The development of a defensible set of radionuclide transport scenarios.** There is concern that too little is known about radionuclide transport phenomena in geological and biological systems to have high confidence in the definition and analysis of meaningful scenarios, the basic building block of quantitative risk assessment. Again, if uncertainty analysis is an integral part of the risk assessment, this problem is minimized.
4. **The uncertainty in the frequency of events that could disturb geologic containment.** A very important part of analyzing the risk of geologic repositories is to be able to estimate the frequency and severity of events that could materially disturb the otherwise natural geologic containment capability. The events of interest are earthquakes, meteorites, volcanic eruptions, human intrusion, etc. The earlier comment about uncertainty analysis applies here as well.
5. **Our ability to predict the behavior of natural and engineered systems far into the future.** The primary complication with this issue relates to the so-called "disturbed" case, as indicated earlier. For the undisturbed case, it appears possible to find sites indicating very long-term geologic stability. Since, in fact, we cannot predict the future, the best approach for the disturbed case is believed to set forth one or more *pro forma* procedures that make sense and on which we can develop some sort of reasonable consensus and then calculate the risks accordingly.

The above are believed to be but a few issues that need to be resolved to enhance the performance assessment work and to have a high expectation of a solution to the nuclear waste management problem.

Conclusion

The quantitative assessment of the risks associated with activities involving radiation is not only feasible, but has been demonstrated by many applications, including the disposal and management of nuclear waste. Risk-based performance assessment is the emerging methodology in the nuclear waste field for quantifying the safety performance of waste management and disposal practices. Although not yet a mature methodology, if practiced in the spirit of the "triplet" definition of risk, which implies a quantification of the uncertainties involved, it can become an important aid to making rational decisions about strategies and programs for the management of this country's nuclear waste. There are obstacles, to be sure, including public acceptance, but quantitative risk assessment is an important first step in the development of a decision analysis framework that clearly displays the available alternatives to nuclear waste management and disposal.

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Discussion

MR. DORNSIFE: Bill Dornsife, Pennsylvania. Although you did not say it, your discussion and the associated methodology were primarily geared toward high-level waste disposal. If you try to apply the same kind of methodology to low level and mixed waste, you could make the problem worse. Because the real problem we have out there is not risk assessment, it's risk communication.

If you use too complex a risk assessment tool, you are going to lose in terms of the risk communication issue. Based on my interactions with the public, I believe that what the public wants to know is that if everything works okay, what's the expected result. And if everything does not work, what's the worst case or the most pessimistic case? What's wrong with a simplistic analysis?

DR. GARRICK: I think that a simplistic analysis is fine if it does the job. I would never advocate making a risk assessment more complicated than it needs to be, but I always fall back on the astute observation that Einstein made on this question. And that is, that you should make things as simple as you can but no simpler.

I do disagree, however, with your point that you cannot use this way of thinking on low-level waste. I have seen nothing that you cannot use this thought process on. Now, this does not suggest that it has to be an elaborate complicated analysis. In most cases, it can be a few-weeks analysis. The thought process is fundamental.

UNIDENTIFIED: I would like to make several points. One thing that I think should be addressed much more clearly is the problem of the complex mixtures that can be present in mixed waste. Most laboratory toxicological tests involve only single chemicals.

Number two, I would like to see your modeling expanded to incorporate the effects of several events that can take place at the same time. It is not accurate to assume that the effects of combinations of events are simply additive.

DR. GARRICK: I agree. Knowledge of the waste form and the source material is the key in terms of being able to develop a model that in fact represents the resulting effects, whether they are due to mixed or specific waste forms.

With respect to combinations of events, what we have found is that if we start with what is judged to be at least one major problem—not always the most critical problem—and move into the more complex situations incrementally, we usually have quite a bit of success.

The nuclear power plant problem had the very issue that you referred to, mainly a multiple number of things going on at the same time. And you have to look at these in terms of timing, and you have to bring that timing into the model. If the combination of events is judged to be important, then of course the models have to get more elaborate. I do not disagree with anything you have said.

DR. KOCHER: David Kocher, Oak Ridge National Laboratory. I was struck by a comment you made. You are emphasizing throughout that you are taking uncertainty into account as a very important factor in your risk assessment. I would certainly agree with that.

And if I heard you correctly, you said that this approach provides an indecisive framework for portraying risk, and yet we must use these very uncertain analyses to make yes/no decisions in a very, hopefully decisive, way. Could you elaborate on your views on this point?

DR. GARRICK: Well, the word indecisive may have been as a result of my upbringing in the rocky mountain west and poor diction, but you are right. I think that all we are saying here is that the first thing we ought to do is tell the truth.

DR. KOCHER: Fess up!

DR. GARRICK: And if the truth does, in fact, encompass large amounts of uncertainty and does not provide the basis for a clear-cut choice, we, as the people who have been asked to make these calculations, have a first and foremost responsibility to convey that to the public. Unfortunately, we very often do not.

And then I think as far as the decision-making process is concerned, then we as the analysts put our citizen's hat on just like everybody else does, and we vote on it on the basis of the evidence and the results, at least in principle.

I think that we have to educate our Congress and educate our public that most decisions are made in the presence of considerable uncertainty.

What is different about this and a credit to the nuclear industry is that until we started to calculate the uncertainty and deal with it and qualify it, we did not fess up to it. I think the public is now pushing us to do so and we need to do so.

DR. RYAN: I am Mike Ryan with Chem-Nuclear. In applying a risk-based calculation to a decision, for example, for a high- or low-level waste site, we do have a deterministic step and that is making a decision either to go forward or not to go forward.

DR. GARRICK: That's right.

DR. RYAN: How do we translate a risk-based analysis with uncertainty to that deterministic decision?

DR. GARRICK: Well, one example of coping with that in the nuclear power industry was to come up with a concept of safety goals. We are always being asked by the regulators and the legal community to use mathematical language just to scalerize our vectors. That is to say, to come up with a utility function that can be judged as acceptable or non-acceptable.

And I can appreciate the value in doing that. I can appreciate the value of the safety goals, although in the end, they have not been a major force in the regulatory process. But they have disciplined us into trying to provide the kind of information and the kind of analysis that would allow us to see where we stand with respect to those safety goals.

So I think that we cannot replace the continuing process of trying to come up with a go/no go criterion, one—zero, or whatever; that is, a binary way of thinking; but that does not relieve us from the responsibility of calculating what the truth really is.

And that's really more of what I am talking about than anything else.

DR. RYAN: I agree with your last point. However, although we have to lay all the truth out, I think we also have an obligation somehow to translate our actions into a decision-making process and to establish a framework for making that ultimate deterministic and binary decision that will enable us to decide whether to go forward.

DR. GARRICK: Yes. And my comment is that I do not think we have done a very good job on that. And I do not think that either the political process or the technical community has done a very good job on that. We need to drive that point home, I think the reason we keep hearing this speech over and over of "how safe is safe enough" is because it's an illogical question. What's safe depends upon the circumstances. What we would accept under an oil embargo condition is very different from what we would accept under a glut condition as we have so many times seen.

So we need a more integrative and cross section of structure for making those decisions here in the case of Yucca Mountain. If we do not want to spend the money to store the waste at Yucca Mountain, what are the alternatives, and what are the costs, risks and benefits of those alternatives? We cannot get rid of the waste. It's here. So it's not a matter of not doing it. It's a matter of choosing the best way to use societal resources to achieve it.

And I think the safety goal concept, the limit line concept, is better. But these fall way short of what, in fact, we probably ought to be doing and what we are able to do.

MR. DORNSIFE: Bill Dornsife again. As you mentioned, the probabilistic risk assessment technique was developed in the nuclear power industry, and it works very well as a tool for assessing weaknesses in design. It could be used for waste disposal as well as assessing weaknesses in the engineering design.

But the problem comes—and it failed miserably in terms of reactor safety—of using risk assessment as a risk communication tool and a risk acceptance tool. That's the struggle we are facing. Risk communication, risk acceptance.

If probabilistic risk assessment is used in waste disposal, it's going to create the same problem as I think it did with nuclear power safety.

DR. GARRICK: Well, I appreciate what you are saying. When I was president of the Society for Risk Analysis, I never did understand for sure what the hoopla was about risk communication. To me, it was a half-hour course; and I was wrong.

But on the other hand, I think that one of the mistakes we very often make is that we get consumed in the process rather than in solving the problem. If you go to a Society for Risk Analysis Conference—which I urge you all to do; they are excellent—80 percent of the papers are probably on or related to risk communication. That's a hot subject. But the important thing to recognize is that risk communication is not fundamental. If you are going to communicate risk, you have got to have something to communicate. And that's where I think we need also to be very attentive. We need to develop the kind of information that will allow us to do an effective job of communication. The two must go hand in hand.

In most instances where I have seen failures of probabilistic risk assessments, the failures have occurred peripherally. It's been in the poor use of risk assessment and so on. But the thought process is fundamental. Its roots are in the fundamentals of logic.

MR. ROHRIG: Norman Rohrig from Lockheed Idaho. If the issues are really acceptability and allocation of resources, should not we be doing similar calculations for other expenditures society makes, such as road improvements, treatment of criminals, improvement of schools, and use of energy sources other than nuclear?

DR. GARRICK: I have a very simple answer for that. Absolutely, we should. There was an excellent treatise developed by Dave Okrent at UCLA on intergenerational responsibility. Dr. Okrent characterizes your question in that study as well as I have ever seen it characterized. And what we are talking about here is the inconsistency with which we apply these methods and on which industries. I agree with you.

MR. SEITZ: Roger Seitz from Idaho National Energy Laboratory. Although my undergraduate work was in decision theory and uncertainty analysis, I currently do hydrology studies. One thing that I have found in trying to apply uncertainty analysis to these types of problems is that, as a technical person, you want to try to solve the problem to find a consequence. So it becomes a problem of characterizing the site and trying to understand the behavior of the waste disposed there. Application of the triplet approach often appears to me to result in a political battle of deciding what likelihood to assign to each of the different possible scenarios.

DR. GARRICK: You are right. The answer to that is to base your likelihood on the evidence. If the evidence is non-supportive, then you should be choosing different likelihood values.

What I have found is that, even in the process of the elicitation of expert opinion, if you provide some room for the information to represent itself in the way it actually exists, then you make genuine progress. That's why I keep putting the emphasis on uncertainty.

If you allow for a range of problems or a range of values, then you very often find that the constipation that otherwise exists is broken and you begin to draw out the information. It's like the first time I was asked to do a reliability analysis for an 800 megawatt turbine generator. Although there were no such generators in existence at that time, I found that by decomposing the problem down to a state at which we had some knowledge we were able to perform the analysis.

When we decomposed the generator into it's 23 subcomponents, we found that a tremendous amount of information and insight was available for 19 of them. We have become so conditioned to thinking of information as things like statistics, and what have you, that we sometimes tend not to give ourselves credit for what we actually know.

DR. RYAN: There is one additional question that Norman Rohrig's comment has stimulated me to ask. I think you have laid out a framework for applying risk-based assessments in a proper way where all the participants are shooting for the right answer. In other words, will it work or not? Is it right or wrong? What's the decision framework?

But how do you guard against the misuse of risk-based assessments when there's an agenda, by those who are misusing this approach, either to do something or not to do something. Unfortunately, there are no certification programs that qualify quantitative risk assessors.

DR. GARRICK: The way it's done in practice, of course, is through that age-old concept of peer review. One of the institutions that relies on the peer review process extensively and has great success with it is the National Academy of Sciences and the National Academy of Engineering. That is one thing that has to be worked on. Another subject needing to be addressed is the tendency in some cases to separate the risk assessment activity from the knowledge base. Probably the only thing that upsets me more than somebody suggesting you cannot do this on low-level waste, is for people to say that you cannot do it because you do not have the statistics.

Statistics and probabilities are different concepts. "Statistics" is a component of establishing a state of knowledge, but it's not the only thing. That is a problem we have to continue to work with. The way we are dealing with it at the present time is through the review process.

Managing the Risks of Radionuclides and Conventional Chemicals

Stephen L. Brown
Risks of Radiation and Chemical Compounds

Abstract

This presentation emphasizes that the limitation of risks to human health and the environment should be a common theme in the management of chemicals and radionuclides. Wastes with generally similar characteristics should be managed similarly with respect to risk, regardless of whether they contain radionuclides, chemicals or both. In order to do so, we need to establish risk management criteria by which we can decide whether the estimated risks of various disposal options are acceptable.

The presentation also summarizes how risk management criteria are defined for individual and population risks and how they differ among different regulatory and guidance structures, particularly between chemicals and radioactive materials. In general, radiation guidance has theoretically allowed greater cancer risks than have chemical regulations, but there are many other differences in the way that the standards are applied that may reduce or explain the difference. Moreover, the existence of a baseline risk due to background radiation may have influenced the regulation of radioactive materials. Nevertheless, chemicals and radiation share many characteristics and their differences in a risk management context may be less than is commonly supposed. Harmonization of radiation and chemical risk management does not require identical risk criteria in all situations, but it does require for differences to be clearly understood by all parties and to be acknowledged as legitimate by the major stakeholders.

As explained earlier in this Symposium, the management of waste generated by the nuclear power industry and the nuclear weapons complex (as well as by other sectors of society such as medicine) requires consideration of both radionuclides and conventional (non-radioactive) chemicals. Any waste classification system should take into consideration both the differences and the similarities between radionuclides and conventional chemicals. A fundamental theme of my presentation, and in fact of the whole Symposium, is that the limitation of risks to human health and the environment should be a common theme in harmonizing the management of chemicals and radionuclides.[1] In brief, it seems reasonable to group wastes with generally similar risk characteristics, regardless of whether it contains radionuclides, chemicals or both.

Drs. Upton and Garrick have already defined risks and indicated how they can be assessed. I will now discuss how those assessments can be used to decide on the need for actions regarding waste and to decide among management alternatives. Because ecological risk assessment needs to consider a wider array of issues than does the assessment of human health risks, I will concentrate on the latter for my examples, recognizing that the extension to ecological concerns may require additional insights. Furthermore, because the risks of exposure to environmental levels of radiation are dominated by cancer, I will focus on the similarities and differences in the management of radionuclides and chemical carcinogens. For many chemicals (even for some that also have carcinogenic properties) the dominant concerns are health effects other than cancer; these are generally managed by keeping exposures sufficiently low that any adverse effect whatsoever is unlikely.

Given those disclaimers, I will now turn to the risk management of carcinogenic chemicals and radiation. We must first understand the two major measures of risk from such substances: individual risk and collective or population risk. Broadly speaking, individual risk is calculated as a probability that an exposed person will develop an exposure-related cancer in the next year or over a lifetime, while population risk is calculated as an estimate of the total number of cancers expected in the entire exposed population over a year, a lifetime or some other defined period. In the case of the underground disposal of high-level radioactive waste, the population risk may be calculated over a period as long as 10,000 y. Individual risk could in principle be calculated for any exposed

[1]Most of what I have to say applies as well to radiation that does not stem directly from the decay of radionuclides, such as x rays from bombardment of a target with electrons, but such exposures are of less interest to the issue of waste classification.

person; in practice it is usually calculated for a hypothetical person who is among the most exposed of the exposed population. This hypothetical person is variously called a "maximally exposed individual" (MEI), a person with "reasonable maximum exposure" (RME), a member of the "critical population group" (CPG), and so on.

The risk-based management of exposure to chemicals and radionuclides requires definition of risk *criteria* by which the acceptability of exposures can be evaluated. A fundamental assumption of cancer risk management is that risk cannot be reduced to zero unless the possibility of exposure is completely eliminated—an undertaking that is often technically impossible and almost always economically prohibitive. Therefore, the regulatory structure in the United States has developed over the past 30 y or so the concept of acceptable risk. While the idea of accepting any possibility of injury to health is unpalatable to many, most people understand that absolute freedom from risk is infeasible[2] for management of hazards, such as radioactive and mixed waste, that already exist. The issue then resolves to choosing the risk criteria by which exposures will be managed. In simplest terms, the risk management decision is made by referring to a diagram such as shown in Figure 1. This figure shows how both MEI risk and population risk might be considered in the decision. More typically, only one dimension is considered in most regulatory decisions. MEI risk is the predominant criterion for regulations regarding chemicals; regulations for radionuclides often emphasize individual risk as well, but are somewhat more likely than chemical regulations to be based on population risk, as for high-level radioactive waste disposal (EPA, 1985). This distinction has historical roots which I will not detail at present but which can be covered in the general discussion to follow, if you like. Fundamentally, the MEI approach emphasizes equity: no one person should have to bear unreasonable risks for the benefit of society. The population risk approach emphasizes public health: no more than a few people should be affected, no matter how the risks are distributed.

How do we decide where to put the "bright line" in Figure 1? Or is there another way of managing hazards according to risk? Of course, quantitative risk assessment is not the only way that society manages risks, nor should it be. Social concerns, attitudes towards risks of different kinds, economics, and the technical feasibility of managing the hazards

[2]If science later discovers that thresholds of exposure exist for carcinogens including radiation, then absolute protection may be at least technically feasible and perhaps economically feasible. Then carcinogens could be managed in the same way as chemicals with the potential to cause effects other than cancer.

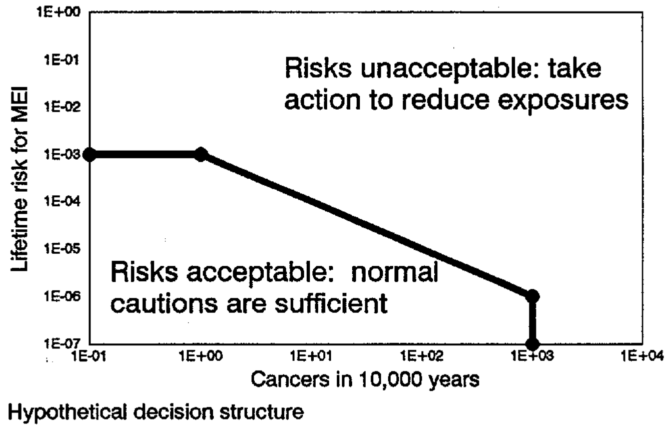

Fig. 1. Decision diagram showing criterion "bright line" based on individual and population risk.

all affect how we manage them. To take only one example, the guidance issued by the U.S. Environmental Protection Agency (EPA) for managing the risks from indoor radon (EPA, 1993) could be interpreted as implying that an MEI risk of about one in a hundred (0.01 or 10^{-2}) is the dividing line between acceptable and unacceptable risk. In fact, neither the EPA nor most observers think that this level of risk is really acceptable (if accurately estimated), but currently available technology is unlikely to reduce exposures much below that level, and EPA has taken a pragmatic approach rather than promulgating guidance that might generate fruitless activities.

Another and in some ways more vexing problem in risk management is that the estimates of risk are fraught with uncertainty, and the use of "bright lines" can result in erroneous decisions even if there was complete agreement about where the bright line should fall. Generally speaking, this problem is addressed by making "conservative" estimates of risk, meaning that the risks are more likely (often much more likely) to be overestimated than underestimated. This procedure biases the process towards controlling hazards that would not be evaluated as needing controls if perfect knowledge were available. Such a bias is widely considered to be prudent public policy, although there is significant debate about the degree of conservatism that is best socially. Because of the more extensive data base on radionuclides and radiation risk, the degree of conservatism in the risk estimates is typically lower than for chemicals, but that is not always the case.

From this point onward, I will focus on risk-based management of cancer hazards based on individual risks. To make this discussion meaningful to those who are not specialists in risk assessment, I will digress first on the subject of risk estimates. Individual risks are expressed in terms of the estimated probability that a person exposed in a defined way will incur a cancer sometime during his or her lifetime as a result of the exposure. This incremental risk is presumed to be in addition to the "baseline" risk of cancer we all experience as a result of our genetic makeup, background, cosmic and terrestrial radiation, natural and artificial constituents of food, and so on. On average, about one in three people will develop a cancer, about one in four will develop a potentially fatal cancer, and perhaps one in six will die of cancer. For most waste management situations, the estimated individual risks are far lower and are often expressed in terms of chances per million of developing cancer. As a shorthand, risk assessors regularly express risks with the exponential notation, as shown in Table 1. To be able to visualize such risks, Figure 2 may be useful. In this figure, the light square represents the cancer cases, while the dark areas represent the rest of the exposed population (assuming identical exposure to all members of that population). Note that the smallest levels of risk shown, one in a hundred thousand and one in a million, are essentially impossible to see. That situation is also true in real life; even where a true risk of 10^{-5} or lower exists, currently available techniques such as epidemiologic investigations are usually not capable of demonstrating whether or not people are actually developing cancers as a result of the exposures in question. Thus, risk management of radioactive and mixed waste will likely proceed without a clearly visible signal that it is either necessary or effective.

It is my belief that risk management practices have developed differently for chemicals and radiation because of different historical factors (Brown, 1992). The impetus for radiation risk assessment arose largely from the nuclear weapons and nuclear energy programs, with an earlier basis in radiation diagnosis and therapy in medicine. Radiation risk assessment very early adopted the premise that virtually any amount of radiation, no matter how small, had some potential for causing cancer. With the advent of molecular biology, this assumption had support from the possibility that even one ionizing event could damage the DNA in a

TABLE 1—*Different ways of expressing individual risk.*

Natural	Mathematical	Exponential	Computerese
One in ten	0.1	10^{-1}	1.0E-01
One in a hundred	0.01	10^{-2}	1.0E-02
One in a thousand	0.001	10^{-3}	1.0E-03
One in ten thousand	0.0001	10^{-4}	1.0E-04
One in a hundred thousand	0.00001	10^{-5}	1.0E-05
One in a million	0.000001	10^{-6}	1.0E-06
One in ten million	0.0000001	10^{-7}	1.0E-07
Five in a million	0.000005	5×10^{-6}	5.0E-06

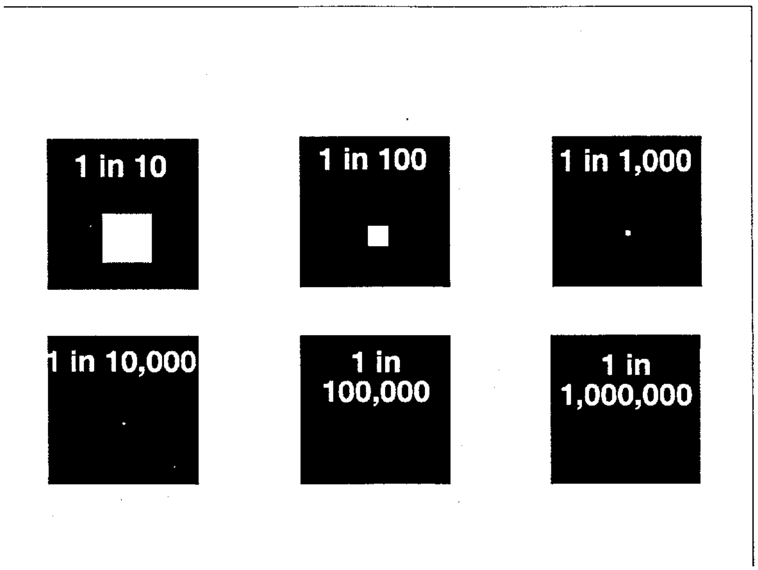

Fig. 2. Envisioning risk. Ratio of areas is as indicated by the text.

cell and that the damage might escape repair through the succeeding stages of cancer development. Because it developed in an environment where substantial benefits were to be reaped from use of radioactive materials (medicine; national security; energy independence), risk was naturally traded off against those benefits (NBS, 1954). Furthermore, radiation risk managers knew that natural sources contributed a virtually inescapable background of exposure: about 1 mSv y^{-1} on average from cosmic, terrestrial and internal sources (NCRP, 1988) and perhaps another 2 mSv y^{-1} from radon.[3] The result, in my view, was that radiation risk managers felt comfortable with an incremental risk near background or even higher, knowing that their efforts would have decreasing effect on total radiation exposures as pushed toward zero. The calculated lifetime cancer risk of 1 mSv y^{-1} of radiation is about five in a thousand (5×10^{-3}); the risk of fatal cancer is about 3.5 in a thousand.

By contrast, chemical risk management developed largely from a beginning in conventional toxicology and food safety, where the goal was to achieve levels of exposure that were "safe," *i.e.,* without any risk whatsoever. The early model of chemical toxicity was based on the premise that every "poison" would have no effect if the dose were sufficiently low. The safety goal could then be defined as to keep exposures below the "threshold" dose with an adequate margin of safety. When some chemical carcinogens began to look like radiation in the sense that no clear thresholds could be established, the chemical risk managers were then faced with developing a management paradigm more like that used in radiation, with an implied acceptable risk. But the natural tendency was to keep risks as near zero as possible. The first proposal was to manage to a lifetime risk level of one in 100 million for chemicals in food (Mantel and Bryan, 1961); the feasibility of this proposal was soon challenged, and much of food additive regulation for carcinogens has proceeded with an implicit target of one in a million cancer risk. This level, originally conceived as applying to virtually the entire United States population, was later adopted for use in environmental regulations, especially at the EPA, where the assumption of broad public exposure was not necessarily true. As in the radiation paradigm, it soon became apparent that management to a one-in-a-million level of cancer risk was not technically and economically feasible in all situations, especially where chemical use had clear public benefits, and many regulations from EPA and other environmental or consumer product agencies have implied less stringent risk limits, ranging up to one in ten thousand or, in some cases, higher. Meanwhile, carcinogen

[3]The extent of background radon risk was not appreciated until fairly recently and it is to some extent controllable. Consequently, most early discussions mention only the former sources.

regulation in the workplace took yet another direction, and acceptable risks implied by occupational regulations are typically a factor of ten higher (*i.e.,* less stringent) than for the general population. Table 2 summarizes some of the risk levels implied by regulatory limits.

As you can see, the range of risk criteria is quite large. Much of the variation can be explained by the legislative, regulatory and judicial framework of the area being regulated. For example, the *Vinyl Chloride* decision regarding the National Emissions Standards for Hazardous Air Pollutants (NESHAPs) required EPA to set first a level of emissions protective of human health and then to provide an ample margin of safety taking into account economic and other factors (Whipple, 1989). But that decision also gave EPA the option of deciding within relatively broad bounds what risk levels were protective of human health. In writing the *Vinyl Chloride* decision, Judge Robert Bork (who later was unsuccessfully nominated to the Supreme Court) did not equate protection as complete freedom from risk. Moreover, workplace standards are typically less protective from a risk standpoint than are standards for the general public. The rationale for that difference seems to include the presumption that workers accept their risks more voluntarily than the public and that, on average, they do not receive exposures as close to the regulatory limit as does the public. In radiation protection, for example, the general standard of 50 mSv y^{-1} for workers is accompanied by the directive to keep exposures "as low as reasonably achievable" (ALARA) (NRC, 1977). (Recently, international radiation protection organizations have proposed to drop the occupational standard to 20 mSv y^{-1} (ICRP, 1991).) In many occupations, the ALARA principle keeps average worker exposures well below the regulatory limit. In some occupations such as radiology, however, many annual exposures are very near the regulatory limit.

