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**TRANSURANIC CONTAMINATED WASTE
FUNCTIONAL DEFINITION
AND IMPLEMENTATION**

S/C # 9101903

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PREFACE

The Nuclear Regulatory Commission (NRC) is developing regulations governing the management, handling and disposal of transuranium (TRU) radioisotope contaminated wastes as part of the NRC's overall waste management program. In the development of such regulations, numerous subtasks have been identified which require completion before meaningful regulations can be proposed, their impact evaluated and the regulations implemented. This report was prepared by TERA Advanced Services Corporation to assist Lawrence Livermore Laboratory (LLL), prime contractor to the NRC, in the development of the technical data base necessary to support rule-making actions dealing with TRU-contaminated wastes.

An earlier report, "Inventory and Sources of Transuranic Solid Waste," presented the waste sources, characteristics and inventory of both Department of Energy (DOE) generated and commercially generated TRU waste. Due to changes in the NRC waste management program and redirection of this program, the scope has been expanded to include the functional aspects of implementing a classification system by addressing the technical aspects of monitoring TRU content in radioactive waste. This document then serves as part of the data base necessary to complete design and initiate implementation of a TRU waste methodology suitable for inclusion in the present waste management program.

It is the purpose of this report to serve as a working document which will be used as appropriate in the TRU Waste Management Program. This report, and those following, will be compatible not only in format, but also in reference material and direction. Comments, clarifications or improved data should be directed to B. G. Kniazewycz at TERA's Berkeley office.

EXECUTIVE SUMMARY

1.0 INTRODUCTION

The Nuclear Regulatory Commission (NRC) is developing regulations governing the management, handling and disposal of transuranium (TRU) radioisotope contaminated wastes as part of the NRC's overall waste management program. As part of this effort it is necessary to examine TRU-contaminated waste and implement a waste classification system covering such waste.

The purpose of this report is to examine the problem(s) of TRU waste classification and to document the development of an easy-to-apply standard(s) to determine whether or not a particular waste package is considered TRU Waste and whether or not this waste package should be emplaced in a geologic repository for final disposition.

The transuranic contaminated wastes include isotopes of americium (Am), berkelium (Bk), californium (Cf), curium (Cm), einsteinium (Es), neptunium (Np) and plutonium (Pu). Some waste generators also include one or more uranium (U) isotopes in classifying a waste TRU-contaminated.

Transuranic wastes are especially significant because they have long half-lives and some are rather radiotoxic. Transuranic radionuclides are primarily produced by single or multiple neutron capture by U-238 in fuel elements during the operation of a nuclear reactor. Reprocessing of spent fuel elements attempts to remove plutonium, but since the separation is not complete, the resulting high-activity liquids still contain some plutonium as well as other transuranics. Likewise, transuranic contamination of low-activity wastes also occurs when the transuranic materials are handled or processed, which is primarily at federal facilities involved in R&D and nuclear weapons production.

Transuranics are persistent in the environment and, as a general rule, are strongly retained by soils. They are not easily transported through most food

chains, although some reconcentration does take place in the aquatic food chain. They pose no special biological hazard to humans upon ingestion because they are weakly absorbed from the gastrointestinal tract. A greater hazard results from inhalation since they behave like normal dust and fractionate accordingly. Production of an adverse health effect in the lung, or elsewhere, depends on the particle size and solubility of the inhaled contaminated dust. Once entered into the bloodstream (either by ingestion or inhalation), TRUs will then readily accumulate in bone and liver tissues, and can significantly increase the risk of cancer. Appendix B presents a more complete overview of TRU radioisotopes.

Similar to other radioactive waste material, TRU-contaminated material can include an entire spectrum of physical and chemical species. The present TRU waste sources and anticipated future sources involve primarily military and commercial activities dealing with either the weapons program and the nuclear fuel cycle, respectively. A wide variety of sources of material has been identified and a large inventory presently exists of retrievable waste which has been stored temporarily and other wastes which, due to past practices, were buried with no consideration for retrievability. Thus, the problem of TRU waste includes not only future waste sources, but past sources and practices dealing with TRU material. In addition to this general problem, the variety of waste materials and their chemical and physical form also make the development of a simple classification scheme very difficult.

2.0 BACKGROUND

On March 20, 1970, the Atomic Energy Commission published the Immediate Action Directive (IAD) No. 0511-21 requiring that wastes from AEC sites with known or detectable contamination of transuranium nuclides above 10 nCi/g (10 one-billionths of a curie per gram) be segregated from other types of wastes and stored in such a fashion that the packages can be retrieved free of external contamination within an interim period of 20 years.

2.1 SOURCE OF RADIOACTIVE TRU WASTE

Nearly all operations that produce or use nuclear materials generate radioactive waste. Most of this waste comes from the Department of Energy's reactors and facilities, commercial nuclear power plants, and federal (military) and commercial nuclear fuel cycle activities—mainly fuel fabrication and reprocessing facilities. No commercial reprocessing facilities are currently operating, but DOE has four reprocessing facilities either in operation or on standby.

High-level liquid waste contains many fission products and small amounts of transuranics, such as plutonium, which are not recovered during the reprocessing operation. As well as being found in high-level waste, transuranic (TRU) materials in various concentrations are also found in other waste. It is generated by plutonium fuel fabrication and fuel reprocessing facilities and also by laboratories which use transuranic elements. This waste generally consists of expendable items such as absorbent paper, clothing, gloves, plastic bags and equipment; ion exchange resins or filters from effluent treatment systems; and fuel cladding hulls which remain after reprocessing.

TRU waste has been disposed of at five of the six commercial burial sites (excluding Barnwell SC) which have supported the commercial LWR industry, as well as Department of Energy (DOE) and its predecessor AEC and ERDA-generated waste. These sites have accepted wastes generated in the fuel cycle, primarily during fuel fabrication and spent fuel reprocessing, as well as wastes from numerous miscellaneous R&D activities and small commercial uses of TRU radioisotopes. The present inventory of TRU-contaminated waste is limited primarily to DOE-generated waste (shipments now terminated) and R&D fuel fabrication activities involving plutonium. The NRC does not have records on the volume of commercial transuranic contaminated waste buried at commercial shallow land burial sites, but estimates that about 123.4 kilograms of plutonium were buried at five of the six sites through 1977. The best available information indicates that the cumulative DOE-generated TRU waste (through 1976) shipped to these commercial burial grounds contained about 7.6 kg of TRU isotopes.

