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A Radioactive Waste Disposal Classification System

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A RADIOACTIVE WASTE DISPOSAL CLASSIFICATION SYSTEM

VOLUME 1

V. C. Rogers

SEPTEMBER 1979

Prepared For

U.S. NUCLEAR REGULATORY CC MISSION

By

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FORWARD

This two volume report presents a proposed system for classifying radioactive waste "according to the requirements for safe disposal." This proposed system was developed under contract to the Nuclear Regulatory Commission (NRC). NRC will consider this report along with the results of other contractual efforts and other available information during the development of regulations for the disposal of commercial low-level radioactive wastes.

Volume I of this report presents in a succinct manner the proposed classification system. Volume II provides the computer program used for performing the calculations and provides a description of the equations representing the potential exposure mechanisms.

Only that information which is basic to the proposed classification system is provided in this report. An earlier progress report, NUREG-0456, "A Classification System for Radioactive Waste Disposal - What Waste Goes Where?", June 1978, provides additional information on the considerations that went into the development of the proposed system. NUREG-0456 also provides information which should be considered in implementing a classification system.

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ABSTRACT

The Nuclear Regulatory Commission, as part of its development of regulations for the disposal of radioactive waste, has contracted for the development of a radioactive waste classification system. The need for removing the waste from man's environment increases as the potential for endangering the health and safety of the public increases. The classification system being proposed is based on the requirements for safe disposal. The steps which were followed are; define safe, determine the pathways through the environment, formulate categories for the classification system and recommend disposal concentration guides for each category. The proposed categories are based on the length of administrative controls, the accessability of the waste and the hydrologic conditions.

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EXECUTIVE SUMMARY

E.1 GENERAL INFORMATION

The Nuclear Regulatory Commission (NRC) is developing regulations for the disposal of radioactive waste. This is part of its charter to protect the health and safety of the public from harmful effects that could potentially result from the commercial nuclear fuel cycle - from the milling of uranium ore to the final disposition of radioactive wastes and from the non-fuel cycle waste which includes much of the medical, research and industrial waste.

In order to regulate the disposal of radioactive wastes, there must be an adequate definition of the classes of waste. Many classification systems have been considered in the past.

In the first phase of the effort to develop a waste classification system, it was determined that the classification system should consider at least three types of actions in handling radioactive waste:

1. Discharge directly to the biosphere similar to handling routine trash.

2. Confine the waste for a period of time in a controlled manner with predictably low release rates.

3. Isolate the waste from the biosphere so that biologically significant releases or inadvertent reentry by mankind into the disposal area is highly unlikely.

The need for removing the waste from man's direct environment increases as the potential for endangering the health and safety of the public increases. An appropriate classification system could be based upon the requirements for safe disposal. We propose the Radioactive Waste Disposal Classification System (RWDCS) which is a classification system in which wastes are categorized according to characteristics relating to their disposal and classes are defined by a consistent application of safety criteria. In other words, wastes are classified according to "what waste goes where" for safe disposal.

Because the potential hazard to the public is directly related to the radioactive materials in the waste, quantified definitions for the classes are given in terms of the maximum average concentration (MAC) of radioactive materials allowed in the class. For a specified level of safety, waste disposal concentration guides (DCG's) can be specified and wastes can be classified to ensure the safe disposal of the waste. Likewise, a given disposal facility can be designated to accept various classes of waste according to the existence of potential pathways to man and other conditions specified in the RWDCS. For example, a particular waste might be classified as Class C by comparing the concentration of radioactive isotopes in the waste with the DCG's associated with Class C waste. If the radionuclide concentrations in the waste are less than the DCG's for Class C waste, the waste can be safely disposed of in a facility licensed to handle Class C waste. Similarly, waste with higher concentrations might be classified as Class B waste and must be disposed of in a more restrictive facility licensed for Class B waste. In this manner, the public is protected against potential hazards from the Class B waste at least to the same extent as they are protected from the Class C waste. Quantifying the desired degree of safety for the public and specifying DCG's for each class allows for a consistent treatment of all radioactive waste.

E.2 STUDY GUIDELINES

If wastes are to be classified based upon their requirements for safe disposal, then those requirements must be defined in such a manner that they may be used consistently. In developing the RWDCS and establishing the DCG's, adequate protection for the public has been defined in terms of the dose rate to the individuals receiving the maximum potential exposure. Limitations of exposures to large populations were considered, but were not found to be restrictive nor applicable to waste classification. In general, if the maximum individual is protected adequately, the total population will be protected adequately. Furthermore, determination of population doses is highly site-specific and is more appropriate in the ALARA consideration of environmental impacts for specific sites.

The study guidelines incorporate the system of dose limitation recommended by the International Commission on Radiological Protection (ICRP) as presented in ICRP Publication 26. From these considerations, the following dose rate guidelines were developed:

1. Individual exposures to a few individuals (10's of individuals) should not exceed 500 mrem/yr to either the whole body or critical organ.

2. Individual exposures to many individuals (100's of individuals) should not exceed 100 mrem/yr to either the whole body or critical organ.

The study guidelines are consequence guidelines, not risk guidelines. Consequence alone is not a complete measure of risk; however, if the consequence from waste disposal will not have an unacceptable result, then the disposal is safe without further statements of risk. Incorporating probabilities of occurrence and thus using risk guidelines introduces an entire new set of unknowns and uncertainties. Therefore, we have chosen to use consequence dose-rate limitations recognizing that the postulated event may never occur or if they do occur, the level of exposure may likely be less than that calculated. Thus, the 500 mrem/yr to a few individuals and 100 mrem/yr to many individuals, as recommended by the ICRP, are used in a conservative manner.

An additional guideline that was established for the study is an assumed 150-year time period for restrictive use of the waste disposal facility. This time period is long enough to allow the major short-lived isotopes in most waste to decay to near the levels of the major long-lived isotopes.

E.3 ENVIRONMENTAL EXPOSURE EVENTS

A desirable method for classifying waste according to safe disposal requirements is to estimate the potential dose rates to the individuals from the disposal of radioactive waste. By comparing the potential dose rates with the study guidelines, the waste concentration, volume or method of disposal can be modified to provide adequate protection to the public.

Potential exposures from disposed radioactive waste can occur either from individuals encountering the waste or from the waste migrating from its disposal location into man's environment.

The mechanisms included in the set by which individuals contact the waste are:

1. Inhalation of dust by a reclaimer digging in the waste, or by residents on the reclaimed site.

2. Ingestion of water from a well dug by a reclaimer.

3. Consumption of food grown in a garden containing contaminated soil.

4. Direct exposure to workers or residents from gamma radiation.

Events in which the radioactivity is transported from the site include:

5. Groundwater migration to a resource waterway.

6. Erosion/corrosion events dependent upon waste cover or containment. For example, wind and water surface erosion of a shallow land burial facility to a resource waterway for food production.

These events were included in many of the analyses and were determined not to be applicable to the RWDCS, since they were found not to be controlling pathways.

When performing an analysis of the transport of radioactive waste from a disposal facility to man and then estimating the maximum

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dose rate, the characteristics of the individual radioactive isotopes in the waste become very important. The exposure event analyses were performed for individual isotopes and corresponding DCG's were determined for the individual isotopes. It is realized that it is not practical to perform a complete radioisotopic assay for every container of waste. However, the DCG's for each isotope and for each waste disposal category are building blocks to form a practical classification system. Also investigated were the effects of decay daughters and the surface contamination and activation of special materials and large pieces of equipment.

E.4 THE WASTE DISPOSAL CLASSIFICATION SYSTEM

The waste disposal classification system which has been developed is given in Figure E.1. The disposal classification system is not directly concerned with disposal methods as such. Rather, it is the existence of potential pathways and the existence of a period of restricted land use which postulated. Class E waste is derived from analyses using no administrative control and ready access to the waste by a reclaimer (eg. municipal sanitary landfill). The DCG's for this class are the lowest of the set.

The Class D waste category is similar to the Class E category except a period of administrative control must be in effect at the disposal site and conditions of disposal are defined better (eg. shallow land burial). Therefore, DCG's for Class D are higher than for Class E.

Class C waste is appropriate for waste disposed of in such a manner that ready access by an unsuspecting reclaimer is unlikely (eg. intermediate depth land burial). However, no administrative control is applied. The disposal is postulated to be such that the well water event limits the concentrations.

Some waste can be disposed of at facilities providing additional cover over the waste (intermediate depth burial), but for which there is no present potential for contaminating a well (no potable aquifer). This waste is Class B. There is still some limitation that should be placed upon Class B waste. Although based upon the well water event, this limitation also serves to limit the consequence of other unanticipated intrusion events that could occur without administrative control. Therefore, we have postulated that for facilities handling this waste, the hydrology could change after 150 years making the well water scenario operable. The DCG's for this class are just the DCG's for Class C modified by applying the 150 year decay factor.

Class A has no upper concentration limit. It is the default class. The concentration limits provided for Class A are the activity density of the pure isotope. Wastes with radioisotopic concentrations exceeding Class B are automatically categorized as Class A. Class A wastes should be disposed of in facilities providing a high degree of isolation.

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WASTE DISPOSAL CLASSIFICATION SYSTEM

CLASS E	NO ADMINISTRATIVE CONTROL WORKER/ RECLAIMER ACCESS
CLASS D	ADMINISTRATIVE CONTROL FOLLOWED BY RECLAIMER ACCESS
CLASS C	NO ADMINISTRATIVE CONTROL AFTER DISPOSAL OPERATIONS NO RECLAIMER ACCESS EXCEPT WELL WATER
CLASS B	ADMINISTRATIVE CONTROL NO RECLAIMER ACCESS EXCEPT WELL WATER AFTER 150 YEARS
CLASS A	"ISOLATION" (REPOSITORY)

FIGURE E.1 CATEGORIES OF THE PROPOSED CLASSIFICATION SYSTEM

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E. 5 QUANTITATIVE APPLICATION OF EXPOSURE EVENTS

Equations have been developed for obtaining MAC's for each of the applicable pathways. These pathways are:

1. Inhalation of dust by a reclaimer.
2. Ingestion of food produced on the disposal site.
3. Well water consumption.
4. Direct gamma radiation exposure.

In addition, groundwater migration and surface erosion were investigated, but are not applicable to the development of the MAC's.

E.6 DISPOSAL CONCENTRATION GUIDES FOR WASTE CLASSIFICATION

The DCG's are the MAC's for the most restrictive pathway for each class and isotope. The classes and their associated DCG's are given in Table E.1.

The DCG's presented in Table E.1 are based upon an individual analysis of each isotope. The reciprocal of the DCG for a mixture of nuclides in waste is obtained from a weighted sum of the fraction of activity for each isotope. The weighting factor is the reciprocal of the DCG for that isotope.

For example, assume a waste containing 0.08 $\mu Ci/cm^3$ of radioactive material. Forty percent of the activity is ^{90}Sr and 60 percent is ^{239}Pu. The DCG for Class D is given by:

$$\frac{1}{\text{DCG (Class D)}} = \frac{.4}{.02} + \frac{.6}{.1} = 26$$

$$\text{DCG (Class D)} = 0.04\ \mu Ci/cm^3$$

The DCG for Class C is

$$\frac{1}{\text{DCG (Class C)}} = \frac{.4}{2.4} + \frac{.6}{90} = .17$$

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TABLE E. 1

DISPOSAL CONCENTRATION GUIDES FOR WASTE CLASSES ($\mu Ci/cm^3$)

Isotope	WASTE CLASS E	D	C	B	A *
^{3}H	0.05	94	94	4.3 +5	2.9 +9
^{14}C	1.2 -3	2.4 -3	140	140	7.1 +6
^{55}Fe	12	*	*	*	1.9 +10
^{60}Co	2.5 -4	2.1 +6	*	*	9.7 +9
^{90}Sr	2.3 -4	0.02	2.4	38	3.6 +8
^{99}Tc	0.05	0.1	64	64	1 +4
^{129}I	0.024	0.3	0.3	0.3	850
^{135}Cs	0.10	0.2	20	20	2.4 +3
^{137}Cs	4.2 -3	0.9	*	*	1.7 +8
^{235}U	0.015	0.03	11	11	41
^{238}U	0.015	0.03	*	*	6.4
^{237}Np	5.4 -4	0.02	0.3	0.3	1.3 +4
^{238}Pu	3.4 -4	0.4	*	*	3.4 +8
^{239}Pu	3.0 -4	0.1	90	90	1.2 +6
^{240}Pu	3.0 -4	0.1	810	810	4.7 +6
^{241}Pu	0.015	5.9 +3	*	*	2.2 +9
^{242}Pu	3.1 -4	0.1	13	13	7.6 +4
^{241}Am	9.2 -4	0.4	*	*	6.4 +7
^{243}Am	9.2 -4	0.3	600	*	3.6 +6
^{242}Cm	0.024	*	*	*	2.6 +10
^{244}Cm	1.5 -3	130	*	*	6.2 +8

* SPECIFIC ACTIVITY OF THE ISOTOPE.

