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DETERMINATION OF ACCEPTABLE RISK CRITERIA FOR NUCLEAR WASTE MANAGEMENT

J. J. Cohen

October 21, 1977

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DETERMINATION OF ACCEPTABLE RISK CRITERIA FOR NUCLEAR WASTE MANAGEMENT

ABSTRACT

The Laboratory and its subcontractors have provided technical support to the U.S. Nuclear Regulatory Commission in its Waste Management Program. Part of this support has been to develop acceptable risk criteria (ARC) for waste management operations. The initial phase of the work performed during FY 1977 consisted of performing a "scoping" study to define issues, determine an optimal methodology for their resolution, and compile a data base for ARC development. The issues, spanning technical, psychological, and ethical dimensions, were categorized in seven major areas: (1) unplanned or accidental events, (2) present vs future risks, (3) institutional controls and retrievability, (4) dose-response

mechanism and uncertainty, (5) spatial distribution of exposed populations, (6) different types of nuclear wastes, and (7) public perception. The optimum methodology for developing ARC was determined to be multi-attribute decision analysis encompassing numerous specific techniques for choosing, from among several alternatives, the optimal course of action when the alternatives are constrained to meet specified attributes. The data base developed during the study comprises existing regulations and guidelines, maximum permissible dose, natural geologic hazards, nonradioactive hazardous waste practices, bioethical perspectives, and data from an opinion survey.

1. EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) retained the Lawrence Livermore Laboratory (LLL) to provide technical support to its Waste Management Program. A part of this work has been to develop acceptable risk criteria (ARC) for waste management (WM) operations. This report

reviews and summarizes the work performed during FY 1977.

Acceptable risk criteria are required to develop meaningful performance criteria for materials and operations in nuclear WM programs. They are intended to define explicitly the objectives of the program. The

lack of definitive objectives has been identified as a serious deficiency in previous WM development programs. Without a defined goal, the probable success of any WM methodology is difficult to assess.

The major portion of LLL's effort in developing ARC during FY 1977 was performed through consultants and subcontractors, including Systems Control, Inc. and Decisions and Designs, Inc., under the direction of the LLL staff. This initial phase of the work entailed performing a "scoping" study to (1) define issues, (2) determine an optimal methodology for their resolution, and (3) compile a data base for ARC development.

Development of ARC requires consideration of both objective and subjective factors. The elements of the problem are:

- Establishment of overall goals and objectives
- Definition of specific issues requiring resolution
- Compilation of a data base
- Development of an optimal methodology for the required decision-making process
- Application of the methodology.

A review of broad basic goals and objectives for nuclear waste management highlighted the issues requiring resolution. These goals and objectives were identified at recent workshops and symposia on the subject,

sponsored by NRC, the Environmental Protection Agency (EPA), and other government agencies. Consistent with these goals and objectives, a summary of needed criteria for WM is listed below, as well as the considerations that should be included in the development of ARC:

- Criteria that cover unplanned or accidental events
- Criteria that can accommodate both present and future risks
- Criteria for institutional controls and retrievability of waste
- Criteria for spatial allocation of risk (i.e., local, regional, national, and global)
- Criteria for allocation of risk among various WM programs (e.g., high-level, low-level, transuranic (TRU), and gaseous wastes) and operations (i.e., waste handling, preparation, transportation, and emplacement)
- Accommodation of predictive uncertainty in ARC-development
- Incorporation of perceived risks^{*} into the ARC-development process.

During FY 1977, significant progress was made in the compilation of a meaningful data base for the development of ARC. We reviewed past and current approaches that have been

^{*}Perceived risks are those that have been expressed and reflect widely held beliefs having no discernible technological basis.

used in risk criteria development for both radioactive and nonradioactive hazards; conducted studies involving moral and ethical questions related to ARC; gathered background information on naturally occurring geologic formations containing hazardous minerals; compiled the existing standards, guidelines, and criteria relevant to WM; and conducted a preliminary opinion survey of professionals in the field of radiation safety regarding their estimate of acceptable levels of radiation exposure resulting from WM operations.

Most of the effort expended during FY 1977 was devoted to determining a methodology for ARC development. This required an investigation of those factors relevant to the decision-making process itself. Study showed that a preferred methodology would be capable of producing the ARC on a timely basis in such a manner that these criteria would be considered defensible, understandable, applicable, and equitable. Various approaches for ARC development were considered and evaluated on the basis of their ability to meet certain preference criteria.

• Multi-attribute decision analysis (MADA)

- Individual dictate
- Expert panel (unstructured)
- Expert panel (structured)
- Public polls and surveys

- Classical decision analysis
- Bayesian analysis
- n-value logic analysis.

We determined that the use of MADA, coupled with the use of structured panels as value sources, showed the greatest promise for successful application.

Preliminary results from a detailed analysis of the optimum structure and function of the expert panels indicate that the Delphi* and Delbecq[†] methods of operation could be used most effectively. The principle advantages of using MADA are as follows:

• Both objective and subjective information can be incorporated into the decision-making process.

*A structured panel, whose members are unknown to each other, responds to questionnaires. Anonymous statistical feedback, sometimes with explanations, is returned to the panel. This process is repeated until a consensus is reached. If a consensus cannot be reached, final results are averaged.

[†]Each expert on the panel makes an initial assessment and presents it to the group, along with the rationale behind it. These assessments are discussed by the panelists; then each makes a final assessment. If a consensus cannot be reached, a weighted average may be used, a Nash solution may be used, or the Pareto optimal frontier may be examined for potential solutions.

- The probability of achieving a predetermined objective or set of objectives can be optimized.

- Desired objectives and the values given to the various attributes considered must be explicitly stated. This is particularly important in WM, where multiple, and sometimes conflicting, objectives must be met.

- The entire process can be reviewed objectively and altered as

needed. That is, new information can be incorporated without disrupting the entire process.

- The methodology can be expeditiously applied to produce the required decisions in a timely and effective manner.

The detailed structure for applying MADA remains to be completed; we anticipate, however, that useful ARC can be determined during FY 1978.

2. PROJECT DESCRIPTION

Since the U.S. Nuclear Regulatory Commission (NRC) retained the Laboratory to provide technical support for its nuclear WM program, LLL's support has consisted largely of developing and documenting sound technical bases for the regulation of WM operations. Some specific tasks and projects in LLL's WM program include the development of performance criteria for solidified, high-level waste forms and site-suitability criteria for high-level waste repositories.

A general systems analysis approach has been used in the development of such criteria. In this approach, the entire WM operations sequence is modeled, so that the effects of various operational conditions can be predicted by such methodologies as fault tree, event tree, and pathway analysis. Thus, the effect of various operational conditions and alternatives

can be determined. The sensitivities of these effects to assumed changes in operational parameters can also be evaluated.

The final selection of performance criteria for various WM materials and operations depends on the ability of the criteria to meet specified objectives and goals. These goals and objectives must be stated in definitive and quantitative terms, so they can be related objectively to the results of the parametric system analysis. The lack of such definitive goals has been identified as a serious deficiency in previous WM research efforts.^{1,2,3} Without a defined objective, the probable success of any WM methodology is difficult to assess. One of LLL's tasks in its technical support of NRC is to develop ARC for WM programs.

Development of ARC is a complex process, requiring consideration of both objective and subjective factors. The basic steps in this process include the following:

1. Define and structure the problem.

2. Compile a data base of technical information to provide insight and perspective for ARC development.

3. Review and assess past and existing approaches to the development of ARC, and determine their potential applicability to WM.

4. Select a preferred approach for timely and effective resolution of the problem.

5. Using this preferred approach, select an optimal methodology for determining ARC.

6. Apply the selected methodology.

This report discusses the progress to date in ARC development and the work planned for the future. A major portion of LLL's effort in FY 1977 was performed by subcontractors, Systems Control, Inc. (SCI) and Decisions and Designs, Inc. (DDI), and by individual consultants under the direction of the LLL staff. The general objective of this initial work phase was to conduct a "scoping" study to (1) define issues, (2) determine an optimal methodology for their resolution, and (3) accumulate a data

base for ARC development. Specific objectives for the project were as follows:

1. Develop a basis for determining ARC for WM.

2. Evaluate alternative methods for developing ARC, considering various levels and types of risks.

3. Provide a technical basis for the findings.

4. Coordinate activities with the National Council on Radiation Protection (NCRP). When the scope of LLL's work for FY 1977 was determined, the NCRP had agreed to perform the following tasks for NRC:

Task 1 - Study the mechanisms for determining what constitutes an acceptable risk to the public and environment from various radioactive wastes.

Task 2 - Select and use an appropriate mechanism to determine what constitutes an acceptable risk in management of radioactive wastes produced in the nuclear fuel cycle.

Task 3 - Provide a set of acceptable risk guidelines that can serve as the basis for the NRC rulemaking procedures for regulating nuclear WM operations in the U.S.

LLL maintained liaison with NCRP; the Laboratory, however, did not direct their effort.

3. PROBLEM DEFINITION

The problem of developing ARC for WM may be structured according to Fig. 1. The elements of this problem are defined below.

Fig. 1. Block diagram illustrating the development of acceptable risk criteria.

1. General Goals and Objectives.

These goals and objectives consist of general statements of desired overall objectives for WM programs (e.g., protect future generations and assure protection of public health). Insight and guidance on WM goals and objectives may be gained from perusal of the proceeding; of recent studies and workshops on the subject.^{2,3}

2. Issues. Issues may be defined as those specific properties requiring definitive, explicit, and quantitative criteria. General goals and objectives must be translated into

explicit, objectively determinable forms. For example, a general objective would be to protect the public from excessive exposure to ionizing radiation. An issue derived from that objective would be to define an acceptable level of radiation exposure and establish criteria for allocating the risk of exposure to a population.

3. Data Base. This consists of developing specific objective data and background information that will provide insight and perspective for determining ARC. The data base includes information on acceptable risk for natural and anthropic phenomena. It also contains information on relevant policies, practices, and precedents that provide a framework for ARC. A sound data base will assure that the resulting ARC are consistent with established precedents, as well as with general rules of logic and reason. Incorporation of such information in the decision-making process will enhance the defensibility of the ARC.

4. Methodology. A methodology is needed to determine optimal methods and procedures for developing ARC on a timely basis. A successful methodology will guide a single decision-maker or a group so they can arrive at the required decisions without lengthy delays. Such delays are

often the result of a natural desire to avoid making decisions until more or complete information is available. In recent years, techniques have been developed for making optimal decisions under conditions of uncertainty, and the feasibility of applying these techniques to the development of ARC was fully investigated.

5. Decision-Making Process. The final decisions on ARC will rest with the NRC. For its guidance, the conclusions of decision-making panels of

experts on the NRC staff and, perhaps, other consultants may be useful in assuring that all significant aspects of the problem have been considered. The "feedback" loops shown in Fig. 1 indicate an iterative process, whereby the decision-making group or groups in their deliberations may uncover the need for further data or methodological approaches. The process should incorporate the capability to meet these needs expeditiously.

4. GOALS AND OBJECTIVES

In recent years, studies, symposia, and workshops have been conducted to develop guidelines and criteria for management of nuclear waste. As a result of these efforts, certain general goals and objectives have been defined for WM programs. Notable among these efforts have been a task force study sponsored by the NRC and two workshops sponsored by the EPA, at Reston, Virginia, and Albuquerque, New Mexico, during 1977.^{2,3} From attendance at, and studies of the reports of, these meetings, we have gained certain insights and made observations about acceptable goals and criteria. These are summarized as follows:

1. Although a degree of uncertainty still exists regarding the potential impacts of nuclear waste

management, sufficient information is now available to develop criteria and standards for the operation. Such development should proceed as soon as possible, to expedite the timely establishment of required criteria.