The TRU solid waste inventory for seven different DOE sites is provided below. Only about 15 percent of this volume of waste is in retrievable storage. By 1984 it is anticipated that the retrievable storage inventory might increase by a factor of two, while the amount of waste in burial sites will remain virtually unchanged. The TRU inventory (as of October 1, 1978) of contaminated wastes, soils and sediment is as follows:

Retrievably stored	494 kg TRU	48,500 m ³
Previously buried	759 kg TRU	268,000 m ³
Contaminated soils and sediments	190 kg TRU	1,218,000 m ³

2.2 TRU WASTE FORMS AND CHARACTERISTICS

The management of TRU waste is complicated not only because of its physical and chemical characteristics, but also because of the level of radioactivity and the necessity of long-term containment required due to its long half-life (LH). TRU-contaminated waste pose a significant problem to the regulatory agencies because the variety of waste to be disposed of in a geologic repository is immense. Not only are there a variety of radioisotopes and radiation fields but also a nearly infinite combination of physical forms and conditions and chemical constituents. Tables A and B present some typical waste streams from the commercial and DOE TRU-contaminated waste generators. These tables are by no means complete, but are provided to illustrate the great variety of materials which must be considered and evaluated in the final design of both the acceptable waste form and package, and the geologic repository.

It is necessary not only to identify waste sources, but also to analyze the composition of waste from various points of generation. This analysis aids in determining useful changes at the source that would reduce the waste generation rate as well as reducing subsequent handling and treatment, identification and

TABLE A
SOURCES OF TRU WASTE FROM A COMMERCIAL
MOX FUEL FABRICATION FACILITY

<u>Waste Category</u>	<u>Waste Description</u>
1. Salt Solutions	Concentrated scrap recovery, decontamination, and off-gas scrub liquids.
2. Surfactants/Detergent Solutions	Laundry wastes, personnel decontamination solutions.
3. Organic Liquids	Pneumatic fluids, oils, laboratory solvents.
4. Wet Particulates	Bead ion exchange resins used for liquid effluent treatment.
5. Dry Particulates	Floor sweepings, etc.
6. Combustible Solids	General trash (cellulosics, plastics, rubber - uncompacted). Ventilation (HEPA) filters (up to 60 wt% combustible).
7. Noncombustible Solids	General trash, PuO_2 cans, etc. (uncompacted). Failed equipment, furnace brick.

TABLE B
TYPICAL DOE TRU-CONTAMINATED WASTE

First Stage Sludge (Reprocessing)	Grit
Second Stage Sludge (Reprocessing)	Blacktop Concrete Dirt & Sand
Organic Set Ups (Oil Solids)	Cement Insulation & Filter Media
Special Set Ups (Cement)	Sand, Slag and Crucibles
Evaporated Salts	Electrorefining Salt
Combustibles (Paper, Rags, Gloves, Poly)	Resin
Non-Compressible, Non- Combustibles	Glass
Dirt	Raschig Rings
Sludge	Metal Scrap
Hot Cell Waste	Equipment Boxes
Americium Process Residue	High-Level Acid
Graphite Wastes	High-Level Caustic
Benelex and Plexiglas	High-Level Sludge/Cement
HEPA Filters	Contaminated Soil
Plastics, Teflon, PVC	Wood
Leaded Rubber Gloves & Aprons	Laundry Sludge
Brick, Fire	Miscellaneous Equipment

development of processes and equipment for treatment to alter the waste form and provide suitable containment in addition to other operational and safety aspects of waste management operation.

3.0 TRANSURANIC WASTE CLASSIFICATION SCHEMES

As a first step in establishing TRU waste classification criteria the existing regulations were reviewed. Some of these regulations, which could be interpreted as establishing concentrations of radioactive materials for disposal, include the following:

- Federal Regulations, Title 10, Part 20
- Federal Regulations, Title 10, Part 30
- Federal Regulations, Title 10, Part 50
- Federal Regulations, Title 10, Part 71
- Federal Regulations, Title 40, Part 190
- Proposed Federal Guidance on Transuranium Elements in the Environment

In the last of the regulations above, the Environmental Protection Agency has proposed (42 FR 60956) federal radiation protection guidance on limits of dose to persons exposed to transuranics in the environment as a result of existing or possible future unplanned contamination. The portion of the text which suggests this guidance follows.

- "1. The annual alpha radiation dose rate to members of the critical segment of the exposed population as the result of exposure to transuranium elements in the general environment should not exceed either:
 - a. 1 millirad per year to the pulmonary lung, or
 - b. 3 millirad per year to the bone.
2. For newly contaminated areas, control measures should be taken to minimize both residual levels and radiation

exposures of the general public. The control measures are expected to result in levels well below those specified in paragraph one. Compliance with the guidance recommendations should be achieved within a reasonable period of time.

3. The recommendations are to be used only for guidance on possible remedial actions for the protection of the public health in instances of presently existing contamination or of possible future unplanned releases of transuranium elements. They are not to be used by Federal agencies as limits for planned releases of transuranium elements into the general environment."

One "millirad per year to the pulmonary lung" is meant to be the equilibrium dose rate resulting from chronic inhalation. The corresponding dose equivalent rate for alpha emitting transuranics is 20 millirem per year.

In addition to these regulations, a number of earlier classification schemes were reviewed.

The most common method of grading radionuclides requires consideration of their toxicity and the risk of biological injury which the radionuclides may cause when they become incorporated into the human body. Typically, no account is taken, in such grading systems, of the biological effects of radiation penetrating the body when the radionuclide is external to it. Information on the metabolism of subsequent biological risk from radionuclides taken into the body has been based upon the Report of Committee II of the ICRP. This information served as the basis for the present grading system and revealed that a factor of about 10^8 exists in relative toxicity between the radionuclides with the highest and lowest toxicity.

At least 14 classification schemes have some potential bearing on a scheme to handle TRU-contaminated waste.

3.1 NRC WASTE CLASSIFICATION SYSTEMS

The development of a waste classification system, supported by the NRC (relative to 10 CFR Part 60), currently identifies five different categories of waste. These are Classes A through E.

The Class A radioactive waste requires isolation in a repository or other disposal facility providing a high degree of containment and isolation, and includes those wastes which: a) because of their initial radiotoxicity require special emplacement procedures to prevent even small accidental releases, or b) will not decay to specified levels during the period of administrative control. Class A waste have no upper concentration limits.

The Class B radioactive waste includes those wastes which require licenses confinement in intermediate depth burial facilities which: will decay to specified levels during the period (150 years) of administrative control.* Class B waste are classified as those waste which are disposed at facilities where no contamination of a potable aquifer occurs during an administrative control period of 150 years. Thus a 150 year decay period is assumed for these wastes.

Class C radioactive waste include those wastes which can be disposed of in such a manner that ready access by a unsuspecting reclaimer is unlikely; however, no administrative control is applied.

The Class D radioactive category covers those wastes which can be disposed in a controlled disposal site with a period of administrative control. This is similar to the present shallow land burial practices.

The Class E radioactive wastes are those innocuous wastes which require an unlicensed confinement (in a similar manner to non-radioactive trash), and include those materials which, because of their very low (essentially non-radioactive) hazard potential, may be disposed of at a regular solid waste disposal

* The EPA proposed criteria (Appendix C) assumes 100 years.

facility as non-radioactive wastes. It should be noted that this class of waste appears to conflict with the proposed EPA criteria mentioned above and reproduced in Appendix C.