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$$DCG\ (Class\ C) = 5.8\ \mu Ci/cm^3$$

Therefore, this waste is Class C waste.

The above procedure is the basis for classifying mixtures of waste that are ready for disposal. Mixtures of isotopes in the waste can be estimated for each different type of process that generates waste. The concentrations of every isotope in every batch of waste will not need to be measured. The total activity concentration of the waste from a specific waste source is all that will be needed to classify the waste.

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1. GENERAL INFORMATION

The Nuclear Regulatory Commission (NRC) is developing regulations for the disposal of radioactive waste. This is part of its charter to protect the health and safety of the public from harmful effects that could potentially result from the commercial nuclear industry. The charter extends not only to the operation of power reactors but also to most phases of the nuclear fuel cycle - from the milling of uranium ore to the final disposition of radioactive wastes and from the non-fuel cycle waste which includes much of the medical, research and industrial waste.

1.1 THE WASTE CLASSIFICATION PROGRAM

In order to regulate the disposal of radioactive wastes, there must be an adequate definition of the classes of waste. Many kinds of classification systems have been considered in the past. In fact, the first phase of the NRC's program in waste classification was to investigate several radioactive waste classification systems.

The major components of the NRC's program in waste classification are shown in Figure 1.1. The first phase also consists of an identification of the basic features of a desirable system. In the second phase, the classification system methodology is developed and the associated data base is formulated. The third phase consists of the application of the methodology and data base to formulate the complete classification system and to specify interface values for the waste classes. The fourth phase is the preparation of the Environmental Impact Statement (EIS) in support of the classification system which will consider the various alternative systems. The EIS, combined with other administrative requirements, provides the supporting material for the proposal of a waste classification system.

1.2 CLASSIFYING WASTE FOR SAFE DISPOSAL

In the first phase of the project,[1] it was suggested that the classification system should contain three types of actions in handling radioactive waste:

1. Discharge directly to the biosphere similar to handling routine trash.

2. Confine the waste for a period of time in a controlled manner with predictably low release rates.

3. Isolate the waste from the biosphere so that biologically significant releases or inadvertent reentry by mankind into the disposal area is highly unlikely.

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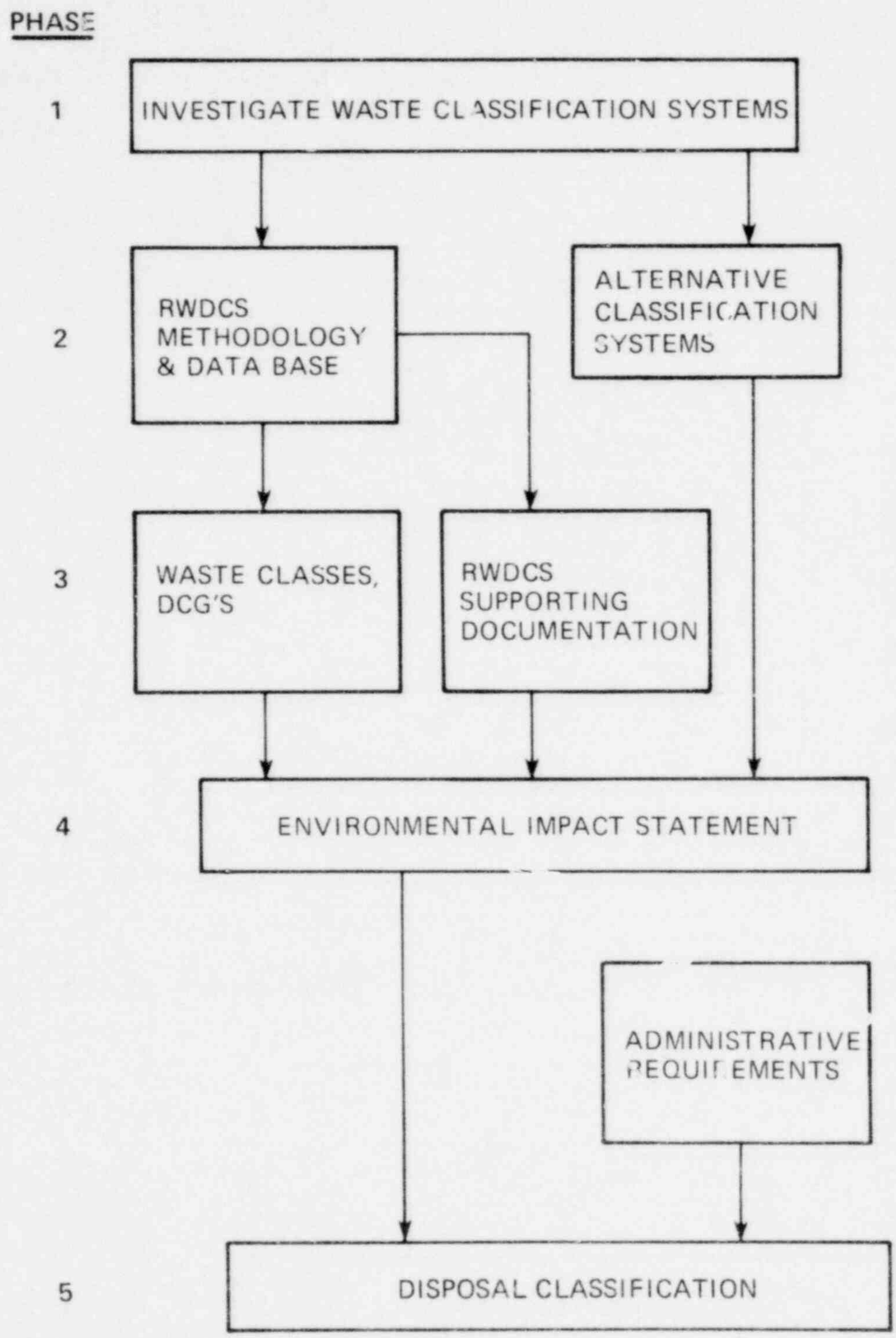

FIGURE 1.1 COMPONENTS OF THE NRC WASTE CLASSIFICATION PROGRAM

As shown in Figure 1.2, the need for removing the waste from man's direct environment increases as the potential for endangering the health and safety of the public increases. Therefore, an appropriate classification system should be based upon the requirements for safe disposal. A classification system is proposed in which wastes are categorized according to characteristics relating to their disposal and concentration limits for each class are determined from a consistent application of safety criteria which pertain to the protection of the health and safety of the public. In other words, wastes are classified according to "what waste goes where" for safe disposal.

The concept of a waste classification system was developed as a key element in the protection of the public health and safety and is only one of many tools the NRC will use to accomplish its charter. The classification system will be used in conjunction with other regulations for the disposal of radioactive waste and the National Environmental Policy Act process. For example, EIS's must be prepared for specific sites and there will be separate regulations concerning the disposal of high-level and low-level waste.

It is important to note that the purpose of the classification system is to classify waste according to the minimum requirements for its safe disposal. It is not to classify disposal facilities, nor is it to be used to estimate all radiological environmental impacts from handling wastes or storing wastes in the facilities.

The waste disposal classification system is derived using conservative assumptions. For example, no credit is taken for waste containers and the waste is assumed to be placed directly in a saturated aquifer in examining well water and groundwater events.

Because the potential hazard to the public is directly related to the radioactive materials in the waste, quantified interface values for the classes are given in terms of the concentration of radioactive materials in the waste. Radionuclide concentrations are a basic parameter characterizing the potential environmental impact of the waste. Hence, for a specified level of safety for the public, wastes can be classified and waste disposal concentration guides (DCG's) can be specified to ensure the safe disposal of the waste. For example, a particular waste might be classified as Class C by comparing the concentration of radioactive isotopes in the waste with the DCG's associated with Class C waste. If the radionuclide concentrations in the waste are less than the DCG's for Class C waste, the waste can then be disposed of safely in a facility licensed to handle Class C waste. Similarly, waste with higher concentrations might be classified as Class B waste and must be disposed of in a facility licensed for Class B waste. In this manner, the public is protected against potential hazards from the Class B waste at least to the same extent as they are protected from the Class C waste, since quantifying the desired degree of safety for the public and specifying DCG's for each class allows

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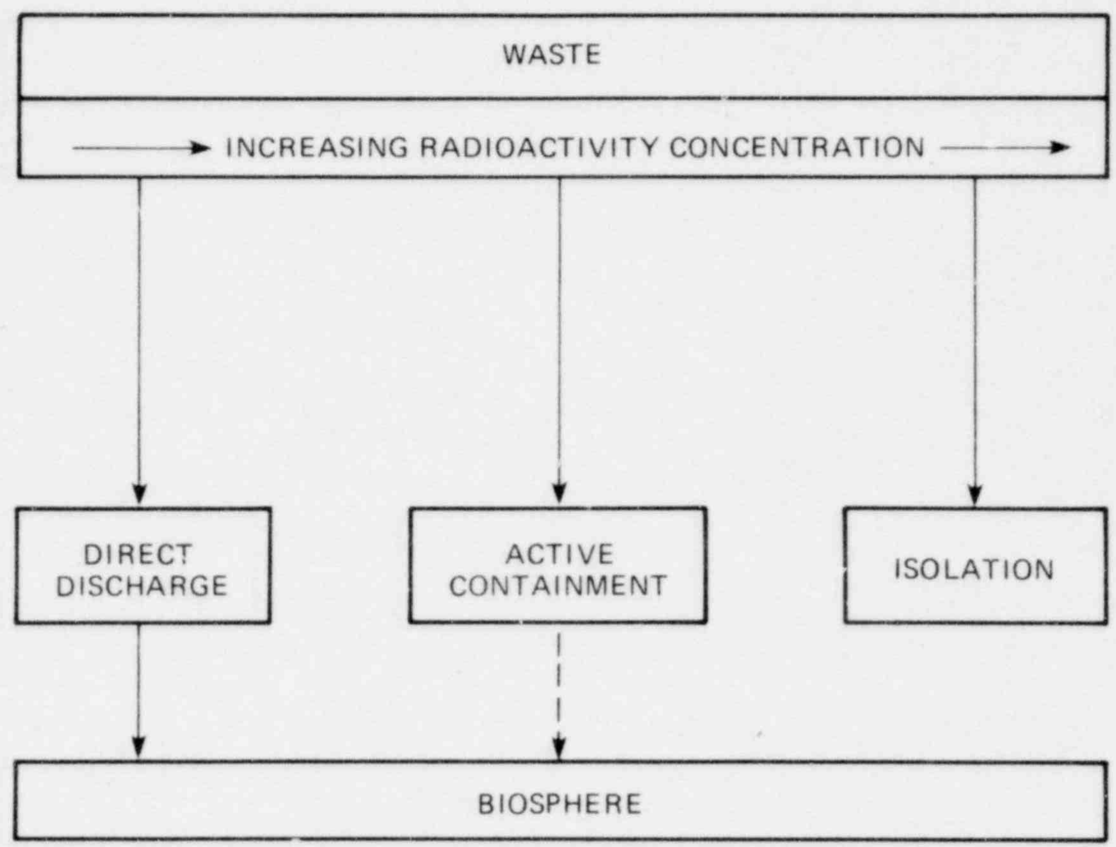

FIGURE 1.2 MAIN FEATURES OF A RADIOACTIVE WASTE CLASSIFICATION SYSTEM

for a consistent treatment of all radioactive waste. It also provides for a classification system that directly addresses the concerns of the public and that can be implemented without an undue burden on the waste generators and the disposal facility operators.

With this system, classification of the wastes according to the nature of radioactivity (transuranic, fission product, activation product, half-life, etc.) is considered only insofar as these characteristics relate to protection of the public health and safety. Also, alpha-emitting material, including transuranics, are not classified separately but follow essentially the same disposal criteria as other radioactive waste material.

Generic and specific disposal facilities have been examined in some detail using the methodology. Those investigations were necessary in developing the methodology and in establishing the data base. Many valuable insights were gained in performing that exercise. However, more complete site-specific EIS's and related studies are required in order to assess the environmental impacts and suitability of a particular disposal site to handle radioactive waste. This is particularly true when dealing with "as low as reasonably achievable" (ALARA) considerations. In general, the population dose (man rem) component of the ALARA principle depends strongly on specific site conditions.

1.3 FORMULATING THE RADIOACTIVE WASTE DISPOSAL CLASSIFICATION SYSTEM

Figure 1.3 contains the steps followed in developing the disposal classification methodology and formulating the classification system (phases 2 and 3 in Figure 1.1). The first step, establishing study guidelines and defining safe disposal, is discussed further in the next chapter. The second step is determining a consistent set of radiation exposure pathways from the disposed waste to individuals and to populations. The analysis of the transport of the radioactive waste materials via these pathways provides the link relating the radioactive material concentrations in the waste to the potential exposures to the public. The pathways and associated parameters are discussed in Chapter 3.