2. It may be difficult, or even infeasible, to develop only one set of criteria that would be applicable to all nuclear waste management activities. Therefore, different criteria may have to be developed for different categories of waste, as classified by waste form or disposal technique.

3. Isolation of high-level waste in suitable geological formations is desirable. During the period when the wastes are being emplaced in a repository, the process should be monitored, and assumptions regarding

isolation techniques should be validated. Once the repository is sealed, however, monitoring should be unnecessary.

4. The selected method for disposal of radioactive waste should be independent of the long-term stability of society.

5. The safety of future generations should be a major factor in criteria development.

6. Cost should be of secondary importance to the primary consideration of safety in the development of WM criteria.

7. Although zero risk and zero dose may be desirable goals, they are impractical ones because they could be attained only if we were to refrain entirely from developing nuclear energy.

8. Risk criteria should not be keyed to any one method of disposal or form of radioactive waste.

9. Accidents and unplanned releases of radioactivity should be considered in the formulation of risk criteria. Traditional risk analysis techniques that are quantitative should be used to the extent feasible, with full recognition of the fact that quantitative risk analysis is, at best, an imperfect tool.

10. Criteria should reflect the international implications of radioactive waste disposal.

11. Perceived risk, as well as calculated risk, is important and should be considered in the establishment of acceptable risk criteria.

12. Risks associated with radioactive waste should be placed in the context of other risks from similar pollutants or environmental hazards. To the degree possible, the context should be familiar to the public, so they can weigh the risks from radioactive waste in relation to risks from other sources.

13. State and local governments should be involved in the decision-making process on radioactive waste criteria. The decision-making process should be open in fact, as well as in appearance.

14. Retrievability should be considered only when safety will not be compromised.

15. Waste management activities should cause no greater risks to future generations than the present generation is willing to accept for itself. The effect on future generations, however, is unclear because the long-term effectiveness of containment systems is uncertain. In any event, criteria should be established to protect adequately the health of present and future generations.

16. Maximum dose limitations for individuals as well as the population in general should be considered in

establishing acceptable risk criteria.

17. Natural background radiation levels are an appropriate lower limit below which we could not justify efforts to clean an area.

18. Establishment of risk criteria should involve a broad-based assessment of public opinion. Despite their shortcomings, public forums are one means of obtaining public opinion.

19. WM activities should be conducted so that society will, as much as possible, retain its options for future action. Operational responsibility for the conduct of WM programs should be assumed by the direct beneficiaries (i.e., this generation) of nuclear power. Decisions on the applications of technology should not be deferred to future generations.

20. The cost of WM should be passed directly to the consumer of nuclear power.

21. The need to handle, treat, and dispose of radioactive waste currently in existence should not dictate the solution of the problem of waste to be generated in the future.

22. Values not easily quantifiable should be included in the decision-making process and weighted according

to their significance, not their quantifiability.

23. Moral and ethical issues should be addressed in the decision-making process.

24. The organizational structure should be able to respond effectively to both gradual and abrupt changes in the rate and scale of nuclear power generation.

25. The existence of scientific, technological, and organizational uncertainties in any WM system should be stated explicitly, along with the logic and procedures used to address these uncertainties.

26. WM systems should comply with all radiation standards, criteria, and regulations established to cover both normal operations and accident situations. The system should be capable of meeting the criteria in all conceivable incidences of radiological release.

27. The time period between the generation of radioactive wastes (in nuclear reactors, other nuclear facilities, or during various activities of the nuclear fuel cycle) and the ultimate disposal of those wastes should be minimized.

5. ISSUES TO BE CONSIDERED IN CRITERIA DEVELOPMENT

Several technical issues should be considered in the development of ARC for nuclear waste in general and for high-level waste in particular. This section summarizes these issues. Later we shall determine if existing approaches to criteria development address these issues; if they don't, we shall identify the elements that must be considered in any criteria-development approach.

The issues of concern are complex and span technical, psychological, and ethical dimensions. The seven areas identified below* cover these issues and are described individually in detail.

1. Unplanned or accidental events
2. Present vs future risks
3. Institutional controls and retrievability
4. Dose-response mechanism and uncertainty
5. Spatial distribution of exposed populations
6. Different types of nuclear wastes
7. Public perception.

Unplanned or Accidental Events

The geologic repositories envisioned for the disposal of high-level waste are planned for locations without effective mechanisms for the transfer of nuclear waste to the human environment. Under "normal" operation of the waste repository, there would be no release of radioactivity. However, even with technical safeguards designed to achieve zero planned release, the threat of possible unplanned release is a key issue in developing ARC for nuclear waste disposal. Public concern over nuclear waste appears to be focused not on the ability to get the waste safely into a repository, but rather on the ability to keep all waste isolated from humans after its emplacement. Unplanned events and accidents, such as (1) the appearance of an underground aquifer at the disposal site that would induce leaching, (2) either intentional or unintentional intrusion into the repository at some future time, and (3) low-probability natural calamities (e.g., earthquakes, meteorites, volcanos) appear to be the most widespread and important concerns relative to protecting the environment. Examination of the above considerations reveals another issue, the perception of risk, which will be discussed later in this section.

*Some of these areas can be quantitatively analyzed by developing a mathematical representation of risk. Such a mathematical treatment is presented in Appendix A.

Although public concern appears to be centered primarily on long-term repository releases, a potentially more serious problem relates to possible releases resulting from pre-emplacment operations, including waste solidification and transportation from the fuel reprocessing plant to the waste repository. Such operations may entail a significant probability for accidental release.

Establishing criteria and standards to address such unplanned events involves implementing concepts different from those used to set previous nuclear radiation standards (e.g., the Uranium Fuel Cycle Standards, 40 CFR, Part 190, in which operational monitoring of detectable releases is implicitly assumed). The probabilities and consequences of unplanned events (particularly low-probability events after a repository is closed), will require a subjective assessment of their relative importance.

Present vs. Future Risks

An additional consideration involving an unplanned release from very long-lived radiation sources is the belief that man-made repositories may ultimately place more risk on future generations than on the present generation. That is, while we enjoy most of the benefits from the raw materials producing the nuclear waste (e.g., electricity, a defense

system), our descendants will bear most of the risk. Obviously, weighting current risks against future risks represents a significant ethical issue.

Perhaps one of the most significant concerns that should be addressed by specific criteria is the length of the terminal phase of disposal. Projections of potential radiation impacts become increasingly uncertain, and perhaps meaningless, when the time frame stretches too far into the future. Specifying the appropriate time frames to consider separate risk indices and assigning an appropriate weighting factor for each time frame are value judgments or equitability issues inherent in the development of ARC. The long-range, future risk problem is apparently perceived by the public to be a unique problem of nuclear waste. This perception should be considered in the development of criteria.

Institutional Controls and Retrievability

Another issue pertinent to the development of nuclear waste management criteria is the potential care of the repository and the available corrective actions following the accidental release of radioactivity. Both concerns require action to minimize the potential for harm from the

disposed waste. Unless this generation assumes the responsibilities, future generations will bear the burdens for those benefits derived by the present generation. The equitability of transferring responsibility must be considered, as well as the effectiveness of any such transfer, even if future generations were to assume this responsibility.

Dose-Response Mechanism and Uncertainty

The uncertainty of dose effects involves health risks to the population from exposure to ionizing radiation near or below naturally occurring levels (less than 0.1 rem/yr). Until recently, it was assumed that genetic risks from background levels of radiation were more important than the somatic risks from the same radiation levels. However, more recent information indicates that a linear, non-threshold relationship should be used as a basis for the conservative estimation of cancer risks from radiation exposures, even though exposure levels are far below background levels.⁴ Essentially, no matter how low the radiation dose (except a dose equal to absolute zero), some calculable level of risk exists. Thus, the developers of nuclear WM criteria cannot institute regulatory standards based on a no-risk threshold; rather, they must

determine the amount of risk (e.g., morbidity, number of cancers, deaths) that is acceptable to the public at large. To compound the difficulty of determining this, the data on which the decision is based has a large measure of uncertainty reflected in the range of risk predictions that can be made. The best available estimates are made using a combination of information from a backward extrapolation of the high-level-dose data associated with A-bomb survivors of Hiroshima and Nagasaki, from certain groups of patients who have received therapeutic x rays, and from groups that have had occupational exposure to radiation. Calculations based on these data from irradiated humans indicate that additional exposure of the entire U.S. population to 5 rem over a 30-yr period (or 0.17 rem/yr for 30 yr) could cause 3,000-15,000 cancer deaths annually.⁴

Spatial Distribution of Exposed Populations

This issue is concerned with the risk borne by populations near the source of release, relative to those far removed from the site. Clearly, during the placement of the nuclear waste in the repository and within the short-term future after the repository is closed, the nearby population is exposed to a higher degree of

risk than the rest of the public. Another aspect of this inequity is that the people close to waste repositories will probably be living far from the big cities. This portion of the public will almost certainly receive fewer benefits from the electricity generated by those nuclear power plants that initially produced the waste.

The nuclear WM criteria will ultimately be expressed in terms of valuations placed on various types of regulatory formats (e.g., rem, man-rem, dose/unit of electricity generated). These indices must be evaluated for specific spatial extents of land areas. Some formats may be averaged over a 100-km radial distance around the repository, whereas other formats may be evaluated over the entire United States land area or on a global basis (e.g., for Krypton-85). To protect the local, as well as national, population properly, an appropriate spatial parameter must be defined, and the proper weight must be given to each such parameter.

Different Types of Nuclear Wastes

Development of criteria and standards for high-level waste currently has a high priority; however, the risk from all types of radioactive

waste should be considered. Because of the various types of wastes (i.e., high-level, intermediate, low-level), the high degree of variability in activities, half-lives, and quantities to be managed, it may be difficult to approach the problem comprehensively. It should be noted that the rem unit, used to express radiation dose, is independent of the radiation source; however, the perceived effects of the exposure may not be source-independent.

Public Perception

Acceptability of risk is dependent upon the public perception of the hazard resulting from nuclear radiation exposure; this issue, therefore, is open to interpretation. The ambiguity surrounding the issue is due partly to the contextual problem of the meanings of "public acceptability" and "long-term risk." While much effort and money has been expended in the past to develop mechanisms for determining acceptable risk, to a certain extent, these were technical tools for the use of technologists. Fundamental questions concerning the criteria and standards development process, as well as the technical issues identified by this process, have serious moral, social, and political ramifications, which must ultimately be decided by the

public. The decision-making process itself will take place in the near future; consequently, the current perceptions of the general public and the NRC decision makers may have a lasting impact on the public health and safety of future generations.

The public's perception of radiation risks is constantly changing and poorly quantified, it is difficult to measure and evaluate this perception because of the imperfect tools used in the psychological and human-behaviour disciplines.

A fundamental issue to be considered in developing criteria is whether the perception of radiation risks, as opposed to the technical predictions, should be considered in the selection of risk index formats and evaluations based on these formats. Regardless of such consideration, the acceptability of the criteria that are developed will be a function of the perceptions of both the public at large and the decision makers responsible for determining the criteria.

6. DATA BASE

During FY 1977, we made significant progress in compiling a meaningful data base for development of ARC. We reviewed past and current approaches that have been used in the development of risk criteria for both radioactive and nonradioactive hazards, conducted studies involving moral and ethical questions related to ARC, and compiled background information on naturally occurring geologic formations. This section reviews the documented data that provides insight and perspective in the development of ARC.