A quantitative basis for delineating the waste classes was determined. The approach was to determine, through reasonably conservative calculations, a Class A/Class B interface level which would not exceed radiological exposure guidelines under the predicted disposal conditions. Interface levels between other classes was evaluated similarly. The exposure guidelines for the Class A/Class B interface are assumed to be 500 mrem/yr where potential exposure of "a few isolated individuals" is involved; 100 mrem/yr to many individuals; and, where large population groups might be involved, the maximum exposure level was assumed to be 1 mrem/yr during the disposal of radioactive waste produced during the generation of one GWe-yr of electricity. Relationships between Class A/Class B interface levels and maximum exposure were determined. If other radiation exposure criteria are applied, altered interface levels may readily be determined based upon these relationships.

Even though the concern in this report is waste classification with emphasis upon that waste requiring deep geologic repository, the application of the modeling approach must determine the concentration limits for the present shallow land burial practice. With these limits the present practice of shallow land burial can continue with waste which meets the TRU concentration guidelines.

The procedure for determining this interface is to examine the environmental impacts from waste disposed in a shallow land burial site. Concentration or inventory limitations for low-level wastes are then determined by comparing the impacts with the radiological dose guidelines presented above.

For this evaluation a reference containment facility was defined and analysis was performed considering numerous potential exposure pathways.

The radiological pathways considered by the NRC included:

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

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

- Groundwater migration to a resource waterway.
- 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.

It is proposed that the classification of TRU-contaminated waste, or potentially contaminated waste, be handled as a subset of present NRC efforts in the area of general radioactive waste classification. In this manner, much of the work and rationale developed can be utilized in the present task.

The proposed limits for Class D (shallow land burial) waste for various TRU isotopes are based upon a disposal concentration guides (DCG) in units of microcuries/cubic centimeter ($\mu\text{Ci}/\text{cm}^3$) and are given in Table C.

4.0 TRANSURANIC RADIOISOTOPE DETECTION

The accurate measurement and analysis of TRU contaminated wastes in a routine manner is an important step in the implementation of a TRU contaminated waste classification system. Various nondestructive analytical methods for TRU isotopes in solid waste were investigated.

TABLE C

DISPOSAL CONCENTRATION LIMITS FOR SELECTED TRU ISOTOPES
TO BE BURIED IN A SHALLOW LAND BURIAL FACILITY

<u>Isotope</u>	<u>Interface $\mu\text{Ci}/\text{cm}^3$</u>
Np-237	2.0×10^{-2}
Pu-238	4.0×10^{-1}
Pu-239	1.0×10^{-1}
Pu-240	1.0×10^{-1}
Pu-241	$5.9 \times 10^{+3}$
Pu-242	1.0×10^{-1}
Am-241	4.0×10^{-1}
Am-243	3.0×10^{-1}
Cm-242	—
Cm-244	$1.3 \times 10^{+1}$

Nondestructive analytical methods for TRU isotopes in solid waste fall into two categories: passive and active analyses. Passive methods use the natural radiation emissions to identify and quantify the isotopes that are present. In active analyses, external radiation is used to induce a measured response or change in the TRU emissions.

The sensitivity for detection, i.e., measuring the nature and amount of radioactivity present, depends primarily on these factors:

- The specific activity, i.e., radioactivity per unit measure of the radiation to be detected
- The nature of the extraneous or matrix solidification material
- The package size or form in which material is available at time of measurement
- The external background from the facility's environment
- The time allotted and accuracy required for the individual measurement

Sophisticated instrumentation will be required to measure the events and skilled personnel will be needed to operate and maintain the equipment as well as to analyze the resulting data.

The techniques evaluated included:

- Passive Analyses
 - Neutron emission from spontaneous fission
 - Prompt gamma-ray emission from spontaneous fission
 - Neutron emission from (α , n) emissions)
 - Production of helium from α decay

- Production of krypton and xenon by spontaneous fission
- Gamma and x-ray emission
- Active Analyses
 - Neutron emission from induced fission
 - Prompt gamma-ray emission from induced fission
 - Production of gaseous krypton and xenon by induced fission
 - Neutron activation

Certain sample characteristics and measurement practices can affect the response of NDA systems. If these are not controlled or properly accounted for in determining the quantity of TRU from the measured activity, errors will be introduced into the final results.

The technical factors (excluding personnel related factors) contributing to the overall uncertainty associated with an NDA measurement are identified in the following four areas:

- The operational characteristics of the NDA systems
- The isotopic composition of the TRU waste
- The TRU waste and matrix materials
- The composition and dimensions of the waste container

4.1 TRU RADIOISOTOPE DETECTION STATUS

The NDA techniques selected should reflect a consideration of the accuracy requirements for the assay and the type of TRU isotopes and containers in the inventory. No single NDA method is capable of universal application, and frequently more than one NDA technique is required to perform the job.

The above mentioned nondestructive analytical methods for measuring low-level TRU contamination can be grouped into four basic detection schemes: neutron counting, photon counting, fission-gas production measurements, and helium production measurements.

Table D is a summary of the minimum theoretical detection limits that are possible for each alpha-emitting TRU isotope ($T_{1/2} > 100$ d) for each of the detection methods. Where blank spaces exist, insufficient data were available on the isotope to calculate a detection level.

The following observations can be made concerning the measurement of small quantities of TRU in waste material using nondestructive testing techniques:

- No simple method exists for measuring the quantity of a TRU in a package of waste in the presence of a gamma-ray background greater than a few milliRoentgen/hr.
- When an interfering background is not present, gamma-ray spectroscopy provides the best method for identifying and quantifying the TRU present in the waste. Several such systems have been developed and are in use today. Major research efforts will continue toward the development of greater sensitivity and better resolution. However, improvements within the next few years are not expected to provide an increase in sensitivity to reduce the detection level of TRU by tenfold.
- Monitoring the production of helium from the alpha decay of the TRU is an untried method that has the potential to measure all TRU isotopes present in waste. The major technical difficulty with this method involves the naturally occurring helium in the air. However, detection sensitivity of the technique appears to be close to the 10 nCi/g level.
- The only other viable measurement method at the 10 nCi/g level involves complex procedure of spontaneous-fission neutron counting, and krypton-xenon sampling and analysis. The delayed-neutron counting is not required because it does not add new data. However, it does provide a confirmation of the krypton-xenon sampling results. Ten TRU isotopes can be measured at the 10 nCi/g level including Pu-239. Elaborate counting and electronic circuits are required to operate the system as