The results of the pathway formulation and analysis provide the basis for establishing a classification system containing five classes. This is presented in Chapter 4. The results of quantitative application of the pathway analysis is summarized in Chapter 5, with basic equations and values of the parameters given in the Appendix.

Chapter 6 contains the values of the DCG's for each of the proposed classes. Instructions are also given for determining the classification of wastes containing a mixture of radioactive isotopes.

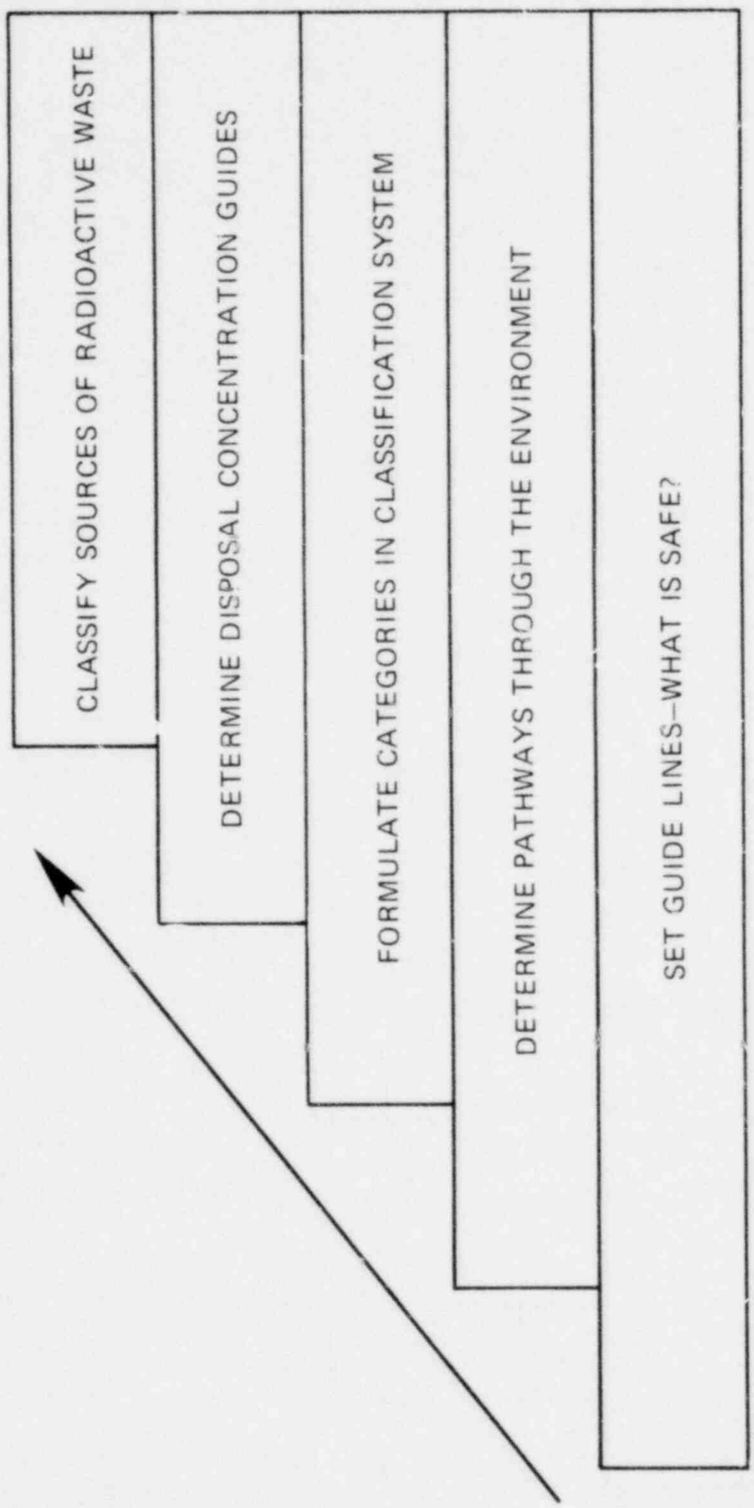

FIGURE 1.3 THE STEPS LEADING TO A CONSISTENT, PRACTICAL WASTE DISPOSAL CLASSIFICATION SYSTEM

A previous report (2), as well as Volume II of this report (3) contains the data base computer program and supporting information. Subsequent work can utilize these data and methods in order to classify waste containing mixtures of isotopes that are representative of the particular activity from which the waste is generated. This step of classifying the waste for representative mixtures from each activity that generates waste will greatly simplify the application and use of the classification system.

2. STUDY GUIDELINES

If wastes are to be classified based upon their requirements for safe disposal, then those requirements must be defined in such a manner that they may be used consistently. When it comes to societal decisions such as the safety of individuals, large groups, or even entire populations, the definition of safe is not absolute. The responsibility of the regulator is to ensure that a predetermined level of safety has been met. In developing the RWDCS and establishing the DCG's, adequate protection for the public has been defined in terms of the dose rate to the individuals receiving the maximum potential exposure. Limitations of exposures to large populations were considered, but were not found to be restrictive. In general, if the maximum individual is protected adequately, the total population will be protected adequately. Furthermore, population doses are highly site-specific and are more appropriate in the consideration of environmental impacts for specific sites.

An additional guideline that was established for the study is an assumed maximum time period for restrictive use of the waste disposal facility. The numerical value contained in this guideline is based upon the degree of benefit derived from the restricted facility use. These study guidelines are discussed in more detail in the following paragraphs.

2.1 DEFINING SAFE DISPOSAL

At the time the study was initiated there was not a generally accepted definition of safe disposal, nor did it appear that there would be such a definition in the near future. Rather than delay the development of the waste classification system until a definition of safe disposal was established, it was decided to provide such a definition for the purpose of the study in the form of "study guidelines."

In the waste classification study, numerous disposal methods and types of waste are investigated and the results of the study must withstand public scrutiny and regulatory review. It was recognized that the study guidelines would have to be comprehensive, defendable, and uniformly applicable to the various disposal methods and waste types without being unduly restrictive.

The study guidelines incorporate the system of dose limitation recommended by the International Commission on Radiological Protection (ICRP) as presented in ICRP Publication 26.(H) These are:

a. The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the commission.

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b. No practice shall be adopted unless its introduction produces a positive net benefit.

c. All exposures shall be kept as low as reasonably achievable, economic and social factors taken into account.

To allow calculations to be performed, this system of dose limitation needs to be quantified. The ICRP recommended a whole body dose-equivalent limit of 500 mrem/yr for individual members of critical groups, provided the average annual dose-equivalent to individual members of the public does not exceed 100 millirem. The ICRP also suggested the use of critical organ weighting factors for comparing non-uniform irradiation to uniform irradiation. The use of the weighting factors would allow significantly greater exposures to critical organs than 500 millirem. However, because of uncertainties regarding the specific values of some of the weighting factors, they were not adopted. From these considerations, the dose rate guidelines, as shown in Figure 2.1, were developed:

1. Individual exposures to a few individuals (10's of individuals) should not exceed 500 mrem/yr to either the whole body or critical organ.

2. Individual exposures to many individuals (100's of individuals) should not exceed 100 mrem/yr to either the whole body or critical organ.

For these guidelines, it is estimated that the maximally exposed individuals will be on the disposal site and their numbers will not exceed 100. For the second guideline, the allowable exposure was reduced as the number of individuals at risk was increased.

To provide a perspective for these guidelines, exposure from natural background, including inhalation of naturally occurring alpha-emitting isotopes was calculated using the same procedures that are used in the waste classification study. The average natural background exposure to the critical organs is 570 mrem/yr.

2.2 DOSE RATE OR RISK?

People generally associate the degree of safety of an action or system with the concept of risk. A safer action has a lower risk. An action or system with a very high risk is not considered very safe. Risk can be defined as the product of the probability of an event occurring with the consequence of its occurrence. For example, suppose an individual is drinking water from a well. Further suppose that if the water is contaminated with a certain class of radioactive waste, the individual would receive a maximum dose rate of 500 mrem/yr. However, the chance of ever having a well being contaminated with the radioactive waste is one out of

STUDY GUIDELINES

DOSE GUIDELINES

1. 500 mrem/yr WHOLE BODY OR CRITICAL ORGAN EQUIVALENT DOSE RATE TO FEW INDIVIDUALS (10's OF INDIVIDUALS).
2. 100 mrem/yr TO MANY INDIVIDUALS (100's OF INDIVIDUALS).

ADMINISTRATIVE CONTROL GUIDELINE

3. CONTROL OF DISPOSAL FACILITIES NEED NOT EXCEED 150 YR AFTER THE LAST DISPOSAL.

OTHER GUIDELINES NOT RELATING TO FINAL CLASSIFICATION

4. 1 mrem/yr EQUIVALENT DOSE RATE TO MANY INDIVIDUALS FROM THE DISPOSAL OF WASTE OF 1 GW_e yr OF ENERGY.
5. "AS LOW AS REASONABLY ACHIEVABLE" POPULATION DOSES SHOULD NOT EXCEED THOSE WHICH COULD BE ACHIEVED AT A REASONABLE COST.

FIGURE 2.1 DOSE RATE AND ADMINISTRATIVE GUIDELINES USED IN THE STUDY a hundred wells. The consequence of drinking the contaminated water is a maximum dose rate of 500 mrem/yr but, because the probability of occurrence is only 0.01, the risk is only 5 mrem/yr.

The relationship among risk, consequence and probability of occurrence is demonstrated in Figure 2.2. In the figure, the consequence of a head-on automobile collision at 50 mph is the same whether it occurs on the curve of a two-lane road or on a four-lane divided interstate. However, the probability of a head-on collision occurring on the interstate is much less than on the curve of a two-lane road. Hence, the risk associated with this action is less on the interstate than on the road. In fact, laws have been instituted which restrict passing on curves, hoping to reduce the frequency of head-on collisions on curves and, thus, reduce the associated risks.

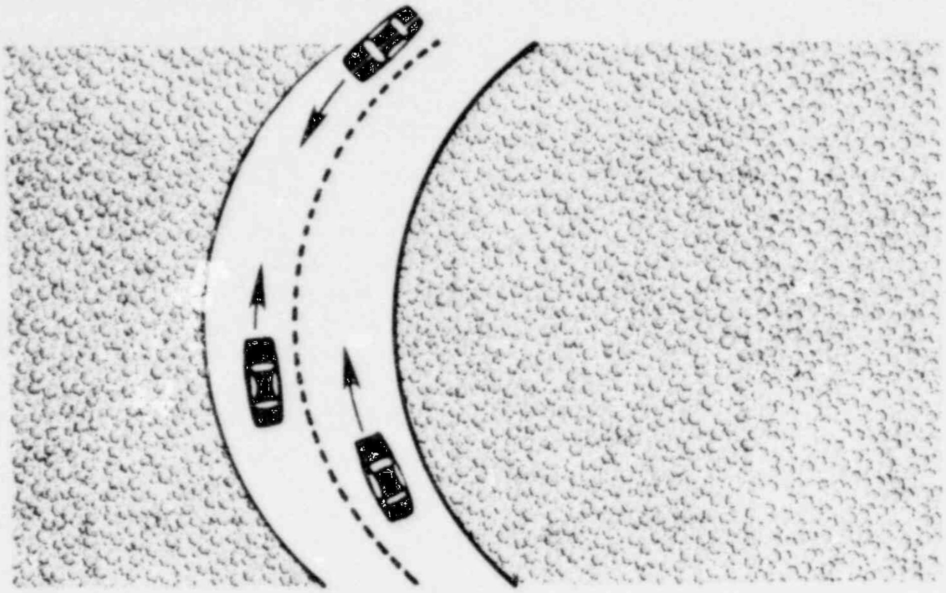
Another way to reduce the risk associated with a head-on collision is to reduce the consequence of the collision. This can be accomplished with the use of safety devices such as seat belts and padded dashboards. The consequence of the collision can also be reduced by reducing the allowable speed of the automobiles, which should also reduce the probability of the collision.

Consequence alone is not an adequate measure of risk. However, if there is an identifiable speed at which head-on collisions would not result in any serious injury, then driving at that speed is safe without any statement of risk. Likewise, if the consequence from waste disposal will not result in any serious injury, then such disposal is safe without statements of risk. In this context, 500 mrem/yr to the maximally exposed individuals is used to define safe disposal and not to estimate the degree of risk. Further, just as the proper design of roads reduces the risk from driving, reasonable caution by future man and other waste management criteria such as careful site selection will reduce the risks far below the levels of the postulated consequences.