Existing Relevant Regulations and Guidelines

A review of existing rules applicable to the conduct of WM operations

is useful in setting constraints on ARC. Federal regulations applicable to the licensing and operation of WM programs are presented below. State regulations concerning WM have not been examined because of the limited scope of nuclear WM operations that states may regulate.

Licensing

1. Title 10, Code of Federal Regulations, Part 51 (10CFR51): Licensing and Regulatory Policy and Procedures for Environmental Protection - This code sets forth the policy and procedures for the preparation and processing of environmental impact statements and related documents. 10CFR51 provides that fuel

reprocessing plants and waste disposal operations (for nonexempt quantities) will require an environmental statement before they are licensed.

2. 10CFR20 - Sections 301-305: Standard for Protection Against Radiation - Waste Disposal - These sections provide for the disposal, by burial or movement to a sanitary sewer, of small quantities of radioactive material. Section 302 requires burial of such material on land owned by either the State or Federal Government. It also requires that pertinent information on the nature of the environment be provided and that procedures be followed to minimize unexpected exposures.

3. 10CFR30 - Rules of General Applicability to Licensing of Byproduct Material - These rules define quantities and concentrations of byproduct material for which licenses are required. "Byproduct material" means any "radioactive material (except special nuclear material*) yielded in or made radioactive by exposure to radiation incident to the process of producing or using special nuclear material."

4. 10CFR40 - Licensing of Source Material - This provides that no person without a license shall own,

use, or handle source material after mining. "Source material" means (1) uranium or thorium, or any combination thereof, in any physical or chemical form or (2) ores that contain, by weight, 0.05% or more of uranium, thorium, or any combination thereof. Source material does not include special nuclear material.

5. 10CFR50, Appendix F: Licensing of Production and Utilization Facilities, Policy Related to the Siting of Fuel Reprocessing Plants and Related Waste Management Facilities - This appendix provides that high-level waste be solidified in 5 years and shipped in 10 years to a Federal repository on federally-owned and controlled land.

6. 10CFR70 - Special Nuclear Material - This establishes license requirements for nuclear materials. "Special nuclear material" means (1) plutonium, uranium-233, uranium enriched in the isotope 233 or in the isotope 235, and any other material that the NRC determines to be special material, but not source material; or (2) any material, other than source material, artificially enriched by any of the foregoing.

Operations

1. 10CFR20 - Standards for Protection Against Radiation - This section details maximum permissible

*For definition, see Item 6, 10CFR70 - Special Nuclear Material.

radiation doses, radionuclide air concentrations, and radionuclide water concentrations that apply to both occupational and public exposure.

2. ERDA Manual, Chapter 0524 - This chapter applies 10CFR20 radiation dose, and air and water concentration limits to contractors who operate ERDA-owned or controlled facilities.

3. 49CFR - Subtitle B, Chapter I, Parts 171-179: Hazardous Materials Regulation Board, Department of Transportation - These parts cover preparation and shipping of hazardous materials, including radioactive materials.

4. 10CFR71 - Packaging of Radioactive Material for Transport and Transportation of Radioactive Material Under Certain Conditions - This describes regulations for the handling and shipping of licensed material. The requirements of 10CFR71 are to be applied in addition to the requirements of 49CFR171-179.

5. ERDA Manual, Chapter 0511: Radioactive Waste Management - This chapter applies to contractors who operate ERDA-owned or controlled facilities. It includes the provision that solid waste containing significant uranium 233 or transuranic contamination greater than 10 nCi/g be segregated and placed in retrievable storage.

6. 40CFR141 - Interim Primary Drinking Water Regulations - This establishes concentration and dose limits in drinking water for man-made and natural radionuclides. Although the burden of compliance with this regulation lies with the drinking-water supplier, these limits must be noted in evaluating discharges into water.

7. 40CFR190 - Environmental Radiation Protection Standards for Nuclear Power Operations - This regulation specifies 25 mrem/yr as the maximum individual dose resulting from the uranium fuel cycle and it sets release limits in terms of Ci/GW.y for some long-lived nuclides. Although it is not applicable to waste disposal sites, the regulation is mentioned for its unique measurement units: (1) dose resulting from fuel cycle rather than from a specific facility; (2) release per unit energy, rather than per unit volume.

Assessment of Regulations

To comply with 10CFR20, Section 302, several specific environmental considerations must be addressed when a waste disposal site is being selected. 10CFR51 requires that an environmental statement be written as a licensing condition for WM operations. Both regulations focus attention on probably the most important

and possibly overriding environmental factor in radioactive waste management, radiation dose to man.

10CFR20 requires that operations at a facility result in releases of radioactivity and radiation exposures that are as low as "reasonably achievable" and less than 0.5 rem/yr to any individual in an unrestricted area. The regulation says that "reasonably achievable" takes into account technology, economics, and public health and safety. If one accepts the linear, no-threshold hypothesis for the biological effects of radiation,⁴ the proper unit of radiation dose in evaluating public health is a man-rem, provided standards for maximum individual dose have been met. Such approach has been taken in Appendix I of 10CFR50.

It is assumed at this time that population doses from WM operations will be very small if operations proceed according to design. However, accidents may contribute as much, or more, population exposure as normal operations. No regulations have been found that apply directly to WM and give guidance to an acceptable level of personal or population exposure under accident conditions. 10CFR100, Reactor Site Criteria, gives some guidance for reactors by setting maximum calculated doses at various distances from the reactor; these

guidelines can be used for evaluating site suitability under maximum accident conditions.

Maximum Permissible Dose

Groups of experts, including the International Commission on Radiological Protection (ICRP), the NCRP,⁶ and the Federal Radiation Council (FRC),⁷ have established certain acceptable limits for human exposure to radiation. The recommendations of these groups are consistent. The dose-limiting recommendations of the NCRP, given in Table 1, typify their standards. These limits are currently accepted and applied in radiation protection programs. Some insight and understanding may be gained from an historical review of the development of these radiation standards. Such review appears in Appendix B of this document.

Natural Geologic Hazards

Since most WM plans call for the underground emplacement of the waste, it is useful, for purposes of perspective, to relate the hazard of nuclear waste burial to that of naturally occurring, geologic formations. A pertinent study⁸ was completed during FY 1977.

Table 1. Dose-limiting recommendations.*

<i>Maximum Permissible Dose Equivalent for Occupational Exposure</i>	
Combined whole body occupational exposure	
Prospective annual limit-paragraphs 229,233	5 rems in any one year
Retrospective annual limit-paragraphs 230,233	10-15 rems in any one year
Long term accumulation to age N years -paragraph 231	$(N - 18) \times 5$ rems
Skin-paragraphs 234,235	15 rems in any one year
Hands-paragraphs 236,237	75 rems in any one year (25/qtr)
Forearms-paragraphs 236,237	30 rems in any one year (10/qtr)
Other organs, tissues and organ systems -paragraphs 238,239	15 rems in any one year (5/qtr)
Fertile women (with respect to fetus) -paragraphs 240,241	0.5 rem in gestation period
<i>Dose Limits for the Public, or Occasionally Exposed Individuals</i>	
Individual or Occasional-paragraphs 245,246,253,254	0.5 rem in any one year
Students-paragraphs 255,256	0.1 rem in any one year
<i>Population Dose Limits</i>	
Genetic-paragraphs 247,248	0.17 rem average per year
Somatic-paragraphs 250,251	0.17 rem average per year
<i>Emergency Dose Limits-Life Saving</i>	
Individual (older than 45 years if possible) -paragraph 258	100 rems
Hands and Forearms-paragraph 258	200 rems, additional (300 rems, total)
<i>Emergency Dose Limits-Less Urgent</i>	
Individual-paragraph 259	25 rems
Hands and Forearms-paragraph 259	100 rems, total
<i>Family of Radioactive Patients</i>	
Individual (under age 45)-paragraphs 267,268	0.5 rem in any one year
Individual (over age 45)-paragraphs 267,268	5 rems in any one year

*Taken from NCRP Rept. No. 39, "Basic Radiation Protection Criteria."

Innocuous Hazard Levels

Storage plans for radioactive waste often caution that surveillance be continued until the hazardous material has decayed to innocuous levels. The term "innocuous" is generally undefined, particularly where the actinides are concerned. The complexity of the problem may be seen by analyzing the relative toxicity of the nuclides as they go through their various decay chains with time. Figure 2, for example, shows the volume of water required to dilute 1 mg of originally pure plutonium to MPC levels for the daughter-nuclides and/or acceptable drinking-water values for lead (Pb). For plutonium-239, the required volume decreases from 10,000 litres of

water to 20 litres after 10 million years, by which time it has essentially all decayed to stable lead. Plutonium-238 varies in toxicity as it decays through uranium-234 and radium-226, finally reaching lead-206, its stable daughter-product. The point at which the 1 mg becomes innocuous is difficult to determine because the stable decay product (Pb) is still quite toxic, unless one takes the view that only radioactive material is harmful. The situation becomes more complex for the uranium decay chains (see Fig. 3). The toxicity of this material actually increases with time because the final daughter-product, lead, is considered more toxic than uranium-238 or uranium-235, reflected in its more restrictive drinking-water standard.

Fig. 2. Plutonium chain toxicity vs time. Time and volume of water required to dilute 1 mg of originally pure plutonium to MPC_w or drinking-water standards.

Fig. 3. Uranium decay chain toxicity vs time. Time and volume of water required to dilute 1 mg of uranium to MPC_w or drinking-water standards.

Nonradioactive Hazardous Waste Practice

In the State of California the rules and regulations governing the disposal of nonradioactive hazardous waste, such as Pb, require disposal at an approved disposal site. (Federal regulations have not yet been promulgated.) The California State Water Resources Control Board stipulated the California regulations for hazardous-waste disposal-site design for a Class 1 site.⁹ The Class 1 site is the most restrictive site intended for the most hazardous nonradioactive wastes. These California rules are not dissimilar to those currently used at low-level radioactive waste (shallow-land) burial sites. In general, they appear to be less restrictive. One difference in the approach to non-radioactive hazardous waste is that there is no quantitative limit in either the concentration or the total inventory for material deposited at any appropriate disposal site. The inconsistency in approach toward management of radioactive vs non-radioactive hazardous waste is evident.

Bioethical Perspectives

Dr. Margaret Maxey, a consultant to LLL, conducted a study¹⁰ on

bioethical considerations relevant to ARC for WM development. A significant conclusion of this study is that concern over adverse effects of a technology to generations in the distant future appears to be unprecedented in human history.

Health Physicist Opinion Survey on ARC

A cursory opinion survey of approximately one hundred health physicists and related professionals was taken as an initial scoping study to determine values for acceptable risk from radiation exposures resulting from WM operations.

All survey respondents had a professional understanding of the biological effects of ionizing radiation. The survey form used and the responses received are presented in Appendix C. The preliminary survey results show that the respondents tended to equate "acceptable" levels of exposure with "innocuous" levels, at least insofar as waste management is concerned. Both "acceptable" and "innocuous" levels ranged between 1 and 100 mrem/yr with a median response at approximately the 10-mrem/yr level. These results are only preliminary and should currently be viewed with caution. Further work is planned.

7. METHODOLOGY

Today, thousands of criteria, standards, and regulations exist to protect human beings from infectious disease, toxic substances, radiation, accidents, etc. A few examples of these include:

- EPA radiation protection requirements
- Ambient water quality standards and criteria for various states
- EPA effluent limitations guidelines for industrial wastewaters
 - Water Act, PL 92-500
 - Clean Air Act and subsequent guidelines
 - Occupational Health and Safety Standards and Guidelines, PL 91-596
 - Pesticides Control Act and subsequent guidelines
 - Highway speed limits
 - Federal aviation guidelines.