TABLE D

SUMMARY OF MINIMUM-DETECTION LEVELS *
FOR ALL TRU ISOTOPES BY NON-DESTRUCTIVE
ASSAY AT A PACKING DENSITY OF 50 KG/M³

TRU	SF Neutron (Ci/g)	Kr-Xe(SF) (Ci/g)	Kr-Xe(1F) (Ci/g)	X Ray or Gamma Ray (Ci/g)	Delayed Neutrons (Ci/g)	He (Ci/g)	Prompt Gamma (SF) (Ci/g)	Prompt Gamma (1F) (Ci/g)
U-233	—	—	1×10^{-9}	9×10^{-9}	5×10^{-9}	—	—	1×10^{-8}
Np-237	$>3 \times 10^{-1}$	$>3 \times 10^2$	2×10^{-6}	5×10^{-10}	1×10^{-5}	—	4×10^{-1}	3×10^{-5}
Pu-236	9×10^{-4}	8×10^{-1}	2×10^{-4}	7×10^{-7}	9×10^{-4}	—	1×10^{-1}	3×10^{-3}
Pu-238	4×10^{-4}	4×10^{-1}	7×10^{-5}	1×10^{-6}	3×10^{-4}	—	5×10^{-2}	9×10^{-4}
Pu-239	2×10^{-1}	2×10^2	5×10^{-9}	3×10^{-7}	2×10^{-8}	—	2×10^{-1}	7×10^{-8}
Pu-240	2×10^{-5}	2×10^{-2}	$>2 \times 10^{-4}$	9×10^{-2}	$>9 \times 10^{-4}$	—	2×10^{-3}	$>2 \times 10^{-3}$
Pu-242	1×10^{-7}	1×10^{-4}	$>1 \times 10^{-6}$	—	$>6 \times 10^{-6}$	—	2×10^{-5}	$>2 \times 10^{-5}$
Pu-244	2×10^{-10}	2×10^{-7}	—	4×10^{-10}	—	—	3×10^{-8}	—
Am-241	3×10^{-1}	3×10^2	7×10^{-5}	1×10^{-10}	3×10^{-4}	$>10^{-8}$	4×10^1	9×10^{-4}
Am-242	—	—	1×10^{-7}	8×10^{-3}	5×10^{-7}	but	—	1×10^{-6}
Am-243	—	—	$>2 \times 10^{-4}$	1×10^{-10}	$>8 \times 10^{-4}$	probably	—	$>2 \times 10^{-3}$
Cm-242	1×10^{-5}	1×10^{-2}	$>4 \times 10^{-2}$	2×10^{-7}	$>2 \times 10^{-1}$	$<10^{-6}$	1×10^{-3}	$>6 \times 10^{-1}$
Cm-243	—	—	5×10^{-6}	3×10^{-9}	1×10^{-5}	for all	—	6×10^{-5}
Cm-244	5×10^{-7}	5×10^{-4}	—	6×10^{-6}	—	isotopes	6×10^{-5}	—
Cm-245	—	—	5×10^{-9}	1×10^{-9}	3×10^{-8}	—	—	7×10^{-8}
Cm-246	2×10^{-9}	2×10^{-6}	—	—	—	—	3×10^{-7}	—
Cm-247	—	—	—	—	—	—	—	—
Cm-248	7×10^{-12}	7×10^{-9}	—	$<10^{-8}$ SF γ	—	—	8×10^{-10}	—
Cm-250	3×10^{-13}	3×10^{-10}	—	$<10^{-8}$ SF γ	—	—	8×10^{-11}	—
Bk-247	—	—	—	2×10^{-9}	—	—	—	—
Cf-248	1×10^{-8}	1×10^{-5}	—	—	—	—	1×10^{-6}	—
Cf-249	3×10^{-6}	3×10^{-3}	2×10^{-7}	6×10^{-10}	7×10^{-7}	—	3×10^{-4}	2×10^{-6}
Cf-250	9×10^{-10}	9×10^{-7}	$>2 \times 10^{-5}$	—	$>1 \times 10^{-4}$	—	1×10^{-7}	$>3 \times 10^{-4}$
Cf-251	—	—	4×10^{-8}	—	2×10^{-7}	—	—	5×10^{-7}
Cf-252	1×10^{-11}	2×10^{-8}	—	$<10^{-8}$ SF γ	—	—	3×10^{-9}	—
Es-252	—	—	—	4×10^{-8}	—	—	—	—
Es-254	6×10^{-7}	6×10^{-4}	—	2×10^{-9}	—	—	8×10^{-5}	—

* To convert these minimum-detection levels to Ci/cm³, multiply by 0.05.

well as to collect and analyze the data. This method has not yet been demonstrated experimentally on small quantities of TRU and technical difficulties are more pronounced with this technique than with the other practical methods.

- Excluding the gamma-analysis method, neither of the other two proposed methods will identify the TRU isotopes present. In the neutron irradiation and counting as well as in the krypton-xenon sampling methods, a foreknowledge of the TRU isotopes present and their relative abundance is required even to quantify the amount of TRU present. If this foreknowledge is unattainable, these methods are useless.
- Counting prompt neutrons from induced fission is not feasible, even when counting in coincidence pairs, because interference from the source neutrons completely masks the prompt-neutron count. No technique has been discovered to overcome this difficulty.
- Raising the minimum detection level to $1 \mu\text{Ci/g}$ (1000 nCi/g) will permit the detection of all 27 TRU isotopes by the helium detection method and 19 of the isotopes by gamma-ray spectroscopy (in the absence of an interfering background).
- If the minimum-detection level were raised to $1 \mu\text{Ci/g}$ (1000 nCi/g), measurement of the prompt fission gammas would be feasible, even in the presence of a 1-R/hr gamma background; additional energy discrimination could be accomplished with shields. However, the isotopes thus detected can be measured at lower activity levels by other methods.
- Lowering the minimum-detection level to 1 nCi/g will make it impossible to measure all TRUs except the five isotopes having the highest spontaneous-fission rates (i.e., Pu-244, Cm-248, Cm-250, Cf-250 and Cf-252).

5.0 TRU-CONTAMINATED-WASTE FUNCTIONAL DEFINITION

The previous discussion revealed that a relatively arbitrary standard of 10 nCi/g of TRU isotope defined what waste required interim storage before disposition at a federal repository. Further it was pointed out that a large inventory of TRU

waste presently exists which must be handled in the future as well as the waste added in the future due to DOE and commercial activity.⁵

The proposed TRU waste functional definition is based upon a large number of studies and evaluations which were reviewed. The TRU waste classification system must:

- Classify TRU waste according to their requirements for safe disposal
- Address the concerns of the public, and
- Implement a system without undue burden of those directly affected by it.

The proposed NRC methodology discussed briefly above and in Section 5.0 is appropriate to establish the TRU concentration limits for waste requiring deep geologic disposal or disposal in an engineered shallow-land facility. Pending final refinement of the analysis methodology, compliance with EPA criteria presented in Appendix C, and the normal licensing rulemaking hearings, then TRU concentration similar to those in Table C can be expected to be implemented. These values, typically greater than 100 nCi/cm^3 (except $\text{Np-237-20 nCi/cm}^3$), are substantially above the 10 nCi/g limit presently implemented and should have a substantial impact on DOE and commercial facilities, as well as plans for handling the present TRU waste inventory. These values were established by developing models and parameters which were utilized in the analysis of TRU waste placed into various waste disposal site scenarios and, as such, constitute guides which will be utilized for "real world" facility designs, operations and analyses.

