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FINAL REPORT ON THE
CLASSIFICATION OF
RADIOACTIVE WASTES

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University of California
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TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1.0 Introduction.....	1
1.1 Purpose of the Program.....	1
1.2 Conduct of the Effort.....	1
1.3 Classification Objectives.....	2
2.0 Radioactive Waste Forms and Volumes.....	5
3.0 Review of Radioactive Waste Classification Systems.....	11
3.1 Introduction.....	11
3.2 IAEA Categories.....	12
3.3 American Standards Institute-AIChE Radioactive Waste Categories.....	14
3.4 Ferruccio Gera's 1968 and 1973 Waste Classification Systems.....	21
3.5 American National Standards Institute Categories of Radioactive Waste (ANSI-N525)...	28
3.6 AEC Manual, Radioactive Waste Management Classifications.....	31
3.7 J. O. Blomeke and C. W. Kee Definitions of Waste Types.....	35
3.8 Summary of Established Content of Proposed Waste Classification Systems.....	38
4.0 Radioactive Waste Classification Systems Proposed by TAP Members.....	40
4.1 Proposed Waste Classification System - 1.....	40
4.2 Proposed Waste Classification System - 2.....	45

TABLE OF CONTENTS (continued)

<u>Section</u>	<u>Page</u>
4.3 Proposed Waste Classification System - 3.....	54
4.4 Proposed Waste Classification System - 4.....	55
4.5 Proposed Waste Classification System - 5.....	57
5.0 Discussion.....	59
5.1 Introduction.....	59
5.2 System-I, Classification System Based on Waste Characteristics.....	60
5.3 System-II Classification System Based on Characteristics of Disposal Means.....	65
6.0 Concerns and Opinions Expressed by Members of the Technical Advisory Panel.....	78
7.0 Summary and Recommendations.....	81
References.....	83
Appendix A - Technical Advisory Panel Members and Participants.....	A-1
Appendix B - Part 173.389 of Title 49, Code of Federal Regulations.....	B-1
Appendix C - Paper by Dr. W. A. Rodger.....	C-1

LIST OF FIGURES

<u>Figures</u>	<u>Page</u>
2.1 Fuel Cycle Wastes from Generation of 1000 MW-years of Electricity by LWRs Using Mixed U-Pu Oxide Fuels	7
2.2 Process Operations and Wastes in the LWR Fuel Cycle.....	8
2.3 Post-Fission Wastes Expected from the LWR Fuel Cycle.....	9
3.1 International Atomic Energy Agency Waste Classification System.....	15
3.2 American Standards Institute - AIChE Waste Classification System.....	20
3.3 Gera's Classification System Based on Duration of Containment	22
3.4 Branca-Gera 1968 Waste Classification System....	25
3.5 American National Standards Institute Waste Categories.....	32
3.6 AEC Waste Classification System.....	36
4.1 Waste Classification System - 1.....	42
4.2 Waste Classification System - 2.....	53
4.3 Waste Classification System - 3.....	54
4.4 Waste Classification System - 4.....	56
4.5 Waste Classification System - 5.....	58
5.1 System I - Radioactive Waste Classification.....	64
5.2 System II - Radioactive Waste Classificaon.....	69
5.3 Considerations in Determining Disposal.....	70

LIST OF FIGURES (Continued)

<u>Figures</u>	<u>Page</u>
Appendix C	
1 Hazard Index of Reprocessing Wastes.....	C-16
2 Hazard Index of Spent Fuel Elements.....	C-17
3 Comparison of Hazard Indices of Reprocessing Waste and Spent Fuel Elements.....	C-18
4 Hazard Index of Leached Hulls.....	C-19

LIST OF TABLES

<u>Tables</u>	<u>Page</u>
3.1 American Standards Institute - AICHE Radioactive Waste Categorization.....	17
3.2 Categories of Liquid and Gaseous Wastes Proposed by Branca and Gera (1968).....	23
3.3 Categories of Solid Wastes According to Activity Concentration and Half-Life Proposed by Branca and Gera (1968).....	24
3.4 Categories of Solid Wastes According to Radiation Index Proposed by Branca and Gera (1968).....	24
4.1 Waste Classification Categories.....	48
4.2 Waste Classification Subcategories.....	50
4.3 Waste Classification.....	51
 Appendix C	
1 Hazard Index of Wastes from Reprocessing.....	C-20
2 Hazard Index of Spent Fuel Elements Treated as Waste.....	C-23
3 Hazard Index of Hulls.....	C-26
4 Maximum Concentrations Expected from On-Site Hull Burial.....	C-29

1.0 INTRODUCTION

1.1 Purpose of the Program

The Nuclear Regulatory Commission has been charged with the responsibility of preparing regulations dealing with the handling, processing, packaging, storing, and disposal of waste containing radioactive materials. In order to provide a foundation for these regulations, a working radioactive waste classification system must be formulated. The purpose of such a system would be to define specific waste categories to allow for a commonly understood basis for managing nuclear waste between various nuclear facilities, particularly those producing and those disposing of the waste. The system should also be based on good management practices for nuclear waste considering public health, operational efficiency, and economics.

This document outlines most of the various radioactive waste classification systems found in the literature and details several other classification systems proposed during the study effort. While possible waste management criteria and associated numerical values are suggested in this document, no attempt is made in this report to formalize or even recommend regulatory quantitative waste management criteria.

1.2 Conduct of the Effort

A Technical Advisory Panel (TAP) was established. This panel represented a broad spectrum of expertise and experience drawn from various governmental organizations, national laboratories, private consultants, and industrial interests. A tabulation of the panel members and invited guests can be found in Appendix A.

A working document was prepared and distributed to TAP members. This document summarized existing waste classification systems, outlined a new system, and provided a bibliography of reference material. The first meeting of the Technical Advisory Panel was held on August 18 and 19, during which time the document was reviewed.

Based on the results of the first TAP meeting and comments from various TAP members, a second working document was prepared. This second document presented five new classification systems, all of which were formulated by TAP members. The second meeting of TAP was held on September 22 and 23. Specific recommendations and technical concerns were solicited in response to the proposed classification systems. The results of these meetings are presented by this final report.

1.3 Classification Objectives

All past and presently formulated radioactive waste classification systems may fall into one of three categories. These are based on: (a) the source of the waste, (b) physical characteristics of the waste, or (c) the nature of the isolation systems used to ultimately contain the various waste materials. Factors used as a basis for waste classification might include the following:

1. The toxicity and/or hazard of the waste
2. The total quantity of waste (in curies)
3. The longevity of waste as expressed in its half-life
4. Potential biological concentration mechanisms for various types of radioactivity
5. A consideration of whether the waste was naturally occurring or of manmade origin
6. Heat production

7. Does the waste have potential value?
8. Its physical state (solid, liquid, gas).
9. Is the entire material to be considered waste or is the waste a form of contamination of some other valuable material?
10. Type of radioactivity (α , β , γ , neutrons, etc.).

In considering all of these factors the Technical Advisory Panel had certain objectives and ground rules for its operation. These included:

- An optimal waste classification would provide for categoric segregation of nuclear waste such that each category of waste can be managed to assure public protection without undue economic penalty.
- The waste classification system should not be so operationally complicated as to discourage its effective application.
- A "perfect" classification system is unattainable. The "optimal" system must be largely based upon technical judgment. There will likely be objections to any system which is developed.
- Development of a waste classification system should be determined primarily by technical considerations primarily involving protection of public health and safety. Economics should be a secondary factor. Political and public opinion aspects may be considered after technical issues are resolved.
- Nuclear waste will be assumed to have no economic value itself; therefore, future recovery will not be considered to be a viable possibility.

- It is important that one reasonably acceptable waste classification system be developed and regulations accordingly promulgated at the earliest possible time. This would be helpful to industry in planning and eliminating confusion. Almost any viable and generally accepted system could be considered superior to having no system at all.

2.0 RADIOACTIVE WASTE FORMS AND VOLUMES

The radioactive waste types and volumes generated by fuel cycle activities depend on the fuel cycle and the number of reactors being serviced. Assuming recycle of both uranium and plutonium, the generation of the following types of radioactive wastes can be expected:

Reactor Wastes -

- Filters
- Adsorbents
- Resins
- General trash
- Aqueous slurries
- Failed hardware
- Failed equipment

Reprocessing Wastes -

- Solidified high-level waste
- Solidified intermediate-level waste
- Spent fuel cladding
- Reactor and fuel hardware
- Large failed process equipment
- General trash
- Ventilation filters

Plutonium Oxide Conversion Wastes -

- Solidified liquid waste
- Resins
- General trash
- Failed equipment
- Ventilation filters

Mixed-Oxide Fuel Fabrication Wastes -

- Solidified liquid waste
- Resins
- General trash
- Failed equipment
- Ventilation filters

Decontamination and decommissioning wastes will also be generated from all of the above facilities. In addition future waste forms may include noble-gas fission products, fission product iodine and carbon-14. There are also various hospital and clinical radioactive wastes.

Three projections of the volume of radioactive waste generated by the backend of the fuel cycle are shown in Figures 2.1, 2.2, and 2.3. The first projection, Figure 2.1, was prepared by J. O. Blomeke and C. W. Kee for a paper entitled "Projections of Wastes to be Generated" dated July 1976. The second projection, Figure 2.2, is from ERDA-76-43, Volume I, Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle. The third set of projections is the most recent. These projections were prepared by LaVerne Trevorrow of Argonne National Laboratory, October 12, 1976.

Fuel cycle wastes from generation of 1000 MW-years
of electricity by LWRs using mixed (U-Pu) oxide fuels

	Volume (m ³)	Activity (MCi)	Mass of Actinides (tons)	Thermal Power (kW)
High-level solidified	3.0	81.5	0.25	450
Cladding hulls	2.6	0.8	0.017	3.3
Noble gases	1.0	0.24	—	0.36
Iodine	0.049	1.25×10^{-6}	—	7.5×10^{-7}
LWR tritium (water)	140	7.4×10^{-4}	—	2.3×10^{-5}
F.P. tritium (solidified)	0.34	0.019	—	0.00062
Carbon-14	—	1.66×10^{-5}	—	—
Low-level TRU	46	0.047	0.004	0.04
Intermediate-level TRU	13.4	0.011	0.00012	0.054
Nontransuranium	600	0.002	—	0.0065

*Assumes approximately one-year aged waste.

FIGURE 2.1

FIGURE 2.2 Process Operations and Wastes in the LWR Fuel Cycle

POST-FISSION WASTES EXPECTED FROM THE LWR FUEL CYCLE

(All Quantities per GWe-yr)

<u>WASTE FORM</u>	<u>VOLUME^a (m³, except as noted)^b</u>	<u>RADIOACTIVITY (Ci)^b</u>
<u>Reactor Wastes</u>		
Slurries	2E2	2E1 ^c
Sludges	3E1	3E1 ^c
Resins	6E1	4E3 ^c
NEPA filters	5E0	1E1 ^c
Charcoal	2E0	1E0 ^c
Trash	2E2	5E0 ^c
Failed equipment	6E0	2E5 ^c
Water filters	4E0	3E2 ^c
<u>Mixed Oxide Fuel Fabrication Wastes</u>		
Combustible solids	6E1	9E2
Noncombustible solids	1E1	2E2
Liquids, slurries	2E0	3E2
NEPA filters	4E0	3E2

^a Volumes(except for high-level fuel reprocessing wastes) represent those of primary waste forms, before volume-reducing treatments.

^b 1E1 to be read as 1×10^1 ; 1E-1 to be read as 1×10^{-1} .

^c Radioactivities of reactor wastes assumed to be based on surveys at shipping time, probably at about 6 months after removal from reactor.

Figure 2.3

POST-FISSION WASTES EXPECTED FROM THE LWR FUEL CYCLE (CONT'D)

(All Quantities per GWe-yr)

Fuel Reprocessing Wastes

WASTE FORM	VOLUME	RADIOACTIVITY		THERMAL POWER (kW)
	(m ³ , except as noted)	(Ci)	(Neutrons/Sec)	
Mulls	1E1	3E5 ^d	6E7 ^d	2E0 ^d
High-level solid	4E0	1E7 ^e	1E11 ^e	6E1 ^e
Low-level liquid	1E6	2E4 ^f		
Gases				
Krypton	3E0 ^g	3E5		
Xenon	3E1 ^g	6E-4		
Iodine	9E3 grams	1E0		
Carbon-14	4E0 grams	2E1		
Tritium	2E0 grams	2E4		
Non-high-level solids				
Combustible TRU	5E1			
Combustible nonTRU	3E1			
Noncombustible TRU	5E1			
Noncombustible nonTRU	1E2			
Slurries, sludges, resins TRU	5E-1			
Slurries, sludges, resins nonTRU	5E0			
Filters TRU	7E0			
Filters nonTRU	5E-1			

^d Based on 5-yr cooling after discharge.

^e Based on 10-yr cooling after discharge.

^f Based on assumption that 70% of tritium in spent fuel will appear in low-level aqueous waste.

^g Gaseous volume at STP.

Figure 2.3 (Continued)

3.0 REVIEW OF RADIOACTIVE WASTE CLASSIFICATION SYSTEMS

3.1 Introduction

During the past few years, there have been several radioactive waste classification systems proposed. These systems include:

- 1) Standardization of Radioactive Waste Categories, Published by the International Atomic Energy Agency, November 1967.
- 2) Proposed Definition of Radioactive Waste Categories, Published by the American Institute of Chemical Engineers, 1967. (Since withdrawn)
- 3) "The Classification of Radioactive Wastes", Ferruccio Gera, Health Physics, Pergamon Press, 1974, Vol. 27.
- 4) "Categories of Radioactive Waste: ANSI-N525", American National Standards Institute. (Draft)
- 5) Part I, AEC Manual, Chapter 0511, "Radioactive Waste Management", Appendix 0511, U.S. Atomic Energy Commission, Approved 19 September 1973. (Now an ERDA Manual Chapter)
- 6) "Projections of Wastes to be Generated", J. O. Blomeke and C. W. Kee, International Symposium on the Management of Wastes from the LWR Fuel Cycle, July 11-16, 1976.

A review of these systems follows.

3.2 IAEA Categories

The November 1967 IAEA technical report tabulated the information submitted by eleven countries concerning their systems of radioactive waste classification.¹ The findings were that no two countries have the same classification system and even within some countries the systems were different.

The IAEA classifications first categorized the waste as liquid, solids or gaseous.

Liquid Wastes

The sub-classification under liquid wastes was based on activity concentration levels as follows:

<u>Category</u>	<u>Activity level (A)</u>	<u>Remarks</u>
1	$A < 10^{-6} \mu\text{Ci/ml}$	not normally treated
2	$10^{-6} < A < 10^{-3} \mu\text{Ci/ml}$	w/o shielding*
3	$10^{-3} < A < 10^{-1} \mu\text{Ci/ml}$	shielding possible*
4	$10^{-1} < A < 10^4 \mu\text{Ci/ml}$	shielding necessary*
5	$10^4 < A \mu\text{Ci/ml}$	cooling necessary

*Treatment by usual methods i.e., evaporation, ion-exchange or chemical treatment.

Solid Wastes

Three considerations are present in the classification of solid waste per the IAEA system. These are:

- 1) For strong beta and gamma emitters the surface dose rate is controlling.
- 2) For strong alpha emitters the activity per volume (Ci/m^3) controls.

- 3) For large amounts of fissile materials, additional packing requirements control, such as IAEA "Regulations for the Safe Transport of Radioactive Materials."

For the three considerations, the following classification is suggested:

Category	Radiation dose (D) on Surface of Wastes (R/hr)	Remarks
1	$D \leq 0.2$	$\left\{ \begin{array}{l} \beta\text{-}\gamma\text{-emitters, dominant;} \\ \alpha\text{-emitters are in-} \\ \text{significant.} \end{array} \right.$
2	$0.2 < D \leq 2$	
3	$2 < D$	
4	α activity expressed in Ci/m^3	$\left\{ \begin{array}{l} \alpha\text{-emitters dominant;} \\ \beta\text{-}\gamma\text{-emitters in-} \\ \text{significant, criticality} \\ \text{is non-problem.*} \end{array} \right.$

* "Criticality is a non-problem" means that: if criticality is a concern with the waste, then it is assumed that the solid wastes are treated and/or packaged to prevent criticality; also it is suggested that Pu and U wastes are potentially retrievable and may be separated for economic reasons.

Gaseous Wastes

The basic consideration for classification of gaseous wastes is activity level as expressed in Ci/m^3 .

Category	Activity ₃ level (A) (Ci/m^3)	Remarks
1	$A \leq 10^{-10}$	Effluents not usually treated
2	$10^{-10} < A \leq 10^{-6}$	Effluents usually treated by filtration
3	$10^{-6} < A$	Effluents usually treated by methods other than filtration

Discussion

Figure 3.1 is a schematic of the IAEA waste classification system. The following waste characteristics must be known to use this system to categorize any given waste:

- Physical state (solid, liquid, gaseous)
- Activity level for α -dominant solids, for liquids and gases
- Radiation dose at the surface for β - γ -dominant solids
- Radiation type, indirectly for solids.

In addition the following factors may be noted:

- The system is relatively uncomplicated.
- Difficult to assess for mixtures of nuclides of different types of radioactivity
- Expression of radioactivity in curies gives little indication of toxicity or hazard potential
- Categories give no direction as to disposal method
- Does not consider half-life or longevity of potential hazard.

3.3 American Standards Institute - AIChE Radioactive Waste Categories

This waste classification system was formulated under the sponsorship of the American Institute of Chemical Engineers and was approved in June 1967.⁴

The premises on which this classification system is based are as follows:

- (a) The major parameter for categorization is the "ratio of radionuclide concentration in the waste (at the time of consideration) to the MPC of the same waste constituents in water, air or

Figure 3.1 International Atomic Energy Agency Waste Classification System

solids" in terms of MPC, MPE (exposure) or MPQI (quarterly intake) as recommended by the International Commission on Radiation Protection (ICRP).

- (b) Categorization should be done as wastes exist in containment or prior to release. Decay during storage may result in reclassification of wastes.
- (c) Individual radionuclide concentrations must be determined for exact categories.
- (d) Liquids and gases are treated as fluids; solids require further considerations.
- (e) The smaller ICRP-MPC value should be used when MPC's are specified for different solubilities.
- (f) Primary categorization parameters do not include: chemical content, physical properties, origin, total amounts of waste, $T_{1/2}$, degree of natural reconcentration once released.
- (g) Definitions proposed are intended for use as descriptive information of the characteristics of wastes, in judgments involving treatment, disposal, regulatory action, definitions of safety.

The waste classification system is summarized by Table 3.1. The use of this table requires the following information:

- (a) Where wastes contain mixtures of radionuclides, the radionuclide concentration to MPC (or etc.) ratio is determined by using the MPC for known mixtures or unidentified mixtures of radionuclides as recommended by ICRP.

American Standards Institute - AICHE

Table 3.1 Radioactive Waste Categorization
(Not Intended for Regulatory Use)

Class A (population level)	
Liquid and gas	$\leq$ maximum permissible concentration (MPC)* for members of the population at large (including persons living in the neighborhood of controlled areas)
Solid	$\leq$ maximum permissible quarterly intake (MPQI) for members of the population at large (including persons living in the neighborhood of controlled areas)/kg. solid
Surface radiation†	$\leq$ maximum permissible whole body dose rate (MPE)* for members of the population at large† (including persons living in the neighborhood of controlled areas)
Class B (occupational level)	
Liquid and gas	> Class A but $\leq$ (MPC)* occupational exposure (40-hr. wk)
Solid	> Class A but $\leq$ (MPQI)** for occupational exposure/kg. solid
Surface radiation†	> Class A but $\leq$ (MPE)† for occupational exposure† (40-hr. wk)
Class C (low level)	
Liquid and gas	> Class B but $\leq 10^4 \times$ Class B
Solid	> Class B but $\leq 10^4 \times$ Class B
Surface radiation	
Class C-1	$\leq$ (MPE)† (occupational) at surface†
Class C-2	> (MPE)† (occupational) at surface†
Class D (intermediate level)	
Liquid, gas, or solid	> Class C but $\leq 10^4 \times$ Class C
Solid	> Class C but $\leq 10^4 \times$ Class C
Surface radiation	
Class D-1	$\leq$ (MPE)† (occupational) at surface†
Class D-2	> (MPE)† (occupational) at surface†
Class E (high level)	
Liquid, gas, or solid	> Class D
Surface radiation†	
Class E-1	$\leq$ (MPE)† (occupational) at surface†
Class E-2	> (MPE)† (occupational) at surface†

*ICRP Publication 6, Recommendations of the International Commission on Radiological Protection, as Amended 1959 and Revised 1962, (1964), Pergamon Press (also references 2 and 3).

†In the 1958 report of ICRP Committee II (3,7) the recommended MPE to the gonads or the whole body is 5 rem./yr. for occupational exposure. For the population at large, it is assumed to be 1/100 of 5, or 0.05, for whole body genetic effect.