To me, the pattern shown in Table 2 suggests that radiation standards have historically been less strict on a risk basis than have standards for chemical carcinogens. There are several reasons why this may be so. First, as illustrated by the ALARA discussion above, radiation standards have tended to be "top down," in the sense that the standard is intended as an absolute cap with management always attempting to reduce exposures and risks further. By contrast, chemical carcinogen management has tended to be "bottom up," in the sense of setting risk criteria that are widely viewed as acceptable, and then relaxing the standard somewhat to cope with unusual circumstances. For example, many EPA regulators would probably respond that their offices consider one in a million to be a *de minimis* risk level sought as a goal. But in practice, risk decisions may imply much higher levels of risk. In the Superfund program, for example, the target level for risk is 10^{-6}, but risk managers are not required to order cleanup if estimated risks for the

TABLE 2—*Precedents for risk management criteria.*

	Typical Risk	Minimum Risk	Maximum Risk
Background radiation	0.005		
Radon in indoor air	0.01		
Radon in drinking water	0.00013		
Radiation facility	0.0013		
Radiation worker	0.1		
Chemical worker	0.001		
NESHAPs	0.00001	0.000001	0.001
Superfund	0.00001	0.000001	0.0001
California Proposition 65	0.00001		
California Hot Spots	0.00001		

reasonable maximum exposure (RME) are less than 10^{-4} (Clay, 1991). In fact, some managers interpret the 10^{-4} prescription to apply only to the exponent of the calculated risk: 3×10^{-4} may then be considered to be acceptable. Similarly, the NESHAPs rules for benzene seem to allow individual risks approaching 10^{-3} when the number of people potentially exposed to a source category is small. And the implied risk levels for both chloroform and dioxin in drinking water both exceed 10^{-4}; for chloroform, the exception is allowed because chlorination of water is so cost-effective for disinfection, while for dioxin, the exception is based on the lack of widely available methods for detecting levels lower than the cited standard.

Another possible reason is the existence of unavoidable background levels of radiation, while at least some chemical carcinogens are produced mostly if not exclusively by human activities. Some people argue that any human-caused radiation risk that is smaller than background is not worthy of concern, especially if the concentrations of a radionuclide or the radiation exposure levels are too low to be distinguished statistically from the corresponding background levels. This may be one reason why the current overall standard for radiation protection of the general public, 1 mSv y^{-1}, is the same as the average background level for radiation exposure (exclusive of radon). Other people see no reason why other sources of exposure should have any bearing on the desirability of risk reduction and argue for a risk-based approach.

Moreover, the distinction between chemicals and radionuclides as to background levels is far from sharp. Essentially all of the elements are naturally present in the environment at measurable levels, as are many inorganic compounds of them. Even for organic compounds, natural processes are often important if not dominant as sources of exposure. Although regulated pesticides are often synthetic chemicals, they have many natural analogues that probably pose more collective cancer risk than do the regulated pesticides. And among the radionuclides, all of the transuranic elements as well as most of the short-lived radioactive isotopes of the elements ordinarily considered "stable" would not be detectible in the environment if not for human activity, and therefore do not have true "background" levels. (Even fuzzier distinctions can be made: if a radionuclide is present on a site because of worldwide fall-out from nuclear weapons testing, does it have the same priority for concern as a radionuclide of similar estimated risk that arose from on-site activities?)

For example, many of the naturally occurring heavy metals are suspected of having carcinogenic potential in addition to any non-cancer toxicity they may possess. Should they be of less concern than synthetic organic chemicals with similar estimated risk levels for this reason?[4] Should they be regulated like exceptionally long-lived radio-nuclides? [The practical difference between a halflife of four billion years (^{238}U) and a stable isotope is to me less than that between the former and a radionuclide with a halflife measured in days.]

Another possible reason for the difference in risk criteria between radiation and chemicals is the ways in which these criteria have traditionally been applied. Most risk-based chemical standards have been promulgated on an individual basis: the risk of asbestos in the work-place should be no more than (about) one in a thousand, and so on. Radiation has often been an aggregate standard: the general public should not receive any more than 25 mrem y^{-1} from any one facility for all radionuclides combined. Therefore, if one added up the potential risks from 50 chemicals all regulated to, say, one in ten thousand risk, the aggregate risk could be computed as five in one thousand, the aggregate risk corresponding to the general population radiation limit of 1 mSv y^{-1}. But this calculation is not exactly fair either, because the chemical standards limit each exposure individually, while the radiation standard applies to any combination of individual radionuclide exposures. Moreover, management of chemicals associated with waste already is comparing aggregate risk with the risk criteria I have cited. At a Superfund site, for example, the cancer risks to the RME of all the chemicals assessed are added and compared with a risk criterion of around one in ten thousand. Although this aggregate risk is usually dominated by no more than three chemicals, the aggregate risk criterion could in some situations mean that no one chemical could exceed a risk of one in a hundred thousand. And at some Superfund sites, both

[4] The calculated risk levels corresponding to background concentrations of heavy metals are generally much lower than for background concentrations of radionuclides, however.

chemicals and radionuclides are present. No good reason occurs to me to do separate calculations for chemicals and radiation, if one has already accepted the idea of adding risks across chemicals before comparing with a risk criterion.

In summary, the current regulatory structure is rather confusing to someone who is looking for a consistent, risk-based policy for the control of hazardous materials. True, many factors are at work that prevent complete consistency (*e.g.*, the nature of the enabling legislation for regulations). True, factors beyond the raw risk numbers are important in decision-making for chemical and radioactive waste as well as other environmental hazards. But in my view, harmonization of radiation and chemical risk management is a worthy goal. Harmonization does not require identical risk criteria in all situations, but it does require for differences to be clearly understood by all parties and to be acknowledged as legitimate by the major stakeholders (Brown, 1992). It is not my role to suggest exactly how the harmonization is to be achieved; I urge all the participants here today to think through the importance of risk considerations relative to other factors in risk management and to let their conclusions be known to EPA, the Nuclear Regulatory Commission, the Department of Energy, and other interested parties.

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Discussion

MR. ITSON: My name is Frank Itson. I am from the IT Corporation. When one considers the difference between the risk calculations for chemicals and radiation, several important technical mismatches become apparent. One is that the carcinogenicity of radiation is usually described in terms of cancer fatalities. For chemicals, it's expressed in terms of cancer incidence. That mismatch has to be reconciled. One group working to achieve this is the ICRP. Another mismatch is that if one is to calculate chemical risks and use the EPA methodology, the slope factors are based on a 95 percent confidence level for risk. In radiation, it's the fiftieth percentile. These are really nuts and bolts issues that have to be worked out if we are going to achieve any kind of harmony at all.

Do you have any idea how these issues might be resolved?

DR. BROWN: Well, you have put your finger on a very important problem of matching the risk assessment and the risk management. The fatality versus incidence thing that you cited represents an important mismatch. It is being addressed within EPA. They are now putting out risk factors for both mortality and incidence. Typically the difference is about a 50 percent higher number for incidence than mortality. With respect to the way that the data are assessed, you are also correct that radiation—because of the better data base and the fact that it's in humans—tends to be assessed on more or less a best estimate approach whereas the chemical risks are assessed at a conservative upper bound kind of level.

And that actually exacerbates the problem. Because what is being done will more likely than not result in an over-estimation of the risk of chemicals, even though a more stringent risk limit is being applied.

UNIDENTIFIED: One of the mechanisms influencing the effects of radiation is the duration of the free radicals. When you expose chemicals, such as tetrachlor, to radiation, you create a completely different environment. Because mixed waste contains both radioactive materials and toxic chemicals, such considerations are important. Assuming that the effects of the individual components, when acting together, are additive is inaccurate—they may be synergistic. Making decisions in the face of these considerations is very difficult.

DR. BROWN: Let me address just briefly the issue of synergism. It's quite correct that, at least from a theoretical point of view, we could have considerable synergism of radiation with other things. At high levels of exposure, we already know, for example, that radon interacts with cigarette smoking with the net result that the effects are more than additive. There's a legitimate question, however, whether this is important for very low-level risk assessment because I think, in a technical sense, the interaction term may tend to drop out as both of the insults or several insults each individually get into the low-level risk range. But that's a technical decision. This is discussion we can pursue during the break.

MR. DORNSIFE: Bill Dornsife, Pennsylvania. I think that perhaps you have fallen into a trap. What I am referring to is the fact that in your slide pertaining to radiation you used the upper occupational dose rate limit in estimating the associated risk; in the case of the chemical worker my impression is that you used a more realistic exposure number. Radiation workers today seldom receive doses anywhere near the limit. If comparisons are to be made, they should be based on comparable numbers—in this case the actual doses being received.

DR. BROWN: Well, for the numbers in the slide I used the quoted literature on what the risk coefficient is, multiplied by the exposure limit that has been specified, taking into account whatever assumptions were necessary to put the numbers together. One such assumption is whether you receive the given dose every day of your life or over a limited period of time. As you noted, these assumptions do not take into account any differences in how you manage the limit. That's why I pointed out that in radiation facilities, they use a top-down approach, while in the chemical industry they use a bottom-up approach. There's not as much of an ALARA tradition on the chemical side.

DR. RYAN: I would like to endorse your idea of harmonization of risk, both in terms of these kinds of workplace limits, which most of those are, and also in terms of environmental limits for radioactivity and other chemical pollutants, and so on. But I endorse Bill Dornsife's comment that it is dangerous to present simplified numbers on a table like that.

For example, on the chemical worker, that's per chemical. How many chemicals are there in a refinery that workers are exposed to? Is there a thousand? If so, the risk assessment should take into consideration the effects of what combination of exposures the workers receive. Each risk number that is calculated applies only to a specific set of circumstances. Care must be taken in making comparisons between different types of situations, each of which involves a different set of parameters.

Having said that, I now have a question: Where do medical exposures factor into your table or do they at all? The reason I ask this is because such exposures represent the single largest contributor to dose in this country in terms of man-made sources.

DR. BROWN: You have raised several issues. I will take the last one first. Medical exposures. I did not put them in there. I assume you meant medical exposures to the patient . . .

DR. RYAN: Yes.

DR. BROWN: . . . as opposed to the administrator. The argument that the M.D.'s make is that they know best in terms of what the risk trade-offs are for the exposures versus the medical benefits. With respect to the issue of multiple chemicals, I agree. In my formal paper, I point out that, typically on the chemical side, the limits apply chemical by chemical. As a result, for the worker assumed to be exposed to a wide range of chemicals, that might imply a risk that is several times the true risk. In any one facility, usually only two or three chemicals dominate, and so you usually do not get an inflation by more than about three. Furthermore, in the evaluation of situations such as Superfund sites, the chemicals are added up before being compared to the risk criterion.

MR. WEBER: Mike Weber from the NRC. Linking your presentation to the previous one, the risk that you are talking about here presumes that the exposure occurs, but does not include the probability of exposure. I believe a more comprehensive, perhaps an engineering risk assessment, would look at the probability of exposure. I wonder if you would care to shed any views on how that might be done?

One example would be to estimate the risk using the Clean Air Act standards for radionuclide discharges. Assuming the probability that an individual would be exposed at the level of the standard under Superfund, what's the probability that somebody's going to move onto a site and will become a farmer growing crops on such facilities and all that sort of things?

DR. BROWN: Thank you for that comment. I will admit that I put this presentation together more from the standpoint of what we call chronic risk assessment. That is the case where releases, or whatever you are worried about, are more or less continuous, and are not tied to events, catastrophes and so on. If catastrophes are to be considered, then the situation becomes comparable to the PRA (probablistic risk analysis) type of analysis conducted within the nuclear power industry. Presumably the two types of analyses can be connected by multiplying the probabilities of these things actually happening by their associated consequences before you start comparing the results with your criterion. That reminds me to say one additional thing. That is, that I did not talk much about uncertainty. And obviously, uncertainty is rampant in the risk estimates.

It is important that all risk analysts and managers understand that. A bright line, "speed limit" type of risk criterion is clearly the wrong approach to apply.

MR. BROOKS: Antone Brooks from the Pacific Northwest Laboratory. One of the things I think we have to keep in mind is the origin of the risk numbers being used. Most of your radiation risk coefficients are derived from human data. Most of your chemical risk coefficients are derived from other types of data, quite commonly, laboratory experiments with animals. To compensate for this fact, you add a safety factor. If all you have are data developed using cells, you add another safety factor. In reality, if you have a complex mixture, the compound that you know the least about drives the risk. I think that's one of the big problems also.

DR. BROWN: I would agree with that. On the risk assessment side, the safety factors that you cite often drive the numbers up. In essence, the application of conservatism puts your point estimate further up. As a result, the procedures used in a conservative chemical risk assessment tend to be even more unrealistic when the associated risks are low.

By the way, I keep saying I am going to say something final. One more thing. All of these risk decisions are trans-scientific in the sense that you cannot say in any scientific way, with the assumption of no thresholds, what the right answer is. All of them involve a social judgment of what we should tolerate, and obviously this type of judgment varies depending on whether you are the one that's affected or the one that's gaining the benefits from the decision. I assume that Susan Wiltshire will talk more about this.

Social and Political Considerations

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Abstract

Developing a system of waste classification for radioactive and mixed waste based on risk is appealing because such a system has the potential to be logical, transparent and straightforward. As noted by other speakers, the current system is based, in some cases, on the origin of the waste; in others it is based on its radioactive composition and concentration. These differences are difficult to explain and even more difficult to discuss in a policy and planning context. Situations can arise in which materials of relatively high radiological hazard are classified as low-level waste; or in which some materials of relatively low radiological hazard are classified as high-level waste, as in the case of certain chemical processing of waste from which key radionuclides have been removed. The picture becomes even more complicated for mixed waste.

Public discussions about siting low-level waste facilities and developing mixed waste plans under the Federal Facilities Compliance Act have highlighted the difficulties the lack of a uniform classification system can cause. The issues are not new and have been raised in other contexts, including the NRC's proposal to establish a policy regarding radioactive material below regulatory concern.

This paper will discuss the following concerns and expectations interested parties have raised about the potential impacts of a new waste classification scheme, particularly as efforts are undertaken for its implementation:

- potential disruption of the legal and regulatory system under which waste is currently managed, including the potentially negative impacts on the authority of the states to regulate waste
- impact on ownership, responsibility and liability for waste
- possible diversion of regulatory, management and citizen attention and time from solving waste management problems to developing the new classification system

- possibility that the new system will be as complex and opaque as the current one
- difficulty in achieving consensus on the risks posed by various toxic chemicals and radionuclides
- the tension between the national need for consistency of protection and commitment of resources and the local need for incorporation of local values and conditions into waste management decisions
- improving the process by making it more transparent
- improving waste management practices through application of a uniform risk-based criterion

Any process for developing a risk-based classification system must allow thorough exploration and discussion of these and other public issues, if the resulting system is to be successfully applied.

Introduction

A proposal to develop a risk-based system of waste classification for radioactive and mixed waste is appealing because such a system has the potential to be logical, transparent and straightforward. As noted by the other speakers, the current classification is based in some cases on waste origin, but in other cases on radioactive composition and concentration. These differences are difficult to explain and even more difficult to discuss in a policy and planning context. Furthermore, they can lead to situations in which materials of relatively high radiological hazard are classified as low-level waste; they may also lead to situations in which some materials of relatively low radiological hazard are classified as high-level waste, as in the case of certain chemical processing waste from which key radionuclides have been removed. The picture becomes even more complicated for mixed waste.

The issues are not new and have been raised in other contexts, including the Nuclear Regulatory Commission's (NRC) proposal to establish a policy regarding radioactive material below regulatory concern. Recent public discussions about siting low-level waste facilities and developing mixed waste plans under the Federal Facilities Compliance Act have highlighted the difficulties which the lack of a uniform classification system can cause in the public policy arena.

Classification of things is supposed to serve as an aid to thinking about and understanding them. However, the current waste classification system presents barriers to public understanding and public discourse. For example, low-level waste is a catch-all category. People are troubled by the fact that low-level waste is defined by what it is not, rather than by what it is. It is difficult to confront a system that works this way, or to be responsible—as states are—for waste that is classified by what it isn't. When people notice that some of the chemical processing waste, classed as high-level waste, may present less hazard than some of the waste they are being asked to manage in their states as low-level, they raise a number of interesting questions. The differences between hazardous and radioactive waste management, the difference between the Environmental Protection Agency's (EPA) philosophy and NRC's—all of these factors also present barriers to public discourse. These are not imaginary barriers; they are real. The question is whether moving to a risk-based system would improve the situation.

The general topic of using risk in decision making is not new. Quite a few of us have been working on the issue of risk-based decision making for some time. In 1991 I was asked to speak at a Department of Energy (DOE), National Laboratory Directors' Forum on risk-based standard setting. To prepare for that talk, I asked a colleague to interview representatives of public interest, environmental and labor/management groups. The goal of the interviews was to help us identify and begin to understand the issues.

Another colleague interviewed a similar group to help me prepare for this Symposium. Neither set of interviews was exhaustive or statistically meaningful, but they did provide an indication of the range of issues that will be raised by proposals to use the concept of risk in decision making. I'd like now to touch briefly on some of the concerns and expectations we heard and draw a few conclusions.

We found those we talked with to be thoughtful and well-informed about risk and waste management issues. The interviews would have been more fruitful if we'd had a definite proposal to discuss, but one thing is clear. Interested parties are prepared and will be able to contribute to discussions about a risk-based classification system, if one is proposed.

Search for Risk-Based Concerns and Expectations Voiced by Interested Parties

The Potential for Disruption of the Legal and Regulatory System

The potential for disruption of the legal and regulatory system is a serious concern to several groups of interested parties.

When a risk-based system is proposed, those who are engaged in siting, building or managing facilities under current regulations, or who have participated in the rule-making process frequently say, "Don't touch a hair on its head! We've finally got moving in some direction. We know where we are. We don't want to change now." Those who have fought the regulatory wars have spent quite a bit of time, money and effort in many hard battles and have made difficult political trade-offs. These people do not want to lose what they have gained. However, those who are less interested or involved in regulatory matters are often freer to focus on the problems, and they wonder what kind of regulations would help solve them better. Some of these people may know little about current regulations and are just beginning to think about how these issues should be approached.

I frequently hear from environmental lawyers that there is a lot of room for common sense in the application of current environmental laws, but that the government does not know how to deal in that arena because the government does not have much experience there. They say that government officials do not yet have a very sophisticated understanding of how to work to solve problems within the regulatory system. These people have concluded that you do not need to make changes in the system until the government tries to use it more creatively.

Some members of the public fear that the move to develop a new classification system will provide an opening to loosen standards under industry pressure. This is always a concern when regulations are reopened.

At federal sites, people are concerned about what a change in classification might do to the states' hard-won foot in the door through the Resource Conservation and Recovery Act (RCRA). They worry that any change will reduce the regulatory role of the states.

The basic point is: you've got to convince people something is broke before they'll agree it needs to be fixed or at least you need to demonstrate that their interests may be better served by another approach.

Impacts on Ownership, Responsibility and Liability for Waste

The potential impact on ownership, responsibility and liability for waste are yet another concern. By and large, we know who is currently responsible for what and where the liabilities fall. Some members of the public express uneasiness about how that might change under a new system.

Diversion of Attention and Time

Others point out that devising a new system will divert considerable attention and time from the "real work." There are disadvantages to expending the regulatory, management and citizen effort it takes to change from one established set of categories to another. Will we need to reopen and modify all environmental laws for the new system to work? Would our time be better spent in using the current system to solve problems? People want to be certain something good can come of this before they put forth any effort. They will need to be convinced there is a possibility of a good outcome and that their time will be well spent before they will be willing to engage in the kind of creative discussion that will be necessary to develop a workable system with broad acceptance.

Possibility That the New System Will Be Just as Complex and Opaque as the Current One

Some people question whether, by the time the discussions end, we will be any closer to solutions. One person wondered whether the new system would decrease the number of regulatory hoops or would become a hoop of its own for people trying to find solutions to waste management or site cleanup problems.

Difficulty in Achieving Consensus on the Risks

It will be difficult to achieve consensus on just what risk is posed by various toxic chemicals and radionuclides. This is the case not just in the public arena, but also within the technical community. Some members of the public question the underpinning of risk assessment and want to know whether the quality of scientific understanding and of data is sufficient to support a risk-based system. In discussions about proposed risk-based decision-making systems we heard, "Do you know enough to do the analysis? Are the data good enough? Do you understand the physical systems well enough to represent them in a risk assessment?" However, as Dr. Garrick pointed out in a previous presentation, a key element of risk assessment is the quantification of uncertainty in the results. He maintains that the quantification of uncertainty can help all parties in policy discussions better understand the current state of knowledge about a particular risk and decide whether it is an adequate basis for taking action or whether more needs to be known or understood. Risk assessment, in his view, must be approached as an iterative process.

Risk is a difficult concept to discuss in the abstract. The conversation always turns to the risks of what and to whom. People want a say in how the risks that affect their lives are defined, and they do want to be part of the discussion. Some are convinced that experts choose which factors to assess much as one looks for a lost article under a street light simply because that's the easiest place to look. For example, cancer morbidity and mortality are the most frequently chosen endpoints for risk assessments. Perhaps this is the case because more information exists about cancer risks than about other health effects (such as neurological problems or genetic defects) that may also be significant and of concern.

People ask about the identification of pathways, receptors and end-points, and want to make certain that risk assessors realize that these attributes are site-specific and may depend on the culture and habits of the people who live around a particular place. Pathways and receptors are not abstract concepts; they are concrete reality. It will be difficult to get consensus on risk in any generalized way, because discussions of risk depend on contexts.

The Tension Between the National Need for Consistency and the Local Need for Incorporation of Local Values and Conditions

People are quite vocal about the tension between the national need for consistency and the local need for incorporation of local values and conditions. Those concerned about national policy desire a level playing field in the use of resources, so that members of the public in different states are treated equally. Some residents of states conclude that they must depend on the federal government for leadership because their states have very poor records on environmental protection. However, people in states with better records frequently want the federal government to stay out of their way. The focus varies, but tension between local and national interests remains.

Improving the Decision Process by Making it More Transparent

The people we interviewed did point to some possible positive aspects of a risk-based system. One is the possibility that the application of such a system could improve the decision-making process by making it more transparent. A risk-based classification system would also provide a basis for facilitating comparisons among various wastes and the methods and sites proposed for their disposal. In essence, such a system has the potential for improving decision making not only by making trade-offs clear but also by providing a scientific basis for their support.

Improving Waste Management Practices Through Application of Uniform Risk-Based Criterion

Another positive possibility which people raise is that improving waste management practices through application of uniform risk-based criterion could reduce costs and the regulatory burden of waste management. Cleanup and waste management are potentially huge resource drains. Expediting cleanup in a less resource-intensive way could prove to be a positive contribution of a risk-based system.

Conclusions

People want to know the intent of proposals and the possible consequences—intended or unintended. They ask why this change is being proposed and why now. They ask whether mixed waste is the central issue. They wonder whether the purpose is to harmonize the chemical and radioactive components in the mixed waste, or to achieve equity across waste types, or to reduce some other set of problems. The purposes and intents of proposals need to be made quite clear to avoid the appearance of a hidden agenda.

The bottom line is the ways in which a new system will affect decisions. Will it help risk managers reach decisions that people will regard as equitable and in their own interests, or will it hamper that process and possibly relax protection? Some hope that clarifying the classification process could open up the discussion and be a way to begin more dialogue. Others worry that these proposals could lead to another case in which professionals will say, "We're technical people, this is the way we analyze risk, and this is what the risk is." They question whether a new system will allow a discussion that takes into account the information, knowledge and preferences of local people.

The concept of risk-based anything carries a lot of baggage. Risk is in vogue now for use as a decision-making tool, but proposals to use risk have an unfortunate history of aborted attempts. Many people don't want to discuss risk unless it is clearly acknowledged that it is not a value-free concept, that risk assessment is not an antiseptic, strictly technical methodology (if there is ever such a thing). People make decisions in every step of the process, using their own presumably expert judgment and these are incorporated in risk assessments. People who are affected by such assessments would like clear explanation of the values on which those judgments are based and to be sure that their own values are recognized and considered.

Knowledge about how a community works and the habits of the people who live there is necessary to identify potential sources, receptors and intake mechanisms in order to make an accurate assessment. When you use a reference person in an analysis, you may miss an important risk if the habits of the local people are different from those on which the standard reference person is based. Tribes are especially concerned about this issue. Their members may be a greater risk from exposure to environmental contamination because their use of local fish, wildlife and plants for subsistence and cultural activities occurs at much higher rates than in the general population. For example, the amount of fish consumed by the Yakama Indian Nation in their traditional diet is many times greater than to the amount that is assumed to be consumed by the reference man.

Beyond that, when risk becomes the thing everyone talks about as the way to make trade-offs and arrive at decisions about what action to take, people fear that risk will become the only consideration. There are many other reasons for cleaning up contaminated sites or for managing waste in a particular way. For example, there is the moral obligation to cleanup what we as a society have contaminated. There are legal obligations. There are the treaty rights of tribes under a government-to-government relationship. There is economic development for the communities that grew up around the sites and for the workers and their families who moved there because the weapons facility offered employment. Do we have an obligation to the people who remain? There are undoubtedly other reasons that could be named. But when risk becomes the overriding decision factor, concerned parties may fear that every relevant factor will have to be described as risk or otherwise lose consideration in decision-making. I saw that develop during work on a multiattribute utility analysis decision making tool for environmental remediation. Many concerns were added in as factors to be taken into account that were more properly overarching factors that should have been beyond the analysis. But because it looked as if decisions would be based on a series of numbers or curves produced by a black box, people tried to force into the system factors that were not compatible with that kind of analysis. To clearly acknowledge that risk is one factor, but not the only important factor, helps the discussion.

Any process for developing a risk-based classification system must allow a thorough exploration and discussion of these and other public issues, if the resulting system is to be successfully applied. People are ready to enter the discussion, if they are convinced the problem needs solving and if they believe their time will be well spent.

Discussion

MR. PASTERNAK: My name is a Alan Pasternak. I am the technical director of the California Radioactive Material Management Forum, which is an association of some 60 corporations and institutions in the four states of the South Western compact. Since 1982, we have been working toward implementation of the Radioactive Waste Policy Act and the regulations promulgated by the Nuclear Regulatory Commission in 1982. The site selected for a disposal facility in California is the Ward Valley site which has received a license, but which has not yet received the necessary transfer of the land from the federal government to the state.

There are license applications pending in three other states. For that reason, I am happy that Susan Wiltshire's presentation was put on this program and that the questions that she's posed have been asked. As she has pointed out, there is a very serious danger in pursuing the development of a risk-based waste classification system, particularly at this time with three applications pending, and one that already has been granted, but now is in litigation. My question is: What are the risks and what are benefits of pursuing this matter at this time? To expand on my question: What will we gain by further tinkering and trying to make the existing system more perfect if it's already adequate? Might the associated consequences include serious disruptions of the existing licensing processes?

The question Ms. Wiltshire asked was: How do we convince people that something that is not broken needs to be fixed? This leads me to my first point. The basic principle of the system is exactly what Ms. Wiltshire said: If it ain't broke, don't fix it. So first we have to identify what's broke and what is not broke. With the restrictions recently placed on the shipment of low-level waste to the existing disposal sites, 31 states now find themselves with no place to send their waste. This needs to be fixed. The waste classification system is not broke. It does not need to be fixed.

Point number two: There are two kinds of people involved in this debate. There are those who want to fix what's broke, and there are those who do not want to fix what's broke. That is, there are people who do not want to see the Low Level Waste Policy Act implemented and new disposal facilities developed.

Point number three: What is the correspondence between what's broke and is not broke, on the one hand, and the people involved in the debate on the other. One group of people are those who want to fix what's broke, and do not want to fix what is not broke. I am in that category. Another group are those who do not want to fix what really is broke, and do want to fix what is not broke.

As Susan Wiltshire pointed out, there might be some unintended consequences of these various types of actions. In keeping with the NRC's system of jargon, rather than using the word "unintended," I should use the word "inadvertent." I say this because those who think that they can fix what is not broke, that is, make the classification system even more perfect, while at the same time fostering the development of new disposal facilities, are really inadvertent intruders upon this effort.

It is also important for us to realize that the controversy is not driven by disposal; it is driven by the use of radioactive materials. For example, the leading opponent of the Ward Valley facility in California is the group that has politically led the opposition, a group that is leading the litigation, has as one of its points of litigation that there should be under existing state law a so called adjudicatory hearing for the license. There have been plenty of hearings, but none fits the description of adjudicatory. The California legislature has refused to change the law, and the courts have already ruled that that's not necessary. But look what they are doing. If they were ever successful in convincing a court somewhere in California that lack of a certain kind of hearing invalidates this license, they would immediately invalidate 2,200 licenses in the state of California for hospitals, for universities, for industries.