1.0 INTRODUCTION

The disposal of any type of hazardous material, whether it be nuclear or non-nuclear, should involve the permanent removal of the material from man's biosphere.¹ This can be accomplished either by converting the hazardous material to nonhazardous material or by disposing of the material in such a way that it cannot affect man's environment. However, most present day schemes for disposal of hazardous material cannot guarantee its permanent removal.¹⁴ The disposal of radioactive waste has special problems not common to the disposal of any other hazardous material. First, the radioactive material can damage a biological system without being incorporated into, or directly contacting it. Second, since the radioactivity of the material is an intrinsic property, the hazard associated with it can only be neutralized through the very difficult process of nuclear transmutation. Third, people are acutely sensitive to the potential dangers of radiation and although they will accept hazards from industrial and domestic accidents and natural disasters, they will not risk being exposed to nuclear radiation. While this may seem illogical, it must be taken into account when considering methodologies or schemes for disposing of radioactive wastes.

In 1970, the Atomic Energy Commission (AEC) directed that all AEC facility-generated wastes contaminated with 10 nanocuries per gram (nCi/g) of transuranic (TRU) radionuclides be segregated from other radioactive waste since the transuranic nuclides pose a significant radiotoxicity hazard and typically have very long half-lives. As a result, it is required that these transuranic wastes be stored in a readily retrievable manner ensuring that the waste packages remain intact and contamination-free for an interim storage period of at least 20 years. When a federal repository becomes operational, this waste is to be retrieved and transported to the facility for deep geologic disposal.¹ A similar requirement was proposed for commercially-generated TRU Waste in the September 12, 1974 Federal Register.

The purpose of this report is to examine the problem(s) of TRU waste classification and to document the development of an easy-to-apply standard(s) to

determine whether or not a particular waste package is considered TRU Waste and whether or not this waste package should be emplaced in a geologic repository for disposal.

1.1 TRANSURANIC (TRU) RADIOACTIVE WASTES

Radioactive wastes are a consequence of the use of either man-made or naturally occurring radioactive materials. These wastes are produced in a broad range of forms, concentrations and quantities. They may occur in the form of gases, liquids, or solids, may be soluble or insoluble in water, and may emit several types of radiation over a wide range of energy and rates. The concentration of wastes varies from highly radioactive spent reactor fuel wastes to very low natural radioactivity in residues from certain mineral processing activities. Between these extremes is a broad range of radioactive wastes of varying radioactivity resulting from medical, industrial, institutional and defense-related radioisotope applications. The two extremes generally encompass the range of sources, potential hazards and inventories of radionuclides that need to be considered in establishing environmental protection criteria for the disposal of materials containing them.⁷

To further complicate the problems of definition posed by this wide variety, virtually everything in use contains some measure of naturally occurring radioactivity. Obviously a drastic narrowing is required to decide which materials should be designated as radioactive wastes; almost any waste would be included if the only required characteristics were that a material be radioactive and have no future use. As a starting point, it seems clear that radioactive wastes should include materials restricted by regulatory controls from discharge to the general environment. This would include artificially produced radioactive materials from nuclear fission or activation, and either naturally occurring or artificially produced wastes removed from effluent streams to meet environmental requirements.

Artificially produced radioactive materials are subject to regulatory controls which limit their discharge to the environment. On the other hand many sources

of naturally occurring radioactive materials are not regulated and often become diffuse waste sources which are not subject to effluent limits on discharge. However, any waste material that is collected and not freely discharged to the general environment is considered radioactive waste in this report and this program as it applies to transuranic waste.

The designation of radioactive wastes and the controls they receive is influenced by their potential for exposure of individuals and populations and the timeframe over which they persist as radiological hazards. The risk associated with such exposure is often described in terms of the toxicity, specific activity, and the half-life of the radionuclides involved.⁷

The transuranic contaminated wastes include isotopes of americium (Am), berkelium (Bk), californium (Cf), curium (Cm), einsteinium (Es), neptunium (Np) and plutonium (Pu). Some waste generators also include one or more uranium (U) isotopes in classifying a waste "TRU-contaminated."

Transuranic wastes are especially significant because they have long half-lives and because some are rather radiotoxic. Transuranic radionuclides are primarily produced by single or multiple neutron capture by U-238 in fuel elements during the operation of a nuclear reactor. Reprocessing of spent fuel elements attempts to remove plutonium, but since the separation is not complete, the resulting high-activity liquids still contain some plutonium as well as other transuranics. Similarly, transuranic contamination of low-activity wastes also occurs when the transuranic materials are handled or processed, which is primarily at federal facilities involved in nuclear research and development programs and nuclear weapons production.

Transuranics are persistent in the environment and, as a general rule, are strongly retained by soils. They are not easily transported through most food chains, although some reconcentration does take place in the aquatic food chain. They pose no special biological hazard to humans upon ingestion because they are weakly absorbed from the gastrointestinal tract. A greater hazard results from inhalation since they behave like normal dust and fractionate accordingly.

Production of an adverse health effect in the lung, or elsewhere, depends on the particle size and solubility of the inhaled contaminated dust. Once entered into the bloodstream (either by ingestion or inhalation), TRUs will readily accumulate in bone and liver tissues, and can significantly increase the risk of cancer.² Appendix B presents a more complete overview of TRU radioisotopes.

Prior to the 1970 ruling for AEC-generated waste and the proposed 1974 requirement, transuranic-contaminated wastes were not segregated from other low-activity wastes. Current federal policy is to segregate and store wastes containing greater than 10 nanocuries (ten one-billionths of a curie) of alpha-emitting TRU radionuclides per gram.⁶

1.2 TRU WASTE MANAGEMENT PROGRAM

The development of the NRC's TRU Waste Management Program by Lawrence Livermore Laboratory requires that extensive information and a data base be established which can be utilized to develop waste classification, form and packaging requirements for transuranic contaminated (non high-level) waste requiring disposal in a deep geologic repository. A practical functional definition of TRU wastes is to be developed which will be used to determine which TRU-contaminated wastes must be placed into a deep geologic repository. An overall TRU radiological source term for this waste will then be developed to estimate the potential radiological risk to the general public after emplacement and closure has taken place.

Waste forms or packages must be considered from the standpoint of both radiological safety and economics. The development of this radiological source term is dependent upon numerous factors. Figure 1-1 presents a proposed scheme for the TRU waste form criteria development program. As can be seen from this figure, TRU wastes are generated from military and Department of Energy (DOE) activities, the commercial sector and other miscellaneous sources. To develop the TRU data base and initiate work based upon this data base, it is necessary to identify the sources of TRU waste, develop the inventory, and identify the various forms of this waste. This information is then utilized to

FIGURE I-1

TRU WASTE FORM CRITERIA DEVELOPMENT PROGRAM

characterize the waste. Based upon this characterization and the development of a waste classification scheme for TRU waste, it is then possible to identify the TRU wastes which require deep geologic disposal.

Based upon this initial work, general criteria selection studies would be initiated and the data base would be revised to develop the base case scenarios which would be utilized for all initial studies and program evaluation.