This chapter provides an overview of past and present approaches to setting general risk criteria, identifying the underlying philosophical and technical bases of resulting criteria, and evaluating these approaches in terms of their applicability to risk criteria for nuclear WM. Because of the volume of criteria now available, we have emphasized the generic approaches common to many criteria. We have not attempted to list all the criteria studied.

Our review of previously developed criteria is covered from two major aspects: (1) the three conceptual approaches that were applied in developing the criteria and (2) the procedural approaches that were used.

Basic Concepts Used to Derive Criteria

Three factors or considerations formed the basis for the development of environmental criteria or standards:

1. Dose-response considerations
2. Economic factors/considerations
3. Subjective considerations.

Although some standards are based on only one of the above, most are based on a combination of all three factors.

Dose-Response Considerations

Many government regulations dealing with health effects on animal and human life take into account some risk-response or dose-response relationship. This is particularly true for the control of the numerous natural and man/made deleterious substances in our environment. The relationship between dose and response can have many forms, as discussed by Rowe.¹¹ Some of the general forms are shown in Fig. 4 and are briefly discussed below.

1. Threshold Relationship - Curve 1 illustrates a threshold con-

Fig. 4. Types of dose-response relationships.

dition where, even though exposure may take place, there is no risk unless the particular threshold is exceeded. This is illustrated by the point where Curve 1 leaves the abscissa. Curve 1 is shown as linear above the threshold, but it may be some other shape.

2. Breakpoint Relationship -

Curve 2 illustrates a nonthreshold case, but there is a distinct breakpoint in the relationship of exposure to risk. While the curves are shown as linear below and above the breakpoint, they may be some other form.

3. Linear/Nonthreshold Relationship -

Curve 3 is the linear dose-response-risk relationship when no threshold exists. Zero response occurs only at zero dose. For regulatory purposes, this is the condition that is assumed to exist for exposure from radiation. It is obtained by

extrapolation from data at high levels of exposure and measures response down to low levels of exposure.

4. Nonthreshold/Lowered Sensitivity Relationship -

Curve 4 is a non-threshold relationship that shows lower sensitivity to dose at lower exposure levels.

5. Nonthreshold High Sensitivity Relationship -

Curve 5 shows the reverse of Curve 4, with increasing sensitivity at lower levels of risk exposure. Curve 5 illustrates the condition in which more sensitive members of a population are affected by risk-exposure conditions.

6. Nonlinear, Nonthreshold, Variable Sensitivity Relationship -

Curve 6 shows a relationship that is highly nonlinear and difficult to characterize with only a few data points. One part of this curve actually has negative slope (i.e., response decreases with increasing dose).

Economic Factors/Considerations

The economic costs associated with reducing environmental risk have been factored into some environmental criteria. Important economic considerations include:

- Direct dollar cost for risk reduction
- Ability of industry to pay the cost
- Impact on employment

- Energy demand changes required
- New technologies soon to be

available.

These economic considerations have been applied in the EPA regulation of industrial waste-water effluents through the development of guidelines¹² for the best practicable control technology that is currently available and the best available technology that is economically achievable. The underlying philosophical concept is to regulate environmental risk without extensive economic and social damage.

Subjective Considerations

Personal judgment plays an important role in the development of most criteria. For example, judgment can be based on the public's or the decision-maker's perception of the actual risk as calculated by dose-response models. One common method of developing risk criteria is to observe people's reactions in a risk environment (custom of usage, revealed performance). In this way, the amount of risk acceptable to people can be determined. Opinions have also been sought through public referenda and polling, or the polling of qualified experts.

Use of Basic Concepts to Develop Criteria

The three basic concepts or considerations described above have been

used in numerous areas to develop criteria. Some of these are described below.

Highway Speed Regulations

Highway speed limits evolved primarily from studies of the speeds at which people drove without regulations. Regulations were based on "custom of usage" and subjective personal judgments. From statistical analyses of highway speeds observed, decision-makers could determine the speeds "acceptable" to society and set speed limits accordingly. Subsequently, accident (risk-response) data were recorded and used to modify the original regulations. In the past few years, new factors, energy cost and availability, played an increasingly important role in the highway speed limits. Today all three basic factors, (1) risk-response, (2) economics, and (3) subjective judgment, are used to establish highway speed-limit criteria.

Criteria on Various Deleterious Substances

Numerous government standards and regulations have been promulgated for the protection of human beings from various deleterious substances. In general, these standards are based on two types of criteria, ambient criteria and release criteria.

1. Ambient Criteria - Ambient criteria are the maximum quantities of deleterious material permitted in the environment. These quantities may be measured in terms of concentrations. Ambient criteria are often determined on the basis of a dose-response relationship. All criteria and standards resulting from such dose-response curves must include subjective, judgmental decisions on the doses and corresponding responses that are acceptable to society. In the case of the threshold dose-response breakpoint shown in Fig. 5, the standard is selected on the conservative (lower risk) side of the breakpoint, with a margin of safety defined on the basis of social attitudes, economics, and other factors. Similarly, in the case of a linear nonthreshold dose-response, also shown in Fig. 5, a standard must be selected by considering all factors. Otherwise, the point on the line designated as the standard would be arbitrary.

Fig. 5. Examples of criteria based on common dose-response relationships.

2. Release Criteria - Standards limiting the release of deleterious materials have been promulgated for all types of wastewater discharges, as well as other pollutants. Wastewater-release standards have been based primarily on economic considerations involving evaluations of "best practicable control technology currently available," and "best available

technology economically achievable." The principle of cost/benefit has been built into these release criteria through two simple concepts of relationship:

- $\frac{\text{Cost of Release Reduction}}{\text{Release Reduction}}$ Ratio
- $\frac{\text{Total Release}}{\text{Total Production}}$ Ratio

The latter cost/benefit concept is used in all the industrial wastewater-release standards.

In many cases, release standards are also determined after consideration of the dose-response associated with the particular release. For example, a wastewater-release standard based on economic and technological considerations alone could cause ambient water-quality problems in a particular stream because of the specific waste-assimilation capacity of that stream. Consequently, the release standard is more stringent to protect the stream from ambient problems.

Criteria for Airline Safety

Airline safety regulations are somewhat analogous to nuclear safety controls because of the low probability but severe consequence events that can occur. Regulations are based on risk characteristics and economic considerations specific to various components of airline operations. The main objective of the regulations is to reduce the expected fatality rate of passengers by reducing the probability of failure of each required component of flight operations. The approach used in these regulations is to place standards on the following:

- Background, natural ability, training, and certification procedures of personnel

- Equipment specifications, including maintenance and replacement guidelines

- Operating procedures.

Each regulation is intended to reduce the probability of human fatality by reducing either the probability of failure or the expected fatality rate if a failure does occur.

Criteria Formats

The many criteria, standards, and regulations reviewed in this study illustrate a broad range of formats or measures. These formats are dependent on which of the basic concepts discussed above are used, and how they are used. The formats vary as a function of many factors; these factors, and examples of how they have been used, are discussed below.

Formats Specific to Time Variations

Many health and safety risks are probabilistic, and have both random and periodic time variations. For example, the concentration of a certain pollutant at a point in a stream may vary as a function of (1) its time-varying release from an industry, (2) its time-varying release from other point sources, (3) the long-term trend of its background concentration, and (4) the time-varying assimilative capacity of the environment. Not only do concentrations vary

in many ways, but the adverse response from a given dose often varies with the dose rate. Adverse response to an instantaneous, acute dose is usually more severe than the response to a chronic dose of the same magnitude. Chronic and acute doses can be limited by setting threshold standards for both the long-term mean and the instantaneous maximum dose rate. This is illustrated in Fig. 6 where Curves 1 and 2 are both probability distributions of dose, and X and Y are standards for mean and maximum levels, respectively. Curve 1 represents a condition in which the mean standard is met, but the maximum standard is exceeded. This condition would theoretically cause acute problems, but not chronic problems. Conversely, Curve 2 exceeds the mean standard, but not the maximum standard, thus causing chronic, but not acute, problems.

Long-term trends are also an important part of environmental standards. For example, many ambient

water-quality standards stipulate that the long-term average (e.g., annual average) water quality cannot decrease at all. Others state that the rate of water-quality degradation cannot exceed a certain amount per year (e.g., average yearly temperature cannot increase by more than 0.5°F per year).

The decay rate of a pollutant adds another consideration related to time variations. Pollutants that very quickly decay into a harmless state are likely to present a problem only near their source. Conversely, pollutants that have no decay or very long-term decay rates may persist in the environment for many generations and eventually spread throughout the world.

Formats Specific to Spatial Variations

Expected pollutant concentrations generally vary with both space and time. The Gaussian plume model, a common pollutant dispersion model, is used to compute air pollutant concentrations from an industrial smokestack (see Fig. 7). The maximum pollutant concentration at the plant (X) should be regulated to protect plant workers. The maximum elevated concentration (Y), or maximum total concentration (Z) outside the plant boundaries should be regulated to protect the local public. The far-

Fig. 6. Example of probability distributions of dose rate.

Fig. 7. Illustration of spatial variations of concentration.

field ambient level, which is generally less than Z, may also need to be regulated to protect the public from regional, national, or global pollutant buildup. The spatial extent of concern is generally a function of the pollutant decay rate, settling rate, and far-field dose-response characteristics. Airborne particulates, with their fast settling rate, are usually considered a local, near-field problem. Conversely, certain radioactive species that persist for centuries, are considered local, regional, national, and global problems.

Corresponding to the various "fields" of concern in ambient pollutant criteria are various pollutant release standards. Standards in each effluent stream, or the total effluent streams of one facility have been used to regulate directly near-field ambient concentrations. Existing radiation waste guidelines¹³ suggest that industry-wide (many facilities)

release criteria be used to control regional, national, and global concentrations.

Dependence on Method Sampling

Standard formats must not only be compatible with the nature of risks (e.g., time and space variability), but should also consider the preferred method of sampling such risks. For example, in an industrial plant, a certain air pollutant must be regulated to protect human health. Regulations in this situation address two criteria, ambient air and human dose.

The first set of criteria is evaluated on the basis of air samples taken around the plant; the second set is based on samples taken directly from exposed human beings. Since the second set of criteria is more directly related to human health risks, it is most applicable to our purposes. However, the measurement of direct human or animal dose is often difficult, if not impossible. Ambient air criteria, therefore, are frequently used instead of human dose criteria.

To select useful criteria, we must also consider the practical aspects of the ease and cost of monitoring compliance. The goal is to select risk criteria for which the required sampling programs are feasible (i.e., reasonable sampling frequencies in

space and time), yet the expected magnitude of undetected risks is acceptable. For example, many wastewater standards are written in terms of "daily-grab" samples, rather than continuous samples. However, for more toxic waste streams, hourly or continuous samples may be required because the risks from uncontrolled toxic wastes may offset the added cost of sampling.

Adherence to Standards

The basic purpose of some standards and criteria is to regulate or limit risks to human health and safety, and to protect our quality of life. Unless the standards are met, these goals cannot be assured. Therefore, a vital part of all useful standards is a capability to verify that those standards are being met. The monitoring aspects, discussed above, are important, but a more basic verification problem is the capability to attribute certain risks directly to certain causes. For example, how can water-quality risks be associated with specific waste discharges, and how can such discharges be regulated? A direct cause-and-effect relationship would be very difficult to establish in a stream where there are many unmonitored discharges and little available ambient data. The latest Water Act

Amendments (PL 92-500) solved the problem by requiring that ambient water criteria be used, along with other factors, to determine waste-release standards for each discharger. Water-quality risks are then regulated by verifying that release standards are being met.