There also appears to be confusion in terms of the objectives of the state versus those of the EPA regional office. In the case of the Ward Valley site, the EPA Region 9 office in San Francisco urged the state of California at one point to disregard NRC's regulations regarding the design requirements for the disposal facility. Later, they gave up on this and came around. Some of the same problems have developed with respect to the NESHAP application. Again, the regional office staff appears to be dragging its feet.

I pray that efforts to develop a risk-based classification system will not contribute to additional delays. There's not really a question in what I have said. Rather, there's a whole bunch of comments that maybe you can respond to.

MS. WILTSHIRE: I have no direct response, but I have a question for you. Can you envision the possibility that a risk-based classification system could be developed for mixed waste that would not disturb the low-level waste situation the way you have described? Would that be acceptable?

MR. PASTERNAK: All of my comments are directed toward getting disposal facilities for low-level waste on line. I am not commenting at all on the mixed waste issue. The California license does not address disposal of mixed waste. I think it was pointed out this morning that only 1.5 percent of all the mixed waste in the country is commercially generated; the rest is being generated by the Department of Defense. We are hopeful that the Department of Energy will accept responsibility for the disposal of commercial mixed waste. I have in other forums pointed out the other difficulties in reconciling the requirements for disposal of hazardous waste under the Resource Conservation Recovery Act on the one hand, and the Atomic Energy Act on the other. The comments I made today are really directed toward low-level waste.

MS. WILTSHIRE: I understand. I was just putting that question on the agenda for anyone who wants to think about it. I do not know what's being contemplated as a proposal, but if it's aimed at mixed waste, perhaps it could be pursued without disturbing the ongoing situation with respect to low-level radioactive waste.

MR. PASTERNAK: Certainly the regulatory system with mixed waste can stand some improvement. I am not saying it's impossible to meet both sets of requirements. Both the NRC and the EPA have put out some design proposals, but it requires a lot of unnecessary fiddling with the design to develop a system that meets both sets of regulations. I really do not have an answer as to how classification systems might improve the situation with respect to mixed waste.

MR. DORNSIFE: Susan, maybe I can help in terms of this issue. One of my ancillary duties is to serve as chair of a National Advisory Council for Environmental Policy and Technology subcommittee that's helping EPA develop their cleanup standards. If one of the purposes of the development of a risk-based waste classification system was to apply it to the waste resulting from facility cleanup, then you may be able to find a very useful purpose for it. Not all of the cleanup waste is going to be acceptable at the new low-level disposal facilities. There's a need for other places where this waste can be disposed and there's going to have to be some system that sorts out where it goes. In that regard, the development of a risk-based system for low-level radioactive waste is both necessary and essential.

MS. WILTSHIRE: Thank you.

DR. PITT: I am Wilson Pitt from Texas A & M University. A couple of comments. When you were talking about the current regulatory environment and the fact that maybe it is not broke, an old story came to mind that sort of describes the situation to me. That is the story about the emperor's new clothes. The other comment is that we need to keep in mind what the risk is of not doing something. That needs to be brought home both to us and to the public at large.

MS. WILTSHIRE: Thank you.

MR. JENSEN: Larry Jensen of the EPA. The RCRA system, I think, does have some things that are broken. I also think that, perhaps with the right amount of pressure, some of these could be fixed. One of the things is that the system for classifying the hazardous characteristics of toxic chemicals includes toxicity, corrosivity, ignitability and reactivity, but it does not include radioactivity. It would be nice if radioactive decay could be used as a mechanism to deal with some of the problems of mixed waste like the NRC applies in terms of medical waste. If you hold such waste for ten halflives, they become essentially non-radioactive and can be readily disposed.

The other thing that's in RCRA, I think, is the brokenness. If you burn or destroy certain toxic chemicals in certain ways, the ash is still considered to be a hazardous waste. So you cannot get such waste out of the system. It's a one-way street. There ought to be some mechanism to do that. If such a mechanism existed, it would be possible to treat mixed waste so that the residual could be classified as radioactive waste and be eligible for disposal under the requirements applicable to that type of waste.

Maybe we ought to look at changes in the RCRA law that would allow us to deal with radioactive materials. Certain waste, such as scintillation fluids that contain ^{14}C and ^{3}H are being routinely incinerated, after which they are allowed to be handled as if they are not radioactive. Technically they are, of course, and probably somebody could even file a lawsuit saying that they are still mixed waste. Nonetheless, under current regulations such waste can be sent to incinerators where they can be destroyed and dealt with. We need to look at possibilities of applying similar thinking to other types of waste.

MS. WILTSHIRE: Thank you.

MR. LIEBENDORFER: Paul Liebendorfer with the State of Nevada. I have a couple of comments. Those of us at the state level have a little bit of concern about how waste is classified. This is particularly true with regards to whether you are talking about mixed waste, as the commenter before me mentioned, low-level waste resulting from defense activities within Department of Energy facilities, or high level waste resulting either from activities within DOE facilities or commercial nuclear power plants. The population at large sometimes has a difficulty in distinguishing between various categories of radioactive waste. The situation becomes more confused when you throw in defense low-level waste which is not covered by NRC regulations. That's one point.

Nationally, the Department of Defense still probably produces 90 percent of the low-level waste that exists in this country. Low-level waste coming from the commercial sector is a small percentage of the total. As everybody knows, Yucca Mountain, which is proposed as the site for the disposal of high-level waste, is located in Nevada. Nevada is also concerned about the disposal of low-level waste since, according to present plans, about 90 percent of the low-level waste that will be shipped, moved off site from DOE facilities—not disposed on site—is actually to be disposed of at the Nevada Test Site. In addition, there's certain quantities of material the Department of Defense has classified as low-level waste which could come very close to being classified as high-level waste if it did not come from a DOE facility. In essence, the definition of what is what is not that clear.

Changes may also occur as DOE decides which of their waste must be classified as radioactive. Depending on the concentrations decided upon, the quantities of waste that have to be dealt with may be an order of magnitude greater than currently estimated. On the other hand, a lot of their mixed-waste problems may in fact not truly be mixed waste because the radioactive content is really so low that the waste can probably be handled as hazardous. One of the things that really needs to be done is to develop a classification system that incorporates a category that is designated as "below regulatory concern." If this were done, certain waste now classified as mixed could be classified as simply hazardous solid waste. To repeat, the current classification system is leading to a lot of ambiguity, particularly to the public at large. This is of concern to those of us in Nevada.

MS. WILTSHIRE: That's another issue that was brought up in some of my discussions. That is, whether or not the mixed waste situation was being complicated because regulators have not found a way to classify mixed waste as one or the other through mechanisms such as taking decay into account. Although I did not mention it, that was one of the potentials that was called to my attention in the interviews. Thank you for bringing up the subject.

Reflecting on the situation, we find that we have worked our way into some complicated schemes for both waste management and classification. But, you know, life is neither logical nor neat. I guess the message I hear is that that's the way things happen as you work through the problems at hand. People wonder: if I started from the beginning knowing what I do now, I would do something more sensible, but here I am in this place, so is it worth doing something completely sensible now or making do with what we have? That's the crux of the concern.

DR. GARRICK: John Garrick. Susan, one of the things that I thought would be useful to get your views on before you leave the podium is this matter of public participation in the process. As you know, the Department of Energy has asked the National Academy of Sciences, National Research Council, to address this question. The idea was to try to get some guidelines on how to do it. All of us are saying that we should involve the public in the process. I am not sure, however, that we are doing a very good job of suggesting an effective way to do that, while having any hope of achieving some of the end objectives. As our spokesperson on public policy, I would appreciate hearing your thoughts on how we might do this and, at the same time, have some probability of spending our resources reasonably well.

MS. WILTSHIRE: Just as the decision on a disposal method is highly site specific, and the choice of cleanup method is highly site specific, deciding on how to involve the public is also highly situation specific. You have to define very clearly what the program, the issue, or the discussion is that you want to involve people in. You have to find out whether they wish to be involved in it, and you must ask them how they wish to be involved. Once this has been done, you then must find a way to carry on the discussion that serves the purposes of the agency and the people you wish to involve. There are lots of mechanisms for doing that, but they have to be applied in a way that's sensible for the problem that's being discussed.

The development of effective methods for involving the public requires the same kind of careful thought about ends and means as any kind of technical program. Public discussion should be focused on real decisions, and people's time should not be wasted. Those are some of principles. Now what do you do? Tell me what the situation is, and I and many others can describe to you a way to carry out a technical program with effective involvement of the public. But you have to know what the proposal is and what level of government is involved. If you are talking about a risk assessment for an activity somewhere in Hanford that's very different and very concrete, you can identify the people who need to be involved and they are used to working together.

What you will need is for the folks who are trying to do the risk assessment to be careful about bringing people in at a time when their advice can be useful. You have probably heard all this many times before, but it means that the person making the proposal and conducting the risk assessment has to think through carefully each of the steps. That person also must identify the points in the risk assessment when values are being incorporated. People will need to be able to tell the risk analyst whether or not they agree with those values. The analyst must think about those points and then think about the way to engage the public in conversation about them. It's a matter of really wanting to involve the public and thinking about the public as people who have something to contribute. You must engage them in helping you figure out how to get their contribution and to fit their involvement into the particular situation. These are the needs on a local basis. The national and state levels are very different because you have broader constituencies. When proposals are at a national or state level, people sometimes do not pay any attention until it affects them, and then they get very concerned about it.

I am on a committee to review the New York State low-level waste site project. During the initial stages, the Siting Commission held meetings on their siting plan in various locations within the state and nobody came. The attendance at a typical meeting, for example, might number 10 people, half of whom were from the agency plus a few more from a local nuclear power plant. Some of these were undoubtedly told that they had to attend. Why did no one else come? Because they did not know it affected them. But when you put pins on a map, people come. That's also a problem at the national level.

I do not think that meetings on regulatory issues like this one will have such a problem. There are groups at the national level who will most certainly get involved and these are groups that local groups trust. In addition, the local groups are now organized. They have their own connections and their own e-mail, and they will sometimes pick their own surrogates to follow certain issues. It's possible to plug into this system and get the kind of involvement at the national level that you need. But first we have got to have a proposal and be able to demonstrate why it's worth people's time to become involved. You also need to talk to people about how they want to be involved. One possible approach is through a dialogue group that stays together. Or you can have periodic workshops or working sessions. There are even ways to engage people in rural areas. I remember one person who put a small Air Stream trailer in a rural parking lot near the little country store. By staying there a week, he was able to talk to people as they came in, engaging them in dialogue in a way that suited their lives. So a great deal is known about how to involve the public. What is required is thought, and the intent to make the contribution real, to use what people can give you, not to waste time, and to make the approach suit the situation.

That's a very long way to say—just think about it and then carry out your plan.

MR. DORNSIFE: Bill Dornsife. I have had some experience in risk communications with real people, and I think it's an uphill battle. One of the problems is, first of all, that the majority of the public does not understand the concept of risk assessment. Unfortunately, many members of the public think that, when you do a risk assessment, the predicted risk is going to be zero. They are unable to accept a risk that is anything other than zero. That's the first problem you run into it.

The second problem is that, in order for them to understand it, the risk assessment has to be very simple. You cannot use a complex system if you expect the public to understand. And finally—and probably most important—is how you communicate the risk to the public. You have to put it in terms they understand. A very elegant and useful tool that we have found is to compare the waste to something the public is familiar with and to compare it on the basis of its toxicity. They understand apples and apples. If you follow those simple suggestions, you have a good chance of dealing with the issue. It's not an easy battle, because the public does not perceive equal risks to be equal. Other things enter the equation. For example, look at the radon issue. It's produced by mother nature, it's a familiar risk, it's in your house, and you have to pay to fix it. That makes the risk decision-making process on the part of the public a lot different than if it's caused by a nuclear power plant.

MS. WILTSHIRE: I would like to take issue with only one thing that you said. It is not necessary, or even prudent, always to simplify. What you want to do is clarify. The two are very different. People will accuse you of "dumbing down." I would not accuse you of that because I think what you want to simplify is the process itself, which is a different issue entirely. Your management process, your decision process needs to be as simple as it can be and yet get the job done. But clarifying complexity should be the aim, not simplifying something that truly is complex in a way that disparages people's understanding. That's easy to talk about, but very hard to do.

Practical Applications of a Risk-Based Waste Classification System

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Abstract

The need for a risk-based waste classification system has been discussed over the past couple of decades and various attempts have been made to develop such a system. To date none of these systems have been successfully implemented because of the many practical problems and concerns with a system that needs to somehow normalize the major institutional and technical differences that exist regarding various toxic materials.

This paper discusses and analyzes: (1) the various components that need to be considered in the development of a risk-based waste classification system, (2) the limitations and critical assumptions associated with each of these components, and (3) the various institutional and technical problems that make the development and implementation of such a system difficult. Finally, examples of risk-based systems that include some of these components are proposed and analyzed to show the practical limitations of such a system.

Introduction

Over the years it has been generally recognized that a risk-based waste classification system, or waste classification by total hazard, is both desirable and necessary to adequately deal with the management and disposal of the ever increasing number of toxic materials (DOE, 1980). This is particularly critical when these toxic materials are combined or "mixed" in the same waste stream. Although various attempts have been made to develop such a system (Smith *et al.*, 1980), these attempts have never been successful due to the very difficult institutional and technical problems inherent in normalizing the risk.

This paper discusses and analyzes the various factors and problems that must be addressed in the development and implementation of a risk-based classification system that adequately handles multiple toxic constituents. The paper is organized as follows:

1. A discussion of the necessary factors and components that must be considered in assessing the risks from waste management, and therefore included in a risk-based waste classification system.
2. An analysis of the difficulty in identifying the appropriate assumptions and specifying the necessary conditions that will affect the magnitude of the components that make up a risk-based classification system.
3. A discussion of the institutional and technical problems inherent in the development and implementation of a risk-based classification system that can handle multiple hazards.
4. A practical example that shows the problems in trying to adapt a simple risk assessment tool, recently developed by the author (Dornsife, 1995), into a more complex system that includes additional components and addresses multiple toxic materials.

Components of a Risk-Based System

The first step in designing a risk-based waste classification system is to determine what are the necessary components that must be included to adequately assess and evaluate the risk. The following factors are possible components of a risk-based classification system. They are discussed in the general order that they would occur from the source to the receptor.

Intrinsic Toxicity

This is a measure of the intrinsic risk due to direct intake of, or exposure to, a waste stream containing multiple toxic materials. It is calculated by dividing the specific activity or concentration of the toxic materials in the waste stream by a suitable and consistent measure of the exposure risk. It also takes into account the physiological transport of toxic material through the human body and the relative sensitivity to insult of the various organs that may be at risk. One of the more common examples of a consistent risk measure from ingestion is the Environmental Protection Agency (EPA) drinking water limits or maximum contamination limits (MCL) (EPA, 1991). Other consistent measures of risk could also be used for other pathways; such as external dose per activity or allowable limit of intake (ALI) for either ingestion or inhalation. The EPA has recently developed risk coefficients that address all three exposure routes (ingestion, inhalation and direct exposure) for radionuclides (EPA, 1994).

Longevity or Persistence

This is a measure of the reduction in concentration, and therefore risk, due to natural physical processes that result from a time delay before exposure occurs. This could include: (1) radioactive decay which is a precise physical atomic property that has been accurately determined for all radionuclides, and (2) organic chemical transformations due to biological processes in a disposal or storage environment which may be less precise to determine. This does not include changes in solubility due to changes in the oxidation or reduction potential of elements or compounds. Therefore, heavy metals are assumed to have no reduction in risk due to this factor.

Build-Up Factor

This is a measure of the increase in risk with time due to natural physical processes that result in the formation of another chemical or elemental form that presents more of a hazard than the original material. Examples include: (1) build-up of radioactive decay progeny that are more toxic than the parent. (This occurs most commonly with primordial naturally occurring radionuclides), and (2) organic chemical changes due to biological activity that result in a new chemical form that is more toxic than the parent. Again, changes which do not affect the chemical or elemental form but only affect solubility are not included in this factor.

Release

This is a measure of the decrease of risk due to consideration of the solubility or availability for release of the toxic material in a given waste form or containment, compared to assumed instantaneous solubility or availability for release. This component includes factors that are related to both the delay in release due to the integrity of engineered barriers, and the solubility or retardation of toxic constituents in their assumed waste form. It should be noted that this factor may increase or decrease considerably with time due to physical and chemical changes in either the waste form or toxic material. This component is best determined by physical measurements or computer performance modeling, and will likely become more uncertain as time increases. Available data indicates that this component can vary significantly based on physical and chemical characteristics of the waste form, containment, transport media and chemical form of the toxic materials (ORNL, 1994; WSRC, 1994).

For waste disposal applications, one of the most important assumptions related to this component is the length of time that credit can be taken for engineered barriers delaying infiltration or intrusion into the waste. This delay will allow for the decay of shorter half-life radionuclides and the biodegradation of toxic organic constituents that typically dominate the risk for early release scenarios.

Retardation or Removal During Transport

This is a measure of the decrease in risk due to the physical or chemical properties of the transport media that tend to delay or remove the toxic material after it is released from the waste form but before it reaches the receptor. Examples include: (1) chemical retardation or absorption factors for transport through soil, (2) resuspension or settlement during atmospheric transport, and (3) self shielding or type of radiation (penetrating versus non-penetrating). If retardation is the mechanism at work, then the total decrease in risk must be closely correlated with the longevity or persistence factor. As with the leachability factor, the available data indicate that this factor can vary significantly based on site specific conditions (Sheppard and Thibault, 1990).

Availability for Uptake

This is a measure of the change in risk caused by pathways that include a secondary transport media, such as uptake from soil though plants. It is only a consideration when the toxic material in its primary transport media is not directly causing the exposure. It can be calculated by dividing the concentration in the secondary media which is being ingested by the concentration in the primary transport media. This factor only applies for certain exposure scenarios and pathways and therefore needs to be used with caution.

Unique Risk Factors

This is a measure of other chemical or physical properties of a toxic material that may enhance the risk, and therefore may not be directly calculated by the intrinsic toxicity factor. Examples include: (1) combined external and internal radiation risks for certain radionuclides [total effective dose equivalent (TEDE)], (2) situations where more than one important pathway may be a contributor to total exposure, (3) synergistic effects caused by the interaction of certain multiple toxic materials, and (4) other properties such as flammability or corrosivity that may present a significant risk of fatality or injury. Although it could be very significant, this factor may be very difficult to normalize and thus include in the classification system.

Sensitivity of the Risk Components to Assumptions and Conditions

There are a number of site specific or scenario related assumptions and conditions that may significantly affect the components of a risk-based waste classification system. Each of these is discussed in the following paragraphs, including their likely effect on specific components.

The Assumed Insult as a Result of the Exposure (Cancer Mortality/Morbidity or Disease)

The intrinsic toxicity component commonly assumes an endpoint for the insult as either cancer mortality or morbidity. Radionuclide studies, for example, generally include risk factors for cancer from both morbidity and mortality. The quantification of the intrinsic toxicity component may not be as straight forward for other toxic materials, particularly where the endpoint for the insult may not be cancer morbidity or mortality. Some of the questions that must be addressed and quantified before any standard can be used to determine the intrinsic toxicity of a waste containing mixed toxics are: (1) How and should the risk from cancer incidence be directly compared with the risk of other possible diseases? (2) Does the standard of choice assume the same risk basis for both radioactive and non-radioactive toxic materials? (3) Are the intake to risk conversion factors comparable? Since these issues will be very difficult to address and quantify, it is recommended that a first generation risk-based waste classification system only include cancer risks.

For the same reasons, the unique risk factors component will be very difficult to effectively incorporate into a risk-based classification system, with the possible exception of the TEDE for internal plus external radiation exposure.

Variability or Uncertainty of a Site or Waste Form Specific Parameter

The leachability, retardation or removal during transport, and availability for uptake components are very sensitive to the assumed or real site specific and waste form specific physical and chemical characteristics. Many of the components that define these factors can only be determined by the results from carefully controlled experiments or by extrapolation of real waste disposal situations. In particular, retardation and absorption in both the soil and waste form are dependent upon situational or site specific parameters such as: degree of saturation, transport media flow rate and dispersion, chemical constituents that are present, pH, and void fraction. As indicated above, these factors can vary substantially; and maybe the best approach is to assume conservative and representative values, such as the mean values for the most representative conditions. In addition, these factors are very dependent upon the point at which the waste is assumed to be evaluated in the total management cycle.

If the components that are sensitive to these factors are to be included in a risk-based waste classification, the best approach may be to consider a two step process. The first step would be to identify those factors that apply in most situations and therefore can be taken into consideration in a generic manner (*i.e.*, certain chemical forms are not readily soluble and are therefore not dependent upon the characteristics of the waste form). The second step could be to develop a more situation specific component that could be substituted into the risk-based classification system for site specific use.

The Assumed Pathway or Predominant Mode of Exposure

All of the above components of a risk-based waste classification system, with the exception of the longevity and build-up, will be greatly dependent upon assumed pathway or mode of exposure. The large variation in results between the different possible pathways dictates that either a predominant pathway must be assumed or an analysis of the likelihood and consequence of various possible pathways must be combined and factored into the classification system. Obviously, the simplest approach is to demonstrate that a single pathway will dominate the risk and base the classification system on this single assumed pathway. However, certain significant radionuclides and other toxics may present a higher risk from an exposure mode other than the assumed predominant pathway.

Some of the specific factors that may cause large differences in risk between the various assumed pathways include the following:

1. Assumed distance between the waste and the receptor. This could depend upon whether the critical exposure is occupational, inadvertent intrusion, nearest individual member of the public, or long-term exposure to the general public.
2. Whether the most likely mode of release is to the groundwater, surface water or air.
3. The assumed phase of waste management (treatment, short or long-term storage, or disposal).
4. The assumed release mechanism for the toxic materials (accident, inadvertent intrusion, or degradation by natural processes).
5. Whether secondary factors such as washout, resuspension or irrigation may cause significant additional exposure.

To be useful a risk-based classification system must be flexible enough to take all of the above factors into consideration. A possible approach for incorporating this major uncertainty into a waste classification system is the following:

1. Identify all of the possible pathways and release mechanisms that may be important.
2. Determine simple and realistic, but conservative, risk-based components for each of the pathways for each toxic constituent.
3. Use the pathway for each toxic constituent that dominates the risk, or combine several pathways if predominant pathway is not obvious.

A special problem exists for disposal systems that include engineered barriers. As discussed above, the engineered barriers will cause a delay in the release component that will tend to reduce the risk from short lived toxic constituents. For LLRW disposal facilities with multiple engineered barriers, it is recommended that this delay is conservatively assumed to be for at least 100 y for infiltration, and 100 to 500 y for intruder protection depending upon the design.

Institutional and Technical Problems That Will Affect the Development of a Risk-Based Waste Classification System

A risk-based waste classification system will no doubt prove very difficult to develop and implement. In addition to the factors mentioned above, there is a number of other technical and regulatory problems that will add to this already difficult task. These problems are discussed below, with recommendations included, where appropriate.

Need to Insure That the System Will Serve Some Useful Purpose

Since the development and implementation of a risk-based waste classification system will likely be very difficult and controversial, beneficial purposes of the system must be established early on, and meaningful goals for the use of the system must be specified. The recognition of the potential benefits will also greatly assist in the acceptance and implementation of the system. Some of the potential benefits could be the following:

1. Allow treatment and disposal of mixed waste as only radioactive or hazardous if the risk is dominated by either.
2. Provide a simple system to screen waste streams to identify problematic constituents and generators.
3. Provide a sensible method to determine where toxic waste should be disposed.
4. Serve as a risk communication tool to compare the toxicity of various types of waste.

Identification of an Appropriate Method for Specifying and Combining the Necessary Components

One of the more difficult problems in the development of a risk-based classification system will be determining how the various components will be specified and combined so that the system remains simple but is still defensible. The most difficult issue will be how to factor in time variance for the various components. The question is whether a single factor should be used that incorporates the time consideration, or should individual time varying components be used. This issue is further complicated by the fact that some of the factors tend to become more uncertain as time increases. A non time varying factor approach is recommended since it will provide for a more useful system.

At What Phase of the Waste Management Cycle Is the Classification System Applied

In order to specify which exposure modes must be considered, it is necessary to establish the point in the waste management cycle at which the classification system is applied. For example, the potential pathways and exposure modes for storage may be very different than disposal. This is further complicated by the fact that differing regulatory philosophies, combined with the dissimilar characteristics of the various toxic materials, may cause the hazardous characteristic to be eliminated by the appropriate treatment process. For example, a mixed waste that initially contains hazardous and radioactive materials may only be radioactive after treatment, and therefore the classification may be totally different before and after treatment. This may dictate the need for more than one classification system: one applied before treatment, another for storage, and finally one for disposal.

Differing Regulatory Requirements May Complicate the Development of a Seamless Waste Classification System

Due to the fact that there are large differences in the regulatory requirements of EPA and NRC regarding the treatment, storage and disposal of toxic materials, a seamless risk-based classification system that treats all toxic materials equally may be very difficult to develop. This is somewhat related to the differences in the characteristics of the materials but much more a function of the different waste management and general standard setting philosophy between the two agencies.

The following are examples of this differing philosophy and how it may affect the development of a uniform waste classification system.

1. EPA hazardous waste disposal regulations are very prescriptive and require isolation for a minimum of 30 y, but are not specific regarding long-term care or institutional control. On the other hand, NRC low-level radioactive waste (LLRW) disposal regulations are performance based, do not specify or rely on engineered barriers, require long-term care for at least 100 y, and additional measures to insure institutional control beyond that time frame. These differences may make it difficult to formulate common exposure scenarios or pathways that would allow some of the components to be directly comparable. Also, the intruder scenario may be difficult to apply to the non radioactive constituents.
2. The land disposal restrictions (LDR) for hazardous waste, which require specified treatment for all hazardous waste before land disposal can be used, will cause a significant difference between the classification of hazardous waste before and after treatment. Since radioactivity cannot be eliminated by treatment, LLRW treatment techniques are primarily used for volume reduction and waste form improvement purposes. NRC disposal regulations do require

treatment to the maximum extent practicable for waste that contain hazardous, infectious or biological constituents. It should be noted that leachability is a characteristic of hazardous waste, which can be eliminated by treatment. Certain radioactive isotopes that do not emit penetrating radiation exhibit similar toxic characteristics, but still must be managed as radioactive waste regardless of the leachability of its waste form.

3. EPA standards for toxic materials are typically based on a lifetime mortality risk of 10^{-4} to 10^{-6}. EPA radiation standards have been set at the higher risk end of this range while other toxic material standards are usually toward the lower end. This is due in part to the fact that the radiation risk is unique because the risk from natural background radiation is in the range of 2×10^{-3} to 6×10^{-3}. Nuclear Regulatory Commission (NRC) standards, on the other hand, are based on a totally different philosophy. An upper limit is established and the ALARA principal is used to reduce exposure to a lower level. Interestingly, both philosophies result in about the same protection to public health and safety, but the standards are not readily comparable.

The Scope of the Toxic Materials World That Should Be Included in a Risk-Based Waste Classification System

There are a number of other toxic materials that are not included in the definition of hazardous or radioactive waste. Examples are: infectious medical waste, technologically enhanced naturally occurring radioactive material (NORM), and toxic materials regulated under the Toxic Substance Control Act (TSCA) such as asbestos and polychlorinated biphenyls. The question is: Can and should these other toxic materials be included in a risk-based waste classification system? Those toxic materials that are included in existing risk-based standards, such as the drinking water MCL's, can easily be analyzed on a comparable basis and probably should be included. Other toxic materials which are not directly comparable because they are not included in current standards, or have an insult other than cancer, will be much more difficult if not impossible to include.

Should Other than Human Health Risks Be Considered?

There are other risks besides human health risks that are required to be protected under current environmental laws and regulations. Protection of the natural environment and the protection of endangered species are examples. Since the risks to the environment are not directly comparable to human health risks, it is recommended that a risk-based waste classification system not include these considerations. These issues should continue to be resolved primarily as part of the siting process for waste management facilities.