Utilizing the various categories defined in the waste classification study, it is necessary to examine and evaluate the treatment technologies available to process the as-generated TRU wastes. Such evaluations should primarily review the generated waste form of the contaminated material and determine if means to reduce the volume, reduce the combustibility possibilities and other similar technical considerations are appropriate. Simultaneously, various means would be examined to immobilize the residue that results from such treatment technologies or the unprocessed waste material. It is noted that not only new generated wastes but old buried wastes should also be considered. With the identification of the new technologies and means of immobilizing the residue to allow ease of transportation and handling before deep geologic disposal, various interactions will be required with other parts of the waste management program dealing with the repository's design limitations as well as occupational concerns and transportation impacts. Tentative criteria would then be developed for the waste form in the final immobilized matrix. Such criteria might be either qualitative or quantitative and would reflect the presently available technology as well as providing the means to determine the applicability of new technologies as such are developed.

With the identification of these technologies and the evaluation of the applicability of such technologies, an economic analysis would be performed to determine the cost impact of the criteria. While Figure 1-1 indicates the general outline and approach of the program, the problem of defining the TRU waste form and potential package options is more complicated since the number of parameters which are being evaluated is quite large. Figure 1-2 presents a

FIGURE I-2

TRU WASTE FORM, CONTAINER AND PACKAGE
CRITERIA EVALUATION METHODOLOGY

schematic indicating the various major parameters of this program, the interactions which must be considered in the development of criteria, and the development of a methodology to evaluate the impact of such criteria on proposed technical solutions to the handling of TRU wastes.

1.3 TRU WASTE CLASSIFICATION

As indicated previously, the purpose of this report is to document the development of an easy-to-apply standard(s) to determine whether or not a particular waste package is considered TRU waste and whether or not this waste package should be emplaced in a geologic repository for disposal.

The development of a waste classification system for TRU waste is a difficult task inasmuch as the characteristics of the TRU waste make any system based upon simple measurements very difficult, if not impossible, to develop and implement. The major radiological characteristics of the TRU radioisotopes are discussed in Appendix B. As indicated in this appendix, the major radiological decay scheme for TRU radiological isotopes is an alpha decay, usually a relatively long-term half-life. Because of the radiological hazards associated with these radionuclides and their long biological half-life within human systems, the entry of TRU isotopes into the human biosphere must be reduced to an absolute minimum. Thus, the major requirement for TRU waste classification is identification of the disposal techniques necessary for various levels of contamination or potential contamination.

It is obvious that the most conservative but least workable system is to indicate that any degree of TRU contamination of waste material requires a long-term disposal such as deep geologic disposal. Such a requirement is neither environmentally nor economically viable, however, since this case represents the most severe and penalizing condition under which a radioactive or potentially radioactive material may be disposed.

Therefore, a scheme must be developed under which TRU waste is evaluated based upon a conservative analysis of disposal techniques and subsequent hazards

and consequent risk to man. This methodology would consider the potential radiological and environmental impact of the disposal technique and would conservatively evaluate the potential impact upon present and future generations of man. At present, it is suggested that three potential levels of disposal might be considered.* The first is the deep geologic disposal approach, such as in a salt or shale mine, in which the TRU-contaminated material would be placed outside the immediate environment of the biosphere; the second would be a shallow land burial technique similar to that presently practiced for the disposal of low-level radioactive waste.^{12,13} This technique would place the TRU waste in an engineered and monitored disposal site with appropriate site characteristics which would ensure that what minimal quantities of TRU contamination might exist would have a minimal potential risk to man. The third technique would be to consider some level of TRU contamination as innocuous or "de minimus" thus requiring no special treatment or monitoring beyond standard land fill operation.¹ The TRU waste classification problem, therefore, is to determine whether these three options are viable for TRU waste, the potential "cut-off" levels of TRU contamination appropriate for each of these three proposed means of disposal, and the technologies necessary to implement such a program.

Similar to other radioactive waste material, TRU-contaminated material can include an entire spectrum of physical and chemical species. The present TRU waste sources and anticipated future sources involve primarily military and commercial activities dealing with the weapons program and the nuclear fuel cycle, respectively.⁵ A wide variety of sources of material has been identified and a large inventory presently exists of retrievable waste which has been stored temporarily and other wastes which, due to past practices, were buried with no consideration for retrievability. Thus, the problem of TRU waste includes not only future waste sources, but also past sources and practices dealing with TRU material. In addition to this general problem, the variety of waste materials and

* Numerous disposal techniques have been postulated and studied as illustrated in References 10 and 14. For the purpose of this report, only continental U. S. land disposal schemes are considered.

their chemical and physical form also make the development of a simple classification scheme very difficult since any scheme chosen must be flexible enough to recognize the waste form characteristics of the contaminated waste and the potential adverse impact such a form may have upon a particular disposal technique.

The TRU waste classification problem is, therefore, a problem of disposal technology and choosing a classification scheme which provides appropriate conservatism in delineating the means of disposal appropriate for a particular or potential level of TRU contamination.

2.0 BACKGROUND

The purpose of this section of the report is to provide a brief overview of the TRU waste problem and to establish the necessary background data from which a meaningful TRU waste classification system may be developed and implemented.

2.1 EXISTING NRC/DOE REGULATIONS CONCERNING TRU CONTAMINATED WASTE

On March 20, 1970, the Atomic Energy Commission published the Immediate Action Directive (IAD) No. 0511-21 requiring that wastes from AEC sites with known or detectable contamination of transuranium nuclides be segregated from other types of wastes and stored in such a fashion that they can be retrieved as contamination-free packages within an interim period of 20 years.²² Because of the IAD, the quantitative limit of transuranium element concentrations in waste was evaluated that would not require segregation and retrievability but could be buried in DOE or commercial burial grounds in a relatively unretrievable fashion.

The Working Group on Sorting of Radioactive Wastes was asked in 1970 to recommend a basis on which the then AEC-generated plutonium-contaminated solid waste should be segregated for readily retrievable storage instead of shallow land burial.²⁴ The Working Group noted that a large number of arbitrary values for such segregation might be used, but narrowed its discussion to the following options:

- OPTION I - ALL TRACES

This option would include all waste with any trace of plutonium or TRU radioisotope detectable by direct measurement on any suspect surfaces, or in which traces of plutonium might reasonably be inferred from knowledge of the operation of the facility generating the waste. This would be the most inclusive of possible definitions; however, because of the non-uniform concentration of plutonium in actual waste situations, this type of all-inclusive definition would mean that relatively little benefit would be gained from any improved waste handling system for a large portion of the waste volume diverted to it.