Formats for Operational Standards

Operational standards are common in regulations covering several areas including (1) airlines, (2) pesticide control, (3) occupational health and safety, (4) highway safety, and (5) nuclear power plants. These standards are generally narrative (i.e., non-quantitative) but are often based on quantitative analyses of risk characteristics. Narrative operational regulations are intended to reduce the probability of adverse effects to human beings by reducing either the probability of accident or the expected effect if an accident occurs.

Cost/Benefit Considerations

Economic considerations often play an important role in criteria development. One of the most widely used concepts applied to criteria development, and also in determining the acceptability of those criteria, is the principle of cost/benefit balance. Many existing standards

have cost/benefit built into them, using one of the two simple relationships:

- $\frac{\text{Cost of Risk Reduction}}{\text{Risk Reduction}}$ Ratio
- $\frac{\text{Total Risk}}{\text{Total Production}}$ Ratio

Other cost/benefit concepts that have been considered, and may be meaningful are:

- $\frac{\text{Total Response}}{\text{(Mortality and/or Morbidity Rates)}}$
- $\frac{\text{Total Risk + Energy Used}}{\text{Total Production}}$
- $\frac{\text{Total Accepted Risk (in \$) + Cost of Risk Reduction}}{\text{Total Production}}$
- $\frac{\text{Cost of Risk Reduction + Cost of Compliance Monitoring}}{\text{Risk Reduction}}$

In general, for the nuclear waste problem, the cost/benefit approach may be incorporated into the selection process of formats and the "acceptable" levels placed on the selected formats (e.g., unit dose/unit power production).

Procedures Used to Establish Criteria

In almost all cases, some subjective considerations and judgments, as well as technical concerns, are required to formulate an environmental risk criterion and standard. In a review of the procedures used previously to obtain subjective inputs to the development of environmental,

health, and safety criteria, several basic approaches were identified. These procedures can apply one or more of the following approaches:

- Custom of usage
- Structured expert panel
- Unstructured expert panel
- Decision analysis
- Dictate
- Individual technical analysis
- Public poll.

In many instances, the specific procedures used to develop criteria in the past have not been identified and published. Therefore, the above approaches are generic, and are not related individually to specific criteria that have been established. To provide a general understanding of these approaches, a short description of each appears below.

1. Custom of Usage. Criteria can be established simply based on how people now choose to act. For example, highway speed limits originally evolved principally from studies of the speeds at which people chose to drive without regulations. From statistical analysis of observed highway speeds, decision makers determined the speeds "acceptable" to society, and set speed limits accordingly. Similarly, NRC could set standards based on the existing medical-profession practices of using x rays, a major source of public radiation.

2. Structured Expert Panel.

Experts are called together to provide specific inputs on which to base a decision. Acquisition and handling of such inputs is done in a formalized, structured manner such as the Delphi Approach.

3. Unstructured Expert Panel. A group of experts is called together to recommend a decision based on some unstructured set of contributions. The final decision may be subject to the following biases:

- Who speaks loudest or most effectively.

- Who speaks last.

- Who interprets the results.

4. Decision Analysis Techniques.

All decision analysis methods consist of choosing from among alternatives the optimal course of action when the alternatives are constrained to meet specified attributes. Generally speaking, all decision analysis methods require numerical inputs in the form of assessed probabilities (p), ratings (r), and weights (w). The assessed probabilities are obtained from technical experts; the ratings and weights, from persons who reflect the values being modeled. Decision analysis methods systematically transpose these inputs into a rating scheme so that the various alternatives can be compared in quantitative terms. This approach usually reveals preferred attitudes and ranks them

quantitatively. Decision analysis is discussed further in Appendix D.

5. Dictate. The governing official sets criteria based on his judgment and preferences, with or without regard to preferences of others or detailed technical considerations.

6. Individual Technical Analysis. Criteria are developed only on the basis of detailed technical analysis of a single person. This analysis may include dose-response, economic, or cost/benefit considerations. Such individual analysis would then provide a recommended set of criteria to be promulgated by the government.

7. Public Polling. Polling uses statistics to evaluate a sample survey and assess public opinion. The response must be representative of a broad cross section of the public. This may be achieved by sequential random sampling of the population or by sampling only previously identified leading opinion groups. If done properly, polling can accurately determine public opinion. In general, statistical confidence can be ascribed to the result of any properly conducted poll. One potential problem with using polling to set radiation criteria is that the public may not be sufficiently familiar with the technical considerations to provide reasonable responses. Appendix D further discusses polling.

The approaches discussed above are not necessarily mutually exclusive; each of these basic approaches could be used alone to derive criteria, or they could be used in combination. For example, decision analysis could be implemented by using a structured expert panel or an expert panel could be used in conjunction with custom of usage. For these reasons, the evaluation of candidate basic approaches (presented in Section 8) has implicitly included the consideration of overlap and combinations of approaches to develop a set of preferred basic approaches, rather than a single approach used alone.

Procedure for Evaluating an Approach to Develop Acceptable Risk Criteria

A systematic procedure was employed to select a preferred approach for criteria development. Appendix D explains how the procedure was chosen. The following procedures were considered potentially applicable to the ARC nuclear WM program:

- Multi-attribute decision analysis (MADA)
- Individual dictate
- Expert panel (unstructured)
- Expert panel (structured - Delphi)
- Public polls and surveys
- Classical decision analysis
- Bayesian analysis
- n-value logic analysis.

Each of these alternative procedures was evaluated by a panel vote to determine whether it was:

- Understandable
- Logical
- Reproducible
- Able to accommodate many viewpoints
- Able to highlight sensitivities
- Defensible
- Applicable to nuclear WM problem.

The procedures used to evaluate these approaches indicate that MADA is the best way to derive acceptable risk criteria for nuclear waste.

MADA and its refinements are described in detail in Section 8. Such a systematic procedure in the evaluation process enhances the acceptability of the formats and subsequent criteria levels chosen. MADA is most acceptable because it can accommodate a wide spectrum of scientific data as well as political issues. The following attributes* are essential to any procedure that will enhance the acceptability of risk criteria that are developed from it:

1. Implementable - Can the approach be successfully used by NRC to develop acceptable nuclear waste manage-

*These attributes were derived from discussions among SCI, NRC and LLL staff.

ment criteria, considering time and funding constraints? Is the approach analytically feasible and not subject to error? Is it flexible enough to be used in varying acceptable risk problems?

2. Defensible - Can the approach and resulting criteria be defended in a court of law or public hearing? Is the approach technically sound? Does the approach lead to internally consistent, unbiased results?

3. Understandable - Can the

approach be understood by the NRC rule-makers and easily explained to average citizens? Are the components of the decision process visible and reproducible?

4. Equitable - Will the approach result in criteria that equitably distribute risks, benefits, and costs, and that are sensitive to divergent public views and varying interest groups? Does this approach avoid inherent bias toward any specific interest group?

8. APPLYING DECISION ANALYSIS TECHNIQUES TO THE GENERATION OF ACCEPTABLE RISK CRITERIA

The Methodology

Decision analysis techniques, which have only recently emerged as practical tools, can be applied to the development of ARC. They afford a rational prescription for making decisions, particularly regarding nuclear waste management. In the past, the generally accepted methods of cost/benefit analysis were applied to decisions on nuclear safety, as stated by Linnerooth.¹⁴ Now, decision analysis, which combines philosophy, theory, and application can be used to introduce logic to decision making. The uncertainty, complexity, and dynamic effects that characterize many decisions, promote problems. To

handle these problems, MADA integrates the axiomatized theories of probability and multi-attribute utility with the modeling theories of large-scale, dynamic systems for application in the area of nuclear safety.¹⁵

MADA consists of modeling a set of values from a value source and selecting the option or alternative that maximizes those values.

Any decision problem contains four questions that must be resolved:

1. What are the options available?
2. What are the uncertainties and the magnitudes of each?
3. What are the consequences of each option?
4. What values does the decision-maker place on these consequences?

MADA addresses these questions separately, quantifying the uncertainties into numerical probabilities and the values of the decision-maker or value source into numerical utilities. The sum of the utilities of all consequences, each weighted by the probability of its consequence, is the "expected utility" for each option. If the probabilities and utilities have been assessed properly, the option with the highest expected utility is the option preferred by the decision-maker.¹⁶ Obviously, a good, intuitive decision-maker will not need such cumbersome procedure for simple decisions; when the problem is complex, however, he will find this formal method useful to ensure that his decisions are consistent with his values or those he wishes to reflect (i.e., his value source). Alternative value sources are best represented by a hierarchical structure as shown in Fig. 8.

Because part of the function of the Nuclear Regulatory Commissioners is to make decisions regarding regulatory policy in the public interest, they could choose acceptable risk criteria within the scope of their role. Thus, decision-making would be done entirely by the NRC (see Fig. 8, node 1.1).

The NRC could reflect its concept of the public's value judgment without consulting experts or the public.

Then the NRC would determine the important attributes, by choosing the effects to regulate, and would evaluate these attributes by assessing a multi-attribute utility function over them (see Fig. 8, node 1.1.1) Alternatively, the NRC could make the decision but be guided by outside consultants (see Fig. 8, node 1.1.2). In either case, the opinions of experts within NRC would have to be resolved into a single value structure for the analysis. If disagreement is evident, the opinions of the experts can be quantified until a consensus is reached. Although several methods can be used to combine the value structure of disagreeing individuals into a value structure that represents the group, the formal techniques of decision analysis for an individual decision-maker seem most acceptable. These include:

1. Statistical Method (Fig. 8,* node 1.1.2.1.2.1) - Initial assessments are combined (usually by taking the weighted or unweighted average) to produce a group consensus. Neither contact nor feedback is required.

2. Delphi Method (Fig. 8, node 1.1.2.1.2.2) - Anonymous judgments are elicited from a panel of experts and anonymous statistical feedback is returned to them, sometimes

*Figure 8 does not display the statistical-Delphi-Delbecq split at nodes 1.1.2 and 1.2.2.

Fig. 8. Potential value sources.

accompanied by written explanations of responses. This procedure is repeated until a consensus is reached. If a consensus cannot be reached, final results are usually averaged.

3. Delbecq Method (Fig. 8, node 1.1.2.1.2.3) - Each expert on the panel makes an initial assessment, presents it to the group, and explains the reasoning behind the assessment. After the group discusses each assessment and its rationale, each expert makes a final assessment. If a consensus cannot be reached, a weighted average may be used, a Nash solution from game theory¹⁷ may be employed, or the Pareto optimal frontier may be examined for a possible solution.

If NRC seeks advice from a panel of experts or the public, it would be advisable to represent all interest groups (e.g., consumer groups, the nuclear industry, Congress) on the panel. This would assure the public at large that regulations were being generated equitably and that public opinion was being considered in the establishment of those regulations. Such panel of experts could be used for indirect or formal assessment.

• Indirect Assessment (Fig. 8, node 1.1.2.1.1) - NRC analysts discuss with the panel (individually or as a group) the issues involved in choosing performance measures. This discussion would center on the consequences of a particular phase of

the nuclear fuel cycle. (These phases are categorized in Fig. 9.) It would encompass the appropriate level for regulation (see Fig. 10), the measures within each level, and the allocation for the measures. After obtaining the opinions of the panel, NRC analysts quantify the appropriate information for the decision analysts.