The above discussion clearly shows the problems of a risk-based classification system that attempts to be all inclusive and tries to apply in all situations. For these reasons a first generation risk-based waste classification system should be limited to human cancer risk and only be used for disposal purposes. This limitation is probably compatible with the current needs.

A Practical Example of a Risk-Based Classification System

The Appendix to this Section that follows below provides an example of several types of risk-based assessment or classification systems that include some of the components that are discussed above. This example will help to identify some of the problems that are mentioned above and how they may be appropriately handled. It will also show some of the potential uses of a risk-based system and lead to a better understanding and acceptance of the advantages of such a system.

Appendix

Introduction

The main body of this paper has described the general concepts relating to a risk-based waste classification system and the difficulties encountered in implementing these concepts toward practical applications. The most effective application of such a system is to actually develop numerical values for some of the components that were identified in the main text. This will clearly show how these components can be developed, demonstrate some of the problems that were identified and show how a system could be effectively used. Provided in this Appendix are two examples of simplified methodologies that will serve to illustrate these ideas.

A Simple Three-Component Risk-Based Screening Tool

Methodology

The first example summarizes a methodology that has been previously developed by the author to perform evaluations of LLRW waste streams (Dornsife, 1995).[1] It uses just three of the components mentioned in the main text: intrinsic toxicity, build-up and longevity. However, it can serve a useful purpose for quickly identifying problematic constituents in various waste streams and provide an effective risk communication tool.

The intrinsic toxicity of each radionuclide is determined by dividing its activity by the waste volume of interest to obtain its concentration, or specific activity. The specific activity of each radionuclide is then divided by the EPA proposed drinking water maximum contamination limit (*MCL*) to normalize the risk. The resultant unitless quantity is a measure of the intrinsic ingestion toxicity of that radionuclide in the LLRW. The equation is as follows:

$$T = \frac{A(k)}{V(MCL)} \tag{1}$$

where:

- T = intrinsic toxicity units of each radionuclide (unitless)
- A = activity of each specific radionuclide (mCi)
- V = volume of interest (ft^3)
- MCL = EPA proposed drinking water limit ($pCi\ l^{-1}$)
- k = conversion factor to balance units = 35.375E(+06)

Results of Applying the Methodology

As an example of the use of this methodology, LLRW shipped for disposal by generators in Pennsylvania for the 2 y period from January 1991 to the end of 1992 (as reported to the Pennsylvania Department of Environmental Resources) was analyzed. The data was sorted and compiled using Microsoft Access and then entered into a Microsoft Excel spreadsheet. A typical Microsoft Excel spreadsheet is shown in Figure 1. This shows all of the Class A waste that was shipped by Pennsylvania generators during 1991 and 1992. As can be seen, the

[1]The referenced paper should be consulted for a more detailed discussion. The paper is available upon request from the author.

only variables that must be changed to evaluate different LLRW quantities are the activity of each radionuclide (fifth column) and the volume of interest (third column). A graphic presentation of these data is shown in Figure 2. For Class A waste, the total toxicity decreases to almost a constant value after about 300 y.

The following discussion shows the usefulness of this methodology as a screening tool for problematic waste streams. It was discovered that most of the naturally occurring radionuclides and much of the ^{241}Am and ^{239}Pu were contained in a one time shipment as a result of the decommissioning of a major fuel cycle manufacturing facility. This is a unique facility that is now totally decommissioned, and therefore no future shipments of this type are expected to occur. Additional analysis of the data indicated that TMI-2 accident waste was also a major contributor to the long lived toxicity. Since the last of the accident generated waste was shipped during this period, this is also considered to be a unique waste stream.

Taking the above factors into consideration, the intrinsic toxicity of a more typical Class A LLRW inventory is shown in Figure 3. This inventory was obtained by subtracting the radionuclides from TMI-2, the recently decommissioned fuel cycle manufacturing facility, and long lived sealed sources. The ^{129}I inventory was also reduced by a factor of 100, since it has been shown to be overestimated by at least this factor. The result is a better estimate of the toxicity of the Class A LLRW that will likely be acceptable for disposal at a future Pennsylvania disposal facility. Comparing this result with Figure 2, the total intrinsic toxicity has been reduced by a factor of about 25 and now ^{14}C dominates the long-term risk.

Figure 4 summarizes the results of applying the same methodology to both more representative and as reported Class A, B and C LLRW; and representative nuclear power plant Class A LLRW. These results are then compared with the radiotoxicity of common soil and a material with an average concentration of 5 pCi/gm of ^{226}Ra. This 5 pCi/gm concentration is the lowest limit that has been suggested for the control of technologically enhanced NORM, and is also the EPA standard for near surface cleanup of uranium mill tailings. It also approximates the lower range of the radiotoxicity of coal ash.

Finally, Figure 5 shows the relative contribution to total intrinsic toxicity from each type of generator for the as shipped Class A LLRW data. The actual intrinsic toxicity of representative nuclear power plant Class A LLRW, common soil and waste containing 5 pCi/gm of ^{226}Ra are also included for comparison purposes. This analysis shows the utility of this methodology as a risk communication tool.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1					**CLASS A LLRW**								
2	**Nuclide**	**Half-life**	**Volume**	**MCL**	**Activity**	**Other**	**New Act**		**Years After Disposal**				
3		**years**	**ft^3 (1)**	**pCi/l (2)**	**mCi (3)**	**mCi (3)**	**mCi (3)**	**0**	**100**	**200**	**300**	**400**	**500**
4	Ag-110m	0.69	297958.53	512	4539.60621		4539.60621	1050.9	3E-41	6E-85	1E-128	4E-172	0
5	Am-241	433	297958.53	6.45	169.913019		169.913019	3122.3	2659	2121.9	1691.1	1318.8	997.1
6	Am-243	7370	297958.53	6.49	0.438		0.438	7.9989	7.947	7.064	6.181	5.298	4.415
7	Ba-133	10.7	297958.53	1520	0.815		0.815	0.0636	1E-04	2E-07	2E-10	4E-13	5E-16
8	Ba-140	0.035	297958.53	582	11029.7489		11029.7489	2246.2	0	0	0	0	0
9	Be-7	0.146	297958.53	43500	1003.6986		1003.6986	2.7347	2E-206	0	0	0	0
10	C-14	5730	297958.53	3200	10370.53977		10370.53977	384.11	379.49	374.93	370.42	365.97	361.6
11	Ca-45	0.447	297958.53	1730	186.854		186.854	12.801	6E-67	3E-134	1E-201	6E-269	0
12	Cd-109	1.24	297958.53	227	2.405		2.405	1.2557	7E-25	4E-49	2E-73	1E-97	0
13	Ce-139	0.377	297958.53	1500	0.642		0.642	0.0507	7E-82	1E-161	2E-241	0	0
14	Ce-141	0.089	297958.53	1890	23.2966		23.2966	1.4609	0	0	0	0	0
15	Ce-144	0.778	297958.53	261	1186.2459		1186.2459	538.69	1E-36	2E-75	5E-114	1E-152	0
16	Cf-252	2.65	297958.53	17	0.001		0.001	0.007	3E-14	3E-14	4E-14	4E-14	5E-14
17	Cl-36	307000	297958.53	1850	8.894		8.894	0.5698	0.5697	0.5696	0.5694	0.5693	0.569
18	Cm-242	0.446	297958.53	145	14.7052152		14.7052152	12.02	0.5662	0.2632	0.1226	0.0572	0.027
19	Cm-243	32	297958.53	8.47	1.11002		1.11002	15.533	1.3691	0.6788	0.3371	0.1678	0.083
20	Cm-244	18.1	297958.53	10	4.7290044		4.7290044	56.05	1.2443	0.7903	0.505	0.3217	0.205
21	Co-57	0.742	297958.53	4870	294.80397		294.80397	7.1748	2E-40	5E-81	1E-121	4E-162	0
22	Co-58	1.96	297958.53	1590	149757.6638		149757.6638	11163	5E-12	2E-27	1E-42	4E-58	2E-73
23	Co-60	5.258	297958.53	218	696312.4682		696312.4682	378574	0.7148	1E-06	3E-12	5E-18	9E-24
24	Cr-51	0.0762	297958.53	38000	584994.2927		584994.2927	1824.6	0	0	0	0	0
25	Cs-134	2.06	297958.53	81.3	103448.9747		103448.9747	150813	4E-10	9E-25	2E-39	5E-54	1E-68
26	Cs-137	30.2	297958.53	119	225332.8717		225332.8717	224430	22621	2280	229.8	23.162	2.335
27	Eu-152	13.4	297958.53	841	25.4409		25.4409	3.5854	0.0203	0.0001	7E-07	4E-09	2E-11
28	Eu-154	8.2	297958.53	573	22.37395		22.37395	4.628	0.001	2E-07	5E-11	1E-14	2E-18
29	Eu-155	5	297958.53	3590	123.31977		123.31977	4.0714	4E-06	4E-12	4E-18	3E-24	3E-30
30	Fe-55	2.7	297958.53	9250	4528343.224		4528343.224	58023	4E-07	3E-18	2E-29	1E-40	1E-51
31	Fe-59	0.1233	297958.53	844	79257.71193		79257.71193	11130	9E-241	0	0	0	0
32	Gd-153	0.66	297958.53	4680	8.706		8.706	0.2205	6E-47	1E-92	3E-138	9E-184	0
33	Ge-68	0.786	297958.53	436000	0.241		0.241	7E-05	3E-43	2E-81	9E-120	4E-158	0
34	H-3	12.33	297958.53	60900	60168.81586		60168.81586	117.1	0.4243	0.0015	6E-06	2E-08	7E-11
35	Hf-181	0.116	297958.53	1170	379.1993		379.1993	38.414	1E-258	0	0	0	0
36	I-125	0.1636	297958.53	151	12346.53583		12346.53583	9691.1	1E-180	0	0	0	0
37	I-129	16000000	297958.53	21	129.7775383		129.7775383	732.46	732.46	732.45	732.45	732.45	732.4
38	I-131	0.0221	297958.53	108	69692.8024		69692.8024	76483	0	0	0	0	0
39	Ir-192	0.203	297958.53	957	0.222		0.222	0.0275	2E-150	8E-299	0	0	0
40	Mn-54	0.8575	297958.53	2010	744681.3785		744681.3785	43911	4E-31	3E-66	2E-101	2E-136	0
41	Na-22	2.601	297958.53	466	6.462		6.462	1.6436	4E-12	1E-23	3E-35	9E-47	2E-58
42	Nb-94	20000	297958.53	707	3.8185		3.8185	0.6401	0.6379	0.6357	0.6335	0.6313	0.629
43	Nb-95	0.962	297958.53	2150	1973.4034		1973.4034	108.79	6E-30	3E-61	2E-92	8E-124	0
44	Ni-59	80000	297958.53	27000	1020.1455		1020.1455	4.4782	4.4743	4.4704	4.4666	4.4627	4.459
45	Ni-63	92	297958.53	9910	68523.25645		68523.25645	819.54	385.86	181.67	85.538	40.274	18.96
46	Np-237	2140000	297958.53	7.19	0.3056		0.3056	5.0376	5.0375	5.0373	5.0372	5.037	5.037
47	P-32	0.0391	297958.53	641	1493.82624		1493.82624	276.21	0	0	0	0	0
48	P-33	0.069	297958.53	1870	2.296		2.296	0.1455	0	0	0	0	0
49	Pb-210	22	297958.53	1.01	1.327		1.327	155.72	6.6731	0.286	0.0123	0.0005	2E-05
50	Pm-147	2.623	297958.53	5240	2545.4088		2545.4088	57.574	2E-10	6E-22	2E-33	7E-45	2E-56
51	Po-210	0.38	297958.53	14	2.103		2.103	17.804	1E-78	7E-158	4E-237	0	0
52	Pu-238	87.4	297958.53	7.15	21.776441		21.776441	360.98	163.47	75.806	35.376	16.461	7.653
53	Pu-239	24390	297958.53	64.9	233.4564698		233.4564698	426.35	425.14	423.93	422.73	421.53	420.3
54	Pu-240	6600	297958.53	64.9	65.05768		65.05768	118.81	117.57	116.34	115.13	113.92	112.7
55	Pu-241	14.3	297958.53	68	6412.15647		6412.15647	11176	3234.1	2580.8	2056.9	1604.1	1213
56	Pu-242	376000	297958.53	68.3	2.0768		2.0768	3.6039	3.6033	3.6026	3.6019	3.6013	3.601
57	Ra-226	1602	297958.53	20.7	262.29055		262.29055	1501.8	34825	30955	27086	23216	19347
58	Rb-86	0.05	297958.53	485	124.9685		124.9685	30.54	0	0	0	0	0

(1) To convert to m^3, multiply by 0.028.

(2) To convert to Bq/l, multiply by 0.037.

(3) To convert to MBq, multiply by 37.

Fig. 1. Sample Microsoft Excel spreadsheet showing intrinsic toxicity for specific radionuclides in Class A LLRW at various times after disposal.

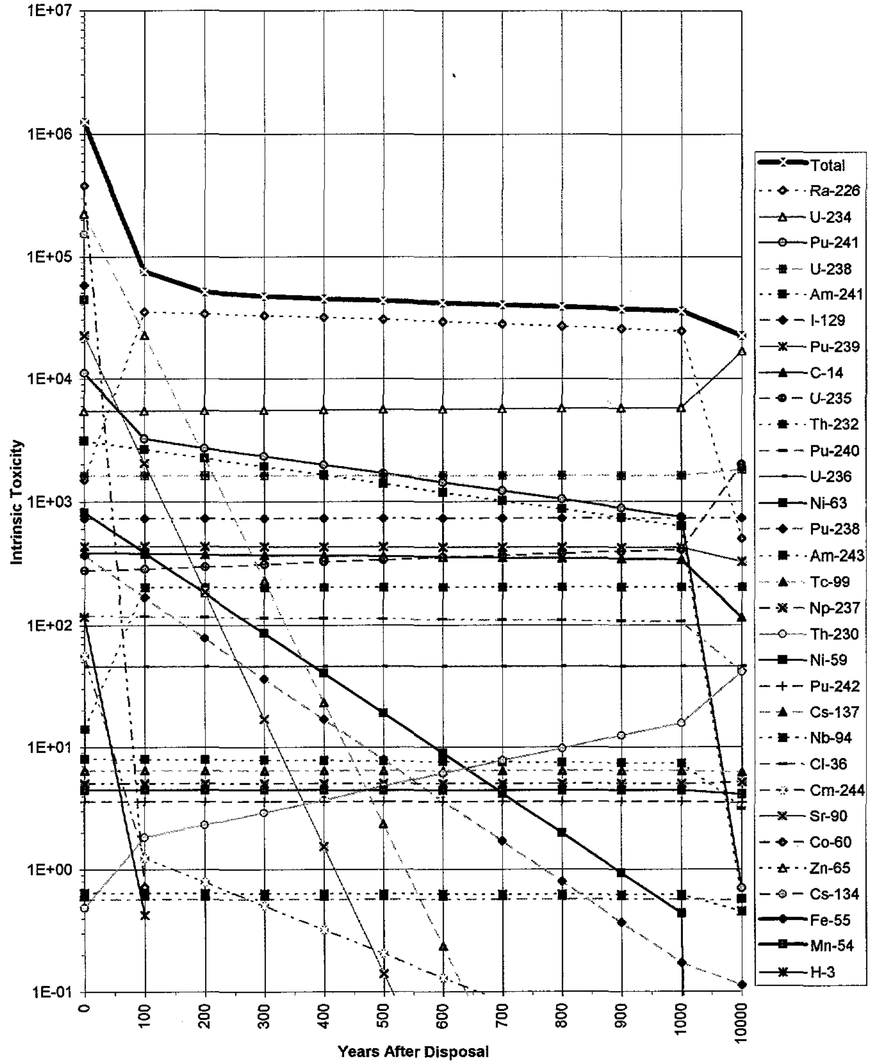

Fig. 2. Intrinsic toxicity of each major radionuclide in Class A LLRW as shipped for disposal by Pennsylvania generators from January 1991 to December 1992.

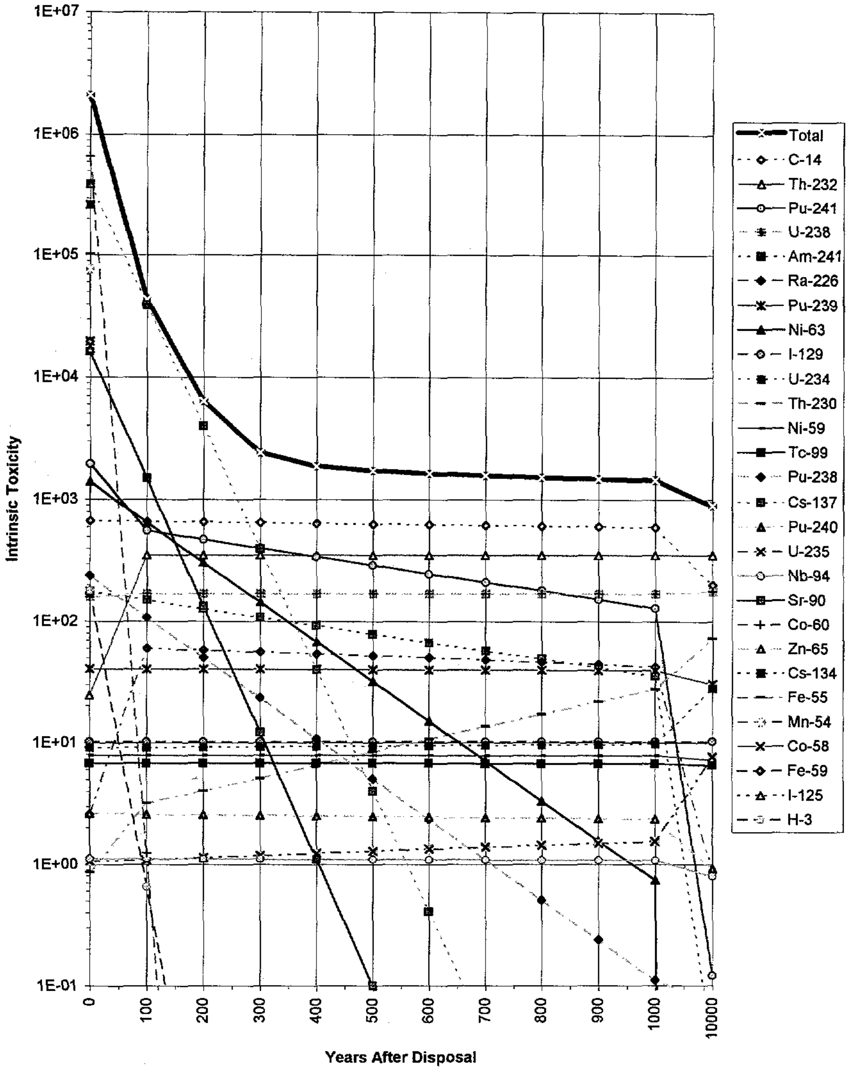

Fig. 3. Intrinsic toxicity of Class A LLRW shipped for disposal by Pennsylvania generators from January 1991 to December 1992, with omission of those waste streams considered to be unique.

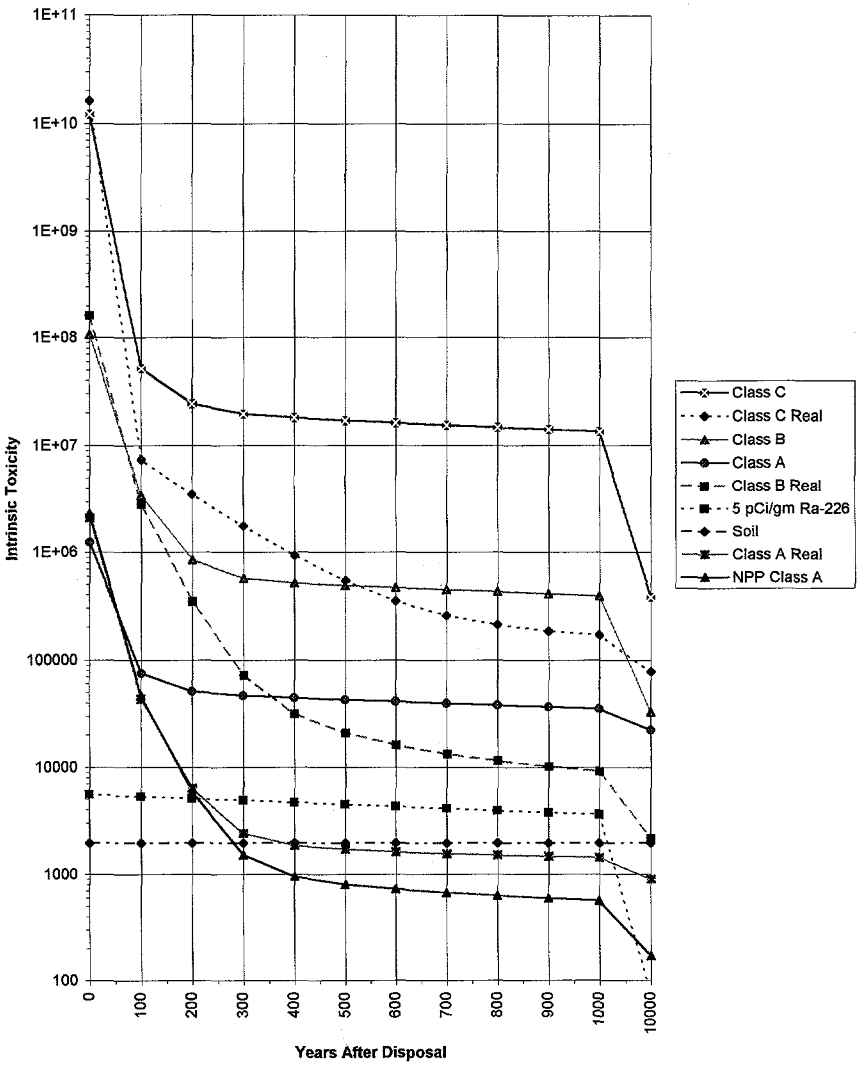

Fig. 4. Total intrinsic toxicity of representative and as shipped Classes A, B and C LLRW from Pennsylvania generators from January 1991 to December 1992; compared to common soil, 5 pCi gm^{-1} ^{226}Ra, and typical nuclear power plant Class A LLRW.

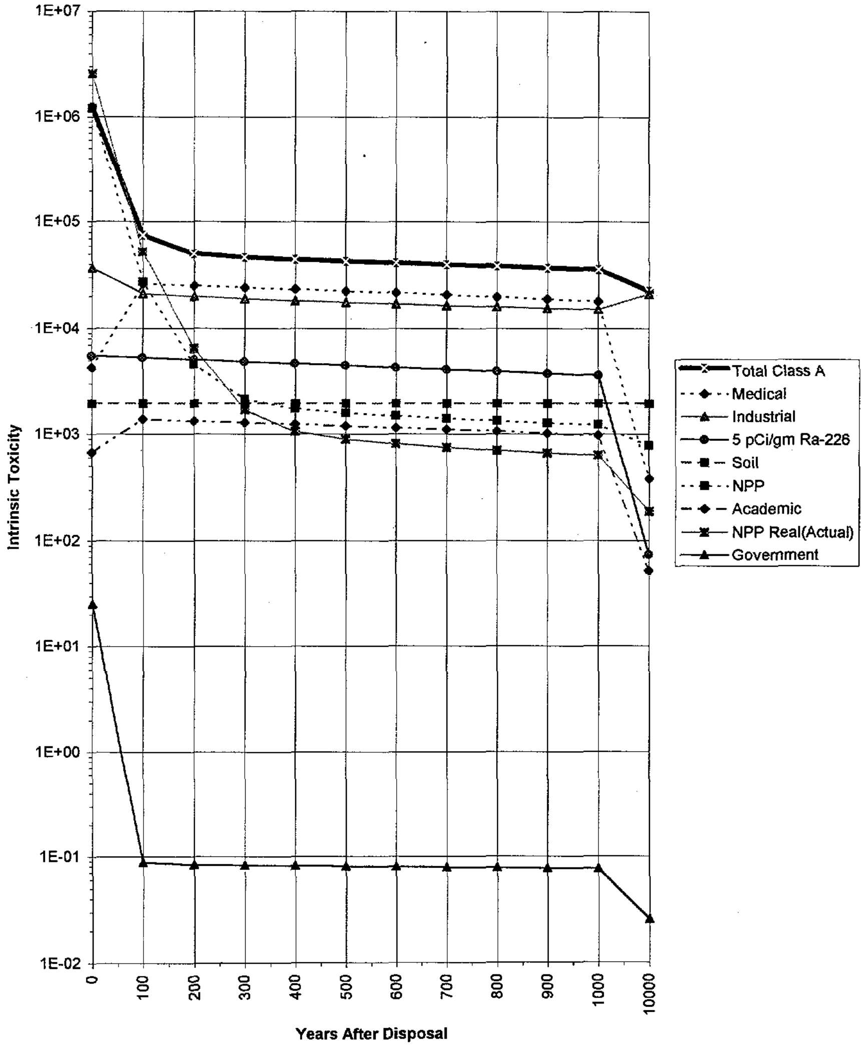

Fig. 5. Relative contribution by various categories of generators in Pennsylvania for Class A LLRW reported as shipped for disposal from January 1991 to December 1992. (Common soil and waste containing 5 pCi gm^{-1} are included for comparison purposes.)

An Example of a Multi-Component Risk-Based Waste Classification System[2]

Introduction

The second methodology was developed specifically for inclusion in this paper. It utilizes five of the components identified in the main text; intrinsic toxicity, longevity, build-up factor,.release, and retardation or *removal during transport.*

This methodology can be more specifically used to address the situation where an inventory of toxic waste has been placed in an engineered disposal facility. It includes the hazard presented first due to release from the engineered disposal facility, followed by its transport in the groundwater, and finally its ingestion as potable water from an adjacent well. In each of the first two phases, *i.e.,* release and transport, there is inherent delay due to the chemical process of retardation, *i.e.,* absorption, desorption and leaching based on the quantity and chemistry of groundwater reaching the waste and the properties of the waste and the waste matrix. Retardation not only tends to spread out the waste plume in water but allows radioactive decay to further reduce the toxicity before ingestion. The overall effect, in each case, is a reduction in the peak concentration, and hence the peak doses from this waste. In reality, there is a further reduction in concentration due to dispersion and dilution of the waste in the aquifer. Such effects have been neglected in this simplistic analysis.

The methodology is general enough to consider toxic radioactive and hazardous waste separately. There is, however, no decay generally associated with hazardous waste. It is also relatively easy to combine the numerical results for the two components for a composite waste stream such as a mixed waste.

As with the first example, this methodology uses EPA's MCL (EPA, 1991) for drinking water at the receptor well as the standard measure of the intrinsic or ingestion toxicity. However, additional attenuation factors for release and transport are included which cause a reduction in the peak concentrations at the point of uptake and thus define a generalized

[2] Acknowledgment should be given to the fact that this methodology and examples were developed primarily by Ajit Bhattachayya and Robert Barkanic, nuclear engineers on the staff of the Pennsylvania Bureau of Radiation Protection.

hazard index (*GHI*) for the waste. These factors are described in more detail in the following sections.

Discussion of the Methodology

Three major components are used in the methodology for the development of the GHI and the example screening calculations. First is the uptake factor, which includes the normalization of ingestion risk using the *MCL*s. The second factor is called the transport attenuation factor. It includes the effects of retardation and decay which occur during transport in the aquifer. The effects of the soil retardation and decay are assumed to occur during transport from the release point at the engineered facility to the receptor well at the site boundary. It should be noted that the calculation of this factor may be very dependent on site specific factors and thus may prove difficult to include in a generic methodology. Finally, the effects of the radionuclide release from an assumed cement based waste form is considered. This third factor is called the release attenuation factor. The product of these three factors comprise the total *GHI.*

The Release Attenuation Factor, F_1

The release attenuation factor is an engineered barrier system specific phenomenon. For purposes of this simple methodology, it is conservatively assumed that interactions occur only with a cement based waste form and not the entire engineered barrier system. The release factor is a function of two components, F_{11}, the liquid/solid partitioning factor and F_{12}, the decay factor.