†Applies to surface of container, object, or pool of liquid.

**MPQI = (MPC_w for 168-hr. occupational exposure) (2,280 ml./day) (91 days/quarter)
= (MPC_w) (2 $\times 10^5$); MPC_w applies to water.

†Section C of "Radiation Protection-Recommendations of the International Commission on Radiological Protection" (adopted Sept. 9, 1958), Pergamon Press, London (1959) (ICRP, Pub. 1).

- (b) Units of MPQI/kg are used for solids because it is comparable to units for liquids and gases; even though solids are not considered ingestible.

As can be seen from Table 3.1, this classification system divides the waste into five major categories, Classes A, B, C, D, and E, in ascending order of radionuclide concentrations. The following statements can be made about each as these categories:

Class A (Population Level)

This category includes waste with radionuclide concentrations not exceeding (uncontrolled) population level MPC values. This should not be construed to mean that there are no restrictions on the release of these wastes to the environment other than constraints such as "ALAP" and ALARA."

Class B (Occupational Level)

One or more of the nuclides or the mixture of radionuclides exceeds Class A limits, but no radionuclide or mixture in liquid or gaseous wastes exceeds the specified MPC (40 hr/wk) for normal occupational exposure and no nuclide or mixture in solid wastes exceeds specified MPQI/kg for normal occupational exposure.

Class C (Low Level)

Limits on radionuclide concentrations pertain to one or more radionuclide or to a mixture of radionuclides. Treatment of some wastes in this category may convert the major fraction to a Class A or B waste, leaving a minor fraction of concentrated wastes.

Subclasses C-1 and C-2 are based on ICRP maximum permissible radiation exposure to the whole body.

This, in many cases, would separate alpha from beta-gamma wastes.

(The category C is based on radionuclide content; the sub-categories are based on surface radiation.)

Class D (Intermediate Level)

Generally, these wastes will be stored for safety and decay purposes, or converted to or incorporated in solids for ultimate disposal. (Incorporation into organic matrix or cement before disposal is considered for Class D wastes.)

Sub-categories are defined similarly to Class C sub-categories.

Class E (High Level)

Generally, these wastes will be stored for safety and decay purposes; or converted or incorporated into radiation-stable solids for disposal.

Sub-categories similar to Class D sub-categories.

Discussion

Figure 3.2 is a schematic of the American Institute of Chemical Engineers waste classification system. The following waste characteristics must be known to use this system to categorize any given waste:

- Physical state (solid, liquid, gaseous)
- Radionuclide content as MPC for liquids and gases or MPQI for solids
- Surface radiation as MPE for solids.

In addition the following factors should be noted:

- Categories are indicative of potential hazards
- Relatively simple

Figure 3.2 American Standards Institute - AIChE Waste Classification System

- Gives guidance as to suitable disposal method
- Considers physical states
- May be operationally complicated
- Does not consider half-lives as duration of hazard.

3.4 Ferruccio Gera's 1968 and 1973 Waste Classification Systems

Gera suggests that radioactive wastes should be classified on the basis of the duration of required containment.² The clear segregation of wastes requiring containment for relatively short times from those presenting a significant environmental hazard for geologic time periods, would probably be sufficient. The point Gera makes is that the destiny of the waste is a relevant classification factor and that half-lives of the radionuclides contained in the waste are a controlling element in future waste management steps. (Figure 3.3 is a schematic of this proposed system).

Tentative limits of concentration of long-lived alpha emitters to be used for the segregation of solid wastes have been proposed both in the United States and in France. These limits are 10 $\mu\text{Ci/kg}$ and 10,000 times MPC_w , respectively. Concentration limits might not be sufficient criteria. It may be necessary to introduce an additional limit on the long-lived activity that can be disposed of in particular burial grounds. This inventory limit should be based on the possible transfer to man after abandonment of the burial ground.

1968-Classification System

Past work by Gera, published in 1968, developed a rigorous waste classification system based on MPC 's, activity concentrations, half-lives and exposure rates. This system is presented in Tables 3.2, 3.3 and 3.4 (schematically in Figure 3.4). A detailed knowledge of the nature of the

Figure 3.3 Gera's Classification System Based on Duration of Containment

THE CLASSIFICATION OF RADIOACTIVE WASTES

Table 3.2 Categories of Liquid and Gaseous Wastes
Proposed by Branca and Gera (1968)

<u>Categories according to MPC multiplication factors</u>	<u>Examples of possible waste categories</u>	<u>Categories according to treatment</u>
A: <MPC	A-1 (Discharge)	1: No treatment.
B: from MPC to 10^3 MPC	A-2 (Treatment; D.F. < 10^3)	Discharge
	B-1 (Discharge)	2: Treatment with
	B-2 (Treatment; D.F. < 10^3)	D.F. up to 10^3
C: from 10^3 MPC to 10^6 MPC	B-3 (Treatment; $10^3 < \text{D.F.} < 10^6$)	
	C-1 (Discharge)	3: Treatment with
	C-2 (Treatment; D.F. < 10^3)	D.F. between
	C-3 (Treatment; $10^3 < \text{D.F.} < 10^6$)	10^3 and 10^6
D: from 10^6 MPC to 10^9 MPC	C-4 (Treatment; D.F. > 10^6)	
	D-1 (Discharge)	4: Treatment with
	D-2 (Treatment; D.F. < 10^3)	D.F. exceeding 10^6
	D-3 (Treatment; $10^3 < \text{D.F.} < 10^6$)	
	D-4 (Treatment; D.F. > 10^6)	
E: > 10^9 MPC	D-5 (Containment)	
	E-1 (Discharge)	5: No treatment.
	E-2 (Treatment; $10^3 < \text{D.F.} < 10^6$)	Containment
	E-3 (Treatment; D.F. > 10^6)	
	E-4 (Treatment; D.F. > 10^6)	
	E-5 (Containment)	

D.F. = Decontamination factor.

Table 3.3 Categories of Solid Wastes According to Activity Concentration and Half-Life Proposed by Branca and Gera (1968)

Category	Group on the basis of half-life	1	2	3
		$T_{1/2} < 250 \text{ days}$ $T_{1/2} > 10^{11} \text{ yr}$	$250 \text{ days} < T_{1/2} < 10 \text{ yr}$ $10^8 \text{ yr} < T_{1/2} < 10^{11} \text{ yr}$	$10 \text{ yr} < T_{1/2} < 10^8 \text{ yr}$
A		$< 10^{-4}$	$< 10^{-5}$	$< 10^{-6}$
B		$10^{-4} - 10^{-1}$	$10^{-5} - 10^{-2}$	$10^{-6} - 10^{-3}$
C		$10^{-1} - 10^2$	$10^{-2} - 10$	$10^{-3} - 1$
D		$10^2 - 10^5$	$10 - 10^4$	$1 - 10^3$
E		$> 10^5$	$> 10^4$	$> 10^3$

Activity concentration in $\mu\text{Ci}/\text{cm}^3$ or $\mu\text{Ci}/\text{g}$.

Table 3.4 Categories of Solid Wastes According to Radiation Index Proposed by Branca and Gera (1968)

Category	Radiation Index $i = k \cdot D^2$
I	< 0.002
II	$0.002 - 0.02$
III	$0.02 - 0.2$
IV	$0.2 - 2$
V	> 2

*Surface of waste item or package, perpendicular to the direction of measurement

$< 1\text{m}^2$	1
$1 - 5\text{m}^2$	3
$5 - 20\text{m}^2$	6
$> 20\text{m}^2$	19

Coefficient k reflects the different attenuation of exposure rate with the distance as a function of source dimensions; the values are taken from "Regulations for the Safe Transport of Radioactive Materials", p. 59 (IAEA, 1967).

$\dot{D}$ is exposure rate in air in R/hr, measured at a distance of 1 m from the waste.

Figure 3.4 Branca-Gera 1968 Waste Classification System

radionuclides and their respective concentrations was required for use of this system. Subsequent work on the development of a functional waste classification systems led Gera to conclude that his 1968 proposed system and those comparable to it were, in his words, "rather impractical and not relevant to the actual needs of waste management."

Gera ventures that a succinct definition of the terminology in use today may be a sufficient classification system. His proposed definitions follow.

1973-Classification System

High-Level Waste:

Only the wastes provided by reprocessing of spent fuels or the spent fuels themselves. These wastes contain the bulk of the fission products and significant amounts of the long-lived α -emitters. Liquid concentrations are in the thousands of curies per liter. Wastes are self-heating. Long-lived α -emitters exist in concentrations too high to allow disposal for periods far exceeding the expected life of engineered storage structures.

Low-Level Waste:

Low hazard potential with activity concentrations not much higher than MPC's. Large volumes that require no shielding and most may be treated with simple filtration or flocculation techniques. Solid wastes that can be handled without particular precautions, often suspect of any contamination.

Alpha-Bearing Waste:

All wastes containing α -emitters in excess of some appropriate threshold value defined as alpha-bearing wastes; in particular, long-lived isotopes of trans-uranium elements.

Cladding Waste:

Cladding hulls and associated fuel assembly hardware from mechanical decladding of spent fuel. Most of the activation products and portions of the sorbed fission products and alpha-emitters are present.

Intermediate-Level Waste:

All wastes not included in the preceeding categories. These wastes cannot be released to the environment, usually require treatment and shielding but not cooling.

Discussion

The 1968 classification system requires the following waste characteristics be well known:

- Physical state
- MPC
- Half-life
- Activity concentration
- Exposure rate

In addition the following considerations should be noted:

- The system is based upon potential hazard potential
- It considers physical states
- Provides guidance on disposition of waste
- Tends to be complex in that it requires detailed knowledge of waste composition.

These imply a detailed knowledge of the radionuclide content also is available for each waste.

The 1973 classification system requires knowledge of the following waste characteristics:

- Source of the waste
- Dominant radiation
- General operational information

In addition the following considerations should be noted:

- The system is simple and practical
- Provides guidance as to disposition of waste.

3.5 American National Standards Institute Categories of Radioactive Waste (ANSI-N525)

In the interest of better communications regarding radioactive wastes between the nuclear energy industry and the public, the Institute set forth definite meanings to terms used to describe broad categories of wastes.³ The classification systems major parameters were the source of the waste in the fuel cycle and the physical nature of the radionuclides contained in the wastes. The waste categories specifically exclude: (a) materials being stored for possible future recovery of radioactive contents of value and (b) materials normally of use which are being stored for possible future removal of the radioactive contaminant(s). For liquid and gaseous wastes, the concepts used for specific concentrations are those of the Federal Radiation Council in the "Radioactivity Concentration Guide" (RCG).

The radioactive waste categories defined below include solid waste sub-categories defined by parameters independent of possible mechanisms of exposure.

High-Level Solid or Liquid Waste: (material meeting either of the following)

- (a) Aqueous waste stream from first cycle of solvent extraction, including waste streams from subsequent cycles separate or added to the first; solids or concentrates prepared from this first cycle and additions to it, where extraction cycles are intended for re-processing (not including research reactors < 1 MW).

- (b) Streams from partial separations where specific activity remains high.
- (c) Fuel elements from reactors (not research reactors < 1 MW).

Low-Level Liquid Waste:

Wastes that after treatment (no more complex than filtration or ion exchange) can be released with reasonable assurance that the concentration in the water at the point of release will be less than the RCG value for the public (weighting individual RCG values by relative abundance of radionuclides present.)

Intermediate-Level Liquid Waste:

Liquid wastes not included in High-Level and Low-Level Liquid Waste categories. Wastes will eventually be treated to yield a processed fraction of low-level liquid wastes and a fraction which will be added to high-level liquid wastes.

Low-Level Gaseous Waste:

Gaseous materials (including entrained or suspended volatile material, vapors, droplets and particulate matter) which after treatment (no more complex than conventional filtration or scrubbing) can be released as specified in the Low-Level Liquid Waste category.

Stored Gaseous Waste: (high-level gaseous waste)

Gaseous or volatile material not defined in the Low-Level Gaseous Waste category, which are stored either in gaseous form or adsorbed in or on a solid media.

SOLID WASTE

-1- Mine and Mill Tailings

Tailings from mining or milling of uranium or thorium ores, in which daughter products are dispersed throughout the tailings so their concentration is no higher in any significant portion of a tailings pile, than it was in original ores.

-2- Natural Uranium and Thorium Materials

Solid waste with no radiation content exceeding the usual criteria for occupational radiation safety, except for natural uranium, enriched uranium or thorium which are the limiting potential hazard in the handling of the wastes.

-3- Nuclear Reactor Waste

Material normally non-radioactive containing no activity except that induced by neutron or other subatomic particle capture.

-4- Solid Waste Category 4

Material containing or contaminated with fission products or other radioactive materials not defined elsewhere, such that the concentration of selected actinides is less than the minimum concentration as stated in solid waste category 5.

-5- Selected Actinide Waste

Material containing or contaminated with U-233, U-232, all transuranium radionuclides and Ra-226 at concentrations of ≥ 10 nCi/g (10 μ Ci/kg). (Ra-226 is included with the actinides because of its comparable properties).

-6- Solid Waste Category 6

Solid material included in High-Level Solid or Liquid Waste category with the notation that relatively small amounts of such materials will not effect the status of solid waste category 4 or solid waste category 5. (e.g., surface contamination on equipment which has been in contact with high-level wastes or samples removed for analytical control purposes.)

Discussion

Figure 3.5 is a schematic of the ANSI radioactive waste categories. The following waste characteristics must be known to use this system to categorize any given waste:

- Physical state
- Source of the waste
- Activity concentrations (liquids and gases)
- Transuranic and Ra-226 concentration.

In addition the following factors should be considered:

- The system specifically excludes materials stored for future extraction of valuable material
- Does not discriminate between man-made and naturally occurring radioactivity. It only addresses potential hazards
- The system does not provide guidance for disposition of waste

3.6 AEC Manual, Radioactive Waste Management Classifications

The classifications specified by the AEC are for use as definitions of wastes and terminology for AEC-assigned responsibilities, authorities and procedures for radioactive waste management.⁵ The definitions do not represent

Figure 3.5 American National Standards Institute Waste Categories

a rigorous, comprehensive classification system, but they do provide existing ground work done by ERDA's predecessor.

Radioactive wastes in general and liquid and solid wastes definitions are as follows:

Radioactive Waste - Materials of no value consisting of, including, or contaminated with radioactive material in excess of the levels or concentrations permitted in AEC Property Management Instructions for unconditional release of excess property. This includes (a) stored liquid, solid, or gaseous residues from chemical or metallurgical processing of radioactive materials; (b) discarded items such as defective equipment and building rubble, not radioactive in themselves but contaminated with radioactive materials; and (c) discarded items containing induced radioactivity. Treated as a separate category are: (1) irradiated fuels stored for possible processing; (2) radioactive scrap stored for possible recovery of useful values; and (3) materials and equipment stored for possible future use following decontamination.

Liquid Radioactive Waste - Solutions, suspensions, and mobile sludges, contaminated with radioactive materials.

Solid Radioactive Waste - Material that is essentially dry but may contain sorbed radioactive fluids in sufficiently small amounts to be immobile when buried in dry soil.

Classifications, based on these definitions are specified for common terminology as follows:

High-Heat Liquid Waste - Liquid waste containing sufficient thermal energy to require some supplemental means of cooling, such as cooling coils.

High-Level Liquid Waste - The aqueous waste resulting from the operation of the first-cycle extraction system, or equivalent concentrated wastes from subsequent extraction cycles, or equivalent wastes from a process not using solvent extraction, in a facility for processing irradiated reactor fuels.

High-Level Waste - (a) high-level liquid waste, or (b) the products from solidification of high-level liquid waste, or (c) irradiated fuel elements if discarded without processing.

Other Liquid Waste - Liquid waste, not within the definitions of high-level liquid waste.

Transuranium-Contaminated Solid Waste - Those contaminated with certain alpha-emitting radionuclides of long half-life and high specific radiotoxicity to greater than 10 nanocuries/gram (10 microcuries/kilogram), subject to the following conditions and understandings:

- a. The radionuclides included are U-233 (with its daughter products), plutonium, and transplutonium nuclides except Pu-238 and Pu-241. (Note that Pu-238 and Pu-241 waste should be handled as transuranium-contaminated waste when so indicated by Pu-239 impurities or when required by local burial criteria.)
- b. The activity density may be averaged over the contents of individual shipping containers, such as 55-gallon drums, including materials added for shielding or sorption of liquids.

Discussion

Figure 3.6 is a schematic of the AEC categorization system. The following waste characteristics must be known:

- Physical state (solid, liquid)
- Thermal energy
- Source of waste
- Transuranic activity concentration

In addition the following factors should be considered:

- Considers physical state
- The specific activity does not indicate the potential of hazard
- Possibly over restrictive.

3.7 J. O. Blomeke and C. W. Kee Definitions of Waste Types

The above authors presented a paper entitled "Projections of Wastes to Be Generated" at the International Symposium on the Management of Wastes from the LWR Fuel Cycle, July 11-16, 1976. The purpose of the paper was to provide a series of projections as to the type and quantities of wastes that will be generated by the nuclear fuel cycle until approximately the year 2000.

The paper identified and discussed the following types of radioactive wastes:

- High-Level wastes
- Cladding wastes
- Noble-gas fission products
- Fission-product iodine
- Tritium wastes
- Carbon-14
- Low-level transuranium wastes
- Intermediate-level transuranic wastes
- Nontransuranium wastes
- Ore tailings

Figure 3.6 AEC Waste Classification System

The paper defined each of these individual waste types as follows:

High-level wastes are composites of the liquid waste streams arising from the reprocessing of spent fuels. These wastes contain more than 99.9% of the nonvolatile fission products, 0.5% of the uranium and plutonium, and all the other actinides formed by the transmutation of the uranium and plutonium in the reactors.

Cladding wastes consist of solid fragments of Zircaloy and stainless steel cladding and other structural components of fuel assemblies that remain after the fuel cores have been dissolved.

Noble-gas fission products, krypton separated from reprocessing plant off-gas and packaged, together with other noble-gases collected.

Fission-product iodine, whose radioactivity at the time of packaging and shipment is due solely to 1.2×10^7 year Iodine-129, is recovered with a yield of 99.9% at the reprocessing plant.

Tritium wastes are generated at nuclear power stations and at reprocessing plants.

Carbon-14 is produced in oxide-fueled reactors principally by an (n,p) reaction with nitrogen-14 impurity in the fuels, but also as the product of an (n, α) reaction with oxygen-17.

Low-Level transuranium wastes are defined as those solid or solidified materials that contain plutonium or other long-lived alpha emitters in known or suspected concentrations greater than 10 nCi/g, and yet have sufficiently low external radiation levels after packaging that they can be handled directly.

Intermediate-level transuranium waste is defined as those solid or solidified materials that contain long-lived alpha emitters at concentrations greater than 10 nCi/g, and have typical surface dose rates between 10 to 1000 millirems per hour after packaging due to fission-product contamination.

Nontransuranium waste is composed of those diverse materials that are contaminated with low levels of beta- and gamma-emitting isotopes, but contain less than 10 nCi of long-lived alpha activity per gram.

Ore tailings are the results of the mining and milling operations for the recovered of yellow cake, U₃O₈.

Discussion

The following properties of radioactive wastes must be specified when using Blomeke and Kee's classification system:

- Source of the waste
- Kr-85, I-129, H-3 or C-14
- Activity concentration for long-lived α -emitters

In addition the following factors should be considered:

- The system is clear-cut in its definitions of categories
- No guidance is provided for the disposition of waste
- Little indication of relative hazard.

3.8 Summary of Established Content of Proposed Waste Classification Systems

Waste classification systems or methods discussed previously present a consensus, among those in the field, on some of the important considerations necessary to satisfy the intent of a classification system. These considerations appear to be:

- Degree of potential hazard
- Measure of potential health hazards such as MPC's
- Physical state; solid, liquid or gaseous.

Of equal emphasis and importance, but less often included in classification systems are the following considerations:

- Hazard duration; half-life
- Disposal options, containers, conditions and permanence
- Specific nuclide content
- Specific emissions; alpha or beta-gamma emissions
- Point of waste generation in the fuel cycle; (i.e., waste stream of first cycle of reprocessing, hulls, etc.)

In many cases, the characteristics of radioactive waste included in the definitions of waste classes are overlapping or redundant. In summary, a determination of the most significant yet independent characteristics of wastes can be made and a classification system developed around that determination.

4.0 RADIOACTIVE WASTE CLASSIFICATION SYSTEMS

PROPOSED BY TAP MEMBERS

The classification systems presented in this chapter are those proposed for discussions in the Technical Advisory Panel's working sessions by the panel members. A few of these systems were developed in some detail. Others represent the basic structure a classification system might have, with only brief analysis of the details which may be necessary in applying such systems to waste management questions.