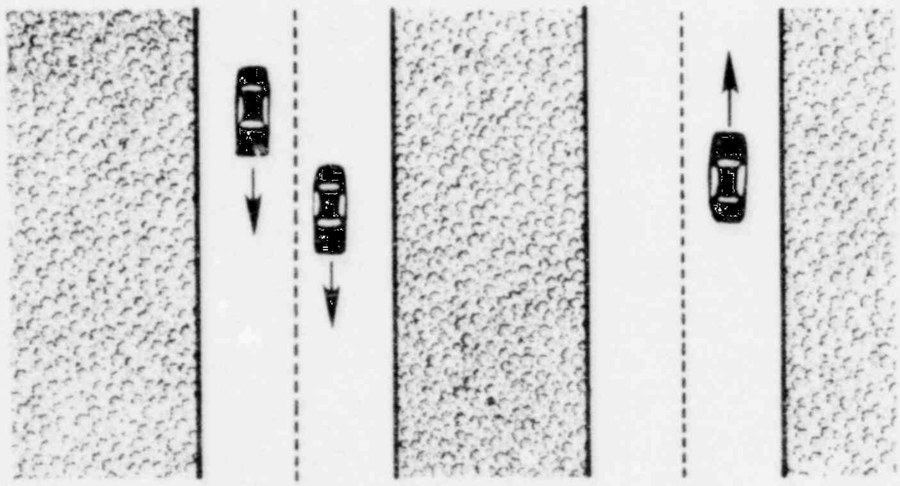
The study guidelines are consequence guidelines, not risk guidelines. Incorporating probabilities of occurrence and thus using risk guidelines introduces an entire new set of unknowns and uncertainties. Therefore, consequence dose-rate limitations have been used recognizing that the postulated event may never occur. Thus, the 500 mrem/yr to a few individuals and 100 mrem/yr to many individuals, as recommended by the ICRP, are conservative as used in waste classification.

2.3 RESTRICTED SITE USE

There has been considerable discussion in recent years as to how long facility restrictions or administrative controls can be maintained. The concern behind most of these discussions has been the length of time for which institutions can be relied on to provide administrative controls. We choose to address the question as to how the benefits of restricted site access vary with



a. 50 mph HEAD–ON COLLISION FROM PASSING ON A CURVE–GREATER PROBABILITY OF OCCURRING = GREATER RISK.



b. 50 mph HEAD–ON COLLISION FROM PASSING ON A 4–LANE DIVIDED INTERSTATE–LOWER PROBABILITY OF OCCURRING = LOWER RISK.

FIGURE 2.2 EXAMPLE OF GREATER RISK FOR SIMILAR CONSEQUENCES time. For waste consisting of short-lived isotopes (less than 10 year half-lives) very short periods of administrative control will greatly reduce the potential exposures to individuals. For very long-lived wastes, if administrative controls were required, they would be necessary for an unreasonably long period of time in order to show any significant benefit.

However, many wastes consist of a mixture of isotopes with half-lives from very short to very long. Then it is instructive to determine what period of decay is required for the shorter-lived isotopes to decay to hazard level less than those for the longer-lived isotopes. For most waste there is not a specific time when the reduction rate of the total radioactivity changes significantly. However, we have found from numerous calculations that for most waste containing a mixture of isotopes a period of 150 years of administrative control is long enough to allow the major short-lived isotopes to decay to near the levels of the major longer-lived isotopes. The resulting study guideline is:

3. The period of required administrative control is disposal facilities need not exceed 150 years after the last disposal.

It should also be noted that administrative control only refers to some limitation on the uses of the site. It could range from restrictions placed on the deed, to the property, to ownership by an appropriate government agency. For some disposal sites the construction of warehouses, parking lots, or an airfield may be acceptable uses of the land while farming the site may not be.

2.4 OTHER STUDY GUIDELINES

All three dose limitation items recommended by the ICRP were considered in the study. However, items b and c given in Section 2.1 were found to be neither restrictive nor applicable to the waste disposal classification system presented in this report.

In considering item b, it was noted that quantifying this recommendation required a judgement as to what constitutes a positive net benefit. A conservative and defendable standard for positive net benefit is no more than one health effect over ten thousand years from the disposal of waste generated as the result of the production of 1 GW_eyr of electrical energy. Assuming, as did ICRP-26,[H] a dose conversion factor of 10^{-4} health effects per man rem dose equivalent and a maximum exposed population of 1,000 individuals, the following guideline was derived:

4. Exposures to many individuals (100's of individuals should not exceed 1 mrem/yr to either the whole body or critical organ as the result of the disposal of waste from each GW_eyr of energy.

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One mrem/yr to 1,000 individuals is the same population dose as 1 manrem/yr. Assuming that the population exposures for the population outside of the 100 individual group would be very low for most scenarios, the guidelines are expressed in the form of dose rates to individuals.

It is clear that this guideline cannot be directly applied to the disposal of waste which does not result from power production. However, the practices used for the safe disposal of waste from power generation should also suffice for the safe disposal of other wastes.

An appropriate study guideline that quantified the recommendation "all exposures shall be kept as low as reasonably achievable, economic and social factors taken into account" or ALARA is difficult to determine. The waste classification study is based on generic considerations. The application of ALARA requires the evaluation of a broad range of factors, many of them specific to a particular disposal site and type of waste. Furthermore, from the analysis it was determined that the requirement for "safe" disposal was usually more restrictive than the likely requirements that would be derived from the consideration of ALARA. Population doses and dose rates were calculated in the study and some cost/benefit considerations were presented in earlier study reports.(2) However, the ALARA guideline was not directly used in formulating the waste classification system. Its use is more appropriate when determining the impacts of specific facilities.

In summary, the recommendations of the ICRP were followed in formulating guidelines for this study. The dose rate guidelines apply to consequences and not to risks, even though the events may not occur as postulated. Therefore, a guideline of 500 mrem/yr to a few individuals and 100 mrem/yr to many individuals is conservatively used in establishing the DCG's of a waste disposal classification system. In addition, it is assumed that there will be restricted site use for some facilities for about 150 years. Finally, ALARA and net positive benefit guidelines are not generally restrictive in waste classification and should be applied to specific site impact analysis.

3. ENVIRONMENTAL EXPOSURE EVENTS

A desirable method for achieving the objectives is to estimate the potential dose rates to the individuals from various exposure events. By comparing the potential dose rates with the study guidelines, the allowable concentration of radioactive materials in waste can be determined for the set of exposure events under various conditions.

The potential exposures from disposed radioactive waste can occur either from individuals encountering the waste or it can occur from the waste migrating from its disposal location into man's environment.

3.1 PATHWAYS THROUGH THE ENVIRONMENT

The analytical procedures for determining the quantitative values of the waste-class interfaces employ three basic steps:

1. Identifying a set of reasonably conservative exposure events.
2. Describing man's encounter with the waste either by intrusion or by the transport of the radioactive materials through the environment to man.
3. Calculating the concentrations or inventories of radioactivity in the wastes that will assure that the doses to the exposed population groups, both from the standpoint of the maximum individual dose and the total population dose, do not exceed the dose guidelines.

The set of potential exposure events formulated for the analysis includes events in which individuals may come into contact with the waste in place at a disposal facility, as well as, events in which the waste is transported off-site either by water or air. The events are categorized in Figure 3.1.

The mechanisms included in the set by which individuals contact the waste are:

1. Inhalation of dust by a reclaimer digging in the waste, or by residents on the reclaimed site.
2. Ingestion of water from a well dug by a reclaimer.
3. Consumption of food grown in a garden containing contaminated soil.
4. Direct exposure to workers or residents from gamma radiation.

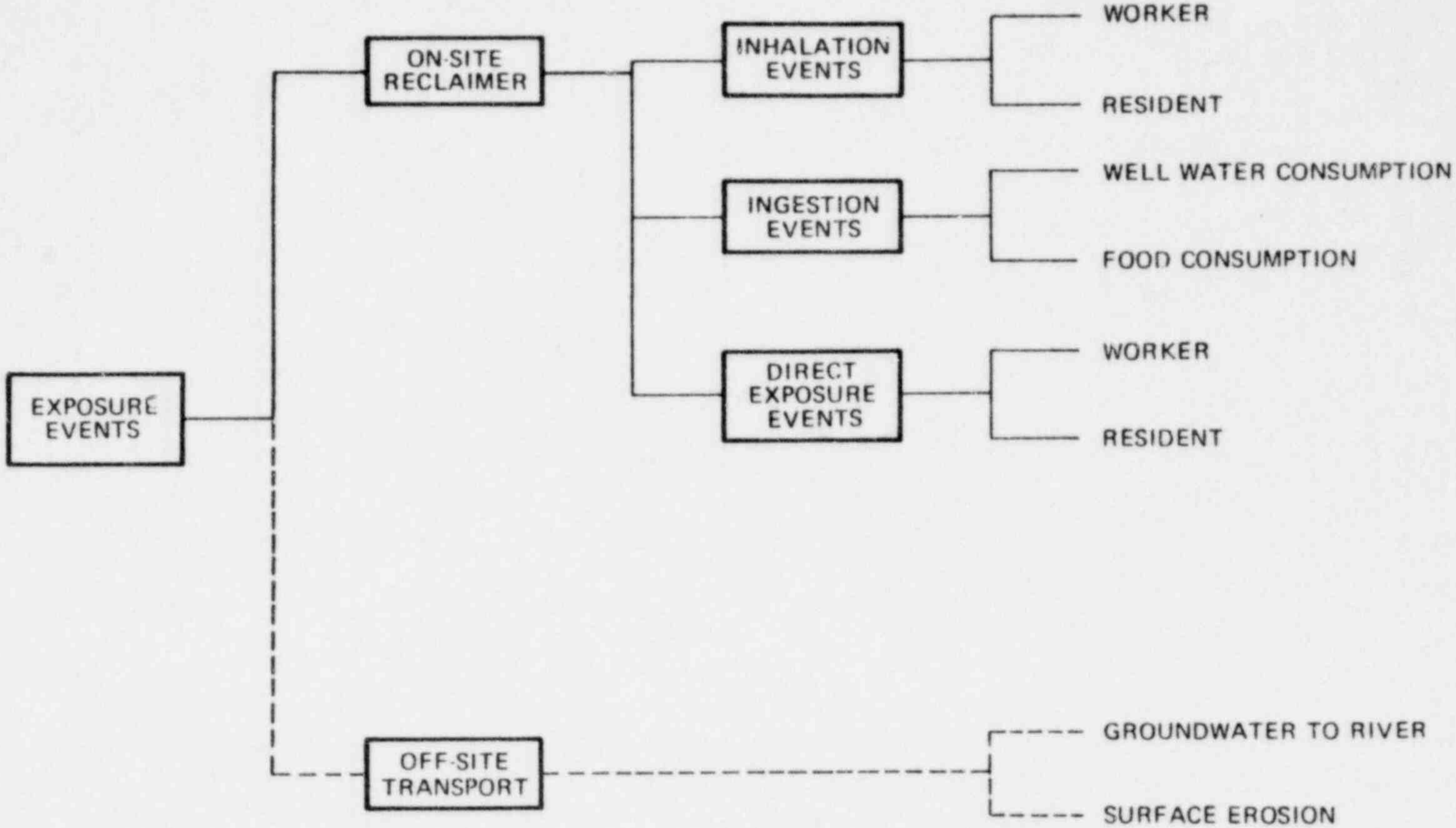


FIGURE 3.1 SET OF ENVIRONMENTAL EXPOSURE EVENTS

Events in which the radioactivity is transported from the site include:

5. Groundwater migration to a resource waterway.

6. Erosion/corrosion events dependent upon waste cover or containment. For example, wind and water surface erosion of a shallow land burial facility to a resource waterway or to land used for food production.

During the conduct of the study, numerous pathways have been considered. However, many of these pathways are either not restricting or are highly improbable. Only those reasonable pathways which are restricting are considered in detail; however, this does not mean that these events will occur. It is the intent of the methodology to establish consistent sets of applicable events to be analyzed in such a manner as to estimate a range of probable impacts. The events are a conservative representation of families of events. For example, many scenarios can be formulated in which a reclaimer inhails some of the radioactive material. The particular worker inhalation of dust-laden air event that was examined quantitatively yields among the highest potential dose rates. The set of events and the first three study guidelines provide a basis for establishing the categories of he classification system, then the dose rate guidelines are used to determine maximum concentrations of radioactive materials (disposal concentration guides) applicable to each category.

3.2 EXPOSURE EVENTS APPROPRIATE FOR WASTE CLASSIFICATION

Since the purpose of the classification system is to classify radioactive wastes, not waste disposal sites, several generic waste disposal facilities were defined in order to determine waste and facility conditions required for safe disposal. After the pathway analysis part of the RWDCS methodology was performed for the generic facilities, the pathway analysis was also performed for several specific waste disposal facilities[2,3] in order to test the applicability of the generic models and also to gain additional insights concerning the RWDCS. It was determined from numerous analyses that the events involving off-site transport of radioactive materials were rarely limiting. Furthermore, the magnitude of the potential impacts was highly specific to the characteristics of each site. It is assumed that reasonable sites will be selected for waste disposal, not worst-case sites. Therefore, these off-site transport pathways should not be addressed as a controlling pathway in the generic waste classification methodology. These pathways are shown by dashed lines in Figure 3.1 to illustrate that they are not applicable to waste classification, even though they were included in the generic and specific site analyses.