- OPTION 2 — ENVIRONMENTALLY DERIVED

In terms of long half-life and high specific radiotoxicity, Pu-239 is comparable to Ra-226. Radium is widely dispersed through the earth's crust, frequently near the surface. The resulting concentration of radium in natural waters is often detectable but is generally well within drinking water standards. It might appear reasonable, therefore, to bury plutonium and other TRU radionuclides not at random, but only at carefully selected sites--in concentrations no more than the upper range of natural radium concentration in the earth. The actual value proposed was 10 nCi per gram. This approach has the advantage of being derived through an environmentally oriented rationale rather than being completely arbitrary. The disadvantage is that present external radiation measurements of waste packages cannot detect the presence of plutonium and other TRU radionuclides at this low concentration. Segregation of packages will have to be done by some indirect means, such as summation of measurements of contaminated wipes of individual items, or a laboratory analysis of samples from appropriate homogeneous materials, such as solidified evaporated sludges, etc. In many cases it would probably be satisfactory to have knowledgeable radiation monitoring personnel designate all waste from certain collection points for certain types of maintenance or operational work as "TRU contaminated."

- OPTION 3 — THE LOW SPECIFIC ACTIVITY DEFINITION

In Department of Transportation (DOT) regulations, materials containing less than 0.1 microcurie per gram of the so-called "Group I" radionuclides (which, in general, refer to alpha emitting radionuclides such as Pu-239) are referred to as "low specific activity" (LSA) material. Above this concentration more restrictive packaging requirements apply. The advantage of using this definition for segregating plutonium waste is that it would not require any additional measurement at those facilities already shipping waste off-site and therefore routinely making "low specific activity" determination. The disadvantage is that the application of criteria (obviously derived from transportation accident considerations) to the drastically different problem of the very long-term adequacy of shallow land burial practices is vulnerable to (justifiable) criticism as being highly arbitrary.

● OPTION 4 -- EXTERNAL RADIATION MEASUREMENT

Because Pu-239 is a special nuclear material, strict safeguard requirements are imposed on the management of plutonium inventories in our many transfers and shipments of plutonium. It is a common practice, in complying with these safeguard requirements, to make external radiation measurements on waste packages after they have been prepared for shipment. This last method is unacceptable since no environmental factors are considered in the establishment of plutonium or other TRU radioisotopic limits.

The Working Group's statement of consideration addressed itself to the specific activity of the waste (radioactivity per unit weight) as a criterion of choice by operators of waste management sites. Measurement methods are to be established and measurements made to determine the presence or absence of transuranium elements. The methods must be sensitive enough to detect contamination levels as low as 10 nCi of transuranium radionuclides per gram of waste. The suggested upper limit of 10 nCi per gram has been generally used since it was first proposed by Soule.²⁶

Soule stated: "In terms of long half-life and high specific radiotoxicity Pu-239 is compared to Ra-226. Radium is widely dispersed through the earth's crust, frequently near the surface. . . It seems reasonable, therefore, to bury plutonium--not at random, but at carefully selected sites--in concentrations no more than the upper range of natural radium concentration in the earth. The actual value proposed is 10 nCi per gram (for pure Pu-239 this is equivalent to 0.16 micrograms of plutonium per gram of waste)."

The present DOE requirements for the disposal of TRU-contaminated waste state that the waste be packaged and managed in such a manner that they can be readily retrieved free of external contamination within a period of 20 years. The NRC (then AEC) developed a dividing line above which the 20-year retrievable storage policy would be applied, but below which it would be reasonable to permit shallow land burial. The value developed for this criterion was 10 nanocuries of transuranic radioisotope per gram of waste.

In 1974, the AEC proposed to prohibit the disposal of commercially-generated transuranic radionuclides by shallow land burial. The proposed rule was an extension of AEC policies implemented in 1970, in which AEC (now DOE) wastes suspected of containing TRU isotopes in concentrations greater than 10 nanocuries per gram were consigned to retrievable storage facilities pending the development of a facility for the ultimate disposal of this waste.

As outlined in the September 12, 1974 Federal Register Notice (39 FR 32921), commercially-generated TRU waste would have been transferred to the AEC (now DOE) for storage as soon as practicable but within five years after generation. The AEC (DOE) would have then assumed responsibility for storage, treatment, and disposal. The limit at which radioactive waste would be considered TRU was suggested to be 10 nanocuries of transuranic elements per gram of waste. Waste that was suspect, but had been measured and was not contaminated with more than 10 nanocuries of transuranic nuclides per gram, would have been consigned to a licensed commercial burial ground.

The NRC has generally found this proposed rule unsatisfactory for several reasons and has initiated a more generic activity to handle all radioactive waste. This activity is discussed in the August 18, 1978 Federal Register and its support document.¹⁹

2.2 SOURCE OF RADIOACTIVE TRU WASTE

Nearly all operations that produce or use nuclear materials generate radioactive waste. Most of this waste comes from the Department of Energy's reactors and facilities, commercial nuclear power plants, and federal (military) and commercial nuclear fuel cycle activities--mainly fuel fabrication and reprocessing facilities. No commercial reprocessing facilities are currently operating, but DOE has four reprocessing facilities either in operation or on standby.

High-level liquid waste contains many fission products and small amounts of transuranics (such as plutonium) which are not recovered during the reprocessing operation. Besides being found in high-level waste, transuranic (TRU) materials

in various concentrations are also found in other waste. It is generated by plutonium fuel fabrication and fuel reprocessing facilities and also by laboratories which use transuranic elements. This waste generally consists of expendable items such as absorbent paper, clothing, gloves, plastic bags and equipment; ion exchange resins or filters from effluent treatment systems; and fuel cladding hulls which remain after reprocessing.⁵

Spent fuel contains all of the fission and transuranium elements that are found in high-level waste and all of the uranium and plutonium not used during the nuclear reaction process. Spent fuel, like high-level waste, is characterized by high levels of penetrating radiation, a high heat generation rate and a long toxic life.

TRU waste has been disposed of at five of the six commercial burial sites* which have supported the commercial LWR industry, as well as Department of Energy (DOE) and its predecessor AEC and ERDA-generated waste. These sites have accepted wastes generated in the fuel cycle, primarily during fuel fabrication and spent fuel reprocessing, as well as numerous miscellaneous R&D activities and small commercial uses of TRU radioisotopes. The present inventory of TRU-contaminated waste is limited primarily to DOE-generated waste (shipments now terminated) and R&D fuel fabrication activities involving plutonium. The NRC does not have records on the volume of commercial transuranic contaminated waste buried at commercial shallow land burial sites, but estimates that about 123.4 kilograms of plutonium were buried at five of the six sites.⁵ The best available information indicates that the cumulative DOE-generated TRU waste (through 1976) shipped to these commercial burial grounds contained about 7.6 kg of TRU isotopes.

* Beatty, NV; West Valley, NY; Maxey Flats, KY; Richland, WA; Sheffield, IL, Barnwell, SC (no transuranic waste at Barnwell except small quantities of Am-241). TRU is defined as concentration greater than or equal to 10nCi/g.