4.1 Proposed Waste Classification System - 1

The primary consideration in the development of classification System - 1 is the method of disposition of the waste material. The basic criteria applied is that the method of disposition will provide reasonable protection to man and his environment.

The disposition methods are divided into four major categories as follows:

1) Release of Effluents. Defined as the release of those radioactive wastes whose concentrations are or can be made to comply with guidelines given in 10 CFR 20 for discharge directly to the environment

2) Interim Storage. Defined as storage for an unspecified length of time of radioactive wastes to await, radioactive decay; special treatment such as solidification, incineration, chemical change, heat dispersal, etc.; shipment, or any other operation that may require retention of the waste for some period of time.

3) Active confinement. Defined as those carefully selected sites where nuclear waste can be disposed without significant insult to man and his environment. Shallow land burial would fall into this category.

4) Isolation. Defined as those methods that isolate the waste from man and his environment for long periods of time. Deep burial in geological formations, deep sea burial, extraterrestrial disposal methods would fall in this category.

All radioactive isotopes could be classified into two groups based on their potential hazard. (Similar to the seven groups established for radioactive shipments as given in 49 CFR 173.389).^{*} It is suggested that all radioisotopes that fall into transport groups I and II be classified as Waste Group I. All other nuclides are classified to Waste Group II with the exception of ^{106}Ru which should go into Waste Group I. This would put all the heavy element alpha emitters (including the TRUs) plus those hazardous beta emitters such as ^{90}Sr and ^{106}Ru in Group I. (Figure 4.1 is a schematic of this waste classification system).

In addition, it is proposed that concentration and total inventory limits be established for each individual site selected for active confinement. The limits for Waste Group I material would be more restrictive than for Waste Group II material. The limits would be further defined as one limit for the immediate time and one limit for 100 years after use of the site. It is suggested that 100 years be picked because this seems a reasonable length of time that control of the site can be maintained and it also is about the time that

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^{*}Included as Appendix B in this report, is Part 173.389 of the Code of Federal Regulations, Title 49. This classification system is used for radioactive waste transportation purposes and has been quite functional.

Figure 4.1. Waste Classification System - 1

Radioactive Waste

fission product nuclides significantly reduce due to decay and the TRU nuclides assume greater relative importance.

The total inventory limits would be established after careful study of the site. Such factors as rainfall, subterranean water flow, ion exchange in the soil, etc. would be used to establish both the immediate and the 100 year limits.

On the other hand however, it would be expected that the concentration limits be the same values for all sites in the country. These limits should be established after careful study of the potential hazard, should an unknowing entry into the buried material take place. Some preliminary numbers to illustrate the point are as follows:

Concentration limits for Waste Group I material could be

for immediate burial -- 1.5 Ci/m^3

for 100 year burial -- 0.15 Ci/m^3

Concentration limits for Waste Group II material could be

for immediate burial -- 15.0 Ci/m^3

for 100 year burial -- 1.5 Ci/m^3

For example, assume a plant has a 55 gallon drum (volume = 0.208 m^3) of waste containing 60% Sr-90 and 40% Ru-106, by activity. The immediate burial limit of 1.5 Ci/m^3 implies the drum may contain at burial:

$$\text{Sr-90} + \text{Ru-106} = (1.5 \text{ Ci/m}^3) (.208 \text{ m}^3) = 0.312 \text{ Ci}$$

$$\text{with } (.6) (.312 \text{ Ci}) = \underline{0.19 \text{ Ci of Sr-90}}$$

$$\text{and } (.4) (.312 \text{ Ci}) = \underline{0.12 \text{ Ci of Ru-106}}$$

¹W. A. Rodger: Critical Evaluation of the Limits of Transuranic Contamination of Low Level Waste, August 1975. Nuclear Safety Associates, Bethesda, Maryland.

The 100-year limit of $0.15\text{Ci}/\text{m}^3$ implies the drum may contain at burial:

$$\text{Sr-90}(e^{-\lambda_1 t}) + \text{Ru-106}(e^{-\lambda_2 t}) = (.15\text{Ci}/\text{m}^3)(.208\text{m}^3) = 0.0312\text{Ci}$$

Since at burial there is $2/3$ as much Ru-106 as Sr-90, then at burial:

$$\text{Sr-90} = \frac{.0312 \text{ Ci}}{(e^{-\lambda_1 t}) + 2/3(e^{-\lambda_2 t})} = 0.34 \text{ Ci}$$

$$\text{and Ru-106} = 2/3(.35) = 0.23\text{Ci}.*$$

Since the immediate burial limits are more restrictive in this case, the amount of Sr-90 and Ru-106 allowed per drum would be 0.19Ci and 0.12Ci respectively.

For a mixture of plutonium isotopes, the governing criterion will be the 100 year burial limits because of the long-half lives of the plutonium isotopes. This is obviously the case for Pu-239 with a 25,000 year half life. For shorter lived Pu-238 ($T_{1/2} = 89\text{y}$) the following example leads to the same conclusion.

Assume a plant has the same 55 gallon drum containing waste with a composition of 80% Sr-90 and 20% Pu-238, by activity. The immediate burial limit of $1.5\text{Ci}/\text{m}^3$ implies an activity limit of 0.25Ci of Sr-90 and 0.062Ci of Pu-238. The 100 year burial limit of ten times less, implies activity limits of 0.15Ci of Sr-90 and 0.038Ci of Pu-238. It can be seen that the 100 year limit is more restrictive in this

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*Note: in this example, the 100 year limit restricting the total activity at burial of Ru-106 is purely academic. Ru-106 has a one year half life and therefore one could bury $7.5 \times 10^{26}\text{Ci}$ of Ru-106 and at 100 years be within the activity limit for that drum.

case involving isotopes of longer half lives although they both are less than 100 years.

For wastes in acceptable containers falling above these immediate and 100 year limits, isolation is required. Wastes destined for isolation from the environment should be divided into two subgroups depending on decay heat generation.

This type of scheme has merit both from a regulatory standpoint and also from the operational standpoint. Again the numbers on limits were rather arbitrary and careful study will be needed prior to establishing these limits.

4.2 Proposed Waste Classification System - 2

The classification system described here was developed to provide the maximum in utility with complete operational coverage.* The system must satisfy the regulatory requirements and should not only be consistent with existing operational systems for hazardous materials, but should blend into them. The classification of a particular material should not change as it moves through an operational system unless the hazard associated with it changes. The system must be readily applicable to all radioactive materials.

Extent of System

The primary consideration of the classification system was to serve the regulatory needs for radioactive wastes. There is a real need to move back into the fuel cycle in order to provide a system consistent with operation of the various processes in these plants. Wastes are generated at each point in the fuel cycle. The radioactive properties which define the hazard of radioactive wastes are also characteristic of many other materials in the fuel cycle, in the nuclear

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*Michael S. Karol, University of Arizona, NRC Contract #AT(49-24)-02-05.

industry in general, and in the entire range of other activities using radioactive isotopes. Thus the inclusion of these materials is virtually automatic in a system designed to meet operational needs by use of the properties and characteristics of radioactive nuclides.

System Design Considerations

The utility of the classification system in meeting regulatory needs requires the system to relate the characteristics of the wastes to the hazards to be controlled. These characteristics include:

- 1) Magnitude of the penetrating radiation
- 2) Hazard Index
- 3) Life of hazard
- 4) Mobility of the material

In addition, the operational requirements must be recognized so that the operators may respond to the precautions inferred by the classification.

The operations that will be affected include:

- 1) Chemical processing operations
- 2) Handling operations
- 3) Emergency responses (e.g., during a fire)
- 4) Transportation
- 5) Waste management - disposal or storage emplacement

Detailed consideration of these factors leads to certain requirements or properties of the waste classification matrix. These are:

- 1) Simplicity - the system must provide ready classification, the classes must be easily recognized and the action implied by the classification readily defined and implemented without ambiguity.

2) Useful - the system must provide information needed in operations and regulations.

3) Complete - the system must include all hazardous radioactive materials.

4) Flexible - the classification system should permit changes in the classification of a material whose hazard has changed and it should also be able to incorporate changes required by changes in regulations, policy, hazard assessment or by new technology.

5) Multilevel - since different properties differ in operational importance for different operations, it is not necessary to have all properties identified for each. A simpler system for these operations can be provided by including different levels of classification.

6) Precise Definition - Each class will be designated by a roman numeral and each subclass by one or more letters.

Primary Categories

The primary categories provide operating and control information needed in the conduct of each of the operations. These relate to the handling requirements, primarily. They are distinguished by the need for cooling, for shielding, and for coping with an existing biological hazard. The most intense of the radioactive materials are those that require cooling. All such materials require shielding and present a large biological hazard. The next less hazardous materials are those requiring shielding but no cooling. The next lower category is that which does not require shielding but contains material with a radioactive hazard if ingested or inhaled. These categories are summarized in Table 4.1.

Table 4.1

Waste Classification Categories

<u>Symbol</u>	<u>Category</u>	<u>Criteria</u>
I	Requires cooling & shielding	400 W/m ²
II	Requires shielding	200 mr/hr @ surface 10 mr/hr @ 0.9m
III	Requires no shielding	would exceed MPC if released
IV	Requires no care	(innocuous)

An additional category has been suggested for materials that would be diluted below MPC in leaving the controlled area.

If adopted, these would be IV and innocuous becomes V.

Subcategories

Subcategories are needed in order to delineate the other factors and properties of concern. One of the most important of these relates to the duration of the hazard. The hazards due to radioactive materials are complex, depending on many physical, chemical, and physiological phenomenon, but they have been quantitatively defined by other authorities so that we may use their definitions. We need only consider the changes in hazard occurring with time. Each isotope decays in a precisely defined manner so that the rate of decrease or growth of each radioisotope and its attendant hazard can be readily calculated. Accurate approximations for certain groups of isotopes such as those from the fission process are also available. We then define a subcategory which classifies the wastes according to the time the material stays within a category. When this time is exceeded it will then drop into the next lower category. This particular subcategory has a special meaning for waste management regulations in that, it is probably the principal criterion for distinguishing between

wastes that may require disposal with assured permanent isolation from the biosphere, and those that may safely be disposed of with less severe restrictions. The time required for the radioactive hazard to decrease to acceptable levels, if short with respect to the anticipated duration of effective management control, would permit the less restricted emplacement system. Radioactive materials that would exist as serious hazards for times that are long compared to the anticipated duration of effective management control would probably be placed in geologic isolation or in some other system isolated from the biosphere. Note that the Transuranics when treated as wastes would be included in this latter subcategory. Other long-lived isotopes, however, may also be included, even some of those with "infinite" half-lives, the stable isotopes, if sufficiently toxic.

The next subcategory defines the physical state or mobility of the waste material and the final subcategory determines whether or not treatment is required for some regulatory consideration. These subcategories are summarized in Table 4.2.

Table 4.2
Waste Classification Subcategories

<u>Symbols</u>	<u>Subcategory</u>	<u>Criteria</u>
a	Life time for changing category. Note: An alternate definition could be life time till waste leaves category III (becomes innocuous).	<10 year
b		10-100 year
c		100-1000 year
d		>1000 year
s	Solid	Immobile
m	Mobil	Will disperse or become airborne if container is spilled
l	Liquid	Will flow onto a flat surface from a small hole
g	Gaseous	Will mix with the atmosphere thru a small hole
t	Treatment	Must be converted to another form before further processing
n	No treatment	--
e	Explosive	Not chemically stable
f*	Fissile	Special nuclear materials

* May be added if desired for completeness but waste materials other than the transuranics should have no significant fissile content.

Waste Classification System

A symbol consisting of several letters can be used to identify the various categories and subcategories. These are summarized in Table 4.3.

Table 4.3

Waste Classification

<u>Symbol</u>	<u>Description</u>
I. $\begin{bmatrix} a & s & t \\ b & m & n \\ c & l \\ d & g \end{bmatrix} e$	Any material with sufficient radio-activity to require cooling. The time required before it becomes II type is shown by a, b, c, or d. The physical state is shown as s, m, l, or g. The need for treatment is t or n and the explosive nature is blank if chemically inert, e if a potential hazard.
II. $\begin{bmatrix} a & s & t \\ b & m & n \\ c & l \\ d & g \end{bmatrix} e$	Any material with sufficient radio-activity to require shielding. The other elements are as described above.
III. $\begin{bmatrix} a & s & t \\ b & m & n \\ c & d \\ d & g \end{bmatrix} e$	Requires control but no shielding- a, b, c, or d now become the consideration for complete release. Other elements as described.
IV.	A material without hazard.

The system can be illustrated by classifying a few materials.

1. Liquid waste from fuel reprocessing which includes the unburned transuranics, as it is stored on-site for eventual solidification.

I (a, l, t)→ remains in category I till 1985

II (c, l, t)→ remains in category II till 2100+3000

III (d, l, t)→ remains in category III till ?

Upon solidification this becomes

I (a, s, n), etc.

2. Filters containing only ^{131}I

II (a, s, n)

A number of facets of the suggested system are arbitrary and can be adjusted to include other considerations or to improve overall consistency.

The following figure is a reduced schematic of the Waste Classification System.

Figure 4.2. Waste Classification System - 2

4.3 Proposed Waste Classification System - 3

Briefly sketched out, the following simple classification system is based on thermal and radiation properties of the wastes. (See Figure 4.3)

Thermal - Radiation would include current wastes:

Hot - Hot "high level waste"

Cool - Hot "hulls"

Cool - Cool "low level waste"

Figure 4.3. Waste Classification System - 3

4.4 Proposed Waste Classification System - 4

The following rough system and required criteria suggest a format for a waste classification system based on the discussions of environmental criteria. (Figure 4.4 is a schematic representation of this system).

"Release-able": waste satisfying conditions less than those set by "lower bound" criteria. These may be directly released as non-hazardous wastes such as normal trash, garbage, or sewage without further treatment.

"short-duration containment": wastes satisfying the following conditions: 1) greater than those set by "lower bound" criteria where "lower bound" criteria might be developed on the basis of:

- a) comparison with natural deposits and natural hazards (re: some acceptable hazard limit)
- b) \$1,00 per person-rem (re: 10 CFR 50, Appendix I)
- c) MPC values less than 10 CFR 20 MPC limits.

and 2) with hazard durations less than those specified by "middle bound" criteria.

"isolation": wastes satisfying conditions greater than those set by "lower bound" criteria but with hazard durations greater than those set by "middle bound" criteria which might be developed on the basis of:

- 1) WASH-1539 (Inventory commitment as discussed in WASH 1539)
- 2) between 100 years and 1000 years (re: W. A. Rodger, Critical Evaluation of the Limit of Transuranic Contamination of Low Level Wastes, August 1975, Nuclear Safety Associates, Bethesda, Maryland).

Figure 4.4. Waste Classification System - 4

4.5 Proposed Waste Classification System - 5

Early on, at the Reston meeting of TAP, a waste classification system based primarily on two disposal modes was suggested. Wastes would be classified first as:

- 1) those wastes to be disposed of at shallow land burial sites and
- 2) those wastes to be disposed of in deep geologic formations.

Those wastes destined for deep geologic disposal would be further categorized as high heat or low heat wastes. Low heat wastes should further be classified as those requiring shielding and those not requiring shielding. Figure 4.5 is a schematic of this system.

Figure 4.5 Waste Classification System - 5

5.0 DISCUSSION

5.1 Introduction

A review of Chapters 3 and 4 indicate that all twelve of the classification systems presented are based on one of the following general conditions:

- (a) The source of the waste
- (b) Physical characteristics of the waste
- (c) Disposition of the waste.

Radioactive waste can be labelled at its source. As an example, waste material could be classified as reactor wastes, spent nuclear fuel, reprocessing wastes, or fuel fabrication wastes. Further, reprocessing wastes could be referred to as spent fuel cladding, liquid process wastes, and general process trash. Such a classification system does not provide any information about the nature of the radioactive waste or the means of handling, processing, or disposal. Such a system does not appear to facilitate the formulation of waste management regulations.

Most of the classification systems reported in the literature are based on the physical characteristics of the radioactive waste. For example, the IAEA recommended in 1970 that radioactive wastes first be classified as solids, liquids, or gases. The liquids and gases were then subdivided by activity levels, curies per milliliter, or curies per cubic meter. The solid wastes were subdivided by surface radiation dose rate, rads per hours. The Technical Advisory Panel generally felt that a functional

waste classification system could be developed based only on physical characteristics.

There are many different ways to dispose of radioactive wastes. It appears that some common features of various disposal options leads to groupings into broader categories of waste disposal methods. These features include the degree of containment achievable, the degree of isolation and the extent of social commitment required for each disposal option. The Technical Advisory Panel also agreed that a functional waste classification system should be developed based on disposal methods. (Disposition).

Having reviewed and discussed the various classification systems, it appeared worthwhile to narrow the field to two prototype systems, each having distinctive attributes. These are:

- System I: A multicompartmented classification system which provides detailed descriptions of the characteristics of wastes in each category. Such a system would provide guidance for all operational aspects of handling the waste.
- System II: A three-category classification intended to give guidance as to final disposal of waste. It would provide that information necessary for transfer of waste from the generator to the disposer of the waste. Information necessary for other waste handling could be given in in-plant operational procedures.

5.2 System-I, Classification System Based on Waste Characteristics

The intent of this classification system is to describe a radioactive waste with an efficient notation conveying the important waste characteristics. Such a system can be used for all phases of waste management.

The important characteristics of the radioactive wastes denoted by this classification system are as follows:

- (a) Magnitude of radiation intensity
- (b) Physical state
- (c) Hazard index
- (d) Duration of hazard

Radiation Intensity

The primary level of classification is radiation intensity. Four levels of intensity have been assigned to provide information on the projected need for forced cooling and/or ranges of shielding required. An example of how these categories can be defined is as follows:

<u>Categories</u>	<u>Requirements</u>	<u>Ci/m³</u>
I	Cooling and Shielding	Above 10^4
II	Shielding	10^{-1} to 10^4
III	No Shielding	10^{-6} to 10^{-1}
IV	No Care	Below 10^{-6}

These general groupings are only guides. It should be recognized that in very large configurations or in containment systems with good insulation, Group II materials may also require some type of cooling. It is also possible to have waste materials that have a Group II level of intensity but require little or no shielding, as might be the case with Pu-238 or Pm-147 contaminated material. As indicated these primary categories are set forth only as examples. The intensity of radiation can also be defined in units of watts per cubic meters or by any of several other energy per volume units.

Physical State

The next level of classification logically falls to physical state of the waste. The simple notation of L, G, and S can be used to indicate liquids, gases, and solids, respectively.

Hazard Index

The third level of classification or subcategory would be by the hazard index appropriate for each physical state. The most commonly used hazard index are $MPC_w^{(a)}$ for liquids, $MPC_a^{(b)}$ for gases and $MPQI^{(c)}$ for solids. An example of how these hazard indexes can be applied to define classes of radioactive materials is as follows:

<u>Hazard Index Subcategory</u>	<u>Range of Hazard Index</u>
A.	
Liquids	$< MPC_w$
Gases	$< MPC_a$
Solids	$< MPQI$
B.	
Liquids	From MPC_w to $10^4 MPC_w$
Gases	From MPC_a to $10^4 MPC_a$
Solids	From $MPQI$ to $10^4 MPQI$
C.	
Liquids	$>10^4 MPC_w$
Gases	$>10^4 MPC_a$
Solids	$>10^4 MPQI$

The number of subcategories can be expanded and the ranges of hazard indexes can be adjusted to suite specific operational or regulatory requirements.

(a) MPC_w - Maximum permissible concentration for water as defined by 10 CFR 20 Appendix B, Table II.

(b) MPC_a - Maximum permissible concentration for air as defined by 10 CFR 20 Appendix B, Table II.

(c) $MPQI$ - Maximum permissible quarterly intake is defined as $(MPC_w)(2 \times 10^5)$. Reference AIChE, Proposed Definition of Radioactive Waste Categories, June 7, 1967.

It should be noted that the use of maximum permissible concentrations as a hazard index is not a direct measure of dose to man. Specific pathways to man must be examined in order to address the question of dose to man. In the case of radioactive iodine, concentrations of iodine below MPC can be concentrated to above MPC levels by the food chain.

Duration of Hazard

The final subcategory is the notation of duration of hazard. The duration of hazard provides information about the length of time required for the hazard index to drop below levels defined by subcategory A. The duration of hazard is a function of both radionuclide concentration in the waste and the half-life of the radioactive material.

An example of duration of hazard subcategories is as follows:

<u>Duration of Hazard Subcategory</u>	<u>Time Required to Reach Hazard Index Subcategory A</u>
a	<10 years
b	10 to 100 years
c	100 to 1,000 years
d	>1,000 years

Again, it should be noted that the range of hazard durations in these specific groupings are examples. More subcategories, or different time periods may be appropriate for regulatory needs.