The on-site reclaimer events are much less dependent upon individual facility and site parameters and are much more dependent upon the intrinsic characteristics of the radioactive waste. In addition, these events are generally limiting by several orders of magnitude. Hence, these events are included in the RWDCS methodology.

3.3 THE IMPACT OF INDIVIDUAL RADIOACTIVE ISOTOPES

When performing an analysis of the transport of radioactive waste from a disposal facility to man and then estimating the maximum dose rate, the characteristics of the radioactive materials in the waste become very important. Furthermore, these characteristics are different for each type of waste and are often different for various batches of the same type of waste. It is impractical to determine these characteristics for every batch of waste. In order to perform a consistent analysis and to develop a technically sound, consistent methodology, the wastes were divided into their most simple components, the individual radioactive isotopes. Even though half-life, retardation factors and radiotoxicity may vary from one isotope to the next, these parameters are the same for each individual isotope. For example, as shown in Figure 3.2, ^{3}H has a half-life of about 12 years and its atoms emit low-energy beta particles and critically affect the whole body. On the other hand, ^{137}Cs has a half-life of 30 years. It decays by the emission of gamma rays and the most critical organ for dose is the liver. The isotope ^{239}Pu has a half-life of 24 thousand years. It emits alpha particles and the most critical organ for dose is the bone.

As a result of these considerations, the exposure event analyses were performed for individual isotopes. Furthermore, corresponding DCG's were determined for the individual isotopes. This information can provide the data base for determining the classification of specific waste batches. It is realized that it is not practical to perform a complete radioisotopic assay for every container of waste. However, the DCG's for each isotope can be used as described in Chapter 6 to determine the classification of a particular type of waste. This will result in a simple classification system that is practical to implement. A good analogy is the use of a pocket electronic calculator. The calculator is reliable, inexpensive and simple to operate. However, as illustrated in Figure 3.3, several complex detailed analyses and operations are needed in order to develop the calculator. Those complex operations are based upon several consistent, simple operations that are combined in different ways, but in its final form the calculator is easy to use.

3.4 KEY PARAMETERS IN EXPOSURE EVENTS CALCULATIONS

The half-life, $T_{1/2}$, and dose conversion factors, DF, were identified in Section 3.3 as key parameters in analysis of exposure events. The short half-life isotopes may largely decay before the postulated exposure event can occur. If the dose conversion factor,

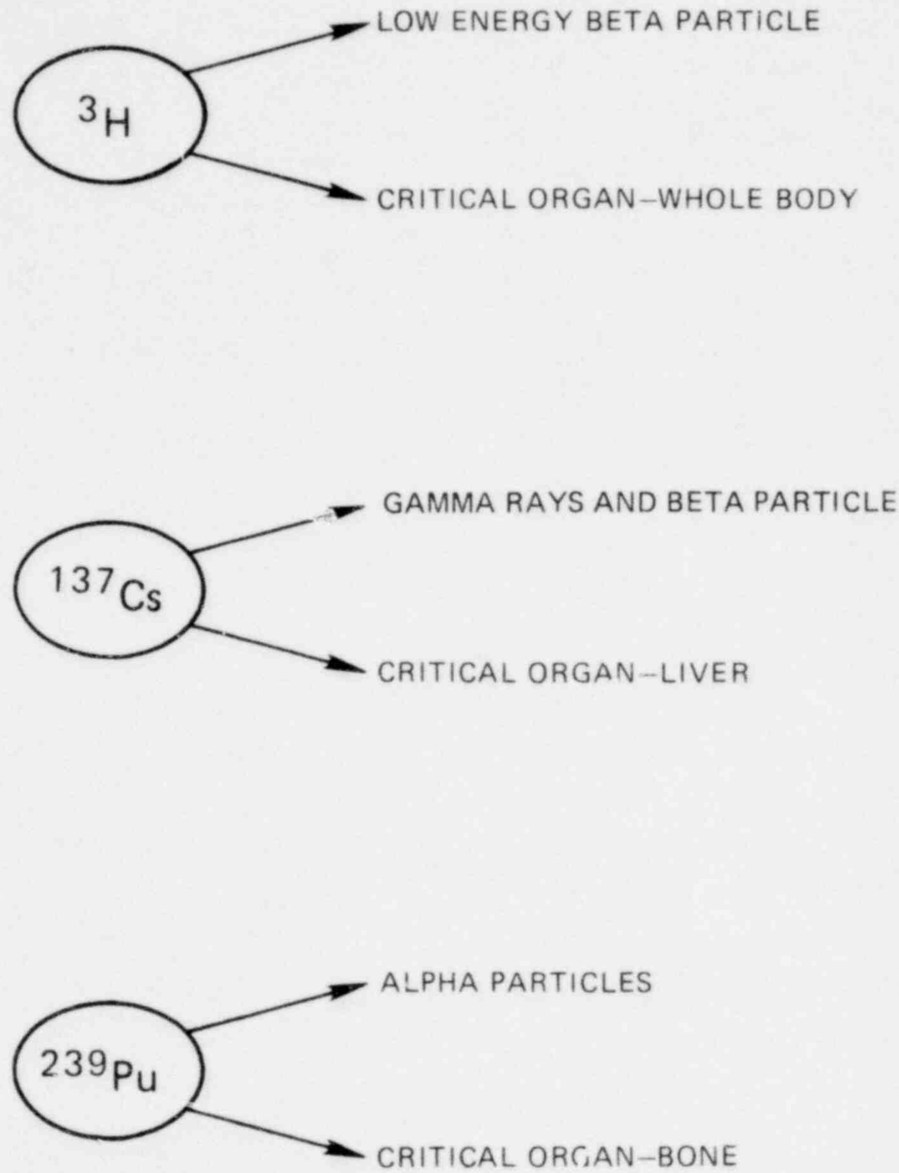
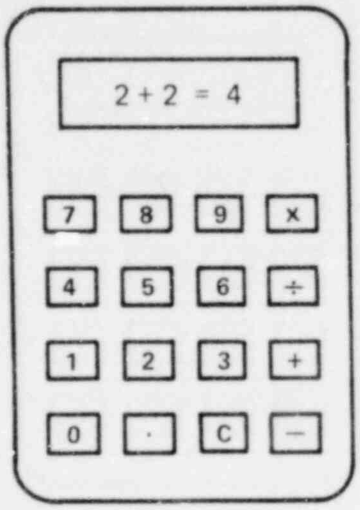
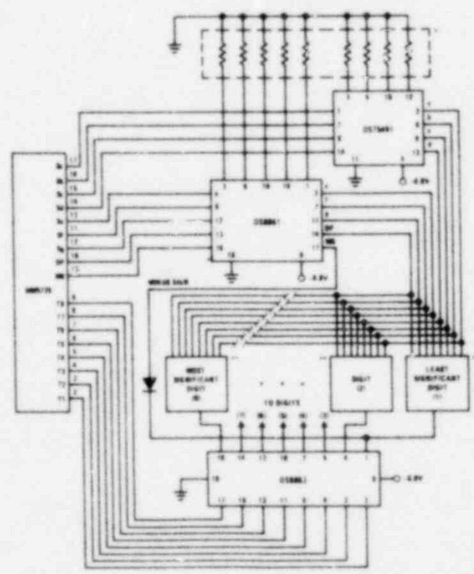


FIGURE 3.2 DIFFERENT IRRADIATIONS AND HEALTH IMPACTS FROM DIFFERENT RADIOACTIVE ISOTOPES



A. SIMPLE OPERATION OF
A CALCULATOR



B. COMPLEX OPERATIONS IN
A CALCULATOR

FIGURE 3.3 USING A GOOD WASTE CLASSIFICATION SYSTEM IS LIKE USING A CALCULATOR – MANY COMPLEX OPERATIONS AND ANALYSES ARE NEEDED TO PRODUCE A TOOL THAT WILL WORK SIMPLY AND RELIABLY.

Which relates a particular amount of intake of the isotope to the resulting dose, is small so that the dose per unit of intake is small, then larger concentrations of waste can be disposed. Another key parameter is the usage factor, U_a. That parameter is the rate of intake of the isotope. The time, T_x, for the intake is also important, as is the density of the waste, ρ. The remaining key parameters are the waste dilution factor in the facility (eg. mixing of dirt with waste packages), f, and the waste dilution factor in the transport medium. For inhalation by the reclaimer, this last parameter is the dust loading of air, A_d. For ingestion of food, it is the bioaccumulation factor of the radioisotope into the food, B_{iv}, and for consumption of drinking water it is dilution factor from the transport, f_o.

Another key parameter is the availability of the waste to enter the pathways. The basic analysis was performed assuming the waste material was decomposed to a soil-like substance as in the reclaimer-inhalation scenario. Analyses were also performed and MAC's given for special materials and large pieces of equipment that had surface contamination or were activated in a radiation field. In addition, the effect of decay daughters is included in the RWDCS.

In summary, the restricting pathways applicable to the classification of radioactive waste are the on-site reclaimer events. Off-site events are generally not restrictive and should be analyzed for ALARA considerations for specific sites. The exposure events are analyzed for specific isotopes and the key parameters are identified.

4. THE WASTE DISPOSAL CLASSIFICATION SYSTEM

In applying the RWDCS methodology, the concentrations of the radioisotopes in the waste are adjusted until the potential maximum dose rates are equal to the dose rate guidelines for every pathway. Examples of the results are shown in Figure 4.1. For ^{239}Pu, the reclaimer-inhalation pathway yields the lowest acceptable concentration. The food pathway is next in limiting the concentration and groundwater migration is many orders of magnitude less significant. The results for ^{90}Sr differ from those for ^{239}Pu. The reclaimer food pathway yields the lowest concentration, followed by the well water pathway. The reclaimer-inhalation pathway is many orders of magnitude less restrictive and the concentrations from the groundwater migration pathway are so large that they are not even on the graph. The period of restricted site access is 150 years for these analyses. This time period has a major influence upon the ^{90}Sr results owing to the short 29 year half-life of that isotope. The 150 year time period as a negligible affect upon the ^{239}Pu results owing to its longer half-life.

4.1 FORMULATING THE CLASSIFICATION SYSTEM

It is observed[2,3] in the study that if the wastes were disposed of in a way to inhibit the unsuspecting reclaimer from encountering them, then higher concentrations of the waste could be allowed. For example, if the wastes were buried by at least 10 meters (intermediate depth burial) instead of one meter, then the reclaimer-inhalation, food consumption and direct gamma exposure are unlikely and can be removed from consideration. The well water event then becomes limiting and higher concentrations are allowed. In formulating the classification system, no credit is taken for the waste container.

As shown in Figure 4.2, the bases for the five postulated waste disposal classification categories are the presence or absence of the 150 year restricted site access and the accessibility of the site or facility by an unsuspecting reclaimer. Access becomes less likely for each succeeding item. Geologic isolation is an example of "the best that we can do".

4.2 PRESENTATION OF THE WASTE DISPOSAL CLASSIFICATION SYSTEM

The factors listed in Figure 4.2 are combined to formulate the classification system given in Figure 4.3. Class E waste is derived from analyses using no administrative control and ready access to the waste by a reclaimer. The DCG's for this class are the lowest of the set. Example of facilities that are appropriate for the disposal of Class E waste are sanitary landfill or fill for construction.