The liquid/solid partitioning factor is calculated by the following equation:

$$F_{11} = 1/(R_f \theta) \qquad (2)$$

where:

R_f = the calculated radionuclide specific retardation factor based on the density based distribution coefficient for cement

θ = its porosity and is assumed to be 0.3

The values of R_f were adapted from Sheppard and Thibault (1990) and DOE (1994).

The decay factor, F_{12} is a function of the release fraction from the cement based waste and the natural decay process. The release fraction is represented by λ_i and is equal to the following equation:

$$\lambda_i = (K/t_w)(q)(R_f) \quad (3)$$

where, for this analysis:

K = the permeability of the engineered cover, assumed to be 10^{-7} cm s^{-1}
t_w = the thickness of the waste, assumed to be 305 cm

The relationship between the decay factor and the release factor is codified in the *GHI* analysis by the following equation:

$$F_{12} = \lambda_i/(1 + \lambda_i) \quad (4)$$

The release attenuation factor is calculated by the following equation:

$$F_1 = (F_{11})\,(F_{12}) \quad (5)$$

The Transport Attenuation Factor, F_2

Representative aquifer parameters are used in the calculation of this factor. They include hydraulic conductivity, porosity, and regional gradient. These parameters are used to calculate the ground water travel time from the point of entry in the aquifer to the receptor using the following equations:

$$(GWTT) = L/v_p \quad (6)$$

and

$$v_p = (K'/\theta')\,(-dh/dl) \quad (7)$$

where:

$(GWTT)$ = ground water travel time from the edge of waste to the receptor (y)
L = distance to the receptor (1,600 ft or ~490 m)
v_p = calculated pore velocity in aquifer (m y^{-1})
K' = assumed aquifer hydraulic conductivity (m y^{-1})
θ' = assumed aquifer porosity
dh/dl = assumed regional gradient

In order to show the results using very conservative assumptions, the hydraulic conductivity for the aquifer is assumed to be 30,000 m y^{-1}. The assumed porosity and regional gradient are 0.3 and -0.002, respectively. The calculated pore velocity using these parameters is 200 m y^{-1} with a corresponding ground water travel time from the waste to the receptor of roughly 2.44 y.

Retardation coefficients were calculated for the minimum K_d's using the relationships shown below (Freeze and Cherry, 1979). Minimum values of distribution coefficients (K_d') for sand are taken from Sheppard and Thibault (1990), DOE (1994), and Allard (1985). The dry bulk density of sandstone was assumed to be 1.6 g cm^{-3}.

$$R_f' = 1 + \rho_b K_d'/\theta' \qquad (8)$$

where:

R_f'	=	calculated radionuclide specific retardation factor
ρ_b	=	dry bulk density of sandstone (g cm^{-3})
K_d'	=	density based radionuclide specific distribution coefficient (ml g^{-1})
θ'	=	aquifer porosity

The calculated R_f's and water travel times can be used to obtain an estimate of the radionuclide specific transport time (*RTT*) for the center of mass of a plume to the receptor, using the formula (Freeze and Cherry, 1979):

$$(RTT) = (GWTT) \cdot R_f' \qquad (9)$$

The transport attenuation factor, is an aquifer specific phenomenon. This factor considers the effects that the soil (liquid/solid partitioning factor), F_{21}, and radiological decay have on the radionuclide. The soil retards the transport of radionuclides with varying effectiveness. Retardation factors are calculated as described above, utilizing radionuclide specific density based distribution coefficients. The transport attenuation factor is calculated as follows:

$$F_{21} = 1/[(R_f')(\theta')] \qquad (10)$$

The decay factor, F_{22}, can be calculated by;

$$F_{22} = e^{-\lambda t} \qquad (11)$$

where λ is the decay constant and t is the radionuclide specific travel time for the waste.

Therefore, the total transport attenuation factor is

$$F_2 = (F_{21})(F_{22}) \quad (12)$$

The Uptake Factor, F_3

The uptake factor is simply the reciprocal of the EPA proposed drinking water *MCL*s (EPA, 1991). This factor is measured in liters per picocurie. In the unit calculation, this represents the volume of water required to dilute the unit concentration to the *MCL*.

$$F_3 = 1 /(MCL) \quad (13)$$

The generalized hazard index (*GHI*) is a product of the three factors and is expressed in units of volume of drinking water per unit concentration of waste.

$$(GHI) = (F_1)(F_2)(F_3) \quad (14)$$

Sample Calculations

The methodology to calculate the *GHI* was used to rank radionuclides and hazardous waste in order of relative toxicity. Several scenarios were investigated.

The first scenario considered a set of radionuclides commonly found in low-level waste streams, assumed a unit concentration for each in the disposal vault, and then calculated a *GHI* for each by using the factors described above. Assuming the tritium *GHI* to be equal to one, the *GHI*s for the other radionuclides were scaled accordingly. The results of this investigation are presented in Table 1. The shaded values in Table 1 represent radionuclides which on a unit concentration basis are deemed more hazardous than ^{14}C.

The next example, presented in Table 2, considered the hazard associated with a toxic chemical inventory. This calculation is similar to that used in Table 1 except that the chemicals are assumed not to decay and the *MCL*s and the concentrations are expressed in units of mass of pollutant per unit volume. The retardation factors attributed to cement and soil are assumed to be identical for the same radioactive and

TABLE 1—*Generalized hazard index for unit concentrations of specific radionuclides.*

Nuclide	General Hazard Index (L/pCi)	Ranking Relative to Tritium	Nuclide	General Hazard Index (L/pCi)	Ranking Relative to Tritium
Ag-110	0.00E+00	0.00E+00	Zn-65	0.00E+00	0.00E+00
C-14	4.38E-12	8.12E-07	Zr-95	0.00E+00	0.00E+00
Cd-109	1.01E-260	1.88E-255	Am-241	1.46E-24	2.70E-19
Co-57	0.00E+00	0.00E+00	Am-243	5.01E-08	9.28E-03
Co-58	0.00E+00	0.00E+00	Np-237	1.82E-04	3.37E+01
Co-60	2.42E-56	4.49E-51	Pu-238	6.51E-32	1.21E-26
Cs-134	0.00E+00	0.00E+00	Pu-239	1.51E-07	2.80E-02
Cs-137	1.85E-44	3.44E-39	Pu-241	1.19E-158	2.21E-153
H-3	5.40E-06	1.00E+00	Pu-242	1.78E-07	3.29E-02
I-125	1.82E-38	3.38E-33	Th-230	1.75E-08	3.24E-03
I-129	4.67E-05	8.65E+00	Th-232	2.31E-08	4.28E-03
I-131	1.70E-222	3.15E-217	Th-234	5.28E-09	9.79E-04
Nb-94	4.55E-11	8.43E-06	U-232	2.61E-08	4.83E-03
Nb-95	0.00E+00	0.00E+00	U-233	7.48E-06	1.39E+00
Ni-59	1.27E-12	2.35E-07	U-234	7.41E-06	1.37E+00
Se-75	0.00E+00	0.00E+00	U-235	7.27E-06	1.35E+00
Sr-85	0.00E+00	0.00E+00	U-236	7.03E-06	1.30E+00
Sr-89	0.00E+00	0.00E+00	U-238	2.71E-05	5.03E+00
Sr-90	2.48E-08	4.59E-03	U-236	7.03E-06	1.30E+00
Tc-99	2.72E-05	5.03E+00	U-238	2.71E-05	5.03E+00

TABLE 2—*Generalized hazard index for unit concentrations of specific chemical.*

Chemical	General Hazard Index (L/mg)	Ranking Relative to Cadmium
Antimony	1.72E-02	9.83E+00
Barium	1.69E-04	9.67E-02
Berylium	2.81E-06	1.60E-03
Cadmium	1.75E-03	1.00E+00
Chromium	3.57E-05	2.04E-02
Mercury	2.49E+00	1.42E+03
Nickel	5.86E-08	3.34E-05
Phosphorous	1.25E-03	7.12E-01
Selenium	1.15E-03	6.59E-01
Silver	1.75E-05	1.00E-02
Tetrachloroethane	2.49E-02	1.42E+01
Toluene	3.56E-03	2.03E+00
Trichloroethylene	4.99E+00	2.85E+03

chemical element. For example, the K_d for chemical cadmium is assumed to be identical to the K_d for ^{109}Cd. The ranking shown in Table 2 is scaled to cadmium.

The next example, Table 3, shows the *GHI*s for selected radionuclides when the contribution of progeny ingrowth is considered. The effects of decay for 100, 1,000, and 10,000 y are considered and the cases where significant progeny growths occur are identified.

Table 4 considers the hazards associated with a specific waste stream: Pennsylvania Class C LLRW shipped for disposal during 1991 and 1992. The method to determine the total *GHI* in this case was similar to that in Table 1, except that the unit hazard index was multiplied by the source specific waste concentration and then summed. Ranking of radionuclides and the total waste *GHI* are then shown relative to that of a unit concentration of tritium.

Table 5 shows the results for a typical mixed waste stream. Again the *GHI* was employed, except that the respective *GHI*s were multiplied by radioactivity and hazardous waste concentrations, respectively, and then summed. The contributions were then compared to determine which constituent was the major contributor.

TABLE 3—*Decay and ingrowth-important nuclides.*

Nuclide	Decay Constant ($1\ y^{-1}$)	Hazard Index			
		Zero Decay	100 y Decay	1,000 y Decay	10,000 y Decay
C-14	1.21E-04	4.38E-12	4.33E-12	3.88E-12	1.31E-12
H-3	5.62E-02	5.40E-06	1.96E-08	2.11E-30	4.56E-250
Nb-94	3.41E-05	4.67E-05	4.65E-05	4.51E-05	3.32E-05
I-129	4.41E-08	4.55E-11	4.55E-11	4.55E-11	4.55E-11
Tc-99	3.28E-06	2.72E-05	2.72E-05	2.71E-05	2.63E-05
Am-243	9.39E-05	5.00E-08	4.95E-08	4.55E-08	1.95E-08
Np-237	3.20E-07	1.80E-04	1.80E-04	1.80E-04	1.79E-04
Pu-239	2.90E-05	1.50E-07	1.50E-07	1.46E-07	1.12E-07
Pu-240	1.10E-04	8.10E-08	8.01E-08	7.26E-08	2.70E-08
Pu-242	1.80E-06	1.70E-07	1.70E-07	1.70E-07	1.67E-07
Th-230[a]	9.00E-06	1.74E-08	1.74E-08	5.60E-07	1.47E-06
Th-232	4.90E-11	2.30E-08	2.30E-08	2.30E-08	2.30E-08
U-232	9.63E-03	2.60E-08	9.93E-09	1.71E-12	4.03E-50
U-233	4.35E-06	7.48E-06	7.48E-06	7.45E-06	7.16E-06
U-234	2.83E-06	7.40E-06	7.40E-06	7.38E-06	7.19E-06
U-235[a]	9.85E-10	7.26E-06	7.46E-06	1.06E-05	5.18E-05
U-236	2.96E-08	7.03E-06	7.03E-06	7.03E-06	7.03E-06
U-238	1.55E-10	2.71E-05	2.71E-05	2.71E-05	2.71E-05

[a]Denotes significant ingrowth.

TABLE 4—*Evaluation of a typical LLRW stream, Class C waste.*

Nuclide	Concentration in Class C LLRW (Ci/m^3)	Unit Hazard Index (L/pCi)	Source Specific Hazard Index (L of water/m^3 of waste)	Hazard Index Relative to Tritium
C-14	1.90E-01	4.38E-12	8.33E-01	1.54E-07
Co-57	8.00E-03	0.00E+00	0.00E+00	0.00E+00
Co-58	5.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-60	2.30E+03	2.42E-56	5.57E-41	1.03E-47
Cs-134	5.00E-02	0.00E+00	0.00E+00	0.00E+00
Cs-137	1.40E-01	1.85E-44	2.60E-33	4.81E-40
H-3	1.50E+01	5.40E-06	8.09E+07	1.50E+01
I-129	5.50E-04	4.67E-05	2.57E+04	4.76E-03
Nb-95	3.20E-01	0.00E+00	0.00E+00	0.00E+00
Ni-59	9.70E-01	1.27E-12	1.23E+00	2.28E-07
Sr-89	1.30E-03	0.00E+00	0.00E+00	0.00E+00
Sr-90	2.90E-04	2.48E-08	7.19E+00	1.33E-06
Tc-99	3.00E-03	2.72E-05	8.15E+04	1.51E-02
Zn-65	5.30E+00	0.00E+00	0.00E+00	0.00E+00
Zr-95	2.40E-03	0.00E+00	0.00E+00	0.00E+00
Total			8.10E+07	1.50E+01

TABLE 5—*Evaluation of a mixed waste stream (contaminated oil).*

Nuclide	Unit Hazard Index (L/pCi)	Waste Concentration (Ci/gm)[a]	Hazard from 1 m^3 of Waste (L of water/m^3 of waste)
C-14	4.38E-12	3.00E-13	9.20E-07
H-3	5.40E-06	2.00E-09	7.55E+03
I-129	4.67E-05	6.00E-14	1.96E+00
Nb-94	4.55E-11	7.00E-17	2.23E-09
Ni-59	1.27E-12	4.00E-11	3.54E-05
Sr-90	2.48E-08	6.00E-07	1.04E+04
Tc-99	2.72E-05	4.00E-11	7.60E+02
Total			1.87E+04

Chemical	Unit Hazard Index (L/mg)	Waste Concentration (mg/L)	Hazard from 1 m^3 of Waste (L of water/m^3 of waste)
Cadmium	1.75E-03	1.20E+00	2.10E+00
Chromium	3.57E-05	1.45E+01	5.17E-01
Mercury	2.49E+00	1.00E+00	2.49E+03
Silver	1.75E-05	1.04E+01	1.82E-01
Lead		8.30E-01	0.00E+00
Selenium	1.15E-03	1.50E+00	1.73E+00
Total			2.50E+03
GRAND TOTAL			2.12E+04
	Relative contribution of hazard:		
	Radionuclides		88.2%
	Hazardous chemicals		11.8%

[a]1 gram = 0.7 cc.

The last example in this Appendix uses a slightly different methodology. The results in Table 6 show the allowable concentrations in curies per cubic meter in the waste form necessary to meet the *MCL*'s at the receptor well, when considering no decay, 100 y decay and 300 y decay. This calculation is comprised of one component each for the waste and the aquifer. The waste form coefficient is equal to F_1.

$$F_1 = [1/(R_f)(\theta)][(e^{-(\lambda + \lambda_i)}T)] \tag{15}$$

Where T is the delay time for the waste to reach the aquifer.

Note that the codified decay factor, $F_{12} = \lambda/(\lambda + \lambda_i)$, has been replaced by a more realistic decay term in this case.

The aquifer coefficient is equal to F_2 where:

$$F_2 = [1/(R_f')(\theta')][(e^{-\lambda t})] \tag{16}$$

The allowable vault concentration is then equal to the *MCL* $[(F_1)(F_2)]^{-1}$

Discussion of the Results

The results presented here should be used only as a scoping and screening tool for the following reasons:

1. Only Kd type release is considered. In reality the releases may be diffusion driven, solubility limited, or influenced by rinse and wash. Furthermore, for some waste forms, *e.g.,* metallic pollutants, such a Kd type release model is questionable and an actual leaching test may be necessary.
2. No dilution and dispersion has been assumed.
3. The data used are generic in nature and have been selected from a wide range of available values. This represents a large source of potential uncertainty.
4. Some representative site and facility specific assumptions had to be used in the development of the GHI. This potentially limits the generic applicability of this methodology.

However, since it is believed that the concepts presented here are designed to capture the essential features of the hazard potential of the waste, this methodology has the potential to be useful as an example of a first generation integrated risk-based classification system and screening tool for the analysis of waste streams containing multiple hazardous constituents.

TABLE 6—*Allowable concentration of radionuclides with delayed release.*

Nuclide	MCL (pCi/L)	Transfer Index	Aquifer Exit Concentration (pCi/L)[a]	Allowable Limit			
				Zero Decay Ci/m^3	100 y Decay Ci/m^3	300 y Decay Ci/m^3	500 y Decay Ci/m^3
Ag-110	1.84E+06	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Be-7	4.35E+04	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
C-14	3.20E+03	1.49E-05	1.49E+05	2.14E-01	2.18E-01	2.26E-01	2.35-01
Ca-45	1.73E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Cd-109	2.27E+02	2.20E-253	2.220E-244	1.03E+246	6.90E+269	—[b]	—[b]
Ce-141	1.89E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Ce-144	2.61E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Co-57	4.87E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Co-58	1.59E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Co-60	2.18E+02	1.21E-49	1.21E-40	1.80E+42	—[b]	—[b]	—[b]
Cs-137	1.19E+02	2.18E-40	2.18E-31	5.45E+32	5.49E+33	5.56E+35	5.63E+37
Fe-55	9.25E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Fe-59	8.44E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
H-3	6.09E+04	9.69E+00	9.69E+09	6.29E-06	1.74E-03	1.33E+02	1.01E+07
Hf-181	1.17E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
I-125	1.51E+02	6.09E-31	6.09E-22	2.48E+23	1.66E+206	—[b]	—[b]
I-129	2.10E+01	1.09E-02	1.09E+07	1.93E-06	1.93E-06	1.93E-06	1.93E-06
I-131	1.80E+02	5.07E-214	5.07E-205	3.55E+206	—[b]	—[b]	—[b]
Mn-54	2.10E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Nb-94	7.07E+02	2.27E-06	2.27E+03	3.11E-01	3.19E-01	3.35E-01	3.52E-01
Nb-95	2.15E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Ni-59	2.70E+04	9.30E-07	9.30E+02	2.90E+01	2.91E+01	2.91E+01	2.91E+01
Ni-63	9.91E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
P-32	6.41E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Rb-86	4.85E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]

TABLE 6—*Allowable concentration of radionuclides with delayed release* (continued).

Nuclide	MCL (pCi/L)	Transfer Index	Aquifer Exit Concentration (pCi/L)[a]	Allowable Limit			
				Zero Decay Ci/m³	100 y Decay Ci/m³	300 y Decay Ci/m³	500 y Decay Ci/m³
Ru-103	1.81E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Ru-106	2.03E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Sb-124	5.63E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Sb-125	1.94E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Se-75	5.74E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Sn-113	1.74E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Sr-85	2.83E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Sr-89	5.99E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Sr-90	4.20E+01	1.06E-04	1.06E+05	3.96E-04	7.33E-03	2.51E+00	8.62E+02
Ta-182	8.42E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Tc-99	3.79E+03	1.14E+00	1.14E+09	3.31E-06	4.43E-06	7.95E-06	1.42E-05
Te-125m	1.49E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Zn-65	3.96E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Zr-95	1.46E+03	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Am-243	6.49E+00	3.89E-06	3.89E+03	1.67E-03	1.91E-03	2.48E-03	3.23E-03
Np-237	7.19E+00	1.45E-02	1.45E+07	4.95E-07	5.60E-07	7.16E-07	9.16E-07
Pu-238	7.15E+00	3.84E-29	3.84E-20	1.86E+20	4.64E+20	2.88E+21	1.79E+22
Pu-239	6.49E+01	1.11E-04	1.11E+05	5.82E-04	6.60E-04	8.49E-04	1.09E-03
Pu-240	6.49E+01	6.41E-05	6.41E+04	1.01E-03	1.16E-03	1.51E-03	1.97E-03
Pu-241	6.26E+01	3.33E-154	3.33E-145	1.88E+146	2.62E+148	—[b]	—[b]
Pu-242	6.83E+01	1.35E-04	1.35E+05	5.06E-04	5.72E-04	7.32E-04	9.63E-04
Ra-226	2.07E+01	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Th-228	1.53E+02	0.00E+00	0.00E+00	—[b]	—[b]	—[b]	—[b]
Th-230	8.27E+01	1.62E-05	1.62E+04	5.11E-03	5.79E-03	7.41E-03	9.49E-03
Th-234	4.01E+02	2.35E-05	2.35E+04	1.70E-02	1.93E-02	2.46E-02	3.15E-02

TABLE 6—*Allowable concentration of radionuclides with delayed release* (continued).

Nuclide	MCL (pCi/L)	Transfer Index	Aquifer Exit Concentration (pCi/L)a	Allowable Limit			
				Zero Decay Ci/m3	100 y Decay Ci/m3	300 y Decay Ci/m3	500 y Decay Ci/m3
U-232	1.02E+01	2.61E-05	2.61E+04	3.91E-04	1.16E-03	1.01E-02	8.90E-02
U-233	2.56E+01	2.14E-03	2.14E+06	1.20E-05	1.36E-05	1.79E-05	2.29E-05
U-234	2.59E+01	2.14E-03	2.14E+06	1.21E-05	1.37E-05	1.75E-05	2.24E-05
U-235	2.65E+01	2.14E-03	2.14E+06	1.24E-05	1.40E-05	1.79E-05	2.29E-05
U-236	2.74E+01	2.14E-03	2.14E+06	1.28E-05	1.45E-05	1.85E-05	2.37E-05
U-238	7.10E+00	2.14E-03	2.14E+06	3.32E-06	3.75E-06	4.80E-06	6.13E-06

[a]Assuming an original concentration of 1 Ci/m^3.

[b]Denotes unrestricted concentration.

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Discussion

MR. LESLIE: Bret Leslie from the Institute for Energy and Environmental Research. Bill, that's a pretty elegant presentation. But one of the things I noted is that you excluded a lot of things, for example, Three-Mile Island waste and decommissioning waste. In essence, are you reclassifying this waste? If so, where do they go? I see how the utility of using your system to evaluate the risk from other types of waste, but what are you suggesting particularly in terms of decommissioning waste?

MR. DORNSIFE: To conduct a proper performance assessment, we have to come up with a source term that reflects what the future waste in Pennsylvania is going to look like. Following that approach, we believe that the source term need not include waste that is not expected to be created. That's why I have excluded those specific types. That does not mean that they do not need to be evaluated at some point.

What I have presented is really a risk communication tool showing that the waste can meet the hazardous life standard. Because as you can well imagine, a lot of people are dubious that that's achievable.

MR. SCHAFFER: I am Steve Schaffer from SC&A. It seems that you made a recommendation to deal only with the cancer risk, in fact, it seems like your MCL approach kind of circumvents that subject. Do you have any comments?

MR. DORNSIFE: Well, you know, the drinking water MCLs, for the most part, are based on cancer risk.

MR. SCHAFFER: What about lead and mercury which are not carcinogens?

MR. DORNSIFE: We used the data we did, because they were available and comparable. If the estimated risks are directly comparable, you can use them. If they are not, then it's going to be very difficult to use them. Obviously the EPA made a judgment that that level of mercury and lead in drinking water is acceptable and comparable to the other contaminants.

MR. SCHAFFER: That's the exact point. By using the drinking water standard, the issue of comparable toxicities goes away because the common denominator now is the MCL and not toxicity.

MR. DORNSIFE: I am not saying that you should not do that. In fact, if you have other toxics that are directly comparable in the same standard, you should use that. In general though, if you are really looking to develop a system, cancer is the only thing you can directly compare for those cases where standards do not exist.

MS. HENDRICKS: My name is Lynnette Hendricks. I am with the Nuclear Energy Institute. I am one of those skeptics, Bill, that you just referred to, about the feasibility and utility of a risk-based system. My comment is that, if anything, you have only increased my skepticism because your approach—you have given yourself so many qualifications: one pathway, one point in time, one step in the management cycle disposal, a hundred year delay, etc.—in fact begins to very much resemble what

NRC has done in 10 CFR, Part 61. They have stuck with some simple classifications of the waste, and then they have done the more complicated performance assessment by using site specific factors and the actual source term that will be present at the site.

In short, I have a lot of concerns about the process of holding out this panacea of a potential risk-based classification that's going to be more meaningful and more useful. I do agree, however, that your approach was interesting and insightful.

MR. DORNSIFE: The only comment I have is that I do not think that a risk-based waste classification system necessarily has to supplant what's already out there. I think my approach can be useful for other purposes, for example, how to decide where contaminated soil resulting from a cleanup can be disposed. You need to have something like this to say that this is the risk and the waste is acceptable for disposal, for example, in a landfill. That will be very helpful.

MR. KOZAK: Matt Kozak from Sandia National Laboratory. I would like to make an observation and see if you agree with it. I really like what you did. The intrinsic toxicity calculation, I think, is valuable. I also agree with you that your approach will be a great tool for informing people just how toxic this stuff is not! Your system, however, is a first step in a performance assessment. The next step is to bring in the transport factors. In reality, a generic classification system, such as you propose, would be appropriate only if you are using site specific information. And you should be very careful about the information that you use.

MR. DORNSIFE: That's exactly the point that I made. And the reason was to show you some of the pitfalls in trying to develop an all inclusive risk-based waste classification that tries to bring all these factors into play and really means something. It's really difficult. As you say, the transport factors are very situational and site specific.

MR. KOZAK: Right. As a result, your allowable concentration will change as you progress through each generation of the performance assessment.

MR. DORNSIFE: In reality, we used the second generation to say, okay, now we know what the intrinsic toxicity is. The next question to be answered is what happens when you take account of what happens in a real waste form under real world conditions. Is the waste a problem anymore?

MR. KOZAK: Right.

MR. DORNSIFE: I think the system can be used for those kinds of basic decisions.

MR. DEHMEL: Jean Claude Dehmel with SC&A. I have one observation and a question. The observation is that you relate the issue of the fee or the concern about tinkering with the A, B, and C classification system. Well, there are some compacts—for example, the state of Connecticut—who are looking at excluding all waste except Class A. Whether this would be a correct decision, that's something else. Some states also are looking very critically as to whether decommissioning waste should be accepted for disposal. My question is . . .

MR. DORNSIFE: Excuse me. Just to follow-up, part of the reason for developing the system was to see how the existing waste meshed with our hazardous life standard. And like I said, there may be the need for additional license conditions to meet the hazardous life standard that will be above and beyond the NRC's classification system. The only way I know of developing such a standard is through a risk-based system like this.

MR. DEHMEL: Thank you. My question is: I know that in the seventies and early eighties, there were efforts sponsored by NRC and DOE regarding the development of a joint risk-based standard to look at both the hazardous and radiologic components of mixed waste. How does your system differ from these early proposals?

MR. DORNSIFE: I am not familiar with the early proposals so I really cannot comment.

DR. JACOBS: Bill, in about 1968 there was an Italian scientist working with me who proposed a similar system. We did not consider non-radioactive materials, only radionuclides. This was at about the time that the burn-up of reactor fuels was increasing to the point that transuranics became a problem. The drinking water standards did not exist, of course, so we divided by the ALIs to calculate a hazard index. We also looked at the problem of radionuclide movement through the environment and decided we did not have enough information on the various radionuclides to assess environmental transport very effectively on a generic basis. Therefore, we just treated it in a conceptual manner.

Included in our assessment were considerations of some rather exotic potential disturbances of a disposal facility, including meteorite strikes, the effects of long-term surface erosion by wind and water, volcanism, and other processes. It's very difficult to try to derive any kind of probabilities for events of this nature.

However, our system is similar to the one you have just described. Later, Jerry Cohen had a contract with the NRC to develop a risk-based classification.

MR. DORNSIFE: Yes, I worked with that group.

DR. JACOBS: Yes, I was on that one, too. But essentially the thing that they added was consideration of the persistence of the radionuclides or materials over time.

MR. DORNSIFE: As I acknowledged in my paper, this is not a new technique. What is new though is the utility of it. The ability to be able to quickly plug in any waste or any activity involved and compare it, using the results as an effective risk communication tool. That's what's unique about it.