The classification system then represents a certain waste with the notation of four symbols, and is schematically represented in Figure 5.1. As an example, high-level liquid

SYSTEM I - RADIOACTIVE WASTE CLASSIFICATION

Figure 5.1

waste from a nuclear fuels reprocessing facility would be referred to as (ILCd). Intermediate-level liquid waste from a reprocessing facility would be (IILCd), or (IILCc), depending on the plutonium concentration. Similar statements can be made about other types of radioactive waste with known compositions. If desired, other notations can be added to the system to denote special features of the waste such as a large content of fissile material, unusual mobility, or chemical stability.

This waste classification system is limited to the description of radioactive wastes. The system can be used to identify radioactive wastes at any point in the generation of such wastes. It does not imply any guidelines for the development of regulations for handling and disposal of radioactive wastes or in the formulation of waste management criteria. These considerations might appropriately come into play when specific hazard indexes, hazard durations, and radiation intensity definitions are developed. For a descriptive waste classification system to be useful in making waste management decisions, the waste characteristics critical to the system must also be those critical to waste management decisions.

5.3 System II - Classification System Based on Characteristics of Disposal Means

The final disposal of radioactive wastes can be considered to be the most important operation in any radioactive waste management program. It is also the operation that requires the most definition. Therefore, if a waste classification system could be formulated on the basis of disposal options, it would provide information and guidance allowing the maximum flexibility for the waste generators implementation of waste management programs.

There are several methods for disposing of radioactive material that have been utilized in the past and several more methods suggested for the future. It is, therefore, very important that a radioactive waste classification system based on disposal be broad enough to include any means of disposal.

The list of suggested methods for management of radioactive waste includes the following:

- Direct discharge or dispersal to either the atmosphere or surface water
- Storage until the radioactive isotopes have decayed to an innocuous level
- Shallow land burial
- Ocean dumping
- Deep geological emplacement
- Ice cap emplacement
- Extraterrestrial disposal
- Ocean disposal (Seabed burial)
- Deep well injection
- Shale fracturing

Common Features

Various statements can be made about the degree of containment, degree of isolation, and degree of social commitment each of these disposal systems provide or require for waste disposal. As an example, direct dispersal to the environment provides no confinement, while deep geological emplacement should provide essentially complete containment for geological periods of time. The degree of social commitment refers to such ongoing functions as record keeping, maintenance, and system and environmental monitoring. Such management systems as surface storage, or

shallow land burial can be expected to require significant social and resource commitment for some period of time. This would include area security, repair of containment barriers, environmental monitoring, and record keeping. This social commitment would extend past the period of time that the disposal facility is actually receiving radioactive material. In contrast, after the operational phase is discontinued, deep geological disposal will require minimal social commitment to the extent of preventing mining or drilling in the disposal area.

It is, therefore, possible to formulate a waste classification system based on disposal methods without being limited to the means of disposal. All disposal systems can be placed in one of the following three categories:

- (1) Disposal by direct dispersal to the environment
- (2) Disposal by methods requiring social commitment
- (3) Disposal by methods that provide long-term isolation.

The following breakdown or categorizing of specific disposal methods would be as follows:

- I. Dispersal to the environment
  - a. Stack discharges
  - b. Liquid effluent discharges
  - c. Solid disposal to sanitary land fills
- II. Disposal methods requiring social commitments
  - a. Shallow land burial
  - b. Storage near surface
  - c. Ocean dumping
  - d. Deep well injection

III. Disposal methods providing long-term isolation

- a. Deep geological emplacement
- b. Ice cap emplacement
- c. Extraterrestrial disposal
- d. Ocean disposal
- e. Shale fracturing

The categorizing of the above disposal methods does not imply that these methods are technically sound or acceptable. The methods listed are ones that have been proposed or utilized in the past.

Having categorized the various radioactive waste disposal systems, how does that help categorize radioactive waste materials? The procedure for classifying waste materials is to review the interfaces or breakpoints between dispersal and methods categorized as requiring social commitment, and between methods requiring social commitment and methods providing isolation. Figure 5.2 is a schematic of the classification system. Figure 5.3 lists a series of considerations which may be important in deciding what type and amount of radioactive waste can be disposed of by the various waste disposal methods. The purpose of the list of considerations is to provide the broadest possible viewpoint for the regulatory agencies charged with the preparation of waste management criteria and regulations.

The first eleven considerations listed on Figure 5.3 relate to the waste management criteria that would dictate whether a radioactive waste material could be dispersed or whether it would have to be contained. The Technical Advisory Panel's opinion was that the goal of any waste management program was to limit the potential radiation dose

SYSTEM II
RADIOACTIVE WASTE CLASSIFICATION

Figure 5.2

Considerations in Determining Disposal

Figure 5.3

to man. Nine of the first eleven considerations deal with various aspects of the dose-to-man question and, therefore, are closely related.

There are several different types of criteria that could be established to limit the type and amount of radioactive material that could be released to the environment by dispersion. As an example, absolute values for one or more of the following could be set.

- Total health effects
- Total person-rem
- Person-rem per unit power production for electricity generated
- Cost-effectiveness guideline
- Maximum credible dose to any individual or critical group.

Any discharge to the environment by dispersal which exceeds a predetermined value would either have to be captured or treated. The resultant radioactive material from such a capture or treatment operation would have to be contained or disposed of by one of the two categories of waste containment methods.

A second means of formulating waste management criteria would be to utilize existing regulations and regulation guides. As an example, present ICRP and NCRP standards could be used to establish limits for materials that could be dispersed. Also EPA's proposed limit of a maximum of 25 millirem exposure per year from nuclear fuel cycle operations including waste disposal to any one person could also be used to limit the quantity of radioactive material that could be dispersed to the environment.

Another approach is to establish an acceptable person-rem cost-effectiveness value. An example would be 10 CFR 50 Appendix I, which establishes a value of \$1,000/person-rem. All individual exposure that could be eliminated at a cost of a \$1,000/person-rem or less would be. A different approach is to establish a regulatory philosophy that the dose to man from the dispersal of radioactive material will be maintained at a level that is "as low as is reasonably achievable." Such a philosophy is already implied by paragraph 20.1(c) of 10 CFR Part 20. This guidance would have to be translated into practical criteria. Previous examples in terms of dollars per man-rem or man-rem per MWe year may suffice. Perhaps some other approach might also be in order.

Two of the eleven considerations listed on Figure 5.3 which do not deal directly with dose to man are detectability and deterioration of resources. There is a strong feeling in some quarters that no level of dispersal of radioactive material to the environment is acceptable. In the case that "no release" be defined as a waste management criteria, then essentially the amount of material that can be released by dispersion would be limited by our ability to detect radioactivity. A strict literal translation of zero release would preclude any operations which involve radioactivity.

The consideration of the deterioration of resources is primarily addressed to Kr-85 releases which contaminate natural Krypton in the atmosphere. A waste management criteria might be set on the basis of acceptable levels of resource deterioration by treating certain environments as potential resource bases.

A combination of two or more of the above approaches could provide a reasonable method for the development of regulations and waste management criteria. For example, an ALARA regulatory philosophy in conjunction with a cost-effective calculation and a maximum acceptable health effect or maximum single-person dose limit could provide criteria defining what could be dispersed and what would require containment.

The next step is to address waste management criteria that can be used to determine that type and amount of radioactive material that can be disposed of by the confinement methods and what material must be placed in isolation. Figure 5.3 lists some of the considerations.

Shallow land burial can be used as an example to discuss this second set of criteria. In discussions dealing with shallow land burial, the Technical Advisory Panel generally reached the following conclusions:

- Shallow land burial should be considered as a disposal method which requires ongoing social commitment.
- During the operational phase and during the first 100 years following decommissioning of a shallow land burial site some low-level discharge to the environment can be expected. Releases of as high as 1×10^{-6} of the total site inventory per year have been experienced in the past.
- The magnitude of these releases is a function of several factors such as site location, area rainfall, geology, hydrology, engineering features, and operational procedures. Release rates are site specific and depend on these factors.

- Surface geology can change significantly in time periods as short as 5,000 to 25,000 years. Social and institutional patterns can also be expected to change during these time periods. Therefore, no long-term containment of radioactive material should be expected to be maintained by near-surface storage or disposal systems.
- Some rate of release of radioactive material to the environment from radioactive waste management programs is acceptable.
- Given a specific shallow land burial site with specific information on meteorology, geology, hydrology, engineering design, and other appropriate information, it is possible to estimate the amount of radioactive material that would be released from that site over a 100-year period.
- A conservative estimate of the duration of social commitment to a disposal site is 100 years.

As indicated, these conclusions are based on shallow land burial disposal. But similar statements can be made about storage facilities, ocean dumping, or deep well injection. Such statements include:

- Degree of containment is procedure and site specific
- Long-term containment (> 1,000 years) cannot be assured
- Some estimate of release for various time frames can be made.

In discussing shallow land burial, TAF reviewed the possible fate of radioactive material placed in shallow land burial. The general opinion was that two time frames must be considered. The first time frame includes the operational phase of the burial ground and the first 100 years following decommissioning. The second time frame was after 100 years.

During the first time frame, release of radioactive material to the environment depends on specific site characteristics, engineering features, and operational procedures. The Technical Advisory Panel generally felt that sufficient data could be obtained to predict the release of radioactivity from a given site within a determined range. It was felt that the release rate can be assumed to be constant for each site, whereas the total quantity released is a function of the site inventory. Accidental intrusion during the first 100 years is not considered to be a problem because of site records and security systems.

Therefore, for the first 100 years total site inventory would be the factor that should be controlled and regulated. The same discussion of waste management criteria previously presented on dispersal, would apply to determining acceptable release from a shallow land burial site.

The second time frame would be after 100 years. It was assumed that no records of the site exist and no security system is operating. It is possible that the site could become an agricultural area or part of a potable water supply system. Therefore, the inventory of radioactive material remaining at the site is important. A detailed analysis of the possible pathways to man from such a site must be done, and a set of waste management criteria must be formulated to define what an acceptable dose to man might be at some time in the future. These criteria for acceptable dose to man in the future may or may not be the same as those applied to the present population.

In addition to the possible exposure to man via the food chain or water, accidental intrusion by man into the site is also possible. Such an intrusion could take the form of drilling, mining, or surface excavation. A reasonable criteria might be that the amount of radioactive material in any one waste package should not be high enough to injure someone who stumbles upon it after 100 years. This consideration would place a limit on the concentration of radioactive material per unit volume of waste.

As indicated earlier, actual numerical values for any limit on either inventory or concentration will be method and site specific. It is important to note that total curies of activity would probably not be the units chosen to define either the inventory or concentration limits. Instead a hazard index would be utilized. Inventory limits could be based on the volume of water required to dilute the total site inventory to MPC_w limits. The reason to choose MPC_w as a basis for inventory limits is that the inventory limits are intended to restrict the quantity of radioactive material slowly released from a given site. The dose to man from the material released is probably by water ingestion or food chain ingestion. Therefore MPC_w is an indication of that potential dose, but not a direct measure.

Other considerations in setting absolute inventory limits is that radioactive materials decay, therefore the total hazard index for a given site is always changing. Also, during the first time frame corrective actions can be taken if higher than expected releases occur, while during the second time frame release would be assumed to go undetected. Therefore, the inventory

limits for the first time period may be several times greater than the inventory limits for the second time frame. This would allow large curie quantities of short-lived radioactive isotopes to be disposed of by the second category of disposal methods, but might limit the longer-lived radioactive isotopes. Detailed analysis of the specific disposal method and disposal site is required to determine which of the three limits would be controlling.

6.0 CONCERNS AND OPINIONS EXPRESSED BY MEMBERS OF THE TECHNICAL ADVISORY PANEL

With few exceptions, members of the Technical Advisory Panel expressed the concern that developing a waste classification system independent of disposal mechanisms might result in an ultimately useless system. This concern was expressed primarily with respect to waste classification systems which were based on engineering parameters of the waste form. The thought was that the disposal mechanisms should be known in order that the correct engineering parameters could be selected for the classification system. An important pitfall to be avoided in a waste classification system is implying more differentiation between methods of treatment, storage or disposal of wastes than is scientifically warranted or technically useful.

Some of the more complex systems, because of the number of categories, appear to have almost as many slots as a complete table of engineering data; but may provide less information than the engineering parameters. For example, with two engineering parameters, the nuclide and the concentration, the hazard index characteristic through life can be plotted. Conversely, with some classification schemes, four parameters provide insufficient data. The choice of the four parameters in System-I was made, hopefully to provide the most pertinent information with regard to waste management problems. This points out the need to develop some foundation in terms of waste management criteria or disposal methods even before a purely descriptive classification system such as System-I can be rigorously developed and defended.

It was suggested that the formulation of environmental criteria for waste management criteria should be the first step in the establishment of regulations.

Several technical cautions arose repeatedly in the meetings of TAP. One that is considered to be answered by System-II is regarding facility decommissioning. While all the various decommissioning wastes, which would be transported from the facility site, can be treated as wastes by either system, the entombed* facility essentially creates a new type of permanent waste site, which is readily classified as a waste requiring social commitments to the waste site.

The questions of environmental hazards and how best to represent them were a prominent point of discussion. To date the various measures of hazards all appear to have some degree of limitation. The most commonly used hazard index is the measure of the volume of water necessary to dilute various wastes to the recommended radioactivity concentrations as listed by either ICRP or 10 CFR 20 for ingestion in soluble form in unrestricted areas. This hazard index does

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*Generally, entombment includes removing the uncontaminated areas of the plant and surrounding (or perhaps filling) the grossly contaminated areas with concrete. To reduce the volume to be entombed, outlying contaminated components may be dismantled and placed inside the structure to be enclosed.

Entombment of nuclear facilities includes the following activities as a minimum: 1) offsite disposal of all solid and liquid radioactive and nonradioactive process materials, 2) controlled public access to site and facility, 3) periodic physical, radiation and environmental surveys and inspections, 4) maintenance and limited operation of lighting systems and fire protection alarms, 5) removal of salvageable uncontaminated equipment, 6) erection of "permanent" (>100 years) barriers to protect the environment from radioelements, e.g., filling radioactive vessels and cells with concrete, and 7) decontamination of the site.

not directly relate to dose to man but does provide a measure of potential dose. A detailed review of the various pathways of the radioactive material to man must be made in order to accurately evaluate the dose to man.

Concern was expressed about the limitation of mathematical models to accurately predict releases of radioactive material from specific disposal methods. It was suggested that in many cases, basic information required by models was not available.

The panel also felt that a risk analysis should be performed on the various waste management options. The information gained from such an analysis would serve as a guide to both the regulatory agencies and to the designers of waste management systems.

Specific comments from Art Carson can be found in the Appendix. Also, a paper by Dr. W. A. Rodger containing recommended waste management criteria with associated numerical values can also be found in the Appendix.

7.0 SUMMARY AND RECOMMENDATIONS

Reviewing the various classification systems and discussions of the TAP, it appears that for in-plant waste management operations a detailed multicompartmented waste classification system such as described in System I in Part 5 of this report would be in order. System I characterizes a given waste at a specific point in time by several judiciously chosen waste characteristics. Such a system provides 144 different classes by which waste may be identified; depending on the operational status of a particular waste (i.e., interim storage, in process or final product form) the crucial characteristics of the waste may be different. As an example, for high-level liquid waste in interim storage it may be most important to know the physical state and the radiation intensity. For a solidified waste product, it may be important to know the duration of hazard of that waste since it may be economically advantageous to store such waste prior to its shipment and ultimate disposal. The emphasis placed on any given waste characteristic will ultimately be based on waste management criteria and final disposal methods. This system allows the operator to economically optimize waste management procedures. For example, it allows for storage of waste at the operator's discretion until such time that it can decay to levels that it might be safely disposed of by some less expensive means. This would be an acceptable practice as long as the waste remains under the operator's responsibility. However, for purposes of final disposal or interfacility transfer, a commonly understood and accepted system of classification might be more appropriate. Since the in-plant classification system would be to a large extent at the discretion of the facility operator, and would be largely

responsive to his own particular operations and problems, it might not serve as a proper basis for general regulation. System I is, therefore, presented here only as a suggestion for a thorough and comprehensive in-plant waste classification system, but it probably would not serve as a suitable basis for general regulation.

For purposes of ultimate disposal and interfacility transfer, a waste classification system as described under System II of Part 5 would be more appropriate. System II is a classification system based on considerations necessary in formulating disposal decisions. Since the principal concerns regarding radioactive waste as a potential radiation exposure to man and the final disposal of such a waste, System II is immediately useful in formulating waste management criteria and is useful in classifying waste for final disposal decisions and regulations.

It is recommended that a waste classification system as described in System II provide the basis for NRC regulations. Prior to promulgation of such regulations it would be necessary to define quantitative criteria for delineating between the waste categories. Specifically, waste requiring isolation (high level), that requiring confinement for periods where social commitment can be assured (low level), and waste whose hazard is so low that direct dispersal to the environment would be considered acceptable.

Some principles and guidelines for quantitative definition of waste categories have been presented in this report. However, further study and deliberation will be necessary to establish a firm and defensible basis for quantitative delineation of waste categories.

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APPENDIX A

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APPENDIX B

PART 173.389

OF TITLE 49

CODE OF FEDERAL REGULATIONS

APPENDIX B

Code of Federal Regulations

§ 173.389

Title 49—Transportation

§ 173.389 Radioactive materials; definitions.

For the purpose of Parts 170-189 of this chapter:

(a) "Fissile radioactive material" means the following material: Plutonium-238, plutonium-239, plutonium-241, uranium-233, or uranium-235, or any material containing any of the foregoing materials. See § 173.396(a) for exclusions. Fissile radioactive material packages are classified according to the controls needed to provide nuclear criticality safety during transportation as follows:

(1) *Fissile Class I.* Packages which may be transported in unlimited numbers and in any arrangement, and which require no nuclear criticality safety controls during transportation. For purposes of nuclear criticality safety control, a transport index is not assigned to Fissile Class I packages. However, the external radiation levels may require a transport index number.

(2) *Fissile Class II.* Packages which may be transported together in any arrangement but in numbers which do not exceed an aggregate transport index of 50. For purposes of nuclear criticality safety control, individual packages may have a transport index of not less than 0.1 and not more than 10. However, the external radiation levels may require a higher transport index number but not to exceed 10. Such shipments require no nuclear criticality safety control by the shipper during transportation.

(3) *Fissile Class III.* Shipments of packages which do not meet the requirements of Fissile Class I or II and which are controlled to provide nuclear criticality safety in transportation by special arrangements between the shipper and the carrier.

NOTE 1: Uranium-235 exists only in combination with various percentages of uranium-234 and uranium-238. "Fissile radioactive material" as applied to uranium-235 refers to the amount of uranium-235 actually contained in the total quantity of uranium being transported.

NOTE 2: Radioactive material may consist of mixtures of fissile and non-fissile radionuclides. "Fissile radioactive material" refers to the amount of plutonium-238, plutonium-239, plutonium-241, uranium-233, uranium-235, or any combination thereof actually contained in the mixture. The "radioactivity" of the mixture consists of the total activity of both the fissile and nonfissile radionuclides. All mixtures containing "fissile material" shall be subject to § 173.396.

(b) "Large quantity radioactive materials" means a quantity the aggregate radioactivity of which exceeds that specified as follows:

(1) Groups I or II (see paragraph (h) of this section) radionuclides: 20 curies.

(2) Groups III or IV radionuclides: 200 curies.

(3) Group V radionuclides: 5,000 curies.

(4) Groups VI or VII radionuclides: 50,000 curies.

(5) Special form material: 5,000 curies.

(c) "Low specific activity material" means any of the following:

(1) Uranium or thorium ores and physical or chemical concentrates of those ores;

(2) Unirradiated natural or depleted uranium or unirradiated natural thorium;

(3) Tritium oxide in aqueous solutions provided the concentration does not exceed 5 millicuries per milliliter;

(4) Material in which the activity is essentially uniformly distributed and in which the estimated average concentration per gram of contents does not exceed:

(i) 0.0001 millicuries of Group I (see § 173.389(h)) radionuclides; or

(ii) 0.005 millicuries of Group II radionuclides; or

(iii) 0.3 millicuries of Groups III or IV radionuclides.

NOTE: This includes, but is not limited to, materials of low radioactivity concentration such as residues or solutions from chemical processing; wastes such as building rubble, metal, wood, and fabric scrap, glassware, paper and cardboard; solid or liquid plant waste, sludges, and slimes.

(5) Objects of nonradioactive material externally contaminated with radioactive material, provided that the

radioactive material is not readily dispersible and the surface contamination when averaged over an area of 1 square meter, does not exceed 0.0001 millicurie (220,000 disintegrations per minute) per square centimeter of Group I radionuclides or 0.001 millicurie (2,200,000 disintegrations per minute) per square centimeter of other radionuclides.

(d) "Normal form radioactive materials" means those which are not special form radioactive materials. Normal form radioactive materials are grouped into transport groups (see paragraph (h) of this section).