• Formal Assessment (Fig. 8, node 1.1.2.1.2) - The opinions of various experts are individually quantified and a consensus is reached by a formal method.

To obtain a fair representation of public opinion, which might not be forthcoming from a panel of experts with vested interests, NRC could conduct public polls (Fig. 8, node 1.1.2.2). The structured methods for sampling public opinion are as follows:

1. Simple Questionnaire (Fig. 8, node 1.1.2.2.1) - A questionnaire addresses the issues, e.g., the importance of regulating the range of detrimental effects of a waste management depository rather than only the radiation effects (see Fig. 11). From the responses to the questionnaire, distributed according to standard random sampling techniques, NRC analysts construct the multi-attribute utility function. A simple questionnaire can be categorized on the basis of the kind of response it elicits:

Fig. 9. Categorization of the consequences of using nuclear materials.

(a) Open Questions (Fig. 8, node 1.1.2.2.1.1) - Respondents are asked general questions which elicit long answers expressing opinions. Decision-makers interpret these answers as a reflection of public opinion.

(b) Closed Questions (Fig. 8, node 1.1.2.2.1.2) - Respondents are

asked specific questions (generally multiple-choice) which they must answer. Decision-makers receive statistical breakdowns of the answers.

(c) Utility Curve (Fig. 8, node 1.1.2.2.1.3) - A small, representative sample of individuals is interviewed, and the total utility curve response of each person is elicited.

Fig. 10. Possible levels for regulation of radiation effects.

These curves are statistically combined (by averaging, for example) and used by the decision-makers.

2. Questionnaire with Modeling Exercise (Fig. 8, node 1.1.2.2.2) - To compensate for the public's lack of knowledge about the advantages and disadvantages of various approaches, a questionnaire can be supplemented with a computer model showing the consequences of different regulatory strategies. This would enable the respondent to intelligently apply his value structure to the varying regulatory strategies as he answered a closed, open, or utility-oriented questionnaire.

Implementing Decision Analysis

Decisions must be made at several echelons when decision analysis is used to generate acceptable risk criteria. Each echelon differs in the considerations and value sources that are appropriate; therefore, the decision analysis approach will be adapted to modeling and optimizing the different value sources for each echelon.

The sources we considered are the public, the Laboratory, and NRC.

NRC is the best source of values concerning organizational, regulatory, and legal constraints. NRC and the public are the value sources concerning implementability and understandability. Values concerning issues of decision theory have their source at LLL. The public is the best source of values concerning social cost and benefit. However, specifying the value source that should be considered in each echelon is a sensitive area, subject to revision. The decision echelons are listed in Table 2 in the order in which they must be resolved. Consequently, this table represents a functional outline of the development of an ARC.

To show explicitly the steps involved in the application of decision analysis techniques to the generation of ARC, we offer a sample scenario. For example, the following

Fig. 11. Detrimental effects of radiation.

decisions have resulted from the first three decision echelons listed in Table 2:

1. The ARC to be generated involve only radiological damage to human beings.

2. The damage results from the WM sector of the nuclear fuel cycle.

3. The damage is evaluated in terms of health effects.

The effectiveness of ARC can be judged by the impact of the WM system

resulting from those ARC. If the value modeling shows that the following two dimensions adequately capture the value-related aspects of the WM system impact:

$$HE_1(t) = \text{nonfatal cancers at time } t$$

$$HE_2(t) = \text{fatal cancers initiated at time } t,$$

then the impact of a WM system can be represented by an event-by-dimension

Table 2. Decision echelons in order of resolution.

Topic of decision	Considerations	Value source
<u>Scope of consequence:</u>		
Should ARC include only radiological risk to humans, or encompass total radiological cost, or extend to non-radiological environmental impact?	Legal and organizational constraints. Social costs.	NRC with technical assistance from LLL re: implications of alternatives.
<u>Scope of regulation:</u>		
Should full nuclear fuel cycle be considered in one analysis, or only waste management, or the narrow field of waste management site suitability?	Legal and organizational constraints.	NRC with technical assistance from LLL.
<u>Process level of evaluation:</u>		
Should impact of waste management system be evaluated in terms of system design, or local release, or ambient concentration, or doses, or health effects?	Decision theory with sensitivity to implementability and understandability.	LLL with NRC input re: implementability and understandability.
<u>Process level of regulation:</u>		
Should regulations be imposed on system design, or local release, or ambient concentration, or doses, or health effects?	Extent to which regulations imposed at each level constrain the results at the level of evaluation. Inefficiency resulting from imperfect prediction from one level to another vs implementability and understandability.	LLL with input from public and NRC re: implementability and understandability.
<u>Regulation format:</u>		
Should regulation be expressed as a limit on man-rems/megawatt-year electric (MR/MWY _e), or as a limit on the function	Empirical findings re: characteristics of social values.	Best feasible representation of public values.

$$C = \int_0^T e^{-rt} [k_1 u_1(HE_1(t)) + k_2 u_2(HE_2(t)) + \dots]$$

Table 2. (Continued)

Topic of decision	Considerations	Value source
where: r = time preference discount rate t = time k = importance weight u = component function HE = $it\frac{1}{2}$ type health effect or as a limit on some other function?		
<u>Regulation limit:</u>		
What limit should be set on each format?	Characteristics of social values, i.e., one-dimensional representations of social cost vs social benefit. ^a	Best feasible representation of public values.

^aIdeally, the regulation limit would be set at the value that maximizes the social preference function. However, given the difficulties in anticipating technical opportunities, it would be best to set the limit at the value that assures a positive net social benefit from any waste management system that meets the ARC.

matrix, as shown in Table 3. The set of events E_1 is mutually exclusive and exhaustive, describing all possible outcomes of the WM system. A probability $p(E_1)$ of occurrence is associated with each event.

The cell entries in this case are the number of health effects of type and time specified by column, given the outcome event specified by row. For example, if, in event E_1 , an undiscovered fissure exists between the repository and the nearest river, or some other event leads to an equivalent release, there will be

five fatal cancers initiated in the first time period, say one decade. Event E_{17} may represent normal release until a drill incursion in the 50th decade, etc.

Since all value sources we considered involve a panel, the first, and perhaps most difficult and crucial, step in the value modeling process is selecting that panel. After the panel has been selected and the survey questionnaires have been assembled in the recommended configuration, the decision analysis proceeds, independent of the particular

Table 3. Matrix showing impact of a WM system.

		$HE_1(t_1)$	$HE_2(t_1)$	$HE_1(t_2)$	$HE_2(t_2)$	...	$HE_2(t_M)$
E_1	$p(E_1)$	5	3	1	0	...	...
E_2	.	3	1	0	0	...	...
E_3	.	9	5	4	2	...	...
.	.	.	.	.	.	...	...
E_N	$p(E_N)$	.	.	.	.	...	...

value source involved. Although we explain a particular ARC-generating method, other methodologies would proceed essentially the same way.

Assume that NRC and LLL have decided to use the decision analysis methodology with an outside panel of public representatives, from whom social preference is elicited using the Delbecq approach applied to decomposed preference judgments. The panel is questioned regarding preference and opinions are freely expressed until a consensus is reached or the panel agrees that a consensus is not attainable. If there is no consensus, a Nash (or other multi-value) solution will be sought. The questions will follow a highly structured outline dictated by principles of decision theory.¹⁷ Questions that test preference assumptions are asked to determine the appropriate form of the multi-dimensional evaluation equation. Then questions are asked to elicit

tradeoff and risk attitudes in the form of parameters of the value junction. Tradeoff attitudes are elicited by such questions as:

Which do you prefer?

Select between $[10HE_1(t_1), 0 HE_2(t_1)]$

and $[0 HE_1(t_1), 7 HE_2(t_1)]$

and between $[10HE_1(t_1), 0 HE_1(t_2)]$

and $[0 HE_1(t_1), 12 HE_1(t_2)]$

Attitudes toward risk (uncertainty) and toward fluctuations between dimensions are elicited by such questions as:

Which do you prefer?

between 0

and 7 $HE_1(t_1)$

where the alternative on the left represents an uncertain situation, with each outcome having a 50% chance of occurring (exclusively).

Although the structure of the questions is very simple, the questions themselves are very difficult to answer. This form of preference elicitation reduces complex decisions involving multi-dimensional uncertain outcomes to basic, fundamental questions. Thus, the social value trade-offs can be addressed directly, without complex outcome matrices. This approach makes it possible for two interest groups that disagree on the best alternative to agree at this decomposed value level. The analysis will pinpoint the reason for disagreement, e.g., particular probabilities, particular tradeoffs, etc.

Decision analysis provides the formal basis for deciding what decomposed questions to pose, and how to aggregate the answers into an evaluation function of the general form:

$$\bar{U}(WMS_i) = \sum_j p(E_j | WMS_i) \cdot$$

$$U(x_{j1}, x_{j2}, x_{j3}, \dots, x_{jM})$$

where:

WMS_i = i th waste management system, resulting from i th ARC.

$p(E_j | WMS_i)$ = probability of i th event given i th WMS

x_{jk} = outcome on k th dimension in the j th event.

The function U reduces multi-dimensional outcomes to a single evaluation number. Summing $p(E_j | WMS_i) U$ over events generates an evaluation number for the entire event-by-dimension matrix to represent attitude toward risk. This form of modeling preference for uncertain outcomes, developed in the 1940's, is formally complete.¹⁸

The essence of decision analysis is to pose preference questions at such a decomposed level that answers to them can be assumed to represent actual preference. The answers are then used to develop an equation that can evaluate a complex outcome matrix, too complex for a person to evaluate intuitively. The techniques outlined here have been used successfully in applications ranging from the siting of a new airport for Mexico City to the design of high-voltage transmission lines.

If the panel fails to agree on answers to decomposed questions, separate utility functions for each group can be assessed, so that a group utility function is defined as a produce of the separate functions. This solution, called the Nash solution, has been shown to correspond in certain cases with other solutions to the multiple value problem, such as the general equilibrium solution in economics.

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APPENDIX A

MATHEMATICS OF RISK

This appendix is a set of notes on the mathematics of risk which illustrate heuristically how risk can be decomposed in space and time as a function of unplanned events, amount released, pathways, and exposed human beings.

RISK => Expected value of "loss function"

$$\Rightarrow \int CP(C)dC \Rightarrow \sum_1 C_1 P(C_1)$$

NOTE: The symbol ">" means "implies."

where

C = Magnitude of unplanned consequence

P(C) = Probability of C occurring

C₁ = Magnitude of 1th consequence

P(C₁) = Probability of 1th consequence.

NOTE: Expected value methods may need improvements to account for:

- "Preferred" value of low-consequence/high-probability event over that of a high-consequence/low-probability event
- Uncertainties in P(C₁).

A mathematical decomposition of P(C) follows:

[Consequence = Exposed Humans + Pathways + Amount Released + Unplanned Event]

NOTE: The symbol "+" means "follow from."

Let E_j = Unplanned events that yield C.

NOTE: P(C) = Function of x, y, z, and t (i.e., space and time).

Decomposing $P(C)$ with respect to t is given below:

$$P(C) = \sum_i P[C(t), E_i] \quad (\text{Using assumption 1 below})$$

$$= \sum_i \sum_{k=0}^{K=t/\Delta t} P[C(t), E_i, t_k] \quad (\text{Using assumption 2 below})$$

$$= \sum_i \sum_{k=0}^{K=t/\Delta t} P[C(t) | E_i, t_k] P[E_i, t_k] \quad (\text{Using assumption 3 below})$$

Assumption 1 - Independent E_i 's

Assumption 2 - E_j is independent in time

Assumption 3 - C and E_j are independent

- Let ρ = Release of radioactivity due to Event E_j utilizing a given control technology.