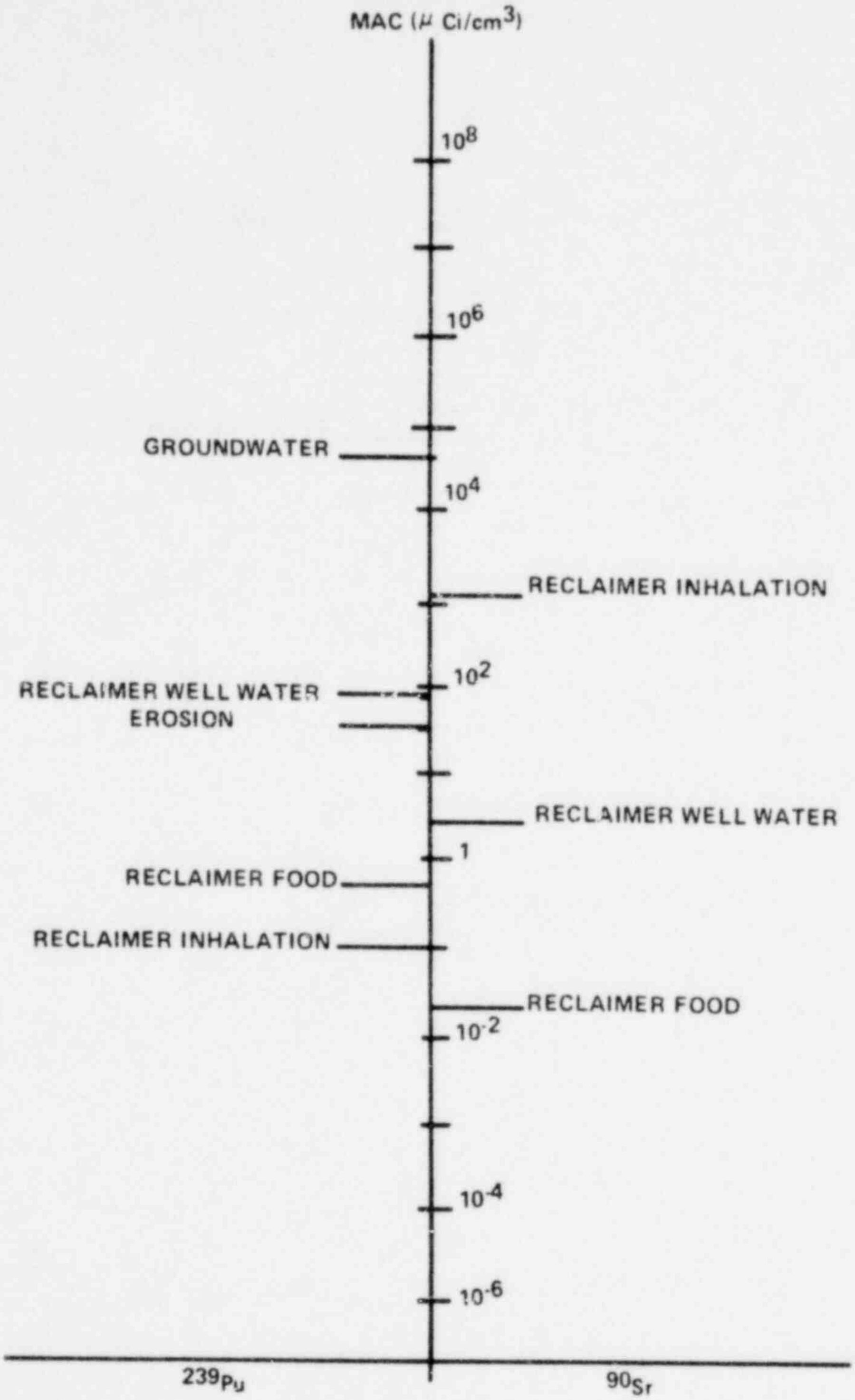


FIGURE 4.1 MAXIMUM AVERAGE CONCENTRATIONS FOR ^{239}Pu AND ^{90}Sr FOR MANY EVENTS

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A. TIME OF ADMINISTRATIVE CONTROL

- NO ADMINISTRATIVE CONTROL
- 150 YEARS OF ADMINISTRATIVE CONTROL

B. ACCESSIBILITY BY A RECLAIMER

- NEAR SURFACE - EASY ACCESS
- INTERMEDIATE DEPTH
- GEOLOGIC ISOLATION

FIGURE 4.2 BASIS FOR WASTE CLASSIFICATION SYSTEM CATEGORIES

WASTE DISPOSAL CLASSIFICATION SYSTEM

CLASS E	NO ADMINISTRATIVE CONTROL READY RECLAIMER ACCESS
CLASS D	ADMINISTRATIVE CONTROL THEN RECLAIMER ACCESS
CLASS C	NO ADMINISTRATIVE CONTROL AFTER DISPOSAL OPERATIONS NO RECLAIMER ACCESS EXCEPT WELL WATER
CLASS B	ADMINISTRATIVE CONTROL NO RECLAIMER ACCESS EXCEPT WELL WATER AFTER 150 YEARS.
CLASS A	"ISOLATION" (REPOSITORY)

FIGURE 4.3 CATEGORIES OF THE PROPOSED CLASSIFICATION SYSTEM

The Class D waste category is similar to the Class E category except a period of administrative control must be in effect at the disposal site and disposal conditions are better defined. Therefore, DCG's for Class D are larger than for Class E.

Class C waste is appropriate for waste disposed of in such a manner that ready access by an unsuspecting reclaimer is unlikely. However, no administrative control is applied after the period of disposal operations. The disposal is postulated to be such that the well water event limits the concentrations. The reason no credit is taken for administrative control in this class is the worst location for the well is on the aquifer downgradient side of the waste and this could be immediately outside the site boundary.

Some waste can be disposed of at facilities appropriate for intermediate depth burial (about 10m or more), but for which there is no present potential for contaminating a well (no potable aquifer). This waste is Class B. There is still some limitation that should be placed upon Class B waste. Although based upon the well water event, this limitation also serves to limit the consequence of other unanticipated intrusion events that could occur without administrative control. Therefore, we have postulated that for facilities handling this waste, the hydrology could change after 150 years making the well water scenario operable. The DCG's for this class are just the DCG's for Class C modified by applying the 150 year decay factor. An example of a facility that may be considered for the disposal of Class B waste is the Hanford Site. If the wastes are buried by about 10 meters, there is no reclaimer access including the well water event.

The category Class A, has no upper concentration limit. Wastes with radioisotopic concentrations exceeding Class B are automatically categorized as Class A.

Ocean dumping is sufficiently unique to warrant a separate classification for wastes that can be appropriately disposed of in the ocean. A preliminary investigation was performed for classifying wastes appropriate for ocean dumping, but that effort was not incorporated into the present waste classification system. Disposal in the ocean is limited by the waste inventory and inventory release rates and not waste concentrations.

The categories of this classification system can be collapsed for regulatory purposes merely by deleting a category and assigning the wastes classified in that category to the next higher category. For example, if it is decided that the 150 year administrative control be applied to all wastes, then the classification system would consist of three categories, D, B and A. Waste that would have been classified as Class E would be classified as Class D. Likewise, waste that would have been classified as Class C would be classified as Class B waste.

In summary, the waste classification system is based upon the requirements for safe disposal. The key factory in formulating the disposal classification system is the period of administrative control and the degree of access by an unsuspecting reclaimer. The Classes E, D, C and B apply to wastes that are disposed in facilities with decreasing site access potentially occurring later in time. The DCG's for each class increase in proceeding from Class E to Class B. Waste not appropriate for any other class is categorized as Class A waste - the best we can do. Finally, the classification system is a step in assuring safe disposal. Further provisions such as proper site selection, design and operation when applicable would further enhance safe disposal.

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5. QUANTITATIVE APPLICATION OF EXPOSURE EVENTS

Equations have been developed for obtaining MAC's for each of the applicable events. These events are:

1. Inhalation of dust by a reclaimer.
2. Ingestion of food produced on the disposal site.
3. Well water consumption.
4. Direct gamma radiation exposure.

In addition, groundwater migration and surface erosion were investigated but are not applicable to the development of the MAC's.

5.1 PATHWAY DEPENDENT MAXIMUM AVERAGE CONCENTRATIONS

A summary of the equations and the values of the parameters is given in the Appendix. A more detailed discussion of the quantitative event modeling is given in References 2-4. The list of MAC's given in Tables 5.1 and 5.2 are the results of the event analysis for 150 year administrative control and for no administrative control. The MAC's given in the table do not contain waste peak-to-average factors; hence, they are a factor of ten less than the parameter used in Reference 2.

Maximum radionuclide inventories were obtained from the groundwater and surface erosion pathway analysis. Concentration limits were derived by dividing the maximum inventory by the waste volume in the reference disposal facilities. These concentration limits are also shown in Tables 5.1 and 5.2. The MAC's are given in parenthesis because they were not used to obtain the DCG's.

The lowest MAC for each nuclide is underlined in Tables 5.1 and 5.2. In general, the reclaimer food pathway is most limiting for the fission products and the reclaimer-inhalation pathway is most limiting for the actinides. Notable exceptions are the short half-life strong gamma emitters ^{60}Co and ^{137}Cs. The other exceptions are ^{3}H in the well water pathway with administrative control and the ^{129}I in the well water pathway with no administrative control.

For the case with administrative control, the MAC's are generally of the order of a few tenths of a microcurie per cubic centimeter of waste. The MAC's for the case with no administrative control are generally of the order of a nanocurie per cubic centimeter of waste. The exceptions are long-lived isotopes whose limiting pathway is reclaimer-food. These isotopes are ^{14}C, ^{99}Tc, ^{135}Cs, ^{235}U, ^{238}U and ^{237}Np. For them, administrative control allows for a factor of two increase in the most limiting MAC.

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TABLE 5.1

MAXIMUM AVERAGE CONCENTRATIONS FOR EXPOSURE EVENTS - WITH 150 YEARS OF CONTROL ($\mu Ci/cm^3$)

Nuclide	MAC-Food	MAC-Inhalation	MAC-Gamma Exposure	MAC-Well Water	(MAC)-Ground-Water	(MAC)-Erosion/Corrosion
^{3}H	390			94	1.1 +6	
^{14}C	2.4 -3[a]	1.6 +5		140	790	6.2 +3
^{60}Co	5.5 +7		2.1 +6			
^{90}Sr	0.02	1.1 +3		2.4		
^{99}Tc	0.1			64	150	2.7 +3
^{129}I	0.3	63	4.6	0.31	1.2	1.9 +3
^{135}Cs	0.2			20	12	880
^{137}Cs	1.1	1.4 +5	0.9			
^{235}U	0.03	7	0.2	11	1.2 +3	21
^{238}U	0.03	8	1.1	12	1.4 +3	22
^{237}Np	0.02	0.2	1.9	0.3	640	14
^{238}Pu	1.2	0.4	6.1			210
^{239}Pu	0.4	0.1		90	3.5 +4	24
^{240}Pu	0.3	0.1	2	810		23
^{241}Pu	1.6 +4	5.9 +3				
^{242}Pu	0.3	0.1		13	1.9 +3	24
^{241}Am	0.4	0.4	0.5			32
^{243}Am	0.3	0.3	0.3	600		22
^{244}Cm	13	200	730			

[a] The term 2.4 -3 means 2.4×10^{-3}.

TABLE 5.2

MAXIMUM AVERAGE CONCENTRATIONS FOR EXPOSURE EVENTS - NO ADMINISTRATIVE CONTROL ($\mu Ci/cm^3$)

Nuclide	MAC-Food	MAC-Inhalation	MAC-Gamma Exposure	MAC-Well Water	(MAC)-Ground-Water	(MAC)-Erosion/Corrosion
^{3}H	0.05	5.8 +3		7.5	8.7 +4	
^{14}C	1.2 -3	400		11	62	6.2 +3
^{55}Fe	12	100				
^{57}Co	7	20				
^{60}Co	0.07	1.2	2.5 -4			
^{90}Sr	2.3 -4	0.07	0.65	0.19		
^{99}Tc	0.05	1.8 +3		5	12	2.7 +3
^{129}I	0.14	0.2	0.6	0.024	0.09	1.9 +3
^{135}Cs	0.1	60		1.6	0.9	880
^{137}Cs	0.02	12	4.2 -3			
^{235}U	0.015	0.02	0.02	0.9	95	21
^{238}U	0.015	0.02	0.3	0.9	110	22
^{237}Np	9 -3	5.4 -4	0.045	0.024	50	14
^{238}Pu	0.2	3.4 -4	0.8			210
^{239}Pu	0.2	3.0 -4		8	2.8 +3	24
^{240}Pu	0.2	3.0 -4	0.3	60		23
^{241}Pu	8	0.015				
^{242}Pu	0.2	3.1 -4		1.0	150	24
^{241}Am	0.2	9.2 -4	0.07			32
^{243}Am	0.2	9.2 -4	0.025	42		22
^{242}Cm	0.2	0.024				
^{244}Cm	0.02	1.5 -3	0.8			

6. DISPOSAL CONCENTRATION GUIDES FOR WASTE CLASSIFICATION

The basis for the waste classification system is presented in Chapter 4. The MAC's for each pathway are discussed in the Appendix and are presented in Tables 5.1 and 5.2. These MAC's provide the necessary information to formulate the DCG's for each category in the waste classification category.

6.1 DISPOSAL CONCENTRATION GUIDES FROM THE MAXIMUM AVERAGE CONCENTRATIONS

As an example of obtaining the DCG's from the MAC's, the provisions of Class E are no administrative control and easy access to the waste by a reclaimer. Hence, the food, inhalation, direct gamma and well water pathways apply and the most restrictive MAC from these pathways becomes the DCG. These concentrations are given under the Class E column in Table 6.1. They are the values that are underlined in Table 5.2.

In a similar fashion, the provisions of Class D are 150 years of administrative control and easy access to the waste by a reclaimer. The most restrictive MAC's for this category are underlined in Table 5.1 and are also given under the Class D column in Table 6.1.