(e) "Radioactive material" means any material or combination of materials, which spontaneously emits ionizing radiation. Materials in which the estimated specific activity is not greater than 0.002 microcuries per gram of material, and in which the radioactivity is essentially uniformly distributed, are not considered to be radioactive materials.

(f) "Removable radioactive contamination" means radioactive contamination which can be readily removed in measurable quantities by wiping the contaminated surface with an absorbent material. The measurable quantities shall be considered as being not significant if they do not exceed the limits specified in § 173.397.

(g) "Special form radioactive materials" means those which, if released from a package, might present some direct radiation hazard but would present little hazard due to radiotoxicity and little possibility of contamination. This may be the result of inherent properties of the material (such as metals or alloys), or acquired characteristics, as through encapsulation. The criteria for determining whether a material meets the definition of special form are prescribed in § 173.398(a).

(h) "Transport group" means any one of seven groups into which normal form radionuclides are classified according to their radiotoxicity and their relative potential hazard in transportation, and as listed in § 173.390.

(i) "Transport Index" means the number placed on a package to designate the degree of control to be exercised by the carrier during transportation. The transport index to be assigned to a package of radioactive materials shall be determined by either subparagraph (1) or (2) of this paragraph, whichever is larger. The number expressing the transport

index shall be rounded up to the next highest tenth; e.g., 1.01 becomes 1.1.

(1) The highest radiation dose rate, in millirem per hour at three feet from any accessible external surface of the package; or

(2) For Fissile Class II packages only, the transport index number calculated by dividing the number "50" by the number of similar packages which may be transported together (see § 173.396), as determined by the procedures prescribed in the regulations of the U.S. Atomic Energy Commission, Title 10, Code of Federal Regulations, Part 71.

(j) "Type A packaging" means packaging which is designed in accordance with the general packaging requirements of §§ 173.24 and 173.393, and which is adequate to prevent the loss or dispersal of the radioactive contents and to retain the efficiency of its radiation shielding properties if the package is subject to the tests prescribed in § 173.398(b).

(k) "Type B packaging" means packaging which meets the standards for Type A packaging, and, in addition, meets the standards for hypothetical accident conditions of transportation as prescribed in § 173.398(c).

(l) "Type A quantity" and "Type B quantity" radioactive materials means a quantity the aggregate radioactivity of which does not exceed that specified as follows:

Transport group (see § 173.390(b))	Type A quantity (in curies)	Type B quantity (in curies)
I.....	0.001	20
II.....	0.05	20
III.....	5	200
IV.....	20	200
V.....	20	5,000
VI and VII.....	1,000	50,000
Special form.....	20	5,000

* Except that for Californium-252 the Type A quantity limit for special form is 1 curies.

(m) "Containment system. Containment system of a radioactive materials package means those components of the packaging including special form encapsulation where used, which have been specified by the package designer as intended to retain the radioactive contents during transport, whether or not individual vessels in the packaging retain their integrity of containment.

(n) "Maximum normal operating pressure. Maximum normal operating pressure means the maximum pressure above atmospheric pressure at mean sea level

§ 173.390

Title 49--Transportation

that would develop in the containment system in a period of 1 year, under the conditions of temperature and solar radiation corresponding to environmental conditions of transport in the absence of venting, external cooling by an ancillary system, or operational controls during transport.

(Amdt. 173-3, 33 F.R. 14822, Oct. 4, 1972; 39 F.R. 19823, Dec. 27, 1988, as amended by Amdt. 173-64, 37 F.R. 14683, July 21, 1972; Amdt. No. 173-66, 37 F.R. 17970, Sep. 2, 1972)

§ 173.390 Transport groups of radionuclides.

(a) List of radionuclides:

Element ¹	Radionuclide ²	Transport group						
		I	II	III	IV	V	VI	VII
Actinium (89)	Ac-227	X						
	Ac-228	X						
Americium (95)	Am-241	X						
	Am-243	X						
Antimony (51)	Sb-122				X			
	Sb-124				X			
	Sb-126				X			
Argon (18)	Ar-37						X	
	Ar-41			X				
	Ar-41 (uncompressed)			X				
	Ar-72				X			
Arsenic (33)	As-74				X			
	As-76				X			
	As-78				X			
	As-77				X			
Astatine (85)	At-211			X				
Barium (56)	Ba-131				X			
	Ba-133				X			
	Ba-135				X			
	Ba-140				X			
Berkelium (97)	Bk-249	X						
Beryllium (4)	Be-7				X			
	Be-10				X			
	Be-11				X			
	Be-12				X			
Bismuth (83)	Bi-209				X			
	Bi-210				X			
	Bi-212				X			
	Bi-214				X			
Bromine (35)	Br-82				X			
Cadmium (48)	Cd-109				X			
	Cd-115m				X			
Calcium (20)	Cd-116m				X			
	Cd-118				X			
Cesium (55)	Ce-45				X			
	Ce-47				X			
Cerium (58)	Ce-134				X			
	Ce-136				X			
	Ce-138				X			
	Ce-140				X			
Carbon (6)	Cf-250				X			
	Cf-252				X			
	Cf-254				X			
	Cf-256				X			
Carbon (6)	C-14				X			
	C-14				X			
	C-14				X			
	C-14				X			
Cesium (55)	Ce-134				X			
	Ce-136				X			
	Ce-138				X			
	Ce-140				X			
Chlorine (17)	Cl-36				X			
	Cl-38				X			
	Cl-39				X			
	Cl-40				X			
Chromium (24)	Cr-51				X			
	Cr-52				X			
	Cr-54				X			
	Cr-55				X			
Cobalt (27)	Co-57				X			
	Co-58m				X			
	Co-58				X			
	Co-60				X			
Copper (29)	Cu-64				X			
	Cu-66				X			
	Cu-67				X			
	Cu-68				X			
Curium (96)	Cm-242				X			
	Cm-244				X			
	Cm-246				X			
	Cm-248				X			
Dysprosium (63)	Dy-159				X			
	Dy-161				X			
	Dy-163				X			
	Dy-165				X			
Erbium (68)	Er-167				X			
	Er-169				X			
	Er-171				X			
	Er-183				X			
Europium (63)	Eu-152				X			
	Eu-154				X			
	Eu-156				X			
	Eu-158				X			
Fermium (100)	F-15				X			
	F-16				X			
	F-17				X			
	F-18				X			
Gadolinium (64)	Gd-153				X			
	Gd-155				X			
	Gd-157				X			
	Gd-159				X			
Gallium (31)	Ga-67				X			
	Ga-72				X			
	Ga-74				X			
	Ga-76				X			

See footnotes at end of table.

Element	Radioisotopes	Transport group						
		I	II	III	IV	V	VI	VII
Germanium (32)	Ge-71				X			
Gold (79)	Au-193			X				
	Au-194			X				
	Au-195			X				
	Au-196			X				
	Au-198			X				
	Au-199			X				
Hafnium (72)	Hf-181			X				
Holmium (67)	Ho-163			X				
Hydrogen (1)	T-3 (see Lithium)			X				
	T-4			X				
Iodine (53)	I-131m			X				
	I-131			X				
	I-132			X				
	I-133			X				
Iridium (77)	Ir-192			X				
	Ir-194			X				
	Ir-196			X				
	Ir-198			X				
	Ir-201			X				
	Ir-202			X				
	Ir-203			X				
	Ir-204			X				
	Ir-205			X				
	Ir-206			X				
Iron (26)	Fe-55			X				
	Fe-57			X				
	Fe-59			X				
	Fe-60			X				
Krypton (36)	Kr-81m			X				
	Kr-81m (uncompressed) 1			X				
	Kr-85			X				
	Kr-88 (uncompressed) 1			X				
	Kr-91			X				
Lanthanum (57)	La-140			X				
	La-141			X				
Lead (82)	Pb-210			X				
	Pb-212			X				
	Pb-214			X				
Lithium (3)	Li-7			X				
	Li-8			X				
Magnesium (12)	Mg-28			X				
	Mg-29			X				
Manganese (25)	Mn-54			X				
	Mn-56			X				
Mercury (80)	Hg-197m			X				
	Hg-197			X				
	Hg-201			X				
	Hg-203			X				
Mixed Fission Products	MFP			X				
Molybdenum (42)	Mo-99			X				
Neodymium (60)	Nd-147			X				
	Nd-149			X				
Neptunium (93)	Np-237			X				
	Np-239			X				
Nickel (28)	Ni-60			X				
	Ni-63			X				
	Ni-64			X				
	Ni-66			X				
Niobium (41)	Nb-93m			X				
	Nb-94			X				
	Nb-95			X				
Osmium (76)	Os-185			X				
	Os-191m			X				
	Os-192			X				
	Os-194			X				
Palladium (46)	Pd-103			X				
	Pd-109			X				
Phosphorus (15)	P-32			X				
Platinum (78)	Pt-191			X				
	Pt-193			X				
	Pt-195m			X				
Plutonium (94)	Pt-197m			X				
	Pt-197			X				
	Pu-238			X				
	Pu-239			X				
	Pu-240			X				
Polonium (84)	Pu-241			X				
	Pu-242			X				
Potassium (19)	Po-210			X				
Potassium (19)	K-40			X				
Praseodymium (59)	Pr-142			X				
	Pr-143			X				

See footnotes at end of table.

Elements ¹	Radionuclides ¹	Transport group						
		I	II	III	IV	V	VI	VII
Promethium (61).....	Pm-147.....				X			
	Pm-149.....				X			
Protactinium (81).....	Pa-230.....		X					
	Pa-231.....		X					
	Pa-232.....			X				
	Pa-233.....			X				
Radium (88).....	Ra-223.....			X				
	Ra-226.....		X					
	Ra-228.....		X					
Radon (86).....	Rn-220.....				X			
	Rn-222.....		X					
Rhenium (75).....	Re-185.....				X			
	Re-186.....				X			
	Re-187.....				X			
	Re-188.....				X			
	Re Natural.....				X			
Rhodium (45).....	Rh-103.....				X			
	Rh-105.....				X			
Rubidium (37).....	Rb-86.....				X			
	Rb-87.....				X			
	Rb Natural.....				X			
Ruthenium (44).....	Ru-44.....				X			
	Ru-101.....				X			
	Ru-102.....				X			
	Ru-104.....				X			
	Ru-106.....				X			
Rutherfordium (104).....	Rf-261.....				X			
	Rf-263.....				X			
	Rf-265.....				X			
	Rf-267.....				X			
	Rf-269.....				X			
	Rf-271.....				X			
	Rf-273.....				X			
	Rf-275.....				X			
	Rf-277.....				X			
	Rf-279.....				X			
	Rf-281.....				X			
	Rf-283.....				X			
	Rf-285.....				X			
	Rf-287.....				X			
	Rf-289.....				X			
	Rf-291.....				X			
	Rf-293.....				X			
	Rf-295.....				X			
	Rf-297.....				X			
	Rf-299.....				X			
	Rf-301.....				X			
	Rf-303.....				X			
	Rf-305.....				X			
	Rf-307.....				X			
	Rf-309.....				X			
	Rf-311.....				X			
	Rf-313.....				X			
	Rf-315.....				X			
	Rf-317.....				X			
	Rf-319.....				X			
	Rf-321.....				X			
	Rf-323.....				X			
	Rf-325.....				X			
	Rf-327.....				X			
	Rf-329.....				X			
	Rf-331.....				X			
	Rf-333.....				X			
	Rf-335.....				X			
	Rf-337.....				X			
	Rf-339.....				X			
	Rf-341.....				X			
	Rf-343.....				X			
	Rf-345.....				X			
	Rf-347.....				X			
	Rf-349.....				X			
	Rf-351.....				X			
	Rf-353.....				X			
	Rf-355.....				X			
	Rf-357.....				X			
	Rf-359.....				X			
	Rf-361.....				X			
	Rf-363.....				X			
	Rf-365.....				X			
	Rf-367.....				X			
	Rf-369.....				X			
	Rf-371.....				X			
	Rf-373.....				X			
	Rf-375.....				X			
	Rf-377.....				X			
	Rf-379.....				X			
	Rf-381.....				X			
	Rf-383.....				X			
	Rf-385.....				X			
	Rf-387.....				X			
	Rf-389.....				X			
	Rf-391.....				X			
	Rf-393.....				X			
	Rf-395.....				X			
	Rf-397.....				X			
	Rf-399.....				X			
	Rf-401.....				X			
	Rf-403.....				X			
	Rf-405.....				X			
	Rf-407.....				X			
	Rf-409.....				X			
	Rf-411.....				X			
	Rf-413.....				X			
	Rf-415.....				X			
	Rf-417.....				X			
	Rf-419.....				X			
	Rf-421.....				X			
	Rf-423.....				X			
	Rf-425.....				X			
	Rf-427.....				X			
	Rf-429.....				X			
	Rf-431.....				X			
	Rf-433.....				X			
	Rf-435.....				X			
	Rf-437.....				X			
	Rf-439.....				X			
	Rf-441.....				X			
	Rf-443.....				X			
	Rf-445.....				X			
	Rf-447.....				X			
	Rf-449.....				X			
	Rf-451.....				X			
	Rf-453.....				X			
	Rf-455.....				X			
	Rf-457.....				X			
	Rf-459.....				X			
	Rf-461.....				X			
	Rf-463.....				X			
	Rf-465.....				X			
	Rf-467.....				X			
	Rf-469.....				X			
	Rf-471.....				X			
	Rf-473.....				X			
	Rf-475.....				X			
	Rf-477.....				X			
	Rf-479.....				X			
	Rf-481.....				X			
	Rf-483.....				X			
	Rf-485.....				X			
	Rf-487.....				X			
	Rf-489.....				X			
	Rf-491.....				X			
	Rf-493.....				X			
	Rf-495.....				X			
	Rf-497.....				X			
	Rf-499.....				X			
	Rf-501.....				X			
	Rf-503.....				X			
	Rf-505.....				X			
	Rf-507.....				X			
	Rf-509.....				X			
	Rf-511.....				X			
	Rf-513.....				X			
	Rf-515.....				X			
	Rf-517.....				X			
	Rf-519.....				X			
	Rf-521.....				X			
	Rf-523.....				X			
	Rf-525.....				X			
	Rf-527.....				X			
	Rf-529.....				X			
	Rf-531.....				X			
	Rf-533.....				X			
	Rf-535.....				X			
	Rf-537.....				X			
	Rf-539.....				X			
	Rf-541.....				X			
	Rf-543.....				X			
	Rf-545.....				X			
	Rf-547.....				X			
	Rf-549.....				X			
	Rf-551.....				X			
	Rf-553.....				X			
	Rf-555.....				X			
	Rf-557.....				X			
	Rf-559.....				X			
	Rf-561.....				X			
	Rf-563.....				X			
	Rf-565.....				X			
	Rf-567.....				X			
	Rf-569.....				X			
	Rf-571.....				X			
	Rf-573.....				X			
	Rf-575.....				X			
	Rf-577.....				X			
	Rf-579.....				X			
	Rf-581.....				X			
	Rf-583.....				X			
	Rf-585.....				X			
	Rf-587.....				X			
	Rf-589.....				X			
	Rf-591.....				X			
	Rf-593.....				X			
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	Rf-601.....				X			
	Rf-603.....				X			
	Rf-605.....				X			
	Rf-607.....				X			
	Rf-609.....				X			
	Rf-611.....				X			
	Rf-613.....				X			
	Rf-615.....				X			
	Rf-617.....				X			
	Rf-619.....				X			
	Rf-621.....				X			
	Rf-623.....				X			
	Rf-625.....				X			
	Rf-627.....				X			
	Rf-629.....				X			
	Rf-631.....				X			
	Rf-633.....				X			
	Rf-635.....				X			
	Rf-637.....				X			
	Rf-639.....				X			
	Rf-641.....				X			
	Rf-643.....				X			
	Rf-645.....				X			
	Rf-647.....				X			
	Rf-649.....				X			
	Rf-651.....				X			
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	Rf-657.....				X			
	Rf-659.....				X			
	Rf-661.....				X			
	Rf-663.....				X			
	Rf-665.....				X			
	Rf-667.....				X			
	Rf-669.....				X			
	Rf-671.....				X			
	Rf-673.....				X			
	Rf-675.....				X			
	Rf-677.....				X			
	Rf-679.....				X			
	Rf-681.....				X			
	Rf-683.....				X			
	Rf-685.....				X			
	Rf-687.....				X			
	Rf-689							

Element ¹	Radionuclide ²	Transport group						
		I	II	III	IV	V	VI	VII
Tungsten (74)	W-181					X		
	W-183					X		
	W-187					X		
	U-230		X	X				
Uranium (92)	U-232 ³		X	X				
	U-234			X				
	U-235			X				
	U-238			X				
	U Natural			X				
	U Enriched ⁴			X				
	U Depleted			X				
	V-48					X		
Vanadium (23)	V-48					X		
	X-125			X				
Xenon (54)	X-131m			X				
	X-131m (uncompressed) ⁵					X		
	X-133			X				
	X-133 (uncompressed) ⁵			X				X
	X-135		X					
	X-135 (uncompressed) ⁵		X					
Ytterbium (70)	Yb-175				X			
	Y-88			X				
Yttrium (39)	Y-88			X				
	Y-90			X				
	Y-91m			X				
	Y-91			X				
	Y-92			X				
	Y-93			X				
Zinc (30)	Zn-65			X				
	Zn-69m			X				
	Zn-69			X				
Zirconium (40)	Zr-90			X				
	Zr-95			X				
	Zr-97			X				

¹ Atomic number shown in parentheses.² Uncompressed means at a pressure not exceeding 14.7 p.s.i. (absolute).³ Atomic weight shown after the radionuclide symbol.⁴ Plastic radionuclide material.

(b) Any radionuclide not listed in the above table shall be assigned to one of the groups in accordance with the following table:

Radionuclide	Radioactive half-life		
	0-1,000 days	1,001 days to 10 ⁵ years	Over 10 ⁵ years
Atomic number 41	Group III.	Group II....	Group I.
Atomic number 82 and over.	Group I..	Group I....	Do.

Note 1: No unlisted radionuclides shall be assigned to Groups IV, V, VI, or VII.

(c) For mixtures of radionuclides the following shall apply:

(1) If the identity and respective activity of each radionuclide are known, the permissible activity of each radionuclide shall be such that the sum, for all groups present, of the ratio between the total activity for each group to the permissible activity for each group will not be greater than unity.

(2) If the groups of the radionuclides are known but the amount in each group cannot be reasonably determined, the mixture shall be assigned to the most restrictive group present.

(3) If the identity of all or some of the radionuclides cannot be reasonably determined, each of those unidentified radionuclides shall be considered as belonging to the most restrictive group which cannot be positively excluded.

(4) Mixtures consisting of a single radioactive decay chain where the radionuclides are in the naturally occurring proportions shall be considered as consisting of a single radionuclide. The group and activity shall be that of the first member present in the chain, except if a radionuclide "x" has a half-life longer than that of that first member and an activity greater than that of any other member including the first at any time during transportation; in that case, the transport group of the nuclide "x" and the activity of the mixture shall be the maximum activity of that nuclide "x" during transportation.

[Amdt. 173-3, 33 F.R. 14923, Oct. 4, 1968]

APPENDIX C

PAPER BY

DR. W. A. RODGER

Critical Evaluation of the Limit of
Transuranic Contamination of Low Level Waste

by

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Throughout this afternoon's session we have heard details of the kinds and quantities of wastes which will be produced at reprocessing plants. It is the purpose of this paper to consider the effect upon these reprocessing wastes, and the potential effect upon reactor and other fuel cycle wastes, of the use of a transuranic limit of 10 nanocuries/gram.

The "limit" of 10 nanocuries/gram has not as yet been set finally and fully in Regulatory concrete. But it is close enough to being set that if vigorous and resolute troweling does not very soon take place, the surface of the walkway will forever be gouged and blemished.

Ten nanocuries/gram is a classic example of regulation by bureaucratic fiat, without consideration of what level is really required, without benefit of environmental impact statement, without benefit of cost-benefit studies—and certainly without benefit of clergy. It is a level selected arbitrarily by the AEC (ERDA Division) as guidance to its contractors for segregation of waste for possible (emphasis mine) later transfer to a National Repository. It is a level which has been suggested by AEC (NRC Division) as a footnote to a proposed rule making. It is a level which has been enthusiastically embraced by over-zealous State Regulatory types to the point it has essentially become law by default. It is a crying shame!

In order to properly determine a limit for transuranic contamination, we must first define what it is we are trying to accomplish. We must establish who it is we are trying to protect and from what. Six years ago in a paper given at Bal Harbour this author suggested that our Regulators had not answered these two questions.⁽¹⁾ They still haven't. There are only two plausible answers to these questions. We are trying either:

- 1) to protect the air and water supply of the general public from contamination at levels approaching MPC, in either the immediate or long-term future, or
- 2) to protect any individual at any time in the future from stumbling onto the material and either eating or more likely breathing the material in sufficient quantity to injure himself.