DR. RYAN: Bill, one comment and then several questions. It's important for everybody to realize that the current system for classifying low-level waste is not based on transport and, as you know, or a receptor's use of a concentration at a facility boundry. It's based on intrusion, a good example being the Class C limits which are based on a dose rate limit for an intruder of 5 mSv y^{-1}. This is spelled out in the draft EIS for 10 CFR Part 61 and is a little bit cryptic in the final EIS—but that's the basis that we have for the classification tables for low-level waste in 10 CFR 61.

MR. DORNSIFE: For Class C. But some of the radionuclides are dominated by transport.

DR. RYAN: Those are the specific activity cases but, if you want to consider them transport, that's fine. I guess that's important because the intruder scenario drives the consideration of impact in that setting. It seems to me that your risk-based system does that same kind of assessment on a radionuclide-by-radionuclide basis and then offers a comparison to soil or whatever else you might want to compare it with. The question is: Why do you need to consider transport in such detail if, in fact, the limiting case is based on direct intrusion into the waste?

MR. DORNSIFE: Let us assume that you start now having to comply with an EPA drinking-water standard that says you have to meet the MCLs in the nearest drinking water supplies. I am not sure whether the previous analysis is going to truly be limiting for the same radionuclides as it was before. If this proves a problem, it's very simple—instead of using the MCLs—to use the ALIs and look at inhalation as the critical pathway.

DR. RYAN: That's the critical point that I think is the focus of my question. You can interchange the radionuclides just as easily as you can the basis for the risk assessment comparison. You always have the ability to plug in parameters for those radionuclides that drive transport. These parameters are either solubility coefficients or K_ds, or whatever other parameter you want to use and end up with a relative assessment. This can be done radionuclide-by-radionuclide using whatever factor you want to consider.

MR. DORNSIFE: To be honest, the main reason that I chose the drinking water limit was a perception issue. Taking that approach gives you the ability to say that you are literally using the ingestion pathway as the basis for your comparison. In a real sense, you can say that you are "eating the waste." That provides a very vivid comparison for the public to understand. It's truly a worst case.

MS. WILTSHIRE: Bill, you made some comments on my talk. I thought I would make one on yours. I would be very interested in being kept up-to-date in, as I recall, your comparison between something, I forgot what, and coal-ash. Since people accept coal-ash, presumably they would be willing to accept the other substance. I would be very interested to follow comparison as it develops.

MR. DORNSIFE: Susan, I have used that already, not in my waste classification system, but in a comparison of hazardous and radioactive waste. This was 10 y ago. My objective was to look at the waste produced by coal plants compared to the waste produced by nuclear plants, by comparing their toxicity. One of the outcomes of that work was a slide that I used as part of the public information program. It shows exactly that—a comparison of low-level radioactive waste to coal-ash—which showed the ash to be as bad or more toxic than the low-level waste. I also compared low-level radioactive waste to natural soil. Oddly enough, never once did anybody suggest that we regulate coal more stringently!

MR. PASTERNAK: Alan Pasternak, again. In introducing Susan Wiltshire, Dr. Jacobs mentioned that she was identified with the League of Women Voters. For those of us in California, the League has done a lot of really good work in publishing citizens' guides for public participation and in facilitating their interaction on issues related to waste management and disposal. I just wanted to take this opportunity to thank her and the other League members for their contributions.

On another subject, Bill Dornsife made the comment that his calculations showed that most of the hazard in the Pennsylvania waste streams was associated with radium rather than with the radionuclides typically generated in nuclear power plants. In going back over some data, we noticed that, in the early eighties, there was a tremendous decrease—by orders of magnitude—in the shipment and disposal of waste containing long-lived alpha emitters, for example, plutonium. Although I am not sure why, there may be several reasons, one of these being the NRC's classification system. Another reason for the decrease may be better operating procedures at the nuclear power plants. When groups try to project what the waste streams are going to look like for the next 30 y, they are often challenged by those who quote the earlier data. That is to say, how can we be sure that waste streams won't return to the previous levels?

MR. DORNSIFE: If indeed we see that waste again, we will have to look at it in light of our hazardous waste standards. Maybe it will not be acceptable. But I think the reason that the data are changing is because people are sharpening their pencils. That's the real reason. In the past . . .

MR. PASTERNAK: Just doing a better job of identifying what's really there?

MR. DORNSIFE: Instead of using the lower limit of detection, they are spending more money in terms of doing the analysis.

MR. PASTERNAK: That's certainly true with the iodine.

MR. DORNSIFE: Let me give you an interesting statistic that we have uncovered looking at this ^{129}I problem. A couple of years ago the nuclear utilities were spending about 95 percent of their money in analyzing various isotopes in Table 1 of 10 CFR Part 61. Unfortunately, they were spending very little money analyzing the data required to compare the waste to the limits specified in Table 2 of Part 61. The Table 1 limits are meaningless from a performance assessment stand point.

MR. PASTERNAK: The other comment I wanted to make is that, in your development of the classification scheme, you really brought in some of the site specific performance assessment analyses and followed them back into a waste classification scheme. There again, it might be helpful to pick, on an arbitrary basis, an inherent toxicity index and stay with it.

When you get into the performance assessment at a given site, there are all kinds of variations. For example, in its review of the NRC's regulations way back in '82, the EPA commented that in arid desert regions ground water contamination was not the concern. In this case, upward movement of the radionuclides may be more important. For that reason, you get into the question of what is going to be the most likely pathway for exposure and the most likely scenario through which it can occur.

MR. DORNSIFE: I do not disagree with you. And that's why I tried to show that this was a problem. There are two factors involved in the transport of the radionuclides. One is transport from the waste form; another is transport through the soil. Of the two, transport from the waste form is probably the bigger contributor in terms of reducing toxicity. Because many of the waste forms are common, transport associated with this aspect can be treated in a more generic manner than transport through the soil.

MR. BOYD: My name is Mike Boyd. I am with the EPA Office of Radiation and Indoor Air. Although I do not have a specific comment related to your presentation, I wanted to take this opportunity before the break to make a couple of points.

First, I want to thank everyone for attending today and to say that EPA is privileged to have had the opportunity to have helped the NCRP in making this Symposium possible. I also want to say that one of our primary purposes in sponsoring this event was to promote the free exchange of ideas among experts. Although the proceedings of this meeting will serve as a source of information, I want to emphasize that it is not our intention to use this as a formal process to collect comments on any proposal that we might make. This is a scientific symposium; it is not a forum for some hypothetical proposal that we might be about to make. Although some of the discussion may be useful in our consideration of various options for the management of the ways to cleanup contaminated sites, its primary use will be in addressing unique waste streams that have not been considered and have not particularly been dealt with by the commercial low-level waste disposal sector. Specific examples of the types of things we are looking at are large volumes of diffuse activity waste, such as soil and ruble, waste from certain decommissioning activities and, of course, mixed waste and NORM waste. I do not think that these waste streams were considered by the NRC during promulgation of 10 CFR Part 61.

We are exploring a number of options for facilitating the disposal of this waste in possibly other than traditional means. And we are very early in that process. We invite your continued involvement in our public participation process which will be getting underway soon. Again, thank you for coming. I appreciate the opportunity to listen to these comments.

MR. DORNSIFE: Just a quick comment, again, from a practical world perspective. Because a landfill radiation alarm went off, we had a problem in Pennsylvania in dealing with the sludges that were created by the treatment of oil and gas lines that contained naturally occurring radionuclides. The highest activities we found were about 200 picocuries per gram of radium. Due to the nature of this waste, not being regulated, it was being sent for disposal in a municipal landfill. As a result, there was concern whether this approach for disposal could continue. Based on the charts I showed, waste containing 200 picocuries per gram of radium are equivalent to class B waste in terms of toxicity. Because our NORM regulations are primarily designed to deal with sealed sources, such as those used in medicine, such waste was not directly addressed in our regulations. Since the regulations contained limits on exempt concentrations and quantities, we did a risk analysis. We discovered that this waste was actually being sent to an industrial-use-only landfill where they were being spread out in the burial pit. This reduced the probability of high localized airborne radon concentrations.

One might ask whether, throughout this process, there were any expressions of concern on the part of the public. Absolutely not, even though the waste was being sent to a landfill. There is a real difference in perception of risks when you are dealing with non-reactor generated waste. In fact, I maintain that NORM waste is the only one for which we can make real radiation protection decisions anymore!

MR. RITTENBERG: Bob Rittenberg with U.S. Ecology. I am the project manager for the Ward Valley low-level waste site. I have only one question. I am looking forward, first off, to taking a look at Bill Dornsife's spread sheet. I think it's going to be a very useful tool in developing some of the educational tools that I need as a front liner. Let's say, however, that I have been asked to address students in one of the local high schools—or my son's teacher wants me to give a talk on relative toxicity. How on earth am I going to talk about Part 61 to 7th graders? That's a tough thing. My questions to Bill are these: First, what kind of a success rate have you had in dealing with disinterested parties, let's say, high schoolers who are not wrapped up around the emotional back axle? Secondly, how successful have you been in dealing with people who have been on the other side of the radioactive waste issue—who have been, let's say for lack of a better term, fighting you for years? Have you shown this to them? If so, what have been their reactions?

MR. DORNSIFE: I have given talks to science teachers and students using this information, and I have also used it in making presentations to the whole gamut of citizens and opponents—you name it. In fact, this information was probably very instrumental in terms of being able to convince people that soil was a good thing to use as a hazardous life standard. Having said that, however, I recognize that one of the problems with this new system is the present version continues to be pretty technical. We are still trying to find a better way to make it more readily understood by laypeople. If we could break it down into one slide, that would be great. We have not yet, however, been able to do that. The real key is to show that most of our low-level waste is not that different in toxicity from soil and other things in our everyday lives. That's what really increases the awareness.

MR. DEHMEL: Jean Claude Dehmel with SC&A. I have several comments. One is that coal-ash is being extensively recycled. About 30 percent of what is produced is being used as an additive in concrete. Some is also being incorporated as an additive in plastic used in making battery casings as well as bowling balls.

Also of interest is the fact that EPA, as I recall, in its annual report to Congress several years ago encouraged the recycling of coal-ash.

MR. DORNSIFE: In Pennsylvania, we are making a systematic effort to look at all the NORM issues, such as the problem with oil and gas sludge. One of our goals is to try to identify which waste is a concern and which is not. As part of this effort, we are in the process of collecting a lot of data. One immediate outcome is that one of the better ways of dealing with the diffuse NORM issue, at least in our state, is to apply the existing residual waste regulations, which include radioactive material. Basically these regulations require an increasing level of isolation, depending on the toxicity of the waste. In essence, all we really need to do is to apply what we already have. There is no need to create a whole new bureaucracy.

NCRP

Summary and Conclusions

Dade W. Moeller
Rapporteur

Introduction

The Program Committee has requested that I, as rapporteur for the Symposium, summarize the key issues that were raised by the people who presented papers, by those who took part in the oral discussions, and by those who submitted written comments. The assigned task included highlighting any areas of consensus, and drawing any conclusions that appear to be justified. Although this is an awesome task, it has been made much easier by the excellence of the oral presentations and discussions that have taken place. Using the sequence of talks and the assigned topics as a guide, my response is as follows.

Characteristics of the Waste

To estimate the associated risks, the nature and characteristics of the waste must be known. As noted by our initial speaker, there is a range of issues related to this subject.

1. One of the first is to identify and confirm the specific characteristics of the waste. This includes not only the physical and chemical nature of the waste, but also factors such as its flammability and corrosivity, its leachability, and the time duration over which it is assumed that the waste remains hazardous, as well as how long the integrity of the waste form and associated container can be assumed to be maintained.
2. Assuming that an adequate array of such characteristics can be defined, related issues include the confidence that the public can have that regulatory officials can conduct a sufficient number of tests on an independent basis to confirm that the data being reported on

the characteristics of the waste shipments, as received at a disposal site, are accurate. Otherwise, it may not be possible to assess and/or predict their potential health and environmental impacts.

3. In cases where waste has been treated prior to shipment to a disposal site, there is a need to be able to confirm that the treatment process was effective and that the target contaminants were properly stabilized.
4. Another important need is for waste management officials to be able to project the quantities of waste within each category that will be generated, and their principal sources.

Environmental Transport

Once our ability to predict releases of contaminants from the waste has been confirmed, the next step is to predict the potential movement of the contaminants to the accessible (off-site) environment. This involves what is generally referred to as "site characterization" and it must encompass the behavior of the disposal facility and accompanying waste both under "normal" conditions, and situations in which the site may be altered due to natural events.

1. Related issues under normal conditions include being able to predict the:
   a. Performance and rate of deterioration of engineered barriers (such as the integrity of the waste form and its containers).
   b. Behavior of natural systems associated with the disposal site over long periods of time into the future.
   c. Movement of groundwater through the facility, the degree to which it will leach out the contaminants, and the degree to which it will transport the contaminants to the off-site environment.
2. Related issues under conditions in which the site and facility may have been altered due to the occurrence of natural events include:
   a. Identifying the events that might lead to such disturbances, their probability or frequency of occurrence, and their associated impacts on the waste and the site.
   b. Having the capabilities to estimate the future likelihood for the occurrence of earthquakes, floods, and other natural events. Predictions of such events are frequently based on the historical record which, at a maximum, covers only a few hundred years.
   c. Being able to determine how far into the future these predictions need to, and can realistically, be made, as well as how wide a range of events must be considered.

Identifying the Impacts to be Considered

One of the first decisions is to determine which impacts are to be taken into consideration in assessing the risks associated with a given disposal facility.

1. These include identifying the endpoints that are to be used. Prominent among these are the need to:
   a. Identify the types of health endpoints that are appropriate for assessing the impacts upon the public. For example, should these be restricted to excess cancers, only, or should they include years of life lost as well as morbidity and associated health care costs and emotional impacts on family members?
   Note: Although the primary long-term effect of chronic exposure to radiation is an excess of cancer cases, toxic chemicals can have a wide range of impacts including neurological effects, alterations of the hormonal system, the enhancement of allergies, etc., as well as cancer. Methods are needed to assess the non-cancer effects. For example, what are the risks associated with an enhanced allergy? What also is the role that heritable abnormalities should play in developing a risk-based system?
   b. Determine the types of endpoints that should be used for assuring protection of the environment. Are we to assume that if people are protected, all other components of the environment will be adequately protected?
2. Assuming that the specific health effects that are to be considered have been identified, the people responsible for assessing the impacts of a waste facility will need to:
   a. Estimate the health effects that may arise from exposures to specific types and quantities of toxic chemicals, exposures to specific types and quantities of radioactive materials, and exposures to combinations of the two.
   b. Account for the difficulties arising from the fact that the production of cancer involves a complex sequence of stages—initiation, *promotion, and progression—and these may differ from one* causative agent to another.
   c. Decide which population group—adults, children, infants—the system should be designed to protect, and what to do about those people who may have a genetic susceptibility to specific diseases. Also requiring decisions will be the degree to which potential effects on the growth and development of the embryo should be considered, and how to account for, and evaluate the importance of, the effects of the facility on animals other than people and on the environment, itself.

d. Adjust or account for the problems and potential errors in extrapolating from high doses and high-dose rates to low doses and low-dose rates, including the selection of the "correct" dose-effect model to be used.
e. Determine whether it is correct to assume a threshold for certain effects and not for others, and on what basis.
f. Determine the degree to which risks to individuals, versus those to society, should be considered and how aggregate societal risks will be estimated.

Assessment of the Risks

The next step in the establishment of a risk-based system for classifying radioactive and mixed waste is to develop a methodology for assessing the risks that might arise should certain types of events impact upon the facility.

1. One of the first requirements in developing such a methodology is to identify a defensible set of scenarios or sequences of events that need to be taken into consideration. Specific tasks involved in this process will be the need to:
   a. Identify the scenarios that encompass and/or bound the full range of important events that may occur.
   b. Determine whether generic or site specific scenarios must be used to assess different waste and different waste disposal facilities.
   c. Assess whether scenarios having a very small probability of occurrence can be disregarded and, if so, to define the guides for making such decisions.
2. It will also be essential that data on the key characteristics of the disposal site be available. For example:
   a. Sufficient data will need to be collected and available to permit changes in the state and transport of the waste components to be properly modeled.
   b. Uncertainties in the data will need to be addressed, particularly with respect to the anticipated frequency and magnitude of natural events that might disturb the performance of the disposal site at some time in the future.
3. Once this has been accomplished, the next step is to apply various computer models to the site and facility to predict the risks that may develop as a result of the sequences of events described in the various scenarios. In this regard:
   a. Computer models will need to be selected, and a determination made that they apply to the facility and site being evaluated.

b. The accuracy of the models must be verified and validated, and the responsible authority identified.
c. A decision must be made on whether the accompanying calculations should be conducted on a realistic or conservative basis.

Establishment of Applicable Standards

Concurrent with the above evaluations will be the necessity of establishing standards to be used in determining the acceptability of a given waste disposal facility. Related issues include:

1. The degree to which exposures from natural sources of radiation and toxic chemicals should be used in determining acceptable risks from artificial sources.
2. Assuming that satisfactory endpoints can be established, a mechanism will need to be established to assure that similar philosophies or approaches will be applied for both the toxic chemical and radionuclide components of the waste.
3. In some cases, the effects of combinations of radiation and toxic chemicals may prove to be synergistic, that is, the combination of exposures may have a larger health effect than the sum of the two contaminants acting independently. A mechanism will need to be established for evaluating these effects.
4. The pathways and exposure modes may differ for waste in storage versus those that have been sent to disposal; they also would be anticipated to differ for waste that has been treated versus those that have not. To resolve related issues, a system will need to be established to determine whether different standards need to be developed for different stages in the waste management cycle, that is, to account for changes in the form or composition of the waste.
5. Radiation sources are currently being regulated using a "top-down" philosophy. This involves setting a limit, which carries with it an acknowledged level of risk, and then applying the as low as reasonably achievable (ALARA) criterion to assure that exposures are well below the limit. Hazardous chemicals, in contrast, are being regulated using a "bottom-up" approach. This involves setting a regulatory limit which is widely viewed as having a minimum level of risk, and then relaxing the limit, as needed, to cope with unusual circumstances. Procedures need to be developed to resolve these differences, and to develop a system through which standards for acceptable risks from chemicals and radiation can be established on a comparable basis.
6. Efforts need also to be undertaken to establish concentrations for radioactive materials and toxic chemicals in waste that can be

considered to have such a minimal associated risk that they can be made exempt from regulatory control. Essential to such an effort is to determine whether there is a level of risk that all members of the public will be willing to accept without concern.

7. Once these issues have been resolved, the next step will be to determine what processes and procedures should be used in establishing an acceptable level of risk. In this regard:
   a. Studies show that the highest doses will probably be received by a person who intrudes into the disposal facility at some later date. Procedures need to be established for determining how this date is to be established, whether exposure limits for these people should be different from those for non-intruders, and whether the limits should be different for the inadvertent, versus the willing, intruder.
   b. A related issue is to identify the specific members of society who are to be protected. One possibility is to seek to protect the "maximally exposed individual"; another is to protect the average member of the "critical group." Also needing attention is the time span over which the system for protection must be assumed to function, and the degree to which risks to humans should be weighed in comparison to risks to other animals and the environment.
   c. Also warranting consideration are cases in which a given technology is considered essential, but adequate methods for disposing of the associated waste is not available (with the result that the risk limits will be exceeded).

Determining the Acceptability of a Waste Facility

Once standards have been established, and methods for evaluating the performance and health and environmental impacts of a given waste disposal facility have been confirmed, there will be a need to establish the criteria for determining the acceptability of a given facility and site. In this regard, decisions will need to be made on:

1. Whether "bright lines" or ranges of risks will serve as the basis for determining such acceptability.
2. Whether, in some cases, it may be desirable to consider only the consequences (and not the probabilities) of an event.
3. Assuming a range of risks is applied, how the review process will be conducted and who will make the decision on the acceptability of the facility and/or site.

Related Societal Issues

Also to be considered is a host of societal issues related to the determination of the risks associated with a waste disposal facility and, in turn, judging whether a given facility is acceptable (that is, that it complies with the standards). In many cases, a given issue will have both technical and societal implications. Issues relevant to this subject include:

1. Whether the standards for waste disposal facilities should be uniform nationwide or should local conditions and public and corporate points of view be taken into consideration? For example:
   a. Public concern and/or opposition to toxic and radioactive waste varies with geographic region (east versus west; north versus south), population density (urban versus rural areas), and by different socioeconomic groups. In many cases, members of the public appear to prefer to have decisions about such issues made at the local level. Procedures need to be developed to determine how these issues are to be considered. A related requirement is consideration of the role of the concept of "environmental justice."
   b. Certain areas (particularly in the west) have dry, arid (desert) sites with low rainfall that provide conditions that appear to be favorable for the disposal of certain types of waste. Policies will need to be established on whether different standards and/or regulations should apply to disposal sites in different parts of the country. A determination will also need to be made on whether people living in areas having more favorable characteristics should be asked to accept the waste from other areas.
2. If the public is to be able to apply sound judgments in making decisions on the selection of sites for waste disposal facilities, they must understand the relevant issues, the limits on control technologies, and the impacts on their lives should certain operations need to be terminated for lack of a place to dispose of the associated waste. In this regard, a process needs to be developed to help the public:
   a. Understand probabilities and be able to recognize that there are no benchmarks for designating what level of performance for a waste disposal facility is "safe" versus what is not.
   b. Be able to view different types of hazards in the same context, for example, when the risks from a toxic chemical and a radioactive material are comparable, it should be possible to apply similar approaches in the evaluation and interpretation of the associated risks.
   c. Be able to conclude that the nation's resources for addressing environmental problems are limited and that monies spent unnecessarily in controlling minor problems might more wisely and effectively be spent on other more pressing issues.

3. The public should also understand that it may not be technically feasible, in every case, to avoid producing hazardous and radioactive waste. In cases where such waste is produced, it may not be readily possible to make them innocuous.
   a. For situations such as these, the public may demand that the waste be disposed in a facility that permanently isolates them from contact with the accessible environment. This leads to questions as to how such isolation can be guaranteed and for how long.
   b. Another possibility is that industries may export the related operations to countries that exercise less stringent requirements on environmental protection. Such a situation has many associated implications.
4. The participants were reminded that, in the case of low-level radioactive waste, a classification system based on the associated health and environmental risks has been in existence for some time.
   a. Under this system, low-level radioactive waste is grouped into three categories (Class A, B, and C) depending on the concentration and halflife of the radionuclides they contain. If this system or approach is deemed to be providing adequate protection, a determination will need to be made as to whether the establishment of a new system is justified. This will include evaluating the advantages of a new or more elaborate risk-based system and whether these advantages justify the effort.
   b. Also to be determined is whether the public will be willing to accept a system that purports to quantify the risks from hazardous chemicals and radioactive materials on a comparable basis?
5. Another issue that has both technical and societal implications is whether current approaches for the disposition of toxic chemical waste represent "disposal" (as is often stated to be the case), or do they more realistically represent "long-term storage?"
   a. Radionuclides decay, so presumably if they can be placed in a facility that will retain them for a sufficiently long period of time, they will no longer be of concern. In contrast, many toxic chemicals (for example, lead, mercury, cadmium and arsenic) will remain problems forever. These differences need to be acknowledged and taken into consideration in comparing the relative risks of the two types of waste both before and after disposal.
   b. Recognition of these differences could lead to the necessity of subsequently removing hazardous chemical waste from their present disposal facilities, and treating and disposing of them in a more permanent manner. One of the advantages of the development of a common risk-based waste classification system might be to harmonize the selection of waste management strategies, with the result being that such situations could be avoided in the future.

Issues Raised During Discussion Sessions

A number of issues were identified and reviewed as a result of the oral discussions that took place following presentation of each of the formal papers. Highlights may be summarized as follows:

1. Many of the participants agreed that the development of a risk-based system was technically sound and would be a useful effort, however, representatives from state regulatory agencies and the commercial sector expressed concern that such a system could imply deficiencies in existing classification systems and that the process could thereby further delay the establishment of new facilities for the disposal of low-level radioactive waste. Although others pointed out that this is a typical response to any type of change that is proposed, it clearly demonstrates that it is essential that the development of any such system be pursued on an evolutionary basis.
2. In this regard, several participants urged that no attempt be made to undertake at this time a detailed revision of Title 10, CFR, Part 61. Rather, their suggestion was that initial attention be directed to the development of a system that would permit decisions to be made for naturally occurring and accelerator produced radioactive materials (so-called NORM and NARM waste) and other types of "orphan" waste, for the development of cleanup standards for contaminated nuclear facilities, and for the provision of guidance on the recycling of contaminated materials. Many agreed that the most important initial applications of a risk-based system would be: (a) to resolve some of the dilemmas faced with regard to the management and disposal of mixed waste, and (b) to help people understand that there are direct links between such a system and the development of standards for facility cleanup, site remediation, recycling of contaminated materials, and waste disposal. Several participants also identified defects in current regulations promulgated under the Resource Conservation and Recovery Act (RCRA) that the development of a risk-based system could help to correct.
3. Other participants urged that a clear distinction be made between the problems being faced by those groups who are generating waste in the commercial sector, versus the waste being produced as a result of operations within the Department of Defense and Department of Energy. Waste from these two Departments often tend to be viewed as one, which they are not. Representatives from the commercial sector stated that their needs are real and immediate. In addition, it was pointed out that there is a need to distinguish between the development of a risk-based system for the management, versus the disposal, of waste.

4. Also cited were the uncertainties that permeate essentially every parameter that must be factored into the development of a risk-based system. These include uncertainties in the characteristics of the waste; the disposal site; the movement, retention, and transformation of individual waste components within the environment (which are largely site specific); knowledge of the health and environmental effects resulting from exposures to the waste (see below); and the models required to perform the accompanying risk assessments. In view of these uncertainties, several participants questioned the value of the outcome of any risk assessment that may be performed. In any case, efforts will need to be made to address and consider such uncertainties in developing risk management strategies.
5. It was also pointed out that, although data exist for quantifying the health and environmental effects of ionizing radiation, the number of existing and new chemicals being developed each year makes it difficult to provide similar data on the effects of hazardous chemicals. Even where information on chemical compounds is available, most of it is based on laboratory studies using animals other than humans. Radiation is one of the few environmental risks for which extensive human epidemiological data are available. Everyone seemed to agree that additional research is needed, particularly with respect to the effects of hazardous chemicals on humans and on the possible additive and synergistic effects of combinations of various types of radioactive and chemical substances.
6. Although several participants stressed the need to involve the public at an early stage in the development of a risk-based system, many expressed frustration in knowing the proper approach. Those knowledgeable in the field stated that it is generally difficult to generate public interest on issues of a national or global nature (it is best to begin with issues of local interest), and that an acceptable approach is heavily dependent on the local situation (that is, that plans must be made on a case-by-case basis). Technical people must also realize that the development of programs for public involvement requires the same type of preparation and thought as do programs for scientific research.
7. Also pointed out was the fact that the acceptability of plans for the management and disposal of a given waste depends on the circumstances. Where the benefits are perceived to be large, people are willing to accept larger risks. Factors such as these need to be taken into consideration in the development of a risk-based system.
8. Also receiving attention were the problems generated by probability that humans might, at some future time, intrude into a waste disposal facility (either inadvertently or purposefully) and be directly exposed to the waste. In fact, assessments of essentially all types of waste disposal facilities show that the consequences of human intrusion dominate the associated risks. Questions were raised as to how long

regulators could reasonably assume that human intrusion would be averted by institutional control and the types of scientific capabilities that risk assessors should assume that future generations might possess. No clear consensus was reached on these issues.

9. Because of a history of what they consider to be abuses, certain groups, particularly the representatives from the Indian Nations, noted that they are skeptical of the goals and purposes behind the development of any new system. Examples cited of past problems included the lack of monitoring of Indian peoples during the United States atmospheric nuclear weapons tests in Nevada and delays in the cleanup of uranium mill tailings sites, some 30 percent of which are reported to be on Indian lands.