Then:

$$P[C(t) | E_j, t_k] = \int P[C(t) | E_j, t_k, \rho] \underbrace{P[\rho | E_j, t_k]}_{\substack{\text{Controllable} \\ \text{via technology}}} d\rho$$

- Let w_n = Pathways of possible release to biosphere.

Then:

$$P[C(t) | E_j, t_k, \rho] = \sum_{n=1}^N P[C(t) | E_j, t_k, \rho, w_n] \underbrace{P[w_n | E_j, t_k, \rho]}_{\substack{\text{Controllable} \\ \text{by geological} \\ \text{setting}}}$$

- Let n = The number of human beings at x, y, z location who are exposed to the dose of release ρ .

Then:

$$P[C(t) | E_j, t_k, \rho, w_n] = \int P[C(t, x, y, z) | E_j, t_k, \rho, w_n, n] \underbrace{P[h | E_j, t_k, \rho, w_n]}_{\substack{\text{Controllable for} \\ \text{small } t \text{ via soci-} \\ \text{etal institutions}}} dn$$

• Summary of math:

1. Combine all equations to get $P(C)$.
2. Multiply by $C =$ to obtain $CP(C)$.
3. Integrate to get $CP(C)dc$ - expected risk; or discretize over "i" and get

$$\sum_i c_i P(C_i).$$

Future work in this area should investigate sensitivity of results to assumptions noted.

APPENDIX B

HISTORICAL REVIEW OF RADIATION STANDARDS

This appendix gives a brief overview of radiation criteria used in the past. More detailed discussions of these criteria can be found in Refs. 1-5.

Since the late 1920's, the International Commission on Radiological Protection (ICRP), and the National Council on Radiation Protection and Measurements (NCRP) shared in the establishment of criteria for radiation exposure. Radiation protection had its foundation within the medical profession in the early part of the twentieth century. Both acute effects and serious late effects were directly observed when man was exposed to sufficiently large doses of radiation from x rays and natural radionuclides. The dose-response relationship was thus established as the cornerstone in radiation criteria development. It was clear that acute effects were observed only above some level of dose. On the other hand, serious late effects, such as malignancy, were more difficult to evaluate because they occurred with such low frequency that they were observed only after substantial exposure of large groups. Consequently, it has never been possible to demonstrate that a threshold dose exists for these late effects. Over a substantial range of doses, from about 50 rads to many hundreds of rads, the level of risk appears to be related to the level of exposure in a manner such that the risk increases with increase in exposure. This consideration, in addition to the adoption of the conservative hypothesis of a linear relationship between biological risks and the amount of dose even at the lowest dose levels, has determined the basic approach to radiation protection during the past 20 years.

During the past 35 years, the ICRP and NCRP have recommended many changes in the maximum permissible exposure levels. As indicated in Table B-1, each of these changes has resulted in a decrease in the occupational exposure values. Several years later, limits of dose to ionizing radiation were suggested for the population-at-large; but, as indicated in Table B-2, each succeeding new value in this case also represented a decrease in the previous value. The actual amount of decrease intended, however, is not clearly evident from the figures given in Table B-2. The standards shown in Tables B-1 and B-2 were taken from Morgan.³

The NCRP recommendation that the dose to the whole body of the maximally exposed individual in the population should be limited to 0.5 rem/yr was adopted by the Federal Radiation Council (FRC) in 1960. The FRC also suggested

Table B-1. Changes in the maximum permissible occupational exposure of the total body to ionizing radiation.

Recommended rate ^a	Comments
0.1 Erythema dose/yr ($\approx$ 0.5 R/wk for 100 kv x rays) and 1 R/wk for 200 kv x rays	Recommended by A. Mutscheller and R. M. Sievert in 1925
0.2 R/day (or 1 R/wk)	Recommended by ICRP in 1934 and continued in worldwide use until 1950
0.1 R/day (or 0.5 R/wk)	Recommended by MCRP on March 17, 1934 and continued in use in United States until 1949
0.3 rem/wk	Recommended by MCRP on March 7, 1949 and ICRP in July 1950 and continued in use until 1956
5 rem/yr ($\approx$ 0.1 rem/wk)	Recommended by ICRP in April 1956 and NCRP on January 8, 1957

^aValues given are in addition to doses from medical and background radiation.

NOTE: Values in parentheses are for a five-day work week.

Table B-2. Suggested limit of dose equivalent to the total body of population-at-large from man-made sources of ionizing radiation.

Total-body rate ^a	Comments
0.03 rem/wk	Suggested by NCRP September 1952 as maximum exposure to any organ
0.5 rem/yr	Suggested by NCRP on April 15, 1958 and by ICRP in July 1959 as maximum exposure to gonads (or total body)
5 rem/30 yr (or 0.003 rem/wk)	Suggested by ICRP on September 9, 1958 as average exposure to gonads (or total body)
0.1 rem/yr (or 0.002 rem/wk)	Suggested by Ad Hoc Committee on May 6, 1959 for consideration by the NCRP for average exposure to any body organ

^aValues given are in addition to doses from medical and background exposure.

as an arbitrary assumption, that the doses to individuals do not differ from the average to that population by more than a factor of three. According to the FRC: "It is critical that this guide be applied with reason and judgment. Especially, it is noted that the use of the average figure, as a substitute for evidence concerning the dose to individuals, is permissible only when there is a probability of appreciable homogeneity concerning the distribution of the dose within the population included in the average." This ratio is applied, for example (on page 11 of FRC Rept. No. 5), to the "critical segment" of the population receiving the highest dose for a given environmental contamination. On this basis, the average annual whole-body dose limit to the critical segment of the population is 0.17 rem. In its Rept. No. 2, the FRC also specified the annual average limits for the thyroid from iodine-131 as 0.5 rem (with the "critical segment" as children), and for the bone marrow from strontium-89 and strontium-90 as 0.5 rem (with the "critical segment" as any age group of the population).

The FRC also recommended an average dose limit to the gonads of the population of 5 rem in 30 years, which would amount to an annual dose limit of 0.17 rem.

Current practice emphasizes that the non-occupationally exposed individual receiving the maximum dose should not be exposed to more than 0.5 rem/yr. This is clearly specified by the regulations of the Nuclear Regulatory Commission (NRC), which requires that its licensees should operate so that no person outside the controlled area is exposed to more than 0.5 rem/yr.

More recently, the concept of cost-benefit has taken a major role in criteria development. The ICRP has recommended the following set of objectives for radiation dose limitation:

- a. To ensure compliance with the dose limits
- b. To avoid the use of unnecessary sources of exposure
- c. To provide for operational control of specific procedures, both individually and in combination, so that the resulting doses are as low as is reasonably achievable, economic and social considerations being taken into account
- d. To provide a more general framework to ensure that these doses are justifiable in terms of benefits that would not otherwise have been received.

Somewhat more specific guidance issued by the ICRP in Publication No. 9 follows:

- The risks associated with the dose limitations should be judged to be appropriately small in relation to the benefits resulting from the practice.
- The limitations must be set at a sufficiently low level so that any further reduction in risk would not be considered to justify the effort required to accomplish it.
- In the case of occupational exposure, the hazards should not exceed those that are accepted in most other industrial or scientific occupations with a high standard of safety.
- The risks to members of the public from man-made sources of radiation should be less than, or equal to, other risks regularly accepted in everyday life, and should be justifiable in terms of benefits that would not otherwise be received.

Combinations of criteria objectives are also recommended in the recent EPA criteria guidelines for the nuclear fuel cycle.⁶ These objectives are:

1. To limit dose per effluent stream of each type of facility;
2. To limit the combined doses of all components of the fuel cycle required to support production of given quantity of electricity;
3. To limit the integrated dose over public of entire industry over X years (committed dose) per unit of electrical energy output.

It is evident that such combinations of criteria objectives are needed to restrict adequately the radiation risk expected.

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APPENDIX C

SURVEY OF RADIATION SAFETY PROFESSIONALS ON ACCEPTABLE RISK CRITERIA FOR NUCLEAR WASTE MANAGEMENT

To obtain a preliminary estimate of quantitative risk levels that might be considered acceptable for waste management operations, a cursory survey of radiation safety professionals was conducted. The form used for the survey appears as Fig. C-1. Most survey respondents, selected on the basis of their familiarity with the biological effects of exposure to ionizing radiation, were members of various University of California staffs (Lawrence Livermore Laboratory, Lawrence Berkeley Laboratory, Los Alamos Scientific Laboratory, University of California at Berkeley, and Lawrence Livermore Laboratory - Nevada) whose jobs involved them directly or indirectly with radiation safety.

One hundred survey forms were completed and returned. Responses were tallied, and the totals are shown in % in italics in Fig. C-1. These data are presented graphically in Figs. C-2 and C-3. The survey results indicate that the respondents tend to equate "acceptable" levels with "innocuous" levels of exposure. For WM operations, the innocuous/acceptable levels range between 1-100 mrem/yr. The geometric mean value is approximately 10 mrem/yr.

A reasonable cost-effectiveness guideline for WM operations was about one dollar per man-mrem averted (or \$1000/man-rem), which is roughly the same as that suggested in App. I - 10 CFR 50 for light-water reactor effluents.

Those who believed they might have given "better" answers if they had more information, gave a range of responses to the questions; however, some common themes were discernible:

- Innocuous/acceptable levels might be determined better if cost data for further dose reduction were available.
- Cost effectiveness guidelines (\$/man-mrem) might be determined better if accurate information about public attitudes were known.

The survey results may prove useful in providing perspective on acceptable risk. It must be stressed, however, that the survey questions were very cursory; the results, therefore, should be interpreted broadly.

LLL WASTE MANAGEMENT STUDY SURVEY

Your assistance is requested in a project to develop acceptable risk criteria for radioactive waste management. Please complete this survey form based upon your knowledge, experience and judgment, and personal values.

Name (Optional)	Occupation	Organization
-----------------	------------	--------------

Which of the following best describes your level of understanding of the biological effects of ionizing radiation:

No response - 5

☐ good understanding <i>??</i>	☐ some understanding <i>18</i>	☐ no understanding
--	--	---

To assist you in answering the questions below, the following information is offered for purposes of perspective:

Annual Dose
(millirems)

Maximum allowable occupational dose	5000
Maximum allowable public dose	500
Typical natural background dose	100
Typical variation in background dose for a given individual (i.e., background = 100 ± 20)	20

Assume you are a prudent and conscientious regulator responsible for minimizing the public exposure to radiation. Also assume a substantial number of people (>one million) will be exposed. Keep in mind, however, that any nuclear waste management operation will involve some increased risk of radiation exposure. Finally, the objective of keeping exposures "as low as reasonably achievable" requires a consideration of social and economic factors. Proposed federal regulations (App. I - 10CFR 50) suggest a level of \$1.00 per millirem per person is a reasonable cost for reducing potential radiation exposure due to nuclear power plant effluents.

- 1) What average level of increased public exposure due to waste management operations most closely approximates what you would consider to be innocuous (i.e., the level below which you believe no further effort toward further reduction would be warranted)?