The first of these goals is a sine qua non for any acceptable waste disposal system. It is highly unlikely that the second can be guaranteed no matter what we do, and it is highly questionable that it should be done, even if it could be done. Let us first consider reprocessing wastes in light of these two goals.

High Level Wastes

Earlier papers in this session have shown that solidified high level waste, the only reprocessing waste which has received any in-depth consideration, represents only 3% of the volume of wastes produced by a reprocessor. This waste is the only self-heating waste produced. It contains essentially all of the fission products, americium and curium from the spent fuel; it also contains 1 to 2 percent of the plutonium and up to 1 percent of the uranium. It has already been edicted that this waste must go to the National Repository—whether because of its fission product content or of its transuranic content is not completely clear.

Figure 1 illustrates the character of the high level waste as a potential contaminator of drinking water. (It is presumed that in any event waste would be buried sufficiently deep that the possibility of air contamination is eliminated.) The left-hand ordinate of Figure 1 gives the volume of water required to dilute the waste products from a tonne of fuel to drinking water tolerance, a value which I have called the hazard index. The right hand ordinate gives the length of time a small creek (10^7 cc/sec = 350 CFS) would have to run to produce the amount of water called for by the hazard index. The abscissa is time of decay. The backup calculations for Figure 1 are given in Table 1. A number of interesting observations can be drawn from Figure 1.

- 1) When the waste is shipped to the repository (after 10 years on-site storage) 28-year Sr-90 accounts for 99% of the total hazard potential. It continues to be greater than half of the total for 300 years.
- 2) At the end of 300 years the hazard potential has dropped by a factor of just about 1000. At that time the flow of our small (10^7 cc/sec) creek would dilute the waste from a tonne of fuel to drinking water tolerance in less than a year.
- 3) From 300 to 1000 years the hazard index is dominated by 458-year Am-241. At the end of 1000 years the total hazard index has dropped by a factor of about 5000 and it is then no greater than that of the natural ore which produced that tonne of fuel in the first place. Our small stream would dilute the entire tonne to drinking water tolerance in about 100 days.

4) From then on decay proceeds more slowly. From 1000 to 10,000 years the hazard index is dominated by 8000-year Am-243. From 10,000 to 50,000 years 24,300-year Pu-239 dominates. This is the only period of time during which any plutonium isotope is the dominant factor. After 50,000 years the hazard index has been reduced by a factor of 70,000 and our small stream would require but three days to dilute the remaining activity to drinking water tolerance.

5) From 50,000 to 2,000,000 years the dominant activity is Ra-226—not a transuranic. After 2,000,000 years the hazard index has been reduced by a factor of 5,000,000. Our small stream would need one hour to dilute the remaining waste products to drinking water tolerance. The waste still exceeds the "magic" 10 nanocuries/gram by a factor of about 100!

6) After 2,000,000 years and for the next 8,000,000 years a transuranic, 2.2 million-year Np-237, takes over as the dominant isotope. During this period, after a total of 4,000,000 years have elapsed, the waste reaches the hazard index of pure U-238 (no U-235 and no daughter products; remember too that U-238 is three to 90 times as toxic as a heavy metal than it is as a radiological hazard). At this point the hazard index has been reduced by a factor of 20 million and our small stream would dilute the remaining waste products to drinking water tolerance in less than 15 minutes. Yet the waste is still about 30 times the "magic" number!

7) After 10^7 years the waste becomes a uranium waste with the 235, 236, and 238 isotopes all contributing. After about 40 million years the waste finally reaches 10 nanocuries/gram, Bingo! At that point the small stream will dilute the 10 nanocuries/gram to drinking water tolerance in a few seconds. Mirabile Dictu!

From the above I draw the following conclusions:

1) In order to meet the first, and most important criterion—the protection of public water supplies—we need design only for the Sr-90 content.

2) By the time any transuranic component becomes important the magnitude of the problem has been reduced by a factor of 1000.

3) I can conceive of no process, geologic or galactic, which would thereafter convert a problem which has been under control for a millenium to one which is out of control.

4) Therefore at the end of 1000 years the problem has been solved.

5) It follows that there is no need to impose any transuranic limit on high level waste insofar as protecting public water supplies, nor or at any time in the future, is concerned.

6) We shall consider the "stumbler number" in connection with other reprocessing wastes.

Spent Fuel Elements

At the present time there is no assurance that spent fuel will ever be reprocessed. And there will be no reprocessing until a favorable "GESMO"⁽²⁾ decision has been made. If recycle of plutonium is not permitted, nuclear energy is not going to go away, as is hoped by many opponents of nuclear energy; instead spent fuel elements will be buried rather than waste. It is of interest, therefore, to note how spent fuel elements compare to reprocessing wastes. Figure 2 is similar to Figure 1 except that the "wastes" discarded are the spent fuel elements themselves. Data backing up Figure 2 are shown in Table 2.

From Figure 2 and Table 2 the following observations can be drawn.

- 1) Spent fuel elements, while they represent a somewhat greater hazard than reprocessing wastes, differ from them only in degree, not in kind.
- 2) Again for the first 200 years the hazard is dominated by Sr-90. At the time the fuel elements would be buried Sr-90 would account for more than 99% of the hazard potential.
- 3) In this case it will take 10,000 years to reduce the hazard potential to that of the ore from which the tonne of fuel originally came (vice 1000 years for reprocessing waste).
- 4) Plutonium isotopes dominate the problem only during the period from 1000 to 50,000 years. In this period the hazard potential is 2.5 to 4 orders of magnitude less than it was originally when dominated by Sr-90.
- 5) From 50,000 to two million years Ra-226 is the dominant activity; from two million to five million years it is Np-237; from five million to ten million years it is Np-237 plus U-236; from ten to 100 million years it is the three uranium isotopes; thereafter it is U-238.
- 6) It takes about a quarter of a billion years to reach the hazard potential of U-238. For all practical purposes fuel elements would never reach 10 nanocuries/gram.

The conclusions drawn in respect to high level waste hold also for spent fuel elements. The comparison of spent fuel with wastes is more easily seen on Figure 3. The integrated area under the spent fuel curve is approximately three times that under the waste curve.

Leached Hulls

We have seen that there is four times as much volume of leached hulls as there is of solidified high level waste. At the present time hulls

would be charged for, and treated as, high level waste—so the cost of disposal of hulls will be several times the cost of disposing of high level waste. This is, of course, an absurdity and presumably some more logical handling of hulls will be developed. By why should hulls go to the Repository in the first place? Table 3 and Figure 4 show the characteristics of hulls as waste as a function of time. These exhibits were prepared deliberately using much too high losses to the hulls. A loss of 0.5% of uranium, plutonium, fission products, and americium and curium to the hulls has been assumed. This should represent the absolute upper limit of losses to hulls. The average loss is about 20% or less of this. Even with this overstatement of loss it can be seen that:

- 1) As we have seen before the waste is initially dominated by Sr-90 and it continues to be so for 200 years.
- 2) After just 100 years the hazard potential of the hulls has fallen to that of the ore which produced the fuel in the first place.
- 3) By the time the first transuranic isotope becomes important (Am-241 after about 300 years) the hazard index has dropped by a factor of over 200, and it is more than an order of magnitude less than that of the initial ore.
- 4) On Figure 4 the I-129 contribution has been shown. I-129 is never present in concentrations greater than 1 nanocurie/gram. Yet its hazard index dominates the total from 5 million years to 100 million years. This well illustrates the fact that any concentration limit ignores the differences in radiological hazard of the various constituents.

Now let us set up a more logical scenario in which hulls are not sent to the Repository at all, but rather are kept at the producing site. I have found that my friends at NFS and AGNS are both sensitive to calculations based on their sites. Therefore I will base the following calculations on an hypothetical site with the following characteristics:

Plant Owner:	AGOTHS Corporation
Capacity:	1000 tonnes/year
Location:	West Barnsmell, New Carolina
Plant Discharges and Site Drainage to:	Lower Three Cat Creek (average flow 10^7 cc/sec = 350 CFS)

Hulls buried in soil with the following characteristics:

Porosity	0.15
Density	2 g/cc
Distance to nearest surface water	3000 cm
Rate of water movement in soil	0.1 cm/day

Ion exchange constants for soil:

Co-60	2500 $\frac{\text{meq/gram solid}}{\text{meq/cc liquid}}$
Sr-90	50
I-129	25
Cs-137	2500
Pu, Am, Cm	2500

Now I am going to assume that hulls from 30 years of operation are buried in this soil and that all of these hulls are at the overly conservative concentration used previously, i.e. 0.5% loss of all components to hulls. And I am going to analyze the possibility that any activity could present itself to Lower Three Cat Creek at concentrations approaching the concentrations permitted by Appendix B of 10 CFR 20.

Numerous mechanisms are operative to provide a defense in depth against abrogation of the burial ground's containment of radioactivity. These mechanisms include:

- Retention of the radioactivity in and on the waste itself.
- Retention of the radioactivity within the burial trench soil.
- Retention of the radioactivity on the soil between the trench and any point of emergence.
- Decay of radioactivity during travel time from the trench to the nearest watercourse.
- Dilution of emergent activity in Lower Three Cat Creek.

A discussion of each of these mechanisms follows.

Mechanism No. 1—Retention in Hulls. More than 95% of the radioactivity associated with the leached hulls is induced radioactivity, primarily Co-60, and is an integral part of the metal itself; therefore, in order for this radioactivity to escape, the metal itself must dissolve. The remainder of the radioactivity associated with hulls is fission product and transuranic species in the form of refractory oxides. All of this radioactivity which remains with the hulls failed to be removed from the hulls during several hours of vigorous boiling in nitric acid and during subsequent washing; consequently, ground water should remove these radioactivities only very slowly, if at all.

To my knowledge there have been no direct measurements made of the rate of removal of activity from buried leached hulls partly because not

many have been buried as yet and partly because the removal rate is so low it is essentially not measurable. It is inconceivable that the removal rate from leached hulls could be within several orders of magnitude of that for mixed trash; however, for this analysis an annual removal fraction from the hulls was assumed to be only one factor of ten below that experienced for general trash burial grounds, i.e. 10^{-7} escape from hulls per year (see Mechanism #2).

Mechanism No. 2—Retention in the Burial Hole. The escape rate of radioactivity from buried waste has been estimated based upon experience in the operation of the commercial burial ground at West Valley, NY. In 1970, a burial trench was filled during just about one year's operation. When completed it contained about 150,000 cubic feet of buried waste (300,000 cubic feet of trench volume) and the estimated gross radioactivity was 40,000 to 45,000 curies. When the trenches are dug they are sloped to one end and filling is started at the other end. During filling, rain and snow collect in the open trench and this water is kept pumped out into a monitoring lagoon. Any leaching operation is greatest at the initial point and tails off with time; therefore, the amount of radioactivity getting into this rain water during the filling period should be a reasonably good measure of the maximum escape rate which would ever be expected. During the approximately one year the trench was being filled about 10^6 gallons of liquid were pumped from the trench into the waste burial lagoon where they were monitored before discard. The activities measured in this water ranged from 10^{-6} to 10^{-4} $\mu\text{c/cc}$ and averaged about 10^{-5} $\mu\text{c/cc}$. At 10^{-5} $\mu\text{c/cc}$ the million gallons accounted for a total of 40×10^{-3} Ci of radioactivity of the estimated total content of 40,000 curies. So the approximate annual escape fraction was 10^{-6} .

Because the fractional escape coefficients for trash burial include factors for both the retention on the waste itself and for the retention within the trench by precipitation and natural ion exchange, no additional retention of the leached hull activity is assumed in this analysis for the ion exchange within the trench itself. However, since the retention of radioactivity on and in the hulls obviously will be much greater than that for mixed trash, the use of an escape rate from the hull trench of 10^{-7} fraction/year (only one factor of 10 lower than that demonstrated for trash burial) is believed highly conservative and the expected release is several orders of magnitude lower.

Mechanism No. 3—Retention of Radioactivity within soil near the trench. If radioactivity were to move out from the initial burial trench, it would be confronted laterally by 3000 cm (100 feet) of soil. Experience with the trash burial trenches has shown that it is not possible to find radioactivity

in the surrounding soil more than a few feet from the trenches, thereby indicating that any radioactivity which does escape the trench is being reabsorbed on the surrounding soil.

The natural ion exchange capacity of the soil through which any activity which escaped the initial trench would have to move before reaching surface water is so vast that no radioactivity, with the exception of tritium (when present) and very long-lived isotopes, would be able to move very far from the trench before it had decayed to insignificance. The effect of the natural ion exchange capacity of the soil is to greatly slow down the rate of movement of the radioactivity through the soil in relation to the movement of ground water through the same soil.

To characterize this slowing down a soil-water equilibrium model was set up, equations developed, and solutions to the equations were accomplished with a relatively simple computer program, INTERLOC. For all values of the problem parameters of practical interest the solution can be approximated very closely as follows:

$$F_i = \frac{1}{(2\pi n) K_{Di} K}$$

$$T_i = \frac{DK_{Di} R}{W}$$

$$n = \frac{D}{W t_e}$$

$$R = \frac{(1-P)\rho}{P}$$

where:

F = maximum fraction of initially released activity which will ever appear at point of discharge (decay neglected), dimensionless.

T = time at which the maximum fraction, F , will be seen at the discharge point, days.

n = a dimensionless parameter which in effect characterizes the number of "equilibrium stages" of ion exchange available during transit.

K_D = equilibrium constant for ion exchange, $\frac{\text{meq/gram solid}}{\text{meq/cc liquid}}$

P = porosity of the soil, cc liquid/cc

ρ = density of soil particles, g/cc

D = distance through which water and radioactivity must travel to reach discharge point, cm

W = rate of travel of water, cm/day

t_e = time for ion exchange equilibrium to be established, day

R = ratio of solid to liquid in soil, gram solid/cc liquid

i = identification of specific nuclide

Equilibrium is reached very quickly—in less than an hour. For conservatism, I have used in these calculations a value of 1 day for t_e . (The use of 1 hr vice 1 day for t_e would produce a value of F a factor of five lower.)

Based on the assumptions outlined above, the following maximum fractions released to surface streams are:

Nuclide	K_D	T, days	Maximum Fraction of Released Activity at Release Point
Co-60	2500	8.5E+08	8E-08
Sr-90	50	1.7E+07	4E-06
I-129	25	8.5E+05	8E-06
Cs-137	2500	8.5E+08	8E-08
Pu-233			
Pu-239			
Pu-240			
Pu-241			
Pu-242			
Am-241			
Am-243			
Cm-242			
Cm-244			

The values of F represent the fraction of the initially released activity which would be seen at the time of maximum discharge concentration if there were no decay during transit. This fraction results simply from the spreading out of the band of released activity through the soil and the holdup of a large fraction of the activity on the solid particles through which the liquid flows.

Mechanism No. 4—Decay during Travel. As indicated above, the effect of the natural ion exchange capacity of the soil is to produce a time of travel for the radioactivity much longer than that for the ground water. The time of appearance of the maximum of the "activity wave" is independent of the assumed equilibrium time (i.e., it is independent of n) but it is a function of K_p . During the time of travel radioactive decay will of course take place such that the fraction of the initially released activity remaining at the time of appearance of the "wave crest" will be:

$$\text{Fraction remaining} = e^{-\lambda_i T_i}$$

For the postulated release this amounts to:

Isotope	Half Life years	λ day ⁻¹	T days	$e^{-\lambda_i T_i}$
Co-60	5.2	3.7E-04	8.5E+08	<E-100
Sr-90	28	6.8E-05	1.7E+07	<E-100
I-129	1.6E+07	1.2E-10	8.5E+06	0.998
Cs-137	30	6.3E-05	8.5E+08	<E-100
Pu-238	86	2.2E-05		<E-100
Pu-239	2.4E+04	7.8E-08		1.6E-29
Pu-240	6.6E+03	2.9E-07		<E-100
Pu-241	13	1.5E-04		<E-100
Pu-242	3.8E+05	5.0E-09		1.4E-02
Am-241	4.6E+02	4.1E-06		<E-100
Am-243	7.8E+03	2.4E-07		2.5E-89
Cm-242	0.5	4.3E-03		<E-100
Cm-244	17.5	1.1E-04		<E-100

Mechanism No. 5--Dilution in Watercourse. We have assumed that the small watercourse into which the burial area drains has an average flow of about $1E07$ cc/sec ($8.6E11$ /day-- $3.1E14$ cc/year) and that this amount of water is available to dilute whatever activity finally reaches the stream. A summary of the calculations outlined above is given in Table 4. It can be seen from that table that the concentration of each isotope is less than E-100 μ c/ml with the exception of I-129, Pu-239, and Pu-242. The highest value is that for I-129, $1.5E-20$ / μ c/cc. This is an unmeasurable, insignificant value 12 orders of magnitude below MPC. Pu-242 is of the same order of insignificance as I-129. Pu-239 is another 23 orders of magnitude lower. The rest are all less than E-100. These extremely low concentrations well illustrate the mathematical trap we fabricate when using negative exponents--there is no zero. One is tempted to say (as does my HP-35) that E-100 is zero, and there is no release.

Thus our first and most important goal, the protection of the public water supplies, can be quite easily met by many well selected sites. The plutonium problem has been blown out of all proportion. To meet this goal we need have no transuranic concentration limit at all. Rather we need to establish total inventory limits based on a particular site's capability for containment of activity.

That leaves us then with the second problem, the 25th century stumbler. If we are to go to great lengths to put these wastes in geologically stable formations, the justification has to be that we are trying to reduce the "stumble quotient", the required expenditures cannot be justified on the basis of protecting water supplies.

So how is our stumbler going to be exposed. First he has to dig into the waste. Then he has either to eat it or to breathe it. The latter seems the more likely. Consider the effect upon a stumbler digging into the overly conservative concentration of hulls we have been considering. At the end of thirty years the total inventory of buried hulls would contain about $7E05$ curies of plutonium alpha activity in about $3E04$ cubic meters. At a density of 2 grams/cc this would be an effective plutonium concentration of about 10,000 nanocuries per gram. At an average specific activity of 0.33 curie/gram, this is equivalent to $6.5E07$ μ grams/m³ or 33 μ grams/gram. Now suppose our "stumbler" were to dig out 1 m³ of this waste in 1 hour, stirring up dust the while. A reasonable dust level for such an operation might be about 1000 μ grams/m³ of air and he would be expected to breathe about 1m³ of air in one hour. Therefore in an hour of vigorous digging into this waste he would have taken into his body 0.001×33 or 0.033 μ gram of plutonium. Cohen has calculated that the required intake of reactor-produced plutonium to produce a cancer (after

15 to 45 years) is about:

Inhalation	260 μ grams
Ingestion	2.3E06 μ grams.

Thus in his one hour of digging the stumbler would have taken in $\frac{0.033}{260}$ or

about 10^{-4} of the amount necessary to acquire a cancer-producing body burden. If he dug up about a third of the total buried waste (it would take him about three years at 8 hours/day), he would have about achieved the intake necessary to have a 50/50 chance of acquiring a cancer in 15 to 45 years. If the stumbling occurred more than 200 years after burial (and it better since the Sr-90 would have gotten him long before the plutonium would do him in) then the toxicity of the plutonium would be about four times less due to the decay of the Pu-238 and he would have to dig up the whole waste body (over about twelve years) to reach 260 μ grams intake.

Of course he could eat the waste. If he did this he would have to eat 2.3E06 or 70,000 grams (150 lb) of the waste.

33

It is possible, but does not seem likely, that one of these events might occur. But in any event we are dealing with an hypothetical individual—not the general public. Furthermore no matter what we do with the waste, I suggest you cannot guarantee that for all time no one will ever stumble on that waste, at which point you must consider the same scenario. In fact I believe that burying waste in salt, an article of commerce and food, almost guarantees that some day someone will dig into it.

Remember also this example is based upon a hulls containing the highest conceivable concentration of transuranics. (Even high level waste would contain no more.)

Consider the same scenario at the proposed 10 nanocurie/gram level. Now our stumbler would have dig up the entire body of waste (over ten years) and he would still have taken in only 0.003 of the plutonium required for a 50/50 probability of latest cancer. Alternatively he would have to eat 150,000 lb of the 10-nanocurie waste.

So on both counts the 10 nanocurie-gram limit is too low. For protection of water supplies no limit at all is necessary. To protect the stumbler, if that even can be done at all, the value is vastly out of line.

Cost

Now what additional costs are imposed by the use of a limit on transuranics of 10 nanocuries/gram. First of all the limit will require that the hulls, which we have shown could be safely buried on the West Barnsmell site, will have to go to the Repository. And at present they would be charged for as high level waste. A recent study suggests that the cost of shipping the hulls to the Repository plus their handling at that site will be between \$20 and \$30 per kg of fuel processed. Thus the additional cost to each reactor will be about \$600,000-\$900,000/year. For the 150-odd reactors now in operation or under construction this amounts to an annual bill of \$ 90,000,000 to \$135,000,000.