Conclusions

On the basis of the interchanges that took place during the Symposium, it can be concluded that the primary issues related to the establishment of a risk-based system for evaluating the disposal of radioactive and toxic chemical waste involve a wide range of:

1. Technical Questions
   These include:
   a. Identifying and selecting an acceptable approach for dealing with the large uncertainties that permeate the data required as input into essentially every aspect of the application of a risk-based waste classification system. This includes the development of a reliable capability for predicting over long periods into the future the performance of various engineered barriers, and the frequency and magnitude of various natural events.
   b. Selecting scenarios for evaluating the releases of contaminants from the disposal facility and their subsequent movement within the environment.
   c. Selecting and validating the computer models to be used for conducting the associated risk assessments.
   d. Determining the characteristics of the waste and the disposal site that are necessary as input for the required analyses.
   e. Identifying and selecting endpoints for evaluating the associated impacts on the health of the public and the environment. Closely allied with this issue is the need to develop a common system for expressing the risks from hazardous and radioactive waste.
   f. Applying the system, once it has been developed. In this regard, most participants agreed that one of the first applications of a risk-based system would be to help resolve problems associated

with mixed waste and with the differences between regulations developed under the Atomic Energy Act and RCRA.

2. Societal Issues

   These include:

   a. Factoring into the exercise the potentially negative impacts that the proposed changes may have on the development of new waste disposal facilities, and enabling current waste generators (particularly those in the commercial sector) to dispose of their waste. There appeared to be general consensus that plans for the implementation of any risk-based system should be evolutionary in nature.
   b. Educating the technical waste management community on the proper approaches for interacting with the public in an effective manner and at the proper stage in the process. Important components of this exercise include enabling members of the public to view different types of hazards (radiation and chemical) with the same perspective and rationality, to understand probabilities, and to recognize that there are no clear-cut benchmarks for designating a "safe" versus "unsafe" disposal facility.
   c. Enabling members of the public to understand the associated economic implications. Prominent among these are that the nation's resources for addressing environmental problems are limited and that monies spent unnecessarily in controlling minor problems will not be available to address more pressing issues.

Although consensus was not reached on a number of issues—nor was this the purpose of the Symposium—certain facts did emerge. There appeared to be general agreement that a risk-based system, properly developed, could be useful as a tool for communicating with the public, and that such a system could have benefits in helping to harmonize the standards and regulations for toxic chemicals and radioactive materials, as well as other risks in our daily lives. At the same time, other participants and speakers pointed out certain negative aspects of such a system. Among the more prominent of these (see Table 1) are the disruption it would cause in the existing legal and regulatory system, as well as the program for developing new disposal facilities for low-level radioactive waste.

TABLE 1—*Advantages and disadvantages of a risk-based system for classifying radioactive and mixed waste.*

Advantages:
Could promote clarification of the issues and allow people to see waste management and disposal problems more clearly, thereby permitting important decision-making questions to be handled on a technical, versus emotional, basis.
Would provide a mechanism for harmonizing standards for site cleanup, remediation, and recycling, as well as waste disposal; this could lead to improvements in practices for managing such operations, with reductions in associated costs.
Might help resolve dilemmas such as those currently being faced with respect to the disposal of mixed waste, which are subject to regulations developed under both the Atomic Energy Act and RCRA.
Would make waste management and disposal decisions more open and transparent.
Could serve as an excellent tool for communicating with the public.
Disadvantages:
Would be disruptive to the current legal and regulatory system; could reduce the role and responsibilities of the states; and could imply serious deficiencies in existing waste management programs, thereby causing additional delays in the establishment of new disposal facilities.
Could lead to revised standards that are just as complex as the existing ones; could lead to standards that are less restrictive than those currently in place.
Because of the large uncertainties associated with the required input data, people would tend to have little faith in the results of the accompanying risk assessments and the conclusions might be largely regarded as meaningless; reducing these uncertainties could require extensive research, thereby diverting time from solving other equally or perhaps more important problems.
Could cause the public to question why the changes are being made and why they are being made now; could raise suspicions of a hidden agenda.
Could impact on the ownership, responsibility, and liability for waste.

Speaker Comments

DR. JACOBS: For anyone else, this would have been a remarkable achievement. But this is the sort of performance that I expect from Dade Moeller, having seen him in action several times before. What we are going to do now is give each of the speakers an opportunity to add some additional comments after having made their presentations and heard discussions from the floor. And we are going to proceed in order of the presentations that were made. So Kitty, would you lead off?

MS. DRAGONETTE: Well, there's one point I would like to make and it's consistent with Susan's point of getting back to defining what's broken and what it is we are trying to fix. Several of the people who have offered questions and comments have pointed out some of the disruptive potential of re-examining the radioactive waste classification system in isolation, rather than focusing on a risk-based system for mixed waste. What's broken is there's no way to dispose of mixed waste. Is there some way to develop a risk system that will help us deal with that issue? To me, that's what's broken.

Although several people have pointed out that the mixed waste produced by the commercial sector represent less that two percent of the total—based on the '90 survey—there is still a large problem with the waste, both mixed and low-level, being generated by the Department of Energy. I hope that we can articulate in some way that that's what's broken, and that's what the agenda should be—to develop a system for making reasonable decisions on how to manage and dispose of mixed waste.

DR. JACOBS: Thank you. We will move right on to Art Upton.

DR. UPTON: There are many participants out there who have been generating cards and questions. I will defer my comments until we have had a chance to hear from the others.

DR. JACOBS: Next, we will hear from John Garrick.

DR. GARRICK: The only comment I want to make about risk assessment that's important is that it is not a process that we should be forcing. It's primarily a thought process, and it should be as natural as we can make it. That does not mean that we do not abuse it, that we do not misuse it, and what have you. But the concepts in applying this kind of thinking that work are the concepts that keep things in perspective. As I see it, it's a "contextualizer." It's a way to put the questions and the answers in some sort of order or framework.

I am reminded of an event that gave me high confidence in this process. That was the first time that risk assessment found it's way into a public hearing in connection with the Zion Indian Point reactors. We were being interrogated with respect to the risk assessment that we had performed. What caused an upshot in my confidence in applying logical thought processes, such as this, to the assessment was when the interveners started putting forth their questions and their issues. Because of the work we had done, we were able to deal with those questions and issues within the context of a framework. That is to say, we were able to acknowledge that these questions ought to be dealt with. If they have not been dealt with, then let's deal with them following the same rules used in dealing with these other questions and see what happens.

What happened, at least as far as the hearing was concerned, was that we suddenly moved the debate and the discussion from an emotional kind of thing—with questioners asking have you thought of this or have you thought of that?—to a much more systematic and deliberate approach. It was quite a revelation! I think that's the direction that we ought to be moving as far as the use of a formal discipline such as risk assessment is concerned. Thank you.

DR. JACOBS: Next, we will call upon Steve Brown.

DR. BROWN: I probably should take Art's route out, too, but, of course I will not. I probably have 24 things that I want to say, but I will try to limit it to a couple. Although some of my comments may irritate some people, I trust they will understand the context in which they are being presented. First of all, one thing that I would recommend to the people that have to do this—fortunately I do not—is that one option to consider is not to have a classification system. Instead, we might develop an approach that, once you tell me the characteristics of the waste, I will tell you what to do with it, without tying the action to a specific classification system.

The second thing that I would like to say is that I am almost painfully aware that when one puts out risk numbers—the kind of risk numbers that I have talked about such as individual risk and population risk, or the kinds of risk numbers that John talked about, such as the probabilities of occurrences of failures or adverse events—we must recognize that those are not the only things that are important. On the other hand, as a professional risk assessor and risk manager, I do think it's important for people to understand how bad "bad" is, and what you might want to do about it. So I think that risk should be on the table, at least as one of the decision-making factors.

In that context, I think it is important to survey the whole field, and at least to understand how different hazards might be managed differently with respect to risk. I was particularly interested in the discussion of naturally occurring radioactive materials, NORM. As of this afternoon, NORM includes things such as coal-ash, oil and gas-pipe scales, and waste from rare earth facilities. Jean Claude could tell us some of the other waste that EPA is considering in its NORM deliberations. I think that when you look at these kinds of waste and you recognize that they produce gamma radiation and they produce radon, and they produce other things, then we find that we must be concerned about them when we develop a system for the management and disposal of radioactive and mixed waste. I have yet to be convinced that radon comes in colors. Actually, gamma rays do come in colors in the sense of wave length differences. So why is it that Bill tells us that, in Pennsylvania at least, coal-ash does not seem to be a disposal issue? Why is it that pipe scale is not a disposal issue? Why is it that radon in homes is not a particularly big issue with the public? There are at least four different explanations for it. My point is that we ought to know what these are. Is it that people do not know about these risks, that is, they have not heard about them? Is it because they do not believe what the scientists tell them? This is a pretty wide-spread reaction to these kinds of things! Is it because some people have alleged that management of a particular waste should depend primarily on who must pay to do something about it? Or is there something sort of intrinsic about where the waste came from that really is like a color that says, well, you know, the radon comes out of the coal-ash that went into the cinder block that went over there? That's really different, because, you know, I sort of like the coal power industry, but I do not like the nuclear industry. Maybe that's all right, but at least it should be more out on the table.

DR. JACOBS: Those comments are liable to generate a whole lot more discussion, Steve. The next speaker that we will call upon is Susan.

MS. WILTSHIRE: Thus far, everyone's been revealing their own personal predilections. I love thinking about things I know little about, learning about something new, trying to organize information. Give me a problem. I like a new problem, particularly if it's something that seems global and has lots of meat to wrestle with. I am just like an old fire horse when the bell goes. As my father, who was a plant ecologist, said, "You are good example of a challenge and respond." Just give me a challenge and I will respond. So I really have to hold back from wanting to recreate the whole system of classification of waste into something that is logical, transparent, and all of those things which are very seductive for us. However, although I have a desire to organize the world in a logical and sensible way, I long ago found that the world does not work in a logical and sensible way. Although we can try to impose order, the world is going to resist us every step of the way. So you have to narrow it down.

One thing that intrigued me was the possibility of initially directing our primary attention to thinking about a risk-based classification system that would be designed specifically to address high volume, low activity soil and rubble. In trying to think about it, I ask myself how that approach might be perceived and where it might go? This would represent something specific to really chew on. Such an approach might also help us resolve the mixed waste issue, and how you compare the risks of organic toxic chemicals and radioactive materials. These are interesting challenges.

DR. JACOBS: The last speaker we will call upon is Bill Dornsife.

MR. DORNSIFE: I don't believe I heard you mention it, Dade, but one of the most useful things that I found in the work that we have done so far in terms of developing a risk-based system is in its application as a screening tool to focus attention on the waste that is really important. I cannot tell you the number of times that our screening process has revealed errors in the recording of data on a form or over-estimations of the radionuclide concentrations in a waste. One of its major attributes is that it provides you a really neat way to get to the things that are important and not waste your time on insignificant issues. This is one of the principal benefits of a risk-based system.

As I stated in my earlier remarks, one of the most difficult things in dealing with anything that involves risk is this concept of risk communication and what risk really means to the public. There's such a different perspective in terms of the things that enter into the public's thought process when they look at risk, that it may be impossible to come up with a system that satisfies everybody. My experience has been that the liability issue, and differences in the way in which the public views naturally occurring versus industry produced waste, are the over-riding issues. The public has little interest in what the real numbers say. Unfortunately, I am not sure how we can solve these problems.

DR. JACOBS: Dade, did you want to make a wrap-up of your wrap-up?

DR. MOELLER: No, thank you.

DR. JACOBS: We are going to open the floor now for additional comments and discussion. If you have any questions you would like to address to any of the speakers or any comments you would like to make, this is your opportunity. Please go to one of the microphones and let us hear what you have to say.

MR. LESLIE: Bret Leslie from the Institute for Energy and Environmental Research. As Susan Wiltshire suggested earlier, people interested in the environment do talk to each other. I wanted to share with you some comments that I have received. This is the opinion of Bill Widell and it represents the down side of using risk analysis. He says that the role of social economic analysis, particularly the attempt to derive meaningful economic costs, is hampered by the use of a risk-based analysis. Because of the low probabilities of many naturally occurring events, this system drives all costs almost to the zero. Also tending to make the costs almost meaningless is the use of discount rates far into the future. For these reasons, he suggests that we need to establish something like a dual track analysis that costs out an event, if it does occur, and that also costs out the probabilistic costs of all occurrences. This concept should be applied to handling the discounted costs of future events. Although he acknowledges that neither estimate for either side of the dual track will be completely correct, I believe that having both type of estimates would help the public make a more informed decision.

DR. RYAN: I think there is one important regulatory item that has not come out today. As I understand it, both the NRC and EPA systems of regulating the components in mixed waste have a provision for seeking delisting. You can seek to delist the hazardous waste, and you can seek exemption of special treatment under a special case provision for a radioactive waste. It would be real interesting to consider the concept that we have talked about today, a risk-based system as the framework for delisting, either on the radioactive side or the hazardous side or determining which should rule. I know of very few delisting petitions in which a risk-based system has been considered, but this might be a framework for thinking about that. I would be curious how our regulator folks would tie this concept to the existing regulations in the concept of delisting or special treatment.

MR. DORNSIFE: Although we did not realize at the time, we used an approach similar to this when we approved the disposal of NORM in a landfill in Pennsylvania. We did go through a risk assessment process, and we looked at developing numbers, using a risk-based approach, to determine whether this waste was acceptable for disposal in other than a radioactive disposal facility.

MR. CHURCH: Bruce Church, Department of Energy, Las Vegas. I would like to ask a question that is on a little different vent from what we have just been discussing. My question pertains to the importance of, and certain aspects related to, the human intrusion scenario. In considering this type of exposure, we assume that institutional controls will apply and be effective for a hundred years. What is the basis for this number?

Even here in the United States we have places where we have had institutional control for well over several hundred years. Elsewhere in the world, there are places that have been identified and preserved for well over thousands of years. It's a very tough concept for me to accept that we cannot create some kind of marker for future posterity that will provide institutional control for well beyond a hundred years. As we proceed down the path of risk-based kinds of systems, we need to look meaningfully at institutional control and it's reality with respect to the associated uncertainties. Otherwise, I think we are really missing the mark by a wide margin. I would appreciate the responses of any of the panel members.

MS. WILTSHIRE: May I respond first? As an example in support of the one hundred year time limit, I am trying to recall an example that someone gave me recently about a waste site that's 30 y old. The location and the memory of it were lost; it was accidentally discovered just again recently. So even within 30 y we can lose it.

MR. CHURCH: I am sorry but I do not think that's an example at all. Let me tell you why. If you set out as a goal to eradicate signs and locations on what has happened at a particular place, I can cite examples where the history and the memory is gone in much less time than that. But I am talking about where you set out to mark a location for posterity. In these cases, you really, truly put in the kind of monuments and records and historical logging that will define that that is a place, a space, an object to be preserved for time and for posterity.

MS. WILTSHIRE: I understand your response to my giving you a single example as not making a difference, but I had a different purpose in mind.

MR. CHURCH: I apologize.

MS. WILTSHIRE: That's perfectly all right because it makes my point even stronger. What we have left from the past is what has survived. What we do not have from the past are the things that have not survived. And there's no way for us to be certain how many of each there are. We may know what survived, but we do not know what did not survive. People always bring the pyramids up. I have been to Egypt and seen pyramids that have collapsed. There are some wonderful ones that are intact, except for the external blocks, but there are plenty that have collapsed. And, of course, they did not protect their contents in any case. I believe that it's arrogant of us to think that what we produce will have any more survivability than that in the past, even with our good intentions.

The same problems apply to the survival of societies. Some years ago I had to argue the point that not all societies, even strong ones, survive for many years. That was changed by the recent collapse of the Soviet Union. As strong as it is, even our own country could collapse quickly. I know some governments have continued for a long, long time. But there are discontinuities in history. Just look back and you see civilizations that just disappeared. And for reasons that we do not necessarily understand. Although we think that that could not happen to us, we should recognize that it could. I have to take the other side of that argument.

MR. DORNSIFE: Let me add an additional comment. First of all, I agree that a hundred years is absolutely arbitrary. In Pennsylvania, though, our law requires long-term care for the hazardous life. In the case of some of the waste, the hazardous life is going to approach 500 y. As a result, we intend to provide long-term care for 500 y for our facility. When we conduct a performance assessment, it will take credit for care over that period of time.

In general, however, the public wants to know what's the worst case. For this reason, and because you need to show that the requirements can be met even under the worst case, you assume arbitrarily that after a hundred years somehow all institutional control goes away. At that point, the assumption is made that natural processes start breaking down the engineered barriers.

MR. CHURCH: I recognize that as an answer, and I can even rationalize the same kind of arguments that both of you have made. However, I think that you have sold our society and us as individuals short a long way. I think you have also sold our technology capability short. As we move into a risk-based kind of system, we need to be able to really put some definition into institutional control. We have a big black box that's part of that equation that is poorly defined at this point in time.

DR. BROWN: I do not have an answer for this. I was just going to ask John Garrick a question. Is there any reason that you could not include the probability of failure of institutional controls after 30, 100, 10,000 y as another variable in your analysis?

DR. GARRICK: I want to make a comment on this whole business of human intrusion. As you saw in my presentation, I included it in the category of episodic events and thereby admitted that it's something we have to deal with and acknowledge and somehow be accountable to. I tend to agree a little bit with Mr. Church about this, that we are underestimating the intelligence of future generations in many respects when we give up on this issue. But I think there's another part of the human intrusion issue that needs to be addressed a little more carefully. That's the part that has to do with the "so what" question. Assume that there is human intrusion. As societies advance, certainly history favors us being able to improve our ability to know what to expect when we are dealing with nature and to know what we have to measure. These processes have improved many-fold just in our own lifetimes. Some people have said, "Let's assume the status quo." Well, there is no status quo. What we have is a tremendous revolution in our ability to understand phenomena and natural processes and to make measurements in a short period of time. Regardless of whether you assume that future generations will or will not be capable of dealing with problems of this nature, these are simply factors that will have to be a part of any analysis that you do in conducting a performance assessment.

One of the things that I also said this morning was that I do not think you can predict the future. On the other hand, I think that there's another way to look at this. That is that human societies have always had to live in an environment of hostile threats. They are always there. In many cases, there was not a particularly deliberate process or attempt to try to acknowledge and recognize them, and assure ourselves that we are going to always be protective of them. It is not as if this is the first time that societies have had to live in an environment that threatens our health and welfare. But it is a big emotional issue. However, it is not a hopeless situation. If it were, then I think that our whole society would have to come to a screeching halt.

MR. DORNSIFE: I have a real problem when we are dealing with mother nature in that there's a good possibility that climate changes, or something like that, could have a significant impact on our ability to predict the future. If we have major climate changes, all bets are off. It's a totally different ball game! A real world example is the Swedish repository that's located underneath the Baltic Sea. Because of glacial uplift, in 500 y that repository is going to be above the sea. They will have a whole new set of scenarios to look at in terms of the long range future.

MS. WILTSHIRE: I just want to clarify something. I think one of my remarks has been misunderstand. I did not mean to express hopelessness about human intrusion or that you can do anything. I just want us to be a little bit more humble about our abilities, and to recognize that our best efforts may not be adequate, and that we therefore need to analyze the possible consequences. It does not mean that we should be hopeless about it or that we should not try. It is simply that we need to be realistic about change. The climate is one of these. Other things can happen through natural processes, and they happen in human society as well. What we need to do is to place confidence bars or something around them. Throwing up our hands and being hopeless is not the answer that I would recommend. What we need to do is to acknowledge the very real limits of our abilities to predict or control the future.

MR. DORNSIFE: There's one other thing about human intrusion that we cannot ignore. Intrusion is a very positive way of addressing an issue that nobody else addresses in the waste disposal issue. Intrusion is the only way that you can show that if somebody lives on the site, under the most adverse set of circumstances, they are not going to suffer a significant impact. Properly used, that can be a positive attribute of the radioactive waste management and disposal system. So let's not throw it out just because we do not like it.

DR. JACOBS: We have another comment or question from the floor.

MR. HOLDEN: Robert Holden with the National Congress of American Indians. The people, the constituency that I represent, have some concerns on being part of the public participation process. We are dealing more along the lines of policy issues. These include not only the need for inclusion in the process, but also the need for respect of tribal governments and indigenous people, but also the need for reverence and understanding of their environment and its relationship with the plants and animals. The tribal governments and their peoples have been inhabitants of this land longer than anyone else—thousands of years. In the last couple hundreds of years, they have developed misgivings, second thoughts, and mistrust of federal government actions, even when they are joined by independent people or independent boards, review boards, commissions, and so forth, who are supposedly there to protect their rights.

About a hundred years ago, the federal government began an overt effort to divest Indian people of their religions. Many of the national denominations went out and proselytized and converted Indian people to different denominations. To decide where they would go, they drew straws. There's a story about one of the missionaries going out to Indian country and wanting to change the minds of the people out there. He was told that if you are going to change the minds of the Indian people, you can speak to the person who they look to for spiritual guidance. The medicine man, if you will. And so the missionary thought let's start there and get it over with. So he went out and visited the medicine man. The medicine man said fine, let's get into this canoe, and we will go out on this little lake and we will talk. So they went out and they talked about their religions. And pretty soon the medicine man said, Excuse me, I have to go relieve myself. They were out in the canoe, they were out in the middle of the lake. He then proceeded to walk a few yards away, and did his business and came back. So the missionary thought this is some kind of trick. Either that or the medicine man has got a lot of power. I do not know what's going on. But anyway, the series of meetings went on for a couple of days. And the medicine man said at other times, Excuse me just a moment, I must relieve myself. I will be right back. So he got out of the canoe, did his business and came back. So the missionary says, my God is more powerful, our ways are more powerful than his. If he can do that, I can do that. So he said well, I have to do the same thing, I will be right back. So he stepped out of the canoe and went straight down. The medicine man had to grab him and pull him back up and help him back into the canoe. The missionary said okay, I give up. I do not know. I am trying to understand what you are saying. And you have similar ways to ours, but what's a trick. The medicine man responded, you have got to know where the rocks are!

It's important to make the extra effort to include tribal government officials, the Indian Health Services, which is part of the Department of Health and Human Services, and the Bureau of Indian affairs in these types of discussions. Many mistakes were made in the forties and fifties. Those mistakes have not been corrected. Several areas in the Indian country are still contaminated. Uranium piles still blow in the breeze—RCRA, Superfund, all the laws—the federal regulatory agencies have not been put together. It's like Humpty Dumpty. They can't put it back together or put it back the way it was. There are severe health problems out there. These have not been corrected. So when you are talking with Indian people about how to prepare for future programs, how do you think they are going to believe that you can prepare, that you can make fail-safe arguments and technology, when you cannot even take care of what's happening there now. It's not just a PR problem. It's a continuing death threat to those people out there. The land is contaminated, the water is contaminated, the plants and animals are contaminated. There are problems there that have not been corrected. On top of that, 30 percent of all uranium is on Indian land.

I was sympathetic to your first accident, Mr. Moeller, and that I as well as others, was relieved that you were not hurt. But it brings to mind that there are animals, there are forces out there, there are things that were they to disappear, would be lost forever. It may be a cultural site, which cannot be identified, and which maybe some of those people will not be able to talk about or will not divulge everything about. But I just tell you that this is important. If the desert tortoise disappeared, if it was the last desert tortoise, there would be grave concern over the disappearance of these things because of what they mean, and how they are part of that cultural integrity. So those are some of the things that we need to think about in this participation process. I am glad that I got the invitation and was able to be here. However, I did find out that some of the people that were invited from Indian country were not able to be here due to a lack of resources. There are a lot of players right here in the Nevada area who have not been part of the EM process or the RW process in terms of the repository or cleanup. And that goes nation-wide because the tribal government has not included them. There's no single status for the Nevada tribes whose land we are sitting on basically at this moment. So I just encourage you to talk to the Indian people every step of the way. This applies particularly to the scientists and engineers. The Indian people, some of the old people out there, might be able to tell you where the rocks are.

MR. DORNSIFE: Robert, I have a question for you before you go away. You know, what you are really talking about is a manifestation, I think, of the environmental justice issue. Would it make a difference if, in terms of dealing with the problems that you state—which I know for a fact are true—that, if there was some attempt to mitigate and correct the existing risks, this would represent a way of dealing with the inequities?

MR. HOLDEN: I think it would make a significant difference. The people that I work with are not unreasonable. I did some tribal emergency preparedness workshops this past summer regarding radiological accidents. As you may know, the Indian tribes have regulatory authority on the transportation of hazardous waste and so forth across Indian lands. Although they retain this jurisdiction, many of them have not exercised it. In this regard, we asked them what they would put into a plan to protect the health and safety of their populations. The response was not unlike the state codes—permitting inspection, imposing speed limits, just normal things that any jurisdiction has. So it's not as if the Indian tribes are overreaching. There is one case of overreaching by one tribe in Minnesota, Perry Island, but one that all thought was exorbitant. But that was a drastic measure because they had been lied to by the utility about what they would do for them. The utility was not a good neighbor to the tribe there. And that was their indigenous territory. There was no baseline study, and nothing was done in terms of environmental quality studies. Nothing had ever been done.

The people to the north of us, Duck Water, Death Valley, Yakama, some of those places up there—they are down winders. The wind blows north, south. As a result of the atomic tests that took place during the forties and fifties, many of the people got sick and died from causes that they know nothing about. And nobody ventured up there to do any kind of health baselines, or environmental quality studies. From what information I could gather in a visit up there, it sounds to me like some people were running around out there with radiation monitoring devices. And some of the people in some of the small towns were wearing TLD's. But many of those studies stopped at reservation borders. There's a significant problem out there. It would go a long way, in terms of environmental justice, if more were done for them. I was glad as anyone to hear about the environmental justice program, but I am not sure at this point what it can do. You know, there are people up there with all of the agencies who have environmental justice programs that are talking about what they are going to do. But thus far they have not done anything. The impact of the environmental justice movement has not reached Indian country, yet. I do not know when it will or whether it will. That's not to say that the people associated with these programs are not sincere, but that does not help. I hope that answers your question.

MR. DORNSIFE: Thank you.

DR. JACOBS: I would like to thank all of you for your participation today and for staying on until the end of the meeting. I think we have had some very interesting discussions. I would like to thank all of the speakers for holding to their time periods and for making their presentations interesting. I would also like to thank the members of the organizing committee for this program, which includes Dade Moeller, Allen Croff, and Paul Slovic and myself. For us, it's been an interesting experience and we have enjoyed it. I hope that you have enjoyed the participation here in the meeting. Again, I look forward to seeing you again in other settings. Thank you very much.

(Whereupon the meeting adjourned at 5:34 p.m.)

Summary of Written Comments and Questions Submitted by Symposium Participants

To encourage and facilitate discussion, each participant at the Symposium was provided with cards for submitting written comments and questions. Approximately 30 people availed themselves of this opportunity, submitting a total of 39 items.

As would be expected, many of the written comments were similar to those presented during the oral discussion sessions; in fact, in several cases participants who submitted written items offered the same comments during the discussion sessions. To assure that this report on the Symposium is complete, the key issues raised in the written comments are summarized below. As will be noted, they covered a wide range of topics. To avoid repetition, similar comments from more than one person have been combined.