	<u>Annual Dose</u> <u>(millirems)</u>		<u>Annual Dose</u> <u>(millirems)</u>
More than 1000	☐ 1	0.1	☐ 6
1000	☐ 2	0.01	☐
100	☐ 23	0.001	☐ 3
10	☐ 40	0.0001	☐ 1
1	☐ 24	Less than 0.0001	☐
		<i>No response</i>	<i>1</i>

Fig. C-1. Survey form. (Page 1 of 2)

Could you have answered this question better if you had more information? ☐ yes ☐ no If yes, what kind of information?

41 50 Blank - 9

- 2) What average level of increased public exposure must closely approximate what you would consider to be "acceptable"?

	Annual Dose (millirems)			Annual Dose (millirems)	
More than 1000	☐	2	0.1	☐	4
1000	☐	4	0.01	☐	2
100	☐	30	0.001	☐	
10	☐	37	0.0001	☐	1
1	☐	17	Less than 0.0001	☐	
			No response		3

Could you have answered this question better if you had more information? ☐ yes ☐ no What kind of information?

35 51 Blank - 14

- 3) What would you consider a reasonable cost for controlling potential radiation exposure resulting from nuclear waste management operations?

Reasonable cost per millirem per person for reduction in exposure:

More than \$1000	☐		\$ 0.10	☐	22
\$1000	☐	1	\$ 0.01	☐	8
\$ 100	☐	4	\$ 0.001	☐	
\$ 10	☐	11	\$ 0.0001	☐	
\$ 1	☐	41	Less than \$0.0001	☐	1
			No response		13

Could you have answered this question better if you had more information? ☐ yes ☐ no What kind of information?

56 36 Blank - 8

- 4) For waste management operations (and others in the LWR fuel cycle), would it be reasonable to relate risk acceptability criteria to the amount of electrical power produced (e.g., man-rem/MWe-yr)?

☐ yes ☐ no ☐ don't know

59 28 13

Question: What average level of increased public exposure due to nuclear WM would you consider to be innocuous? ☐ acceptable? ☒

Fig. C-2. Responses related to acceptable risk question.

Question: What would you consider a reasonable cost for reducing radiation exposure from nuclear WM?

Fig. C-3. Responses related to cost question.

APPENDIX D

SELECTION OF A PREFERRED METHODOLOGY

INTRODUCTION

This appendix describes the selection process by which a panel produced a list of methods to generate candidate ARC. The list of possible ARC-generating methods was developed in several stages:

1. A structured-panel voting procedure was used to select the technique for choosing among ARC-generating method categories. The technique selected was a version of multiple-attribute decision analysis (MADA).
2. The MADA technique was used to choose the most appropriate ARC-generating method category. The category chosen was decision analysis.
3. A complete list of ARC-generating methods in the decision analysis category was developed.

Figure D-1 illustrates the integration of these three stages.

The panel that worked on this problem consisted of:

J. Cohen	Lawrence Livermore Laboratory
A. Toy	Lawrence Livermore Laboratory
D. Denham	Lawrence Livermore Laboratory
T. Holdsworth	Lawrence Livermore Laboratory
R. Schainker	Systems Control, Inc.
P. Grimsrud	Systems Control, Inc.
D. Budenaers	Systems Control, Inc.

Fig. D-1. Procedures for selecting a method of generating ARC.

SELECTION OF A TECHNIQUE FOR CHOOSING AMONG CATEGORIES OF METHODS TO GENERATE ARC

This section presents, in a self contained way, the evaluation procedure by which a technique was selected to evaluate categories of methods for generating ARC. The objective of the technique is to organize and systematize the several alternative categories of methods that could be used to establish ARC. The attributes and characteristics of potential techniques are listed; then candidate techniques are listed. The panel of experts assesses and notes on whether the techniques achieve the desired attributes. In a sense, this procedure is a very informal application of MADA.

The following techniques were considered potentially applicable to the ARC problem:

1. Multi-attribute decision analysis (MADA)
2. Dictate
3. Expert panel (unstructured)
4. Expert panel (Delphi)
5. Public poll
6. Classical decision analysis
7. Bayesian analysis
8. n-value logic

Each of these techniques was evaluated by the panel in terms of the following characteristics:

1. Understandable to NRC
2. Logical
3. Reproducible
4. Able to accommodate many viewpoints
5. Able to illuminate sensitivities
6. Defensible
7. Applicable to nuclear WM problem.

ABSTRACTS OF TECHNIQUES CONSIDERED

Multi-Attribute Decision Analysis

MADA provides a systematic way of merging divergent views into a final, preferred decision. Suppose that several alternatives are to be assessed with

respect to a set of attributes which describe an accepted objective. Further suppose, an alternative with maximum expected worth must be selected. Then the MADA procedure would be as follows. First, the attributes and alternatives are organized in a matrix as shown in Table D-1. Then the best alternative is selected as follows:

Let W_i^* = expected worth of alternative a_i in meeting all specified attributes

then

$$W_i^* = \sum_{j=1} (P_{ij} W_j)$$

The optimum alternative is the alternative with maximum expected worth. That is:

A^* = optimum alternative

$A^* = A_i$, where W_i^* is maximum

It should be noted that this method is not the formally complete multiple-attribute utility analysis of the Keeney-Raiffa school that forms the basis for the ARC-generating method recommended in the body of this report.

Table D-1. Alternatives and attributes.

Importance weights	W_1	W_2	W_3
Attributes	O_1	O_2	O_3
Alternatives			
A_1	P_{11}	P_{12}	P_{13}
A_2	P_{21}	P_{22}	P_{23}

where:

O_1, O_2, O_3 = attributes of an objective; e.g., defensible, understandable

A_1, A_2, A_3 = alternatives; e.g., expert panel, polling, MADA

W_1, W_2, W_3 = importance weights of attributes

P_{ij} = change of attribute j being realized by alternative i

Dictate

Dictate refers to a decision handed down to the public by a single person without consulting outside groups. The dictated decision may be derived through analysis and private consultation, but the decision-maker is solely responsible for it. A dictate is operable in countries with dictatorship type governments, but is probably inoperable in the United States, particularly in the case of nuclear WM.

Unstructured Expert Panel

An unstructured expert panel is a group of highly qualified people who recommend a decision based upon some unstructured set of contributions. These people should be (but are not always) representative of all opposing public views. Their individual recommendations, therefore, are often conflicting. The final recommendation is usually subject to arbitrary choice based on:

- Who speaks loudest (or most effectively).
- Who speaks last.
- How voting is conducted.
- Who interprets the results.

Delphi Method

The Delphi method provides a structured means of obtaining and interpreting recommendations from an expert panel. The procedure is characterized by three features that distinguish it from the usual methods of group interaction: (a) anonymity, (b) iteration with controlled feedback, and (c) statistical group response.

1. Anonymity - During a Delphi sequence, the group members are not known to each other. In addition, the interaction of the group members is handled in a completely anonymous manner through the use of questionnaires. This avoids the possibility that a specific opinion will be identified with a particular person. As a result, the originator of an opinion can change his mind without publicly admitting that he has done so, and thereby possibly losing face. It also means that an idea can be considered on its merits, without regard to whether the originator is held in high or low esteem by individual members of the group.

2. Iteration with Controlled Feedback - The group interacts on responses to questionnaires and the individual or agency responsible for the questioning extracts from the questionnaires only those pieces of information that are relevant to the issue and presents these to the group. The individual serving as a decision-maker thus is informed only of the current status of the collective opinion of the group, and the arguments for and against each point of view. He is not subjected to a harangue or an endless restatement of the same arguments. Both majority and minority views are presented to the group, but in such a way that they do not overwhelm the opposition merely by weight of repetition. The primary effect of this controlled feedback is to prevent the group from taking on its own goals without being distracted by self-chosen goals such as winning an argument or reaching agreement for the sake of agreement.
3. Statistical Group Response - Typically, a group will produce a decision that contains only a majority viewpoint. It will represent simply that on which a majority of the group were able to agree. There may, at most, be a minority report if the remainder of the group feels strongly about the issue. However, any indication of the degree of difference of opinion that may have existed within the group is unlikely. Instead, the Delphi procedure presents a statistical response, which includes the opinions of the entire group. On a single question, for instance, the group response may be presented in terms of a median and the two quartiles; i.e., a number such that half the group were above it, and half below; and the two numbers that separate the inner half of the group from the outer quarters. In this way, each opinion within the group is taken into account in the median, and the spread of opinion is shown by the size of the interquartile range.

Public Polls

The polling method uses statistics to conduct a sample survey to assess public opinion. The criterion for polling is that the response be representative. This criterion is achieved by a combination of sequential random sampling of the population and a sampling of only previously identified leading opinion groups. Polling can be a very accurate way of determining public

opinion. In general, statistical confidence can be ascribed to the result of any poll.

Classical Decision Theory

The classical decision theory model portrays the decision-maker as making a choice from among a set of alternatives, $A = [a, a, \dots a]$, given: (1) a set of states of nature $S = [s, s, \dots s]$, over which there is no control, but for which the probabilities of occurrence $P = [p, p, \dots p]$ are known; and (2) a payoff in terms of costs or benefits, v , associated with each alternative state-of-nature pair. Once these elements are specified, the preferred alternative may be determined by computing the expected value, $E(V)$, of each alternative, where:

$$E(V_i) = \sum_{j=1}^n (V_{ij} P_j)$$

and selecting the alternative with the highest expected value

$$E(V^*) = \max_i (E(V_i)) .$$

Bayesian Analysis

Bayesian analysis is used in conjunction with classical decision analysis to update the probabilities of occurrence of the states using Bayes' rule. That is, new empirical information can be folded in the decision matrix to update the process to select the best alternative. Under certain conditions, Bayesian analysis is equivalent to the classical minimax decision procedures.

n-Value Logic

The application of n-value logic provides a method to deal with multiple alternative decision problems under uncertainty. It is assumed that all the alternatives in the choice set can be characterized by a number of aspects, and that information is available to assign weights to these aspects and to construct a rating scheme for the various aspects of each alternative. The method consists of:

1. Computing weighted final ratings for each alternative
2. Comparing the weighted final ratings

3. Accounting for uncertainty in the assessment of the ratings using n-value logic (e.g., three-value logic might have a black level, gray level, and white level for each attribute)
4. The final evaluation consists of the degree of membership in an n-value set of alternatives ranking first

RESULTS OF VOTE ON ALTERNATIVE APPROACHES TO THE DEVELOPMENT OF ARC

Table D-2 summarizes the results of the vote on alternative approaches conducted by the panel. To compare and select the best approach, they assigned a weight to ability of each approach to achieve the desired attribute. Thus, the largest score that could be entered was seven, since seven people participated in the voting process. The alternatives were then compared by means adding the votes for each. This method of ranking alternatives is a simple and logical way of comparing alternatives and summarizing the voting procedures.

From Table D-2, it is clear that multi-attribute decision analysis ranked highest, with n-value logic and the Delphi technique ranking next highest. On the other hand, dictate and expert panel rank lowest. The other decision theoretic methods tend to rank in the middle, along with polling.

Table D-2. Results of vote on alternative approaches.

Alternative approach	Characteristic Under-standable 1	Logical 2	Repro-ducible 3	Accommodates many views 4	Sensi- tivity 5	Defen- sible 6	Appli- cable 7	Total
Multiple-attribute decision analysis	6	7	6	7	7	7	7	47
Dictate	7	0	0	0	0	1	2	10
Delphi	5	4	6	7	3	7	7	40
Expert panel	2	0	0	7	0	3	4	16
Poll	5	0	4	7	4	6	6	32
Classical decision analysis	7	7	6	0	0	5	6	31
Bayesian	1	7	4	7	5	2	4	30
n-value logic	1	7	6	7	7	4	7	39