The 10-nanocurie limit will also dictate that most, if not all, of the 180,000 cu ft/year of other waste from the reprocessing plant would have to go to the Repository. Since all of these wastes would have transuranic contents well below that of the super hulls I have used for illustrative purposes in this paper, all of them could be safely buried either on the producing site or in one of the commercial burial grounds. The cost penalty for sending them to the Repository, vis-a-vis a commercial burial ground, will be not less than \$25/cu ft. Thus the penalty from a single 1500-tonne reprocessing plant will be \$4,500,000/year. Such a reprocessing plant can service about 50 reactors so the annual cost for the 150 reactors already in being or under construction is between 10 and 15 million dollars per year.

Finally there is the trash from the reactors themselves to consider. At 10 nanocuries/gram there is no way in which a reactor operator can prove that he meets this limit. It is therefore entirely possible that this reactor waste also must go to the Repository. If this were to happen an additional cost to the consumer of from \$35,000,000 to \$45,000,000/year would result. Thus the total annual tribute to be laid on the altar of 10 nanocuries/gram ranges from \$135,000,000/year to \$200,000,000/year.

Benefit

Now \$200,000,000/year while it is a lot of money, if is not a disqualifying amount of money. So if we really got anything for the money, we could afford to pay it. The question is, what are we getting for that \$200,000,000?

First lets consider what we are not getting for the money. We are not getting anything in the way of increased protection of the public air and water supplies for the immediate (next millenium) or long-term (forever) future. In any event the possibility of indiscriminate

contamination of water or air has been taken care of. The total justification for the expenditure of this \$200,000,000/year, 5 billion dollars for the rest of this century (1975 dollars), must be based on the presumed additional protection of inadvertent stumblers into this waste in future millennia.

To justify this expenditure on a cost-benefit basis we would have to conclude that we had prevented 10,000 stumblers from dying. Personally I find it hard to believe that transferring waste from an inedible "silty till", for instance, into edible salt will do that. Nor do I see that a culture (ours) which is systematically raping the limited fossil fuel reserves of our planet and thus setting up vast numbers of future "health effects" should be able to soothe its conscience by pretending that as a by-product of reducing that rape (by the rational use of nuclear energy) we have protected a few stumblers over the next several million years.

Because the calculation of the "benefit" side of this equation is fraught with imponderables and subjective judgments, the range of answers obtained is likely to be wide. The fact that it is not easy to do does not justify not doing it. And our Regulators have no business putting forth this limit—or any other limit for that matter—without first making as careful a cost benefit analysis as practicable. There is no other way to determine what is as low as reasonably achievable.

So I have the following proposals to make in regard to the setting of limits for transuranics in waste.

1) Apply the principle of BITODB—back to the old drafting board. Before NRC issues its next proposed rule for comment the problem should be restudied and the necessary environmental statement and as low as reasonably achievable analysis made.

2) I recognize that 10 nanocuries/gram has become ingrained in a lot of minds and will probably be hard to change. So I propose simply that it be redefined—properly this time. Ten nanocuries/gram is not a proper dividing point between on-site or commercial burial and the National Repository; it is, however, a proper limit to apply below which a waste could be put on the city dump or used in one's back yard as mulch for the tomatoes. In short it is the limit of complete innocuousness, and that is what it should be used for.

3) A limit should be established for deciding between on-site (or commercial) burial and the Repository. There should be two aspects to that limit. One should be a total site inventory limit. This would be

site dependent and would be based on the capability of the site to protect the public water supplies in the area surrounding that site. The second aspect would be a concentration limit which would be based on reasonable expectations of how a stumbler might eat or breathe the waste and upon recognition of the fact that this limit is not needed for protection of the general public—but rather for the protection of a very limited number of hypothetical individuals and as such does not deserve the application of the usual superimpositions of over-conservative assumptions piled upon one another serially so as produce an absurd result.

The new limit should be determined on the basis of realistic assumptions, as outlined herein. The result should be a far cry from 10 nanocuries/gram. This discussion suggests that it should be higher by several orders of magnitude. Such a limit would provide entirely adequate protection for distant archeologists and no limit on transuranics is needed to provide protection for public water supplies.

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FIGURE 1

HAZARD INDEX OF SPENT FUEL ELEMENTS

FIGURE 3
COMPARISON OF HAZARD INDICES OF REPROCESSING WASTE AND SPENT FUEL ELEMENTS

FIGURE 4

Table 1.
Hazard Index of Wastes from Reprocessing

page 1 of 3

Isotope	Isotopic Content, curies/tonne			Half-Life years	λ year ⁻¹	MPC $\mu\text{C/cc}$ ^c	Hazard Index cc/tonne ^d	Hazard Index after decay, cc/tonne					
	Fuel Waste ^a	Mixed Oxide ^a Fuel Waste	Mixed Waste ^b					10 years	50 years	100 years	200 years	300 years	400 years
Cu-242	1.73E+04	1.52E+05	5.1E+04	0.5	1.55	2E-05	2.6E+15	4.6E+08	-	-	-	-	-
LaPu-238	4.32E+01	1.39E+02	6.7E+01	90	7.7E-03	5E-06	1.3E+13	6.1E+13	4.5E+13	3.0E+1	1.3E+13	5.9E+12	2.7E+12
LaU-234	-	-	-	2.5E+05	2.8E-06	3E-05	-	2.8E+08	1.3E+09	2.1E+0	3.1E+09	3.5E+09	3.7E+09
LaTh-230	-	-	-	8.0E+04	8.7E-06	2E-06	-	1.8E+05	4.3E+06	1.6E+0	5.0E+07	9.3E+07	1.4E+08
LaRa-226	-	-	-	1.62E+03	4.3E-04	3E-08	-	1.6E+04	2.1E+06	1.6E+0	1.0E+08	3.0E+08	6.2E+08
Chain Total	-	-	-	-	-	-	2.6E+15	6.1E+13	4.5E+13	3.0E+1	1.3E+13	5.9E+12	2.7E+12
Pu-241	1.53E+03	3.96E+03	2.1E+03	13	5.3E-02	2E-04	1.1E+13	6.2E+12	7.6E+11	5.5E+10	7.9E+08	1.5E+06	8.0E+03
LaAm-241	1.67E+02	9.00E+02	3.5E+02	4.58E+02	1.51E-03	4E-06	8.8E+13	9.2E+13	9.6E+13	8.9E+1	7.6E+13	6.5E+13	5.6E+13
LaNp-237	-	-	-	2.2E+06	3.15E-07	3E-06	-	3.9E+08	2.0E+09	4.0E+0	7.5E+09	1.1E+10	1.3E+10
LaU-233	-	-	-	1.6E+05	4.33E-06	3E-05	-	8.1E+02	2.1E+04	8.6E+0	3.3E+05	7.2E+05	1.2E+06
Chain Total	-	-	-	-	-	-	9.8E+13	9.9E+13	9.5E+13	8.9E+1	7.6E+13	6.5E+13	5.6E+13
Am-244	2.54E+03	4.82E+04	1.4E+04	18	8.05E-02	7E-06	7.0E+15	1.3E+15	2.8E+14	3.9E+13	7.6E+11	1.5E+10	2.9E+08
LaPu-240	7.10E+00	1.70E-01	9.5E+00	6.6E+03	1.05E-04	5E-06	1.9E+12	4.4E+12	8.3E+12	9.2E+12	9.1E+12	9.1E+12	9.0E+12
LaU-236	-	-	1.25E-03	2.4E+07	2.90E-08	3E-05	4.2E+07	4.2E+07	4.3E+07	4.5E+0	5.0E+07	5.4E+07	5.9E+07
Chain Total	-	-	-	-	-	-	2.0E+15	1.4E+15	2.9E+14	4.8E+1	1.0E+13	9.2E+12	9.0E+12
Am-243	1.80E+01	2.27E+02	7.0E+01	8.0E+03	8.70E-05	4E-06	1.0E+13	1.7E+13	1.7E+13	1.7E+13	1.7E+13	1.7E+13	1.7E+13
LaPu-239	4.85E+00	5.8E+00	5.1E+00	2.43E+04	2.85E-04	5E-06	1.0E+12	1.0E+12	1.0E+12	1.0E+12	1.1E+12	1.1E+12	1.2E+12
LaU-235	-	-	8.75E-05	7.0E-08	9.90E-10	3E-05	2.9E+06	2.9E+06	2.9E+06	3.0E+06	3.0E+06	3.0E+06	3.0E+06
Chain Total	-	-	-	-	-	-	1.9E+13	1.9E+13	1.9E+13	1.9E+13	1.9E+13	1.9E+13	1.9E+13
Pu-242	1.50E+02	1.70E-01	5.4E-02	3.8E+05	1.82E-06	5E-06	1.1E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10
LaU-238	-	-	1.7E-03	4.5E+09	1.54E-10	4E-05	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07
Chain Total	-	-	-	-	-	-	1.1E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10
Transuranic Total	7.60E+04	4.62E+04	5.7E+04	28	2.40E-02	3E-07	4.7E+15	1.6E+15	4.5E+14	1.9E+14	1.2E+14	6.9E+13	8.7E+13
Sr-90	1.07E+05	1.10E+05	1.1E+05	30	2.30E-02	2E-05	5.5E+15	4.6E+15	1.7E+15	5.5E+14	3.4E+13	5.4E+12	5.4E+11
Ca-137	-	-	-	-	-	-	2.4E+17	1.9E+17	7.1E+16	7.2E+16	7.2E+16	7.2E+16	7.2E+16
Total Cs&Sr	-	-	-	-	-	-	2.4E+17	1.9E+17	7.1E+16	7.2E+16	7.2E+16	7.2E+16	7.2E+16
TOTAL	-	-	-	-	-	-	2.4E+17	1.9E+17	7.1E+16	7.2E+16	7.2E+16	7.2E+16	7.2E+16

Table 1 (cont)

page 2 of 3

Hazard Index of Wastes from Reprocessing

Isotopes	Hazard Index after Decay, cc/tonne											
	500 yrs	1000 yrs	5000 yrs	10,000 yrs	50,000 yrs	100,000 yrs	500,000 yrs	1,000,000yrs	2,000,000yrs	3,000,000yrs	4,000,000yrs	5,000,000yrs
Cm-242	-	-	-	-	-	-	-	-	-	-	-	-
²³⁸ Pu	1.2E+12	2.1E+10	-	-	-	-	-	-	-	-	-	-
²³⁴ U	3.8E+09	3.8E+09	3.8E+09	3.7E+09	3.3E+09	2.9E+09	9.5E+08	2.3E+08	1.4E+07	8.5E+05	5.2E+04	3.1E+03
²³⁰ Th	1.9E+08	4.4E+08	2.4E+09	4.7E+09	1.9E+10	2.9E+10	2.0E+10	5.2E+09	3.1E+08	1.9E+07	1.1E+06	7.0E+04
²²⁶ La	1.1E+09	4.9E+09	9.3E+10	2.4E+11	1.2E+12	1.9E+12	1.3E+12	3.5E+11	2.1E+10	1.3E+09	7.7E+07	4.7E+06
Chain Total	1.2E+12	3.0E+10	9.9E+10	2.5E+11	1.2E+12	1.9E+12	1.4E+12	3.5E+11	2.1E+10	1.3E+09	7.8E+07	4.7E+06
Pu-241	4.2E+01	-	-	-	-	-	-	-	-	-	-	-
²⁴¹ Am	4.8E+13	2.3E+13	5.4E+10	2.8E+07	-	-	-	-	-	-	-	-
²³⁷ Np	1.5E+10	2.3E+10	2.9E+10	2.9E+10	2.9E+10	2.8E+10	2.5E+10	2.1E+10	1.5E+10	1.1E+10	8.0E+09	5.8E+09
²³³ U	1.8E+06	6.0E+06	5.4E+07	1.1E+08	5.5E+08	1.0E+09	2.3E+09	2.2E+09	1.7E+08	1.2E+09	8.9E+08	6.3E+08
Chain Total	4.8E+13	2.3E+13	8.4E+10	3.0E+10	3.0E+10	3.0E+10	2.8E+10	2.4E+10	1.7E+10	1.3E+10	9.1E+09	6.6E+09
Cm-244	5.7E+06	-	-	-	-	-	-	-	-	-	-	-
²⁴⁰ Pu	8.9E+12	8.5E+12	5.6E+12	3.3E+12	4.9E+10	2.5E+08	-	-	-	-	-	-
²³⁶ U	6.3E+07	8.4E+07	2.2E+08	3.2E+08	4.7E+08	4.7E+08	4.7E+08	4.6E+08	4.5E+08	4.3E+08	4.2E+08	4.1E+08
Chain Total	8.9E+12	8.5E+12	5.6E+12	3.3E+12	4.9E+10	7.2E+08	4.7E+08	4.6E+08	4.5E+08	4.3E+08	4.2E+08	4.1E+08
Am-243	1.7E+13	1.6E+13	1.1E+13	7.3E+12	2.2E+11	2.9E+09	-	-	-	-	-	-
²³⁹ Pu	1.2E+12	1.4E+12	2.4E+12	3.0E+12	1.6E+12	4.5E+11	5.3E+06	-	-	-	-	-
²³⁵ U	3.0E+06	3.1E+06	4.4E+06	6.6E+06	2.4E+07	3.2E+07	3.5E+07	3.5E+07	3.5E+07	3.5E+07	3.5E+07	3.5E+07
Chain Total	1.9E+13	1.8E+13	1.4E+13	1.1E+13	2.0E+12	4.6E+11	4.0E+07	3.5E+07	3.5E+07	3.5E+07	3.5E+07	3.5E+07
Pu-242	1.1E+10	1.1E+10	1.1E+10	1.1E+10	9.9E+09	9.0E+09	4.3E+09	1.7E+09	2.8E+08	4.5E+07	7.2E+06	1.2E+06
²³⁸ U	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07
Chain Total	1.1E+10	1.1E+10	1.1E+10	1.1E+10	9.9E+09	9.0E+09	4.4E+09	1.8E+09	3.2E+08	8.7E+07	5.0E+07	4.4E+07
Transuranic Total	7.7E+13	5.0E+13	2.0E+13	1.5E+13	3.3E+12	2.4E+12	1.4E+12	3.8E+11	3.9E+10	1.5E+10	9.7E+09	7.1E+09
Sr-90	1.1E+12	8.0E+06	-	-	-	-	-	-	-	-	-	-
Cs-137	5.3E+10	5.2E+05	-	-	-	-	-	-	-	-	-	-
Total Sr&Cs	1.5E+12	9.1E+06	-	-	-	-	-	-	-	-	-	-
TOTAL	7.9E+13	5.0E+13	2.0E+13	1.5E+13	3.3E+12	2.4E+12	1.4E+12	3.8E+11	3.9E+10	1.5E+10	9.7E+09	7.1E+09

Table 1 (cont)

page 3 of 3

Hazard Index of Wastes from Reprocessing

Isotope	Hazard Index after Decay, cc/tonne						
	1E+07	5E+07	1E+08	2E+08	3E+08	4E+08	5E+08
Cm-242	-	-	-	-	-	-	-
²³⁸ Pu	-	-	-	-	-	-	-
²³⁴ U	-	-	-	-	-	-	-
²³⁰ Th	-	-	-	-	-	-	-
²²⁶ Ra	3.8E 00	-	-	-	-	-	-
Chain Total	3.8E 00	-	-	-	-	-	-
Pu-241	-	-	-	-	-	-	-
²⁴¹ Am	-	-	-	-	-	-	-
²³⁷ Np	1.2E+09	2.7E+03	-	-	-	-	-
²³³ U	1.2E+08	3.0E+02	-	-	-	-	-
Chain Total	1.3E+09	3.1E+03	-	-	-	-	-
Cm-244	-	-	-	-	-	-	-
²⁴⁰ Pu	-	-	-	-	-	-	-
²³⁶ U	3.5E+08	1.1E+08	2.6E+07	1.4E+06	7.9E+04	4.4E+03	2.4E+02
Chain Total	3.5E+08	1.1E+08	2.6E+07	1.4E+06	7.9E+04	4.4E+03	2.4E+02
Am-243	-	-	-	-	-	-	-
²³⁹ Pu	-	-	-	-	-	-	-
²³⁵ U	3.5E+07	3.3E+07	3.2E+07	2.9E+07	2.6E+07	2.4E+07	2.1E+07
Chain Total	3.5E+07	3.3E+07	3.2E+07	2.9E+07	2.6E+07	2.4E+07	2.1E+07
Pu-242	1.2E+02	-	-	-	-	-	-
²³⁸ U	4.3E+07	4.2E+07	4.2E+07	4.1E+07	4.1E+07	4.0E+07	3.9E+07
Chain Total	4.3E+07	4.2E+07	4.2E+07	4.1E+07	4.1E+07	4.0E+07	3.9E+07
Transuranic Total	1.7E+09	1.9E+08	1.0E+08	7.1E+07	6.7E+07	6.4E+07	6.0E+07
Sr-90	-	-	-	-	-	-	-
Cs-137	-	-	-	-	-	-	-
Total Sr&Cs	-	-	-	-	-	-	-
TOTAL	1.7E+09	1.9E+08	1.0E+08	7.1E+07	6.7E+07	6.4E+07	6.0E+07

Table 2

page 1 of 2.

Hazard Index of Spent Fuel Elements Treated as Waste

Isotope	Isotopic Content curies/tonne ^a	Half-Life year	λ year ⁻¹	MPC µC/cc ^b	Hazard Index cc/tonne ^c	Hazard Index after Decay, cc/tonne							
						10 years	50 years	100 years	200 years	300 years	400 years	500 years	1000 years
Cm-242	1.73E+04	0.5	1.55	2E-05	8.7E+14	1.6E+08	-	-	-	-	-	-	-
LaPu-238	2.88E+03	90	7.7E-03	5E-06	5.8E+14	5.5E+14	4.0E+14	2.7E+14	1.2E+14	5.3E+13	2.4E+13	1.1E+13	1.9E+11
LaPu-234	-	2.5E+05	2.8E-06	3E-05	-	2.7E+09	1.1E+10	1.9E+10	2.8E+10	3.1E+10	3.3E+10	3.4E+10	3.4E+10
LaTh-230	-	8.0E+04	8.7E-06	2E-06	-	1.7E+06	4.0E+07	1.4E+08	4.5E+08	8.4E+08	1.3E+09	1.7E+09	3.9E+09
LaRa-226	-	1.52E+03	4.3E-04	3E-08	-	1.7E+05	2.0E+07	1.4E+08	9.5E+08	2.7E+09	5.5E+09	9.5E+09	4.4E+10
Chain Total					1.4E+15	5.5E+14	4.0E+14	2.7E+14	1.2E+14	5.3E+13	2.4E+13	1.1E+13	2.7E+11
Pu-241	1.02E+05	13	5.3E-02	2E-04	5.1E+14	3.0E+14	3.7E+13	2.6E+12	1.4E+10	7.4E+07	3.9E+05	2.1E+03	-
LaAm-241	1.67E+02	4.58E+02	1.51E-03	4E-06	4.2E+13	3.4E+14	6.9E+14	6.8E+14	5.9E+14	5.1E+14	4.4E+14	3.7E+14	1.0E+14
LaNp-237	-	2.20E+06	3.15E-07	3E-06	-	8.8E+08	1.1E+10	2.6E+10	5.3E+10	7.7E+10	9.7E+10	1.1E+11	1.7E+11
LaU-233	-	1.60E+05	4.33E-06	3E-05	-	1.4E+03	9.3E+04	4.8E+05	2.2E+06	5.0E+06	8.7E+06	1.3E+07	4.5E+07
Chain Total					5.5E+14	6.4E+14	7.2E+14	6.9E+14	5.9E+14	5.1E+14	4.4E+14	3.7E+14	1.8E+14
Cm-244	2.54E+03	18	3.85E-02	7E-06	3.6E+14	2.4E+14	5.1E+13	7.1E+12	1.4E+11	2.7E+09	5.3E+07	1.0E+06	-
LaPu-240	4.73E+02	6.6E+03	1.05E-04	5E-06	9.5E+13	9.5E+13	9.5E+13	9.5E+13	9.4E+13	9.2E+13	9.2E+13	9.1E+13	8.6E+13
LaU-236	2.50E-01	2.4E+07	2.90E-08	3E-05	8.3E+09	8.3E+09	8.4E+09	8.4E+09	8.4E+09	8.5E+09	8.5E+09	8.6E+09	8.8E+09
Chain Total					4.6E+14	3.4E+14	1.5E+14	1.0E+14	9.4E+13	9.3E+13	9.2E+13	9.1E+13	8.6E+13
Am-243	1.80E+01	8.0E+03	8.7E-05	4E-06	4.5E+12	4.5E+12	4.5E+12	4.5E+12	4.4E+12	4.4E+12	4.3E+12	4.3E+12	4.1E+12
LaPu-239	3.23E+02	2.43E+04	2.85E-05	5E-06	6.5E+13	6.5E+13	6.5E+13	6.4E+13	6.4E+13	6.4E+13	6.4E+13	6.4E+13	6.3E+13
LaU-235	1.75E-02	7E+08	9.9E-10	3E-05	5.8E+08	5.8E+08	5.8E+08	5.8E+08	5.9E+08	5.9E+08	5.9E+08	5.9E+08	5.9E+08
Chain Total					6.9E+13	6.9E+13	6.9E+13	6.9E+13	6.9E+13	6.9E+13	6.8E+13	6.8E+13	6.7E+13
Pu-242	1.00E 00	3.8E+05	1.82E-06	5E-06	2.0E+11	2.0E+11	2.0E+11	2.0E+11	2.0E+11	2.0E+11	2.0E+11	2.0E+11	2.0E+11
LaPu-238	3.33E-01	4.5E+09	1.54E-10	4E-05	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09
Chain Total					2.1E+11	2.1E+11	2.1E+11	2.1E+11	2.1E+11	2.1E+11	2.1E+11	2.1E+11	2.1E+11
Transuranic Total					2.5E+15	1.6E+15	1.3E+15	1.1E+15	8.7E+14	7.3E+14	6.2E+14	5.4E+14	3.3E+14
Sc-90	7.60E+04	28	2.4E-02	3E-07	2.5E+17	2.0E+17	7.6E+16	2.3E+16	2.1E+15	1.9E+14	1.7E+13	1.5E+12	9.1E+06
Cs-137	1.07E+05	30	2.3E-02	2E-05	5.4E+15	4.3E+15	1.7E+15	5.3E+14	5.3E+13	5.2E+12	5.2E+11	5.2E+10	5.0E+05
Total Cs&Sr					2.6E+17	2.1E+17	8.0E+16	2.4E+16	2.2E+15	2.0E+14	1.8E+13	1.6E+12	1.0E+07
TOTAL					2.6E+17	2.1E+17	8.1E+16	2.5E+16	3.1E+15	9.2E+14	6.4E+14	5.4E+14	3.3E+14