1. Several commenters expressed concerns that:
   a. Development and application of a risk-based system could have detrimental effects on efforts to establish new low-level radioactive waste disposal facilities, both in terms of harming the mechanisms for moving such programs along and in terms of possibly upsetting the underlying regulatory structure.
   Note: In line with this thinking, several participants suggested that the development of a risk-based waste classification system be viewed as an evolutionary process that is designed to improve, rather than replace, the present system. Such an approach would provide a more extended period for peer review and refinement than is normally possible under normal procedures. They also

pointed out that untoward disruption of current regulations of the U.S. Nuclear Regulatory Commission, as expressed in Title 10, CFR, Part 61, could cause significant additional delays in the establishment of new disposal facilities.

b. Too little attention was being directed to the problems of industrial and commercial waste, as contrasted to those being generated by various Federal government activities.
   Note: This was also a key comment brought out in the oral discussion sessions.
c. Too much attention was being given to including within the risk-based waste classification system extensive consideration of the characteristics of the disposal site. In some cases, it may be necessary to classify waste without knowledge of where they are to be disposed.
d. Political considerations might unduly interfere with or negate full evaluation of some of the scientific factors that should play a major role in the final decision on how waste is to be classified. For example, political considerations might lead to the selection of unreasonable scenarios for use in the accompanying risk assessments.
e. A risk-based system could make socioeconomic analyses difficult, especially when it is necessary to derive meaningful costs for events that might occur at some time far into the future.
f. A risk-based system might not be able to account properly for whether the risk was voluntary or imposed. This is important because of the strong differences in public reactions depending on the source and nature of the risk.
g. A risk-based system might fail to provide a method for taking into account proper evaluation of those cases in which the risks from waste is being borne by individuals and communities that derive little or no benefit from the activities that generated them.
h. The system may not properly account for the extent to which the waste in question may be imposing risks on future generations, and the extent to which institutional control can be assumed to continue.

2. Several commenters urged that any risk-based system that might be developed:
   a. Be suitable for application to a full range of radioactive and mixed waste, including NORM and NARM waste as well as those generated by remedial actions and by decommissioning and decontamination operations.
   b. Be designed to serve as a guide for setting standards for recycling materials within various industrial and commercial operations.
   c. Not include methods for defining an exempt class of waste; however, other commenters stated that a risk-based system might be useful in designating radioactive waste that is below regulatory

concern and toxic chemical waste that is *de minimis*, thereby permitting them to be classified either as low-level radioactive waste or hazardous chemical waste, rather than as mixed waste. This could lead to significant reductions in the amounts of mixed waste that must be handled.

   d. Include factors that would encourage the minimization of the generation of waste, including the substitution of non-toxic for toxic materials in various industrial processes. This could be facilitated by identifying those specific constituents that represent the major sources of the risk.
   e. Be flexible enough to apply to all phases of waste production, management and disposal, including generation, treatment, packaging, transportation, storage, and disposal.

3. Several participants suggested that in identifying endpoints for assessing the impacts of various waste on people and the environment, those responsible for making these selections:
   a. Be careful to consider the full range of people within society. Special attention may, for example, need to be directed to the unborn, to infants and children, and to those who may be particularly susceptible to the harmful effects of radiation and/or toxic chemicals.
   b. Include consideration not only of cancer mortality, but also of morbidity and a full range of other potential health effects, including allergies and neurological effects.
   c. Include consideration of possible synergistic effects, especially between ionizing radiation and toxic chemicals.
   d. Include consideration of effects on aquatic and terrestrial ecosystems, without assuming that protection of humans guarantees that other life forms will be protected.
4. As would be expected, there were several comments that did not specifically fall into any category:
   a. Several commenters urged that human intrusion be given special consideration, particularly since in several instances it appears to be the dominant source for the health consequences associated with waste disposal facilities. Questions were also raised as to whether human intrusion is currently being treated in a similar manner in the evaluation of hazardous, versus radioactive, waste facilities.
   b. Noting that the U.S. Department of Energy is one of the biggest generators of mixed waste, one commenter asked whether that agency might develop a plan for managing all such waste, thereby providing relief to people in the commercial sector who were facing similar problems.
   c. Another subject was how best to stimulate public involvement at an early stage in the process of developing a risk-based waste classification system. In this regard, it was noted that the public is

generally not interested in national problems; they become interested primarily when a problem affects them personally at the local level;

d. Comments were also made relative to the increasing attention that is being directed to studies that appear to show that low-doses of radiation may have beneficial effects. How might these observations be factored into a risk-based system?
e. Other participants questioned whether those in favor of developing a risk-based system had considered the potential effects of such actions on waste disposal programs in other countries of the world?
f. One participant raised questions about the possible role of Congress in the development of a risk-based waste classification system. Will such actions be helpful or will they require a completely different approach?

NCRP

The NCRP

The National Council on Radiation Protection and Measurements is a nonprofit corporation chartered by Congress in 1964 to:

1. Collect, analyze, develop and disseminate in the public interest information and recommendations about (a) protection against radiation and (b) radiation measurements, quantities and units, particularly those concerned with radiation protection.
2. Provide a means by which organizations concerned with the scientific and related aspects of radiation protection and of radiation quantities, units and measurements may cooperate for effective utilization of their combined resources, and to stimulate the work of such organizations.
3. Develop basic concepts about radiation quantities, units and measurements, about the application of these concepts, and about radiation protection.
4. Cooperate with the International Commission on Radiological Protection, the International Commission on Radiation Units and Measurements, and other national and international organizations, governmental and private, concerned with radiation quantities, units and measurements and with radiation protection.

The Council is the successor to the unincorporated association of scientists known as the National Committee on Radiation Protection and Measurements and was formed to carry on the work begun by the Committee.

The Council is made up of the members and the participants who serve on the scientific committees of the Council. The Council members who are selected solely on the basis of their scientific expertise are drawn from public and private universities, medical centers, national and private laboratories and industry. The scientific committees, composed of experts having detailed knowledge and competence in the particular area of the committee's interest, draft proposed recommendations. These are then submitted to the full membership of the Council for careful review and approval before being published.

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Currently, the following committees are actively engaged in formulating recommendations:

SC 1 Basic Radiation Protection Criteria
- SC 1-3 Collective Dose
- SC 1-4 Extrapolation of Risk from Non-Human Experimental Systems to Man
- SC 1-5 Uncertainty in Risk Estimates
- SC 1-6 Basis for the Linearity Assumption

SC 9 Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV

SC 46 Operational Radiation Safety
- SC 46-8 Radiation Protection Design Guidelines for Particle Accelerator Facilities
- SC 46-10 Assessment of Occupational Doses from Internal Emitters
- SC 46-11 Radiation Protection During Special Medical Procedures
- SC 46-12 Determination of the Effective Dose Equivalent (and Effective Dose) to Workers for External Exposure to Low-LET Radiation
- SC 46-13 Design of Facilities for Medical Radiation Therapy

SC 57 Dosimetry and Metabolism of Radionuclides
- SC 57-2 Respiratory Tract Model
- SC 57-9 Lung Cancer Risk
- SC 57-10 Liver Cancer Risk
- SC 57-14 Placental Transfer
- SC 57-15 Uranium
- SC 57-16 Uncertainties in the Application of Metabolic Models

SC 63 Radiation Exposure Control in a Nuclear Emergency

SC 64 Radionuclides in the Environment

SC 64-6 Screening Models
SC 64-17 Uncertainty in Environmental Transport in the Absence of Site Specific Data
SC 64-18 Plutonium
SC 64-19 Historical Dose Evaluation

SC 66 Biological Effects and Exposure Criteria for Ultrasound
SC 69 Efficacy of Radiographic Procedures
SC 72 Radiation Protection in Mammography
SC 75 Guidance on Radiation Received in Space Activities
SC 77 Guidance on Occupational and Public Exposure Resulting from Diagnostic Nuclear Medicine Procedures
SC 84 Radionuclide Contamination
SC 84-1 Contaminated Soil
SC 84-2 Decontamination and Decommissioning of Facilities

SC 85 Risk of Lung Cancer from Radon
SC 86 Hot Particles in the Eye, Ear or Lung
SC 87 Radioactive and Mixed Waste
SC 87-1 Waste Avoidance and Volume Reduction
SC 87-2 Waste Classification Based on Risk
SC 87-3 Performance Assessment

SC 88 Fluence as the Basis for a Radiation Protection System for Astronauts
SC 89 Nonionizing Electromagnetic Fields
SC 89-1 Biological Effects of Magnetic Fields
SC 89-3 Extremely Low-Frequency Electric and Magnetic Fields
SC 89-4 Modulated Radiofrequency Fields
SC 89-5 Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields

SC 91 Radiation Protection in Medicine
SC 91-1 Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides
SC 91-2 Dentistry

SC 92 Policy Analysis and Decision Making
SC 93 Radiation Measurement

In recognition of its responsibility to facilitate and stimulate cooperation among organizations concerned with the scientific and related aspects of radiation protection and measurement, the Council has created a category of NCRP Collaborating Organizations. Organizations or groups of organizations that are national or international in scope and are concerned with scientific problems involving radiation quantities, units, measurements and effects, or radiation protection may be admitted to collaborating status by the Council. Collaborating Organizations provide a means by which the NCRP can gain input into its activities from a wider segment of society. At the same time, the relationships with the Collaborating Organizations facilitate wider dissemination of information about the Council's activities, interests and concerns. Collaborating Organizations have the opportunity to comment on draft reports (at the time that these are submitted to the members of the Council). This is intended to capitalize on the fact that Collaborating Organizations are in an excellent position to both contribute to the identification of what needs to be treated in NCRP reports and to identify problems that might result from proposed recommendations. The present Collaborating Organizations with which the NCRP maintains liaison are as follows:

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American Academy of Environmental Engineers
American Academy of Health Physics
American Association of Physicists in Medicine
American College of Medical Physics
American College of Nuclear Physicians
American College of Occupational and Environmental Medicine
American College of Radiology
American Dental Association
American Industrial Hygiene Association
American Institute of Ultrasound in Medicine
American Insurance Services Group
American Medical Association
American Nuclear Society
American Pharmaceutical Association
American Podiatric Medical Association
American Public Health Association
American Radium Society
American Roentgen Ray Society
American Society of Health-System Pharmacists
American Society of Radiologic Technologists
American Society for Therapeutic Radiology and Oncology
Association of University Radiologists
Bioelectromagnetics Society
Campus Radiation Safety Officers
College of American Pathologists
Conference of Radiation Control Program Directors
Council on Radionuclides and Radiopharmaceuticals
Electric Power Research Institute
Federal Communications Commission
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Health Physics Society
Institute of Nuclear Power Operations
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National Aeronautics and Space Administration
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National Electrical Manufacturers Association
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Society of Nuclear Medicine
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United States Department of Transportation
United States Environmental Protection Agency
United States Navy
United States Nuclear Regulatory Commission
United States Public Health Services
Utility Workers Union of America

The NCRP has found its relationships with these organizations to be extremely valuable to continued progress in its program.

Another aspect of the cooperative efforts of the NCRP relates to the Special Liaison relationships established with various governmental organizations that have an interest in radiation protection and measurements. This liaison relationship provides: (1) an opportunity for participating organizations to designate an individual to provide liaison between the organization and the NCRP; (2) that the individual designated will receive copies of draft NCRP reports (at the time that these are submitted to the members of the Council) with an invitation to comment, but not vote; and (3) that new NCRP efforts might be discussed with liaison individuals as appropriate, so that they might have an opportunity to make suggestions on new studies and related matters. The following organizations participate in the Special Liaison Program:

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Defense Nuclear Agency
Health Council of the Netherlands
International Commission on Non-Ionizing Radiation Protection
Japan Radiation Council
National Radiological Protection Board (United Kingdom)
National Research Council (Canada)
Office of Science and Technology Policy
Office of Technology Assessment
South African Forum for Radiation Protection
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United States Air Force
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The NCRP values highly the participation of these organizations in the Special Liaison Program.

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American College of Radiology Foundation
American Dental Association
American Healthcare Radiology Administrators
American Industrial Hygiene Association
American Insurance Services Group
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The NCRP seeks to promulgate information and recommendations based on leading scientific judgment on matters of radiation protection and measurement and to foster cooperation among organizations concerned with these matters. These efforts are intended to serve the public interest and the Council welcomes comments and suggestions on its reports or activities from those interested in its work.

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22	*Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (1959) [Includes Addendum 1 issued in August 1963]
23	*Measurement of Neutron Flux and Spectra for Physical and Biological Applications* (1960)
25	*Measurement of Absorbed Dose of Neutrons, and of Mixtures of Neutrons and Gamma Rays* (1961)
27	*Stopping Powers for Use with Cavity Chambers* (1961)
30	*Safe Handling of Radioactive Materials* (1964)
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102 *Medical X-Ray, Electron Beam and Gamma-Ray Protection for Energies Up to 50 MeV (Equipment Design, Performance and Use)* (1989)
103 *Control of Radon in Houses* (1989)
104 *The Relative Biological Effectiveness of Radiations of Different Quality* (1990)
105 *Radiation Protection for Medical and Allied Health Personnel* (1989)
106 *Limit for Exposure to "Hot Particles" on the Skin* (1989)
107 *Implementation of the Principle of As Low As Reasonably Achievable (ALARA) for Medical and Dental Personnel* (1990)
108 *Conceptual Basis for Calculations of Absorbed-Dose Distributions* (1991)
109 *Effects of Ionizing Radiation on Aquatic Organisms* (1991)
110 *Some Aspects of Strontium Radiobiology* (1991)
111 *Developing Radiation Emergency Plans for Academic, Medical or Industrial Facilities* (1991)
112 *Calibration of Survey Instruments Used in Radiation Protection for the Assessment of Ionizing Radiation Fields and Radioactive Surface Contamination* (1991)
113 *Exposure Criteria for Medical Diagnostic Ultrasound: I. Criteria Based on Thermal Mechanisms* (1992)
114 *Maintaining Radiation Protection Records* (1992)
115 *Risk Estimates for Radiation Protection* (1993)
116 *Limitation of Exposure to Ionizing Radiation* (1993)
117 *Research Needs for Radiation Protection* (1993)
118 *Radiation Protection in the Mineral Extraction Industry* (1993)
119 *A Practical Guide to the Determination of Human Exposure to Radiofrequency Fields* (1993)
120 *Dose Control at Nuclear Power Plants* (1994)

Binders for NCRP reports are available. Two sizes make it possible to collect into small binders the "old series" of reports (NCRP Reports Nos. 8-30) and into large binders the more recent publications (NCRP Reports Nos. 32-120). Each binder will accommodate from five to seven reports. The binders carry the identification "NCRP Reports" and come with label holders which permit the user to attach labels showing the reports contained in each binder.

The following bound sets of NCRP reports are also available:

Volume I. NCRP Reports Nos. 8, 22
Volume II. NCRP Reports Nos. 23, 25, 27, 30
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Volume IV. NCRP Reports Nos. 38, 40, 41
Volume V. NCRP Reports Nos. 42, 44, 46
Volume VI. NCRP Reports Nos. 47, 49, 50, 51
Volume VII. NCRP Reports Nos. 52, 53, 54, 55, 57
Volume VIII. NCRP Report No. 58
Volume IX. NCRP Reports Nos. 59, 60, 61, 62, 63
Volume X. NCRP Reports Nos. 64, 65, 66, 67
Volume XI. NCRP Reports Nos. 68, 69, 70, 71, 72
Volume XII. NCRP Reports Nos. 73, 74, 75, 76
Volume XIII. NCRP Reports Nos. 77, 78, 79, 80
Volume XIV. NCRP Reports Nos. 81, 82, 83, 84, 85
Volume XV. NCRP Reports Nos. 86, 87, 88, 89
Volume XVI. NCRP Reports Nos. 90, 91, 92, 93
Volume XVII. NCRP Reports Nos. 94, 95, 96, 97
Volume XVIII. NCRP Reports Nos. 98, 99, 100
Volume XIX. NCRP Reports Nos. 101, 102, 103, 104
Volume XX. NCRP Reports Nos. 105, 106, 107, 108
Volume XXI. NCRP Reports Nos. 109, 110, 111
Volume XXII. NCRP Reports Nos. 112, 113, 114
Volume XXIII. NCRP Reports Nos. 115, 116, 117, 118

(Titles of the individual reports contained in each volume are given above.)

NCRP Commentaries

No. Title

1 *Krypton-85 in the Atmosphere—With Specific Reference to the Public Health Significance of the Proposed Controlled Release at Three Mile Island* (1980)
3 *Screening Techniques for Determining Compliance with Environmental Standards—Releases of Radionuclides to the Atmosphere* (1986), Revised (1989)
4 *Guidelines for the Release of Waste Water from Nuclear Facilities with Special Reference to the Public Health Significance of the Proposed Release of Treated Waste Waters at Three Mile Island* (1987)
5 *Review of the Publication, Living Without Landfills* (1989)

6 *Radon Exposure of the U.S. Population—Status of the Problem* (1991)
7 *Misadministration of Radioactive Material in Medicine—Scientific Background* (1991)
8 *Uncertainty in NCRP Screening Models Relating to Atmospheric Transport, Deposition and Uptake by Humans* (1993)
9 *Considerations Regarding the Unintended Radiation Exposure of the Embryo, Fetus or Nursing Child* (1994)
10 *Advising the Public about Radiation Emergencies: A Document for Public Comment* (1994)
11 *Dose Limits for Individuals Who Receive Exposure from Radionuclide Therapy Patients* (1995)

Proceedings of the Annual Meeting

No. Title

1 *Perceptions of Risk*, Proceedings of the Fifteenth Annual Meeting held on March 14-15, 1979 (including Taylor Lecture No. 3) (1980)
3 *Critical Issues in Setting Radiation Dose Limits*, Proceedings of the Seventeenth Annual Meeting held on April 8-9, 1981 (including Taylor Lecture No. 5) (1982)
4 *Radiation Protection and New Medical Diagnostic Approaches*, Proceedings of the Eighteenth Annual Meeting held on April 6-7, 1982 (including Taylor Lecture No. 6) (1983)
5 *Environmental Radioactivity*, Proceedings of the Nineteenth Annual Meeting held on April 6-7, 1983 (including Taylor Lecture No. 7) (1983)
6 *Some Issues Important in Developing Basic Radiation Protection Recommendations*, Proceedings of the Twentieth Annual Meeting held on April 4-5, 1984 (including Taylor Lecture No. 8) (1985)
7 *Radioactive Waste*, Proceedings of the Twenty-first Annual Meeting held on April 3-4, 1985 (including Taylor Lecture No. 9) (1986)
8 *Nonionizing Electromagnetic Radiations and Ultrasound*, Proceedings of the Twenty-second Annual Meeting held on April 2-3, 1986 (including Taylor Lecture No. 10) (1988)
9 *New Dosimetry at Hiroshima and Nagasaki and Its Implications for Risk Estimates*, Proceedings of the Twenty-third Annual Meeting held on April 8-9, 1987 (including Taylor Lecture No. 11) (1988)
10 *Radon*, Proceedings of the Twenty-fourth Annual Meeting held on March 30-31, 1988 (including Taylor Lecture No. 12) (1989)
11 *Radiation Protection Today—The NCRP at Sixty Years*, Proceedings of the Twenty-fifth Annual Meeting held on April 5-6, 1989 (including Taylor Lecture No. 13) (1990)
12 *Health and Ecological Implications of Radioactively Contaminated Environments*, Proceedings of the Twenty-sixth Annual Meeting held on April 4-5, 1990 (including Taylor Lecture No. 14) (1991)
13 *Genes, Cancer and Radiation Protection*, Proceedings of the Twenty-seventh Annual Meeting held on April 3-4, 1991 (including Taylor Lecture No. 15) (1992)

14 *Radiation Protection in Medicine*, Proceedings of the Twenty-eighth Annual Meeting held on April 1-2, 1992 (including Taylor Lecture No. 16) (1993)

15 *Radiation Science and Societal Decision Making,* Proceedings of the Twenty-ninth Annual Meeting held on April 7-8, 1993 (including Taylor Lecture No. 17) (1994)

Lauriston S. Taylor Lectures

No.	Title
1	*The Squares of the Natural Numbers in Radiation Protection* by Herbert M. Parker (1977)
2	*Why be Quantitative about Radiation Risk Estimates?* by Sir Edward Pochin (1978)
3	*Radiation Protection—Concepts and Trade Offs* by Hymer L. Friedell (1979) [Available also in *Perceptions of Risk*, see above]
4	*From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review* by Harold O. Wyckoff (1980)
5	*How Well Can We Assess Genetic Risk? Not Very* by James F. Crow (1981) [Available also in *Critical Issues in Setting Radiation Dose Limits*, see above]
6	*Ethics, Trade-offs and Medical Radiation* by Eugene L. Saenger (1982) [Available also in *Radiation Protection and New Medical Diagnostic Approaches*, see above]
7	*The Human Environment—Past, Present and Future* by Merril Eisenbud (1983) [Available also in *Environmental Radioactivity*, see above]
8	*Limitation and Assessment in Radiation Protection* by Harald H. Rossi (1984) [Available also in *Some Issues Important in Developing Basic Radiation Protection Recommendations*, see above]
9	*Truth (and Beauty) in Radiation Measurement* by John H. Harley (1985) [Available also in *Radioactive Waste*, see above]
10	*Biological Effects of Non-ionizing Radiations: Cellular Properties and Interactions* by Herman P. Schwan (1987) [Available also in *Nonionizing Electromagnetic Radiations and Ultrasound*, see above]
11	*How to be Quantitative about Radiation Risk Estimates* by Seymour Jablon (1988) [Available also in *New Dosimetry at Hiroshima and Nagasaki and its Implications for Risk Estimates*, see above]
12	*How Safe is Safe Enough?* by Bo Lindell (1988) [Available also in *Radon*, see above]
13	*Radiobiology and Radiation Protection: The Past Century and Prospects for the Future* by Arthur C. Upton (1989) [Available also in *Radiation Protection Today*, see above]
14	*Radiation Protection and the Internal Emitter Saga* by J. Newell Stannard (1990) [Available also in *Health and Ecological Implications of Radioactively Contaminated Environments*, see above]
15	*When is a Dose Not a Dose?* by Victor P. Bond (1992) [Available also in *Genes, Cancer and Radiation Protection*, see above]

16 *Dose and Risk in Diagnostic Radiology: How Big? How Little?* by Edward W. Webster (1992) [Available also in *Radiation Protection in Medicine*, see above]
17 *Science, Radiation Protection and the NCRP* by Warren K. Sinclair (1993) [Available also in *Radiation Science and Societal Decision Making*, see above]
18 *Mice, Myths and Men* by R.J. Michael Fry (1995)

Symposium Proceedings

No. Title

1 *The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack*, Proceedings of a Symposium held April 27-29, 1981 (1982)
2 *Radioactive and Mixed Waste—Risk as a Basis for Waste Classification,* Proceedings of a Symposium held November 9, 1994 (1995)

NCRP Statements

No. Title

1 "Blood Counts, Statement of the National Committee on Radiation Protection," Radiology **63**, 428 (1954)
2 "Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol., Radium Ther. and Nucl. Med. **84**, 152 (1960) and Radiology **75**, 122 (1960)
3 *X-Ray Protection Standards for Home Television Receivers, Interim Statement of the National Council on Radiation Protection and Measurements* (1968)
4 *Specification of Units of Natural Uranium and Natural Thorium, Statement of the National Council on Radiation Protection and Measurements* (1973)
5 *NCRP Statement on Dose Limit for Neutrons* (1980)
6 *Control of Air Emissions of Radionuclides* (1984)
7 *The Probability That a Particular Malignancy May Have Been Caused by a Specified Irradiation* (1992)

Other Documents

The following documents of the NCRP were published outside of the NCRP Report, Commentary and Statement series:

Somatic Radiation Dose for the General Population, Report of the Ad Hoc Committee of the National Council on Radiation Protection and Measurements, 6 May 1959, Science, February 19, 1960, Vol. 131, No. 3399, pages 482-486

Dose Effect Modifying Factors In Radiation Protection, Report of Subcommittee M-4 (Relative Biological Effectiveness) of the National Council on Radiation Protection and Measurements, Report BNL 50073 (T-471) (1967) Brookhaven National Laboratory (National Technical Information Service Springfield, Virginia)

The following documents are now superseded and/or out of print:

NCRP Reports

No.	Title
1	*X-Ray Protection* (1931) [Superseded by NCRP Report No. 3]
2	*Radium Protection* (1934) [Superseded by NCRP Report No. 4]
3	*X-Ray Protection* (1936) [Superseded by NCRP Report No. 6]
4	*Radium Protection (1938)* [Superseded by NCRP Report No. 13]
5	*Safe Handling of Radioactive Luminous Compound* (1941) [Out of Print]
6	*Medical X-Ray Protection Up to Two Million Volts* (1949) [Superseded by NCRP Report No. 18]
7	*Safe Handling of Radioactive Isotopes* (1949) [Superseded by NCRP Report No. 30]
9	*Recommendations for Waste Disposal of Phosphorus-32 and Iodine-131 for Medical Users* (1951) [Out of Print]
10	*Radiological Monitoring Methods and Instruments* (1952) [Superseded by NCRP Report No. 57]
11	*Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water* (1953) [Superseded by NCRP Report No. 22]
12	*Recommendations for the Disposal of Carbon-14 Wastes* (1953) [Superseded by NCRP Report No. 81]
13	*Protection Against Radiations from Radium, Cobalt-60 and Cesium-137* (1954) [Superseded by NCRP Report No. 24]
14	*Protection Against Betatron-Synchrotron Radiations Up to 100 Million Electron Volts* (1954) [Superseded by NCRP Report No. 51]
15	*Safe Handling of Cadavers Containing Radioactive Isotopes* (1953) [Superseded by NCRP Report No. 21]
16	*Radioactive-Waste Disposal in the Ocean* (1954) [Out of Print]
17	*Permissible Dose from External Sources of Ionizing Radiation* (1954) including *Maximum Permissible Exposures to Man, Addendum to National Bureau of Standards Handbook 59* (1958) [Superseded by NCRP Report No. 39]
18	*X-Ray Protection* (1955) [Superseded by NCRP Report No. 26]
19	*Regulation of Radiation Exposure by Legislative Means* (1955) [Out of Print]
20	*Protection Against Neutron Radiation Up to 30 Million Electron Volts* (1957) [Superseded by NCRP Report No. 38]
21	*Safe Handling of Bodies Containing Radioactive Isotopes* (1958) [Superseded by NCRP Report No. 37]
24	*Protection Against Radiations from Sealed Gamma Sources* (1960) [Superseded by NCRP Reports No. 33, 34 and 40]

26 *Medical X-Ray Protection Up to Three Million Volts* (1961) [Superseded by NCRP Reports No. 33, 34, 35 and 36]
28 *A Manual of Radioactivity Procedures* (1961) [Superseded by NCRP Report No. 58]
29 *Exposure to Radiation in an Emergency* (1962) [Superseded by NCRP Report No. 42]
31 *Shielding for High-Energy Electron Accelerator Installations* (1964) [Superseded by NCRP Report No. 51]
33 *Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV—Equipment Design and Use* (1968) [Superseded by NCRP Report No. 102]
34 *Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Structural Shielding Design and Evaluation Handbook* (1970) [Superseded by NCRP Report No. 49]
39 *Basic Radiation Protection Criteria* (1971) [Superseded by NCRP Report No. 91]
43 *Review of the Current State of Radiation Protection Philosophy* (1975) [Superseded by NCRP Report No. 91]
45 *Natural Background Radiation in the United States* (1975) [Superseded by NCRP Report No. 94]
48 *Radiation Protection for Medical and Allied Health Personnel* (1976) [Superseded by NCRP Report No. 105]
53 *Review of NCRP Radiation Dose Limit for Embryo and Fetus in Occupationally-Exposed Women* (1977) [Out of Print]
56 *Radiation Exposure from Consumer Products and Miscellaneous Sources* (1977) [Superseded by NCRP Report No. 95]
58 *A Handbook of Radioactivity Measurements Procedures*, 1st ed. (1978) [Superseded by NCRP Report No. 58, 2nd ed.]
66 *Mammography* (1980) [Out of Print]
91 *Recommendations on Limits for Exposure to Ionizing Radiation* (1987) [Superseded by NCRP Report No. 116]

NCRP Commentaries

No. Title

2 *Preliminary Evaluation of Criteria for the Disposal of Transuranic Contaminated Waste* (1982) [Out of Print]

NCRP Proceedings

No. Title

2 *Quantitative Risk in Standards Setting*, Proceedings of the Sixteenth Annual Meeting held on April 2-3, 1980 [Out of Print]