The provisions of Class C are similar to those of Class D except the unsuspecting reclaimer does not have direct access to the waste except via the well water pathway. This could be accomplished by burying the waste at least 10 meters. Hence, the MAC's from the well water pathway in Table 5.1 becomes the DCG's for Class C.

For some disposal facilities that qualify for Class C waste, potential exposure to a reclaimer, even via the well water pathway, is not realistic. For example, there may not be a potable aquifer beneath the site. However, there should be a limit to the concentration of waste that can be disposed of in such a facility. Since hydrologic conditions at the sites are subject to change, the potential for the well water event after 150 years is used to provide the limit. Hence, the DCG's given in the Class B column of Table 6.1 are obtained by correcting the DCG's of Class C by T_d, the radioactive decay factor.

The limits for Class A or isolation cannot be determined generally. The choice of a repository site, its design and operation, waste form and packaging need to be analyzed in a specific manner. A repository and Class A waste should be considered as a system and the results will likely be "the best that we can do". Thus, the DCG's assigned to this category are just the specific activity densities of the isotopes. Concentrations or types of waste not appropriate for the other waste categories will be classified as Class A waste.

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TABLE 6.1

DISPOSAL CONCENTRATION GUIDES
FOR WASTE CLASSES (μCi/cm^3)

	WASTE CLASS				
Isotope	E	D	C	B	A
^{3}H	0.05	94	94	4.3 +5	2.9 +9
^{14}C	1.2 -3	2.4 -3	140	140	7.1 +6
^{55}Fe	12				1.9 +10
^{60}Co	2.5 -4	2.1 +6			9.7 +9
^{90}Sr	2.3 -4	0.02	2.4	38	3.6 +8
^{99}Tc	0.05	0.1	64	64	1 +4
^{129}I	0.024	0.3	0.3	0.3	850
^{135}Cs	0.10	0.2	20	20	2.4 +3
^{137}Cs	4.2 -3	0.9			1.7 +8
^{235}U	0.015	0.03	11	11	41
^{238}U	0.015	0.03			6.4
^{237}Np	5.4 -4	0.02	0.3	0.3	1.3 +4
^{238}Pu	3.4 -4	0.4			3.4 +8
^{239}Pu	3.0 -4	0.1	90	90	1.2 +6
^{240}Pu	3.0 -4	0.1	810	810	4.7 +6
^{241}Pu	0.015	5.9 +3			2.2 +9
^{242}Pu	3.1 -4	0.1	13	13	7.6 +4
^{241}Am	9.2 -4	0.4			6.4 +7
^{243}Am	9.2 -4	0.3	600		3.6 +6
^{242}Cm	0.024				2.6 +10
^{244}Cm	1.5 -3	13			6.2 +8

Particular entries are omitted in Table 6.1 if the DCG for that class exceeds the Class A DCG for that isotope.

6.2 DISPOSAL CONCENTRATION GUIDES FOR MIXTURES

The DCG's presented in Table 6.1 are based upon an analysis of each individual isotope. The reciprocal of the DCG for a mixture of nuclides in waste is obtained from a weighted sum of the fraction of activity for each isotope. The weighting factor is the reciprocal of the DCG for that isotope, i.e.

$$\frac{1}{DCG_m} = \sum_{i=1}^{n} \frac{f_i}{(DCG)_i} \qquad (6.1)$$

where,

n = number of isotopes in the mixture

f_i = radioactivity fraction of i^{th} isotope in the mixture

$(DCG)_i$ = DCG for i^{th} isotope

DCG_m = DCG for the waste mixture

For example, assume a waste with the following characteristics:

Isotope	Concentration ($\mu Ci/cm^3$)
^{90}Sr	0.012
^{129}I	0.016
^{238}Pu	0.012
^{239}Pu	0.04
Total Activity	0.08

What are the DCG's for Classes C, D and E of this waste?

First, the activity fractions must be determined. They are obtained by dividing the concentration of each isotope by the total activity concentration of the waste. The f_i for ^{90}Sr is 0.012/0.08 = 0.15. The f_i's for ^{129}I, ^{238}Pu and ^{239}Pu are 0.2, 0.15 and 0.5, respectively.

Then the (DCG) mixture is obtained by applying Eq. (6.1) for each class.

Class E

$$\frac{1}{DCG_m \text{ (Class E)}} = \frac{.15}{2.3 \; -4} + \frac{.2}{.14} + \frac{.15}{3.4 \; -4} + \frac{.5}{3.0 \; -4} = 2761$$

Then,

DCG_m (Class E) = 3.6×10^{-4} $\mu Ci/cm^3$

Class D

$$\frac{1}{DCG_m \text{ (Class D)}} = \frac{.15}{2.0 \; -2} + \frac{.2}{.3} + \frac{.15}{.4} + \frac{.5}{.1} = 13.5$$

Then,

DCG_m (Class D) = 0.074 $\mu Ci/cm^3$

Class C

$$\frac{1}{DCG_m \text{ (Class C)}} = \frac{.15}{2.4} + \frac{.2}{.31} + 0 + \frac{.5}{90} = 0.71$$

Then,

DCG_m (Class C) = 1.4 $\mu Ci/cm^3$

Comparison of the total activity concentration of the mixture with the corresponding DCG's reveals that the mixture is Class C waste. The 0.08 $\mu Ci/cm^3$ concentration exceeds the DCG's for Class E and D but is less than the DCG for Class C.

The above procedure is the basis for classifying mixtures of waste that are ready for disposal. Mixtures of isotopes in the waste can be estimated for each different type of process that generates waste. The concentrations of every isotope in every batch of waste will not need to be measured. From the estimated f_i's for each type of waste generation activity, DCG's for that waste mixture can be determined. Then, the total activity concentration of the waste from a specific waste source is all that will be needed to classify the waste.

6.3 CONCLUSIONS

In conclusion, a radioactive waste classification system has been developed. The system is based upon the requirements for safe disposal. The DCG's are the interface parameters between waste classes. Higher values of the DCG's are associated with greater protection against potential exposures from the disposed waste. The list of DCG's are given for the main isotopes of interest in radioactive waste disposal. However, a complete list of DCG's should be generated for all isotopes, especially for the Class E category. Finally, DCG's for mixtures of isotopes can be determined in a straightforward manner.

APPENDIX

EQUATIONS AND PARAMETERS FOR EXPOSURE EVENTS

The purpose of this Appendix is to present in summary form, the mathematical formulation and numerical values of key parameters used in the exposure event analysis. A more detailed discussion of the equations and the values of the parameters are given elsewhere.[2,3]

A.1 INHALATION OF DUST BY A RECLAIMER

The first occurrence presented is the reclamation of the waste disposal facility after 150 years. For this event, people are exposed to contaminated dust while moving earth at the site. The equation relating the dose rate of the few individuals to the MAC of the radioactive contaminant in the waste is:

$$C_m = \frac{D_e T_d \rho}{A_d U_a T_x f_w (DF)_m} \qquad (A.1)$$

where,

D_e = dose rate guideline (500 mrem/yr)

C_m = MAC of isotope m in the waste at the time of burial, (μCi/cm^3)

A_d = dust loading in the air

U_a = breathing rate of exposed individuals

T_x = time period of exposure

f_w = dilution factor of waste with soil or other facility material

$(DF)_m$ = dose rate conversion factor for isotope m (mrem/yr/μCi inhaled for reclaimer after administrative control, mrem/μCi inhaled for continuous exposure without administrative control)

λ_m = radioactive decay constant for isotope m (yr^{-1})

T_d = correction for decay during 150 year control period (if applicable)

ρ = density of waste material

For the base case event, the exposure is to a few individuals who work in dusty air loaded with 500 micrograms of dust per m^3 of air. Values of other parameters are given in Table A.1 for cases with and without administrative controls. Using the 50 year dose commitment factor of 3.05 mrem/pCi from Reference 5 to obtain $(DF)_m$ for ^{239}Pu and the other values as given, a MAC of 0.1 µCi/cm^3 is obtained for ^{239}Pu in waste with administrative control. Concentrations in waste up to this value would result in doses to workers under the stated conditions of less than 500 mrem/yr from the exposure.

The above approach was applied to the significant nuclides in radioactive waste. The list of MAC's given in Tables 5.1 and 5.2, are obtained using Eq. (A.1) and dose conversion factors from Reference 5.

The inadvertent or unknowing exposure to disposed wastes could occur as a result of several future actions. Assuming that disposal is by some near-surface method such as shallow land burial, possible courses of exposure to the wastes include efforts to reclaim the disposal site for productive use, such as housing, farming or resource exploration. Archeological activities or salvage of apparently useful disposed items could also occur. Both the duration of the resultant exposures, and the amount of buried waste involved can vary over large ranges. Some engineering judgement is required to select the most reasonable values to be used in any analysis of the effects of the potential reclamation events. Factors most dependent upon the detailed reclamation event are the dust loading and the exposure time period.

Typical dust loadings around the country average about 40 µg/m^3 in rural areas and about 150 µg/m^3 in urban areas. Over 90 percent of all measurements are less than 300 µg/m^3. Plowing fields raise dust loadings up to 30 times the average values for farms.(6) Obviously, the wind speed and duration, orientation of the excavation and composition of the disposed wastes all influence the dust loading. There is an obvious correlation between dust loading and the probable exposure time. The higher the dust loading, the less time a person stays exposed because of physical discomfort, while a lower dust loading can be tolerated for a much longer period. The relationship between dust loadings, exposure times and resultant dose rates to the exposed individuals are shown in Figure A.1.

Besides the base exposure of a few individuals involved in construction to an elevated dust loading, other exposure events can be postulated. If 200 homes are built on the site, with five occupants each, this 1,000 person population may be exposed to dust from the wastes carried to the surface by construction activities. Presuming that significant stabilization of the exposed waste mixed with soil does not occur until one year has elapsed after initial occupation of the homes (typical time to get lawns in place), and that the waste in the dust is further diluted (by a factor of three) with the clean surface soil and that the annual

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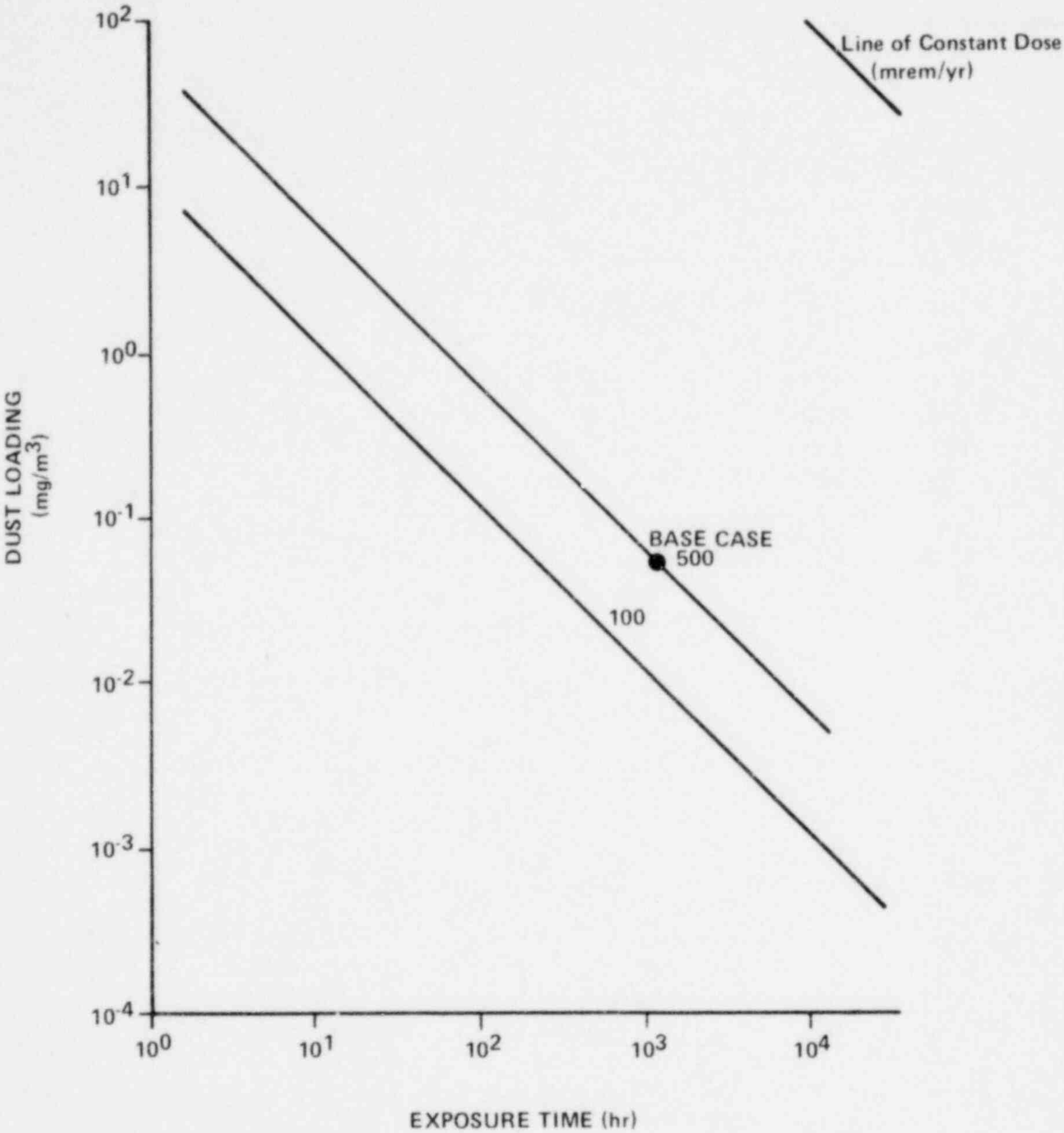