Table 2 (cont)
 Hazard Index of Spent Fuel Elements Treated as Waste

Page 2 of 2

Isotope	Hazard Index after Decay, cc/tonne													
	3000 yrs	10,000 yrs	30,000 yrs	100,000 yrs	500,000 yrs	1E+06 yr	2E+06 yr	3E+06 yr	4E+06 yr	5E+06 yr	1E+07 yr	3E+07 yr	1E+08 yr	3E+08 yr
Cm-242	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LuPu-238	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LuPu-236	3.0E+10	3.3E+10	3.0E+10	2.6E+10	8.3E+09	2.1E+09	1.3E+08	7.7E+06	4.6E+05	2.8E+04	-	-	-	-
LuPu-230	2.1E+10	4.2E+10	1.7E+11	1.6E+11	1.8E+11	4.6E+10	2.8E+09	1.7E+08	1.0E+07	6.2E+05	-	-	-	-
LuPu-226	8.3E+11	2.2E+12	1.1E+13	1.7E+13	1.2E+13	3.1E+12	1.9E+11	1.1E+10	5.9E+08	4.2E+07	3.4E+01	-	-	-
Chain	8.9E+11	2.2E+12	1.1E+13	1.7E+13	1.2E+13	3.1E+12	1.9E+11	1.2E+10	7.0E+08	4.2E+07	3.4E+01	-	-	-
Pu-241	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LuPu-241	4.2E+11	2.2E+08	-	-	-	-	-	-	-	-	-	-	-	-
LuPu-237	2.2E+11	2.2E+11	2.7E+11	2.1E+11	1.9E+11	1.6E+11	1.2E+11	8.4E+10	6.1E+10	4.4E+10	8.7E+09	2.1E+04	-	-
-233	4.1E+08	8.6E+08	4.7E+09	7.9E+09	1.8E+10	1.7E+10	1.3E+10	9.1E+09	6.6E+09	4.6E+09	3.4E+08	2.7E+03	-	-
Chain	6.4E+11	2.3E+11	2.3E+11	2.3E+11	2.1E+11	1.8E+11	1.3E+11	9.6E+10	6.9E+10	5.0E+10	9.9E+09	2.8E+04	-	-
Am-244	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LuPu-240	5.7E+13	3.1E+13	3.0E+11	2.6E+09	-	-	-	-	-	-	-	-	-	-
LuPu-236	1.9E+10	1.1E+10	1.3E+10	1.3E+10	1.3E+10	1.2E+10	1.2E+10	1.2E+10	1.1E+10	1.1E+10	9.5E+09	3.0E+02	7.0E+06	3.9E+07
Chain	5.7E+13	3.4E+13	5.1E+11	1.5E+10	1.3E+10	1.2E+10	1.2E+10	1.2E+10	1.1E+10	1.1E+10	9.5E+09	3.0E+02	7.0E+06	3.9E+07
Am-243	2.9E+12	1.5E+12	3.8E+10	7.4E+08	-	-	-	-	-	-	-	-	-	-
LuPu-239	5.6E+13	4.9E+13	1.6E+13	3.9E+12	4.5E+07	3.1E+01	-	-	-	-	-	-	-	-
LuPu-235	6.8E+08	6.8E+08	8.7E+08	9.4E+08	9.6E+08	9.6E+08	9.6E+08	9.6E+08	9.6E+08	9.6E+08	9.4E+08	9.1E+08	8.7E+08	7.9E+08
Chain	5.9E+13	5.1E+12	1.6E+13	3.9E+12	1.0E+09	9.6E+08	9.6E+08	9.6E+08	9.6E+08	9.6E+08	9.5E+08	9.1E+08	8.7E+08	7.9E+08
Pu-242	2.0E+11	1.8E+11	1.8E+11	1.7E+11	9.0E+10	3.2E+10	5.2E+09	8.3E+08	1.3E+08	2.1E+07	2.3E+03	-	-	-
LuPu-238	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.2E+09	8.1E+09
Chain	2.1E+11	2.1E+11	1.9E+11	1.7E+11	8.9E+10	4.0E+10	1.3E+10	9.2E+09	8.3E+09	8.3E+09	8.3E+09	8.3E+09	8.2E+09	8.1E+09
Transuranic	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	1.2E+14	6.6E+13	2.8E+13	2.1E+13	1.2E+13	3.3E+12	3.5E+11	1.3E+11	9.0E+10	7.0E+10	4.9E+10	1.2E+10	9.8E+09	8.9E+09
SE-90	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca-137	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca-60	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL	1.2E+14	8.8E+13	2.8E+13	2.1E+13	1.2E+13	3.3E+12	3.5E+11	1.3E+11	9.0E+10	7.0E+10	4.9E+10	1.2E+10	9.8E+09	8.9E+09

Notes for Table 1

- a SAR West Valley Plant, Nuclear Fuel Services
Docket 50-201, Table III-2-1
- b 75% UO_2 fuel, 25% mixed oxide fuel
- c 10CFR20, Appendix B
- d Quantity of water required to dilute isotopic content to MPC, cc/tonne

Notes for Table 2

- a SAR West Valley Plant, Nuclear Fuel Services
Docket 50-201, Table III-2-1
- b 10CFR20, Appendix B
- c Quantity of water required to dilute isotopic content to MPC, cc/tonne

Table 3
Hazard Index of Hulls

page 1 of 3

Isotope	Isotopic Content curies/tonne	Half-Life years	λ year ⁻¹	MPC µC/cc	Hazard Index cc/tonne	Hazard Index after Decay, cc/tonne						
						10 years	50 years	100 years	200 years	300 years	400 years	500 years
Cm-242	2.55E+02	0.5	1.55	2E-05	1.28E+13	2.32E+06	-	-	-	-	-	-
Am-241	2.20E+01	90	1.7E-03	5E-06	4.40E+12	4.3E+12	3.12E+12	2.09E+12	9.32E+11	4.16E+11	1.86E+11	8.31E+10
Am-243		2.5E+05	2.8E-06	3E-05	-	2.09E+07	8.97E+07	1.50E+08	2.17E+08	2.46E+08	2.60E+08	2.66E+08
Am-243		8.0E+04	8.7E-06	2E-06	-	1.37E+04	3.10E+05	1.10E+06	3.53E+06	6.56E+06	9.85E+06	1.33E+07
Am-243		1.62E+03	4.3E-04	3E-08	-	1.32E+03	1.53E+05	1.11E+06	7.42E+06	2.13E+07	4.35E+07	7.43E+07
Chain Total	2.77E+02				1.72E+13	4.30E+12	3.12E+12	2.09E+12	9.32E+11	4.17E+11	1.86E+11	8.35E+10
Pu-241	7.0E+02	13	5.3E-02	2E-04	3.50E+12	2.07E+12	2.54E+11	1.84E+10	9.68E+07	5.09E+05	2.60E+03	1.41E+01
Am-241	1.75E+00	4.58E+02	1.51E-03	4E-06	4.38E+11	2.47E+12	4.84E+12	4.81E+12	4.16E+12	3.58E+12	3.07E+12	2.64E+12
Am-243		2.2E+06	3.15E-07	3E-06	-	6.69E+06	7.74E+07	1.83E+08	3.77E+08	5.43E+08	6.87E+08	8.10E+08
Am-243		1.6E+05	4.33E-06	3E-05	-	1.09E+01	6.73E+02	3.46E+03	1.55E+04	3.53E+04	6.16E+04	9.36E+04
Chain Total	7.02E+02				3.94E+12	4.54E+12	5.10E+12	4.83E+12	4.16E+12	3.58E+12	3.08E+12	2.64E+12
Cm-244	7.0E+01	18	8.85E-02	7E-06	1.00E+13	6.74E+12	1.40E+12	1.95E+11	3.82E+09	7.45E+07	1.46E+06	2.84E+04
Am-240	3.2E+00	6.6E+03	1.05E-04	5E-06	6.40E+11	6.51E+11	6.69E+11	6.70E+11	6.63E+11	6.56E+11	6.50E+11	6.43E+11
Am-243	1.25E-03	2.4E+07	2.9E-08	3E-05	4.17E+07	4.17E+07	4.18E+07	4.20E+07	4.23E+07	4.26E+07	4.29E+07	4.33E+07
Chain Total	7.32E+01				1.06E+13	7.40E+12	2.07E+12	8.65E+11	6.67E+11	6.57E+11	6.50E+11	6.43E+11
Am-243	3.5E-01	8.0E+03	8.7E-05	4E-06	8.75E+10	8.74E+10	8.71E+10	8.67E+10	8.60E+10	8.52E+10	8.45E+10	8.38E+10
Pu-239	1.7E+00	2.43E+04	2.85E-05	5E-06	3.40E+11	3.40E+11	3.40E+11	3.39E+11	3.38E+11	3.38E+11	3.37E+11	3.36E+11
Am-243	8.75E-05	7.0E+08	9.9E-10	3E-05	2.92E+06	2.92E+06	2.92E+06	2.92E+06	2.93E+06	2.93E+06	2.94E+06	2.95E+06
Chain Total	2.05E+00				4.28E+11	4.31E+11	4.30E+11	4.29E+11	4.28E+11	4.26E+11	4.25E+11	4.23E+11
Pu-242	1.8E-02	3.8E+05	1.82E-06	5E-06	3.60E+09	3.60E+09	3.60E+09	3.60E+09	3.60E+09	3.60E+09	3.60E+09	3.60E+09
Am-243	1.7E-03	4.5E+09	1.54E-10	4E-05	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07
Chain Total	1.97E-02				3.64E+09	3.64E+09	3.64E+09	3.64E+09	3.64E+09	3.64E+09	3.64E+09	3.64E+09
Sc-90	3.35E+02	28	2.4E-02	3E-07	1.12E+15	8.78E+14	3.35E+14	1.01E+14	9.10E+12	8.21E+11	7.41E+10	6.69E+09
Cs-137	5.5E+02	30	2.3E-02	2E-05	2.75E+13	2.18E+13	8.67E+12	2.73E+12	2.72E+11	7.70E+10	2.66E+09	2.66E+08
Co-60	6.0E+03	5.24	1.32E-01	3E-05	2.00E+14	5.33E+13	2.70E+11	3.64E+08	6.59E+02	-	-	-
I-129	1.9E-04	1.6E+07	4.33E-08	6E-08	3.17E+09	3.17E+09	3.17E+09	3.17E+09	3.17E+09	3.17E+09	3.17E+09	3.17E+09
Fission Product Total	6.89E+03				1.35E+15	9.53E+14	3.44E+14	1.04E+14	9.38E+12	8.51E+11	8.00E+10	1.01E+10
TOTAL	7.94E+03				1.38E+15	9.70E+14	3.55E+14	1.12E+14	1.56E+13	5.93E+12	4.42E+12	3.80E+12

Table 3 (cont)
Hazard Index of Hulls

page 2 of 3

Isotope	Hazard Index after Decay, cc/tonne										
	1000 yrs	5000 yrs	10,000 yrs	50,000 yrs	100,000 yrs	500,000 yrs	1,000,000 yrs	2,000,000 yrs	3,000,000 yrs	4,000,000 yrs	5,000,000 yrs
Cm-242	-	-	-	-	-	-	-	-	-	-	-
LsPu-238	1.48E+09	-	-	-	-	-	-	-	-	-	-
LsU-234	2.70E+08	2.67E+08	2.63E+08	2.35E+08	2.05E+08	6.66E+07	1.64E+07	9.27E+05	6.01E+04	3.64E+03	2.20E+02
LsTh-230	3.06E+07	1.67E+08	3.28E+08	1.32E+09	2.01E+09	1.40E+09	3.63E+08	2.20E+07	1.33E+06	8.07E+04	4.69E+03
LsRa-226	3.48E+06	6.53E+09	1.70E+10	8.51E+10	1.32E+11	9.38E+10	2.43E+10	1.48E+09	8.95E+07	5.42E+06	3.28E+05
Chain Total	2.13E+09	6.96E+09	1.78E+10	8.67E+10	1.35E+11	9.53E+10	2.47E+10	1.50E+09	9.09E+07	5.50E+06	3.33E+05
Pu-241	-	-	-	-	-	-	-	-	-	-	-
LsAm-241	1.24E+12	2.93E+09	1.52E+06	-	-	-	-	-	-	-	-
LsU-237	1.21E+09	1.56E+09	1.56E+09	1.54E+09	1.51E+09	1.33E+09	1.13E+09	8.19E+08	5.92E+08	4.29E+08	3.10E+08
LsU-232	3.14E+05	2.86E+06	6.10E+06	2.95E+07	5.32E+07	1.24E+08	1.20E+08	8.66E+07	6.41E+07	4.64E+07	3.35E+07
Chain Total	1.24E+12	4.54E+09	1.61E+09	1.61E+09	1.61E+09	1.49E+09	1.29E+09	9.32E+08	6.74E+08	4.88E+08	3.53E+08
Cm-244	-	-	-	-	-	-	-	-	-	-	-
LsPu-240	6.10E+11	4.00E+11	2.36E+11	3.51E+09	1.82E+07	-	-	-	-	-	-
LsU-236	4.48E+07	5.44E+07	6.19E+07	7.25E+07	7.25E+07	7.17E+07	7.07E+07	6.78E+07	6.67E+07	6.48E+07	6.29E+07
Chain Total	6.10E+11	4.00E+11	2.36E+11	3.58E+09	9.07E+07	7.17E+07	7.07E+07	6.87E+07	6.67E+07	6.48E+07	6.29E+07
Am-243	8.02E+10	5.66E+10	3.66E+10	1.12E+09	1.44E+07	-	-	-	-	-	-
LsPu-239	3.32E+11	3.02E+11	2.67E+11	9.00E+10	2.19E+10	2.53E+05	-	-	-	-	-
LsU-235	2.97E+06	3.18E+06	3.41E+06	4.48E+06	4.87E+06	4.99E+06	4.99E+06	4.99E+06	4.98E+06	4.98E+06	4.97E+06
Chain Total	4.16E+11	3.61E+11	3.03E+11	9.11E+10	2.18E+10	5.25E+06	4.99E+06	4.99E+06	4.98E+06	4.98E+06	4.97E+06
Pu-242	3.59E+09	3.57E+09	3.54E+09	3.29E+09	3.00E+09	1.44E+09	5.79E+08	9.31E+07	1.50E+07	2.41E+06	3.87E+05
LsU-238	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07	4.25E+07
Chain Total	3.63E+09	3.61E+09	3.58E+09	3.33E+09	3.04E+09	1.44E+09	6.22E+08	1.36E+08	5.75E+07	4.49E+07	4.29E+07
Sr-90	4.00E+04	-	-	-	-	-	-	-	-	-	-
Cr-137	2.58E+03	-	-	-	-	-	-	-	-	-	-
Co-60	-	-	-	-	-	-	-	-	-	-	-
I-129	3.17E+09	3.17E+09	3.17E+09	3.16E+09	3.15E+09	3.10E+09	3.03E+09	2.90E+09	2.78E+09	2.66E+09	2.55E+09
Fission Product											
Total	3.17E+09	3.17E+09	3.17E+09	3.16E+09	3.15E+09	3.10E+09	3.03E+09	2.90E+09	2.78E+09	2.66E+09	2.55E+09
TOTAL	2.27E+12	7.79E+11	5.67E+11	1.89E+11	1.65E+11	1.01E+11	2.97E+10	5.54E+09	3.67E+09	3.27E+09	3.00E+09

Table 3 (cont)
Hazard Index of Nulils

page 3 of 3

Isotope	Hazard Index after Decay, cc/tonne						
	1E+07 yrs	5E+07 yrs	1E+08 yrs	2E+08 yrs	3E+08 yrs	4E+08 yrs	5E+08 yrs
Cm-242	-	-	-	-	-	-	-
↳Pu-238	-	-	-	-	-	-	-
↳U-234	-	-	-	-	-	-	-
↳Th-230	-	-	-	-	-	-	-
↳Ra-226	-	-	-	-	-	-	-
Chain Total	-	-	-	-	-	-	-
Pu-241	-	-	-	-	-	-	-
↳Am-241	-	-	-	-	-	-	-
↳Np-237	6.15E+07	1.46E+02	-	-	-	-	-
↳U-233	6.65E+06	1.58E+01	-	-	-	-	-
Chain Total	7.00E+07	1.67E+02	-	-	-	-	-
Cm-244	-	-	-	-	-	-	-
↳Pu-240	-	-	-	-	-	-	-
↳U-236	5.45E+07	1.71E+07	4.01E+06	2.21E+05	1.22E+04	6.72E+02	3.70E+01
Chain Total	5.45E+07	1.71E+07	4.01E+06	2.21E+05	1.22E+04	6.72E+02	3.70E+01
Am-243	-	-	-	-	-	-	-
↳Pu-239	-	-	-	-	-	-	-
↳U-235	4.95E+06	4.76E+06	4.53E+06	4.11E+06	3.73E+06	3.38E+06	3.07E+06
Chain Total	4.95E+06	4.76E+06	4.53E+06	4.11E+06	3.73E+06	3.38E+06	3.07E+06
Pu-242	4.15E+01	-	-	-	-	-	-
↳U-238	4.24E+07	4.22E+07	4.19E+07	4.12E+07	4.06E+07	4.00E+07	3.94E+07
Chain Total	4.24E+07	4.22E+07	4.19E+07	4.12E+07	4.06E+07	4.00E+07	3.94E+07
Sr-90	-	-	-	-	-	-	-
Cs-137	-	-	-	-	-	-	-
Co-60	-	-	-	-	-	-	-
I-129	2.05E+09	3.64E+08	4.17E+07	5.50E+05	7.25E+03	9.55E+01	1.26E 00
Fission Product							
Total	2.05E+09	3.64E+08	4.17E+07	5.50E+05	7.25E+03	9.55E+01	1.26E 00
TOTAL	2.22E+09	4.28E+08	9.20E+07	4.61E+07	4.43E+07	4.34E+07	4.25E+07

C-28

8/29/75

Table 4
Maximum Concentrations Expected
from On-Site Hull Burial

Isotope	Total Inventory after 30 yrs curies	Mechanisms 1 & 2 Fraction Escape	Mechanism 3 Max Fraction at Discharge	Mechanism 4 Decay	Mechanism 5 Conc in Stream $\mu\text{c/cc}$
Co-60	4.45E+07	1E-07	8E-08	E-100	E-100
Sr-90	7.2E+06		4E-06	E-100	E-100
I-129	5.7E 00		8E-06	0.998	1.5E-20
Cs-137	1.2E+07		8E-08	E-100	E-100
Pu-238	5.9E+05			E-100	E-100
Pu-239	5.1E+04			1.6E-29	2E-47
Pu-240	9.6E+04			E-100	E-100
Pu-241	1.05E+07			E-100	E-100
Pu-242	5.4E+02			1.4E-02	2E-22
Am-241	5.1E+04			E-100	E-100
Am-243	1.05E+04			2.5E-89	E-100
Cm-242	1.65E+05			E-100	E-100
Cm-244	1.25E+06			E-100	E-100