FIGURE A.1 RELATIONSHIP BETWEEN DUST LOADING AND EXPOSURE TIME ON DOSE RATES AT CONSTANT CONCENTRATION LIMIT IN WASTES

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TABLE A.1

REFERENCE VALUES OF KEY PARAMETERS

Parameter	Value With Administrative Control	No Administrative Control
A_d, dust loading in air	5×10^{-4} g/m^3	5×10^{-4} g/m^3
U_a, breathing rate	0.91 m^3/hr	0.91 m^3/hr
T_x, period of exposure	500 hrs	1920 hr/yr
f_w, waste dilution factor	0.5	1.0
ρ, waste density	1.6 g/cm^3	1.6 g/cm^3
T_d, correction for decay	exp (150 λm)	1
f_2, mixing factor for growing food	10	10
f_3, fraction of consumed food grown on-site	0.5	0.5
m_v, aquifer flow per unit volume of waste	2.2 yr^{-1}	0.17 yr^{-1}
v_1, aquifer flow velocity for region 1	10 m/yr	10 m/yr
v_2, aquifer flow velocity for region 2	100 m/yr	100 m/yr
D, aquifer dispersion coefficient	10 m^2/yr	10 m^2/yr

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average dust loading from the wastes is 50 μg/m^3, a person who resided there full time for one year, breathing at a moderate activity rate would receive a dose rate of about 100 mrem/yr from buried wastes containing 0.1 μCi/cm^3 of ^{239}Pu. Most of the 1,000 people, of course, will not spend full time outside in that area and average breathing rates are lower than the value used. Therefore, the 100 mrem/yr is a very conservative value with the actual average value expected to be much less.

A.2 INGESTION OF FOOD PRODUCED ON THE DISPOSAL SITE

Some contamination of the surface soil could eventually result from reclamation activities. Vegetables possibly could be grown in the contaminated soil, or milk cows or beef raised on contaminated grass. Consumption of these foodstuffs would then result in exposures to the few individuals involved in eating the produce. Equation (A.2) gives the relationship between the MAC of radioactivity in the wastes and the dose guideline, dose conversion factor and consumption and uptake factors for each nuclide:

$$C_m = \frac{D_e \; f_2 \; T_d \; \rho}{(DF)_m \; B_{mv}(U_{ap}^{meat} \; F_f Q_a + U_{ap}^{milk} \; F_m Q_a + U_{ap}^{veg}) \; f_w f_3} \qquad (A.2)$$

where,

f_2 = mixing factor for buried materials transferred to surface and intermingled with clean soil at surface

$(DF)_m$ = dose conversion factor from Reference 5 for mth nuclide (mrem/pCi)

B_{mv} = vegetative bioaccumulation and uptake factor for mth nuclide by vth plant from Reference 5 (concentration in vegetable/concentration in soil)

U_{ap}^{i} = usage factors from Reference 5 (U_{ap}^{milk} = 310 ℓ/yr; U_{ap}^{meat} = 110 kg/yr; U_{ap}^{veg} = 520 kg/yr)

Q_a = animal consumption rate from Reference 5 (50 kg/day)

F_f = stable element transfer coefficient relating animal consumption rate to concentration in edible meat from Reference 5 (day/kg)

F_m = stable element transfer coefficient relating animal consumption rate to concentration in milk from Reference 5 (day/ℓ)

f_3 = fraction of annual food consumption produced on site

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Tables 5.1 and 5.2 contain a list of the MAC's for nuclides in waste based on this pathway.

A.3 WELL WATER RECLAMATION EVENT

Another event which deserves attention is the use of contaminated groundwater from the aquifer immediately below the site. The maximum radionuclide concentrations in the aquifer would occur on the downgradient edge of the site shortly after the time of disposal, and are a function of the radionuclide leach rate constants and the aquifer flow rate normalized to a unit volume of waste:

$$C_m = \frac{D_e \; m_v}{\lambda_L f_o U_b (DF)_m} \qquad (A.3)$$

where,

m_v = aquifer flow rate per unit volume of waste (m^3/yr per m^3 of waste)

λ_L = nuclide leach constant (yr^{-1})

U_b = water consumption factor for maximum or average individual from Reference 5

f_o = peak ratio of quantity of nuclide arriving in groundwater at well to that leaving waste in first year

The parameter m_v relates a unit volume of waste with the amount of aquifer contaminated by it. It is dependent upon the aquifer and waste properties directly upgradient from the well. It is not dependent upon the total waste inventory nor the total aquifer flow.

The quantity f_o is determined from groundwater migration calculations usir a spatially dependent source and element dependent leach cons ts, λ_L, and retardation factors, K. For a one-region aquifer fl ystem, the following equation is used to obtain f_o:

$$f_o = \left[\frac{1-e^{-40\lambda_E}}{40\lambda_E}\right]\frac{1}{2}\sum_{i=1}^{N}\left\{\exp\left[\frac{vXi}{2D} - \lambda_E t - a_i d\right]\operatorname{erfc}\left[\frac{a_i - 2bt}{2t^{1/2}}\right]\right\} \qquad (A.4)$$

where,

v = aquifer flow rate (m/yr)

$a_i = \sqrt{K/D \; X_i}$

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$$b = \sqrt{v^2/4KD - \lambda_L}$$

$$\lambda_E = \lambda_L + \lambda_m$$

D = aquifer dispersion coefficient (m^2/yr)

In this equation, the spatial source has been represented by N mesh points, each with a distance X_i from the mesh point to the use point of the aquifer (well or river).

The first term in brackets corrects for the fact that the waste is placed in the disposal facility over a period of 40 years; hence, for some isotopes decay and leaching can occur during the 40 year loading period.

For most calculations, a two-region aquifer system was assumed allowing for variations in the matrix through which the groundwater flowed. The equation[2,3] representing the radionuclide migration is very similar to Eq. (A.4) except that it contains four exp and erfc terms.

Values of m_v, v and D are given in Table A.1. The values of nuclide and element specific parameters are given in Table A.2. The resulting MAC's for the well water event are given in Tables 5.1 and 5.2.

A.4 DIRECT GAMMA EXPOSURE

For some gamma-emitting radionuclides, the limiting concentration is associated with the reclaimer digging into the waste or living on the waste and receiving an external gamma dose. The equation relating the limiting concentration in the waste, (C_m), to the resulting gamma exposure is:

$$C_m = \frac{2\mu D_e\ T_d}{(0.0575)G(\mu/\rho)_t E_m T_x f_w} \qquad (A.5)$$

where,

μ = effective gamma ray attentuation coefficient for soil (cm^{-1})

G = gamma emission rate per μCi of radionuclide (γ/sec/μCi)

$(\mu/\rho)_t$ = mass absorption coefficient for tissue (cm^2/g)

E_m = average energy of the emitted gamma rays (MeV) times the multiplicity of average energy gamma rays

and the other terms as defined previously.

TABLE A.2

CHARACTERISTICS OF NUCLIDES

Nuclide	Sorption Coefficient (K)	Half-Life (yr)	Decay Constant, λ_m (yr^{-1})	Leach Constant, λ_L (yr^{-1})
^{3}H	1	1.23 +1	5.62 -2	1 -1
^{14}C	1 +1	5.73 +3	1.21 -4	1 -4
^{55}Fe	3.3 +3	2.70	2.57 -1	1 -1
^{60}Co	3.3 +3	5.3	1.32 -1	1 -1
^{90}Sr	1 +2	2.9 +1	2.43 -2	1 -2
^{99}Tc	1	2.13 +5	3.25 -6	1 -4
^{129}I	1	1.59 +7	4.36 -8	1 -1
^{135}Cs	1 +3	2.3 +6	3.01 -7	1 -3
^{137}Cs	1 +3	3.01 +1	2.3 -2	1 -3
^{235}U	1.4 +4	7.04 +8	9.85 -10	1 -5
^{238}U	1.4 +4	4.47 +9	1.55 -10	1 -5
^{237}Np	1 +2	2.14 +6	3.24 -7	1 -5
^{238}Pu	1 +4	8.78 +1	7.89 -3	1 -5
^{239}Pu	1 +4	2.44 +4	2.84 -5	1 -5
^{240}Pu	1 +4	6.54 +3	1.06 -4	1 -5
^{241}Pu	1 +4	1.5 +1	4.62 -2	1 -5
^{242}Pu	1 +4	3.87 +5	1.79 -6	1 -5
^{241}Am	1 +4	4.33 +2	1.60 -3	1 -5
^{243}Am	1 +4	7.37 +3	9.40 -5	1 -5
^{242}Cm	3.3 +3	4.5 -1	1.55	1 -5
^{244}Cm	3.3 +3	1.79 +1	3.87 -2	1 -5

Tables 5.1 and 5.2 contain MAC's of the major gamma-emitting radionuclides in the waste for the worker who is directly exposed to the waste. Comparison of these limiting maximum concentrations with a typical radionuclide mix in waste reveals that ^{137}Cs is the dominant contributor to the total gamma exposure for times less than about 500 years, then several transuranics become dominant.

A.5 ANALYSIS OF OTHER EVENTS

The exposure events were analyzed during the development of the RWDCS. As explained previously, these events did not have a direct application in the final form of classification system. However, they must be considered in the environmental impact analysis of individual waste disposal facilities to ensure that the health and safety of the public is protected from any adverse consequences resulting from the operation of that facility. Two events discussed herein are: groundwater migration and erosion/corrosion of the disposal facility. It is informative to compare the concentration limits obtained from the analyses of these to two exposure events for reference facilities with the MAC's from the other pathways.

The groundwater migration was assumed to occur for the same hydrologic conditions as the well water scenario, except the aquifer length of the second region was set at 1,000 meters, after which it flowed into a surface river with a flow rate of 500 m^3/sec. Application of the dose guidelines yielded a maximum waste inventory.

A concentration limit was obtained by dividing the maximum inventory by the waste volume in the reference disposal facilities. These concentration limits are shown in Tables 5.1 and 5.2. For the generic reference disposal facilities, these concentrations are not limiting.

Erosion/corrosion events were considered for the reference facility by performing a pathway analysis of surface erosion of the cover materials in the reference facilities.

It is reasonably conservative to assume that future containment facilities will not be sited in areas where substantial erosion is likely to occur. However, they were located in an area where wind or water erosion were occurring, some contamination could ultimately be released to surface waters or dispersed into the atmosphere. Design features, such as covering the filled burial area with pebbles through which vegetation could be established, would tend to minimize erosion processes.

For the sake of estimating the impacts from erosion, a straightforward, conservative calculation based on a representative erosion rate was performed. There are a number of site specific parameters influencing erosion rates. Some of these are surface slope, amount of precipitation, distances to watercourses, distances from peaks, amount and type of vegetation and soil properties. However, sixty tons of soil per acre per year is a typical sheet erosion rate.[7,8] Using this rate and soil density of 1.6 gm/cm^3, it will require 120 years for one meter surface cover to be eroded away before the buried wastes begin to erode.

The concentration limits in the waste for sheet erosion of the wastes into the river is given by Eq. (A.6).

$$C_m = \frac{D\,\dot{m}_t d T_d}{F_e U_a (DF)_m V_w} \exp(120\lambda m) \qquad \text{(A.6)}$$

where,

- d = dilution with clean dirt
- F_e = fraction of waste eroded from the site per year (1.0×10^{-3}) (for a thickness of waste of 8 meters)
- $\dot{m}_t$ = surface river flow rate

and other parameters are as defined earlier.

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The Nuclear Regulatory Commission, as part of its development of regulations for the disposal of radioactive waste, has contracted for the development of a radioactive waste classification system. The need for removing the waste from man's environment increases as the potential for endangering the health and safety of the public increases. The classification system being proposed is based on the requirements for safe disposal. The steps which were followed are; define safe, determine the pathways through the environment, formulate categories for the classification system and recommend disposal concentration guides for each category. The proposed categories are based on the length of administrative controls, the accessability of the waste and the hydrologic conditions.

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