The TRU solid waste inventory for seven different DOE sites is provided below. Only about 15 percent of this volume of waste is in retrievable storage. TRU waste sources for both commercially- and DOE-generated waste are addressed in detail in Reference 5. By 1984 it is anticipated that the retrievable storage inventory might increase by a factor of two while the amount of waste in burial sites remains virtually unchanged. The TRU inventory (as of October 1, 1978) of contaminated wastes, soils and sediment is as follows:⁵

Retrievably stored	494 kg TRU	48,500 m ³
Previously buried	759 kg TRU	268,000 m ³
Contaminated soils and sediments	190 kg TRU	1,218,000 m ³

A proposed amendment to the NRC's regulations will ban the burial of commercial transuranic contaminated waste. Regulations would require that those producing such waste should ship it to DOE for storage as soon as practical, but no later than five years after generation. DOE would then be responsible for storage and disposal of the waste at a federal waste repository.¹⁹

2.3 TRU WASTE FORMS, CHARACTERISTICS AND TREATMENT TECHNOLOGY

The management of TRU waste is complicated, not only because of its physical and chemical characteristics, but also because of the level of radioactivity and the necessity of long-term containment required due to its long half-life.

TRU-contaminated wastes pose a significant problem to the regulatory agencies because the variety of waste to be disposed of in a geologic repository is immense. Not only are there a variety of radioisotopes and radiation fields but also a nearly infinite combination of physical forms and conditions and chemical constituents. Tables 2-1, 2-2, and 2-3 present some typical waste streams from the commercial and DOE TRU-contaminated waste generators. These tables are by no means complete, but are provided to illustrate the great variety of

TABLE 2-1
SOURCES OF TRU WASTE FROM A
COMMERCIAL MOX FUEL FABRICATION FACILITY⁵

<u>Waste Category</u>	<u>Waste Description</u>
1. Salt Solutions	Concentrated scrap recovery, decontamination, and off-gas scrub liquids.
2. Surfactants/Detergent Solutions	Laundry wastes, personnel decontamination solutions.
3. Organic Liquids	Pneumatic fluids, oils, laboratory solvents.
4. Wet Particulates	Bead ion exchange resins used for liquid effluent treatment.
5. Dry Particulates	Floor sweepings, etc.
6. Combustible Solids	General trash (cellulosics, plastics, rubber - uncompacted). Ventilation (HEPA) filters (up to 60 wt% combustible).
7. Noncombustible Solids	General trash, PuO_2 cans, etc. (uncompacted). Failed equipment, furnace brick.

TABLE 2-2
SOURCES OF TRU WASTE FROM A
COMMERCIAL REPROCESSING PLANT⁵

<u>Waste Category</u>	<u>Waste Description</u>
1. Salt Solutions	Composited, concentrated decontaminations and miscellaneous liquids. Iodine scrub solutions.
2. Precipitates and Slurries	Water treatment slurry (iron hydroxides, clays, miscellaneous precipitates). Slurry from UF ₆ off-gas treatment
3. Surfactant/Detergent Solutions	Miscellaneous surfactant-containing decontamination solutions. Laundry wastes may also be included in this category
4. Organic Liquids	Degraded TBP solvent. Miscellaneous lubricants, oils, hydraulic fluids, lab solvents, etc.
5. Wet Particulates	Bead ion exchange resins used to purify solvent and process condensates. Adsorbents/ion exchange minerals used for condensate and UNH purification.
6. Dry Particulates	Iodine removal adsorbents, zeolite. Ruthenium adsorbent beds. UF ₆ adsorbent beds. UF ₆ fluorinator beds and fines.
7. Combustible Solids	Miscellaneous combustible trash (uncompacted). Ventilation filters (up to 60 wt% combustible).
8. Noncombustible Solids	General trash. Failed equipment, packaged deep bed filters.

TABLE 2-3
TYPICAL DOE TRU-CONTAMINATED WASTE²⁹

First Stage Sludge (Reprocessing)	Grit
Second Stage Sludge (Reprocessing)	Blacktop Concrete Dirt & Sand
Organic Set Ups (Oil Solids)	Cement Insulation & Filter Media
Special Set Ups (Cement)	Sand, Slag and Crucibles
Evaporated Salts	Electrorefining Salt
Combustibles (Paper, Rags, Gloves, Poly)	Resin
Non-Compressible, Non-Combustibles	Glass
Dirt	Raschig Rings
Sludge	Metal Scrap
Hot Cell Waste	Equipment Boxes
Americium Process Residue	High-Level Acid
Graphite Wastes	High-Level Caustic
Benelex and Plexiglas	High-Level Sludge/Cement
HEPA Filters	Contaminated Soil
Plastics, Teflon, PVC	Wood
Leaded Rubber Gloves & Aprons	Laundry Sludge
Brick, Fire	Miscellaneous Equipment

materials which must be considered and evaluated in the final design of both the acceptable waste form and package and also the geologic repository.

It is necessary not only to identify waste sources, but also to analyze the composition of waste from various points of generation. This analysis is necessary for determining useful changes at the source that would reduce the waste generation rate as well as subsequent handling and treatment, identification and development of processes and equipment for treatment to alter the waste form and provide suitable containment in addition to other operational and safety aspects of waste management operation.

Generically, three major categories of solid TRU-contaminated waste exist: combustible wastes, liquid and sludge wastes, and non-combustible wastes. The treatment of wastes, once generated, involves the design of a system for sorting and classification appropriate to volume reduction and passivation treatment to minimize adverse reaction potential of the waste during handling and storage. A typical TRU waste management system flow diagram illustrating potential waste treatment alternatives is shown in Figure 2-1. This figure illustrates the management methods typically being considered for transuranic contaminated waste from the three major waste sources--commercial, Department of Energy (DOE), and the waste that is now or will be placed in interim storage and require further treatment.

Combustible waste is one of the largest volumes of waste generated throughout any fuel cycle activity. It is generally accepted that this waste should be incinerated (and volume thereby reduced) for three reasons:

- 1) Radiolysis of the hydrocarbons can release hydrogen during storage
- 2) The waste represents a large fuel loading and therefore, a fire hazard
- 3) The waste represents a large volume of material that could be reduced 90-95%

FIGURE 2-1
TREATMENT OPTIONS FOR "AS GENERATED" TRU WASTE

By reducing the volume, disposal costs and consequent risks would be substantially reduced in addition to the immobilization of the ash that will stabilize the wastes for final disposition. Numerous different incineration concepts which have been proposed (including such systems as fluidized bed, acid digestion, molten salt, pyrolysis, and controlled air incineration) are the subjects of a separate report.

A large percentage of solid waste results from the conversion of liquid wastes to solid form. Low-level liquid waste is processed through a typical waste disposal facility based upon clariflocculation, filtration and evaporation technology. Approximately 99 percent of the radioactivity is removed during such processes and the resultant sludge can be either dried to a solid or mixed with an appropriate agent to form a solid matrix.

The general criteria governing the treatment of liquid wastes and sludges are that sludges/liquids should be converted to a solid low-leachable form and that the waste should be converted to a form acceptable for disposal since, once solidified, further treatment is difficult if not nearly impossible. Various DOE programs are underway for treatment to reduce the generation as well as the volume of this waste, decontaminate the liquid waste, remove radioactivity where practical, and convert the waste to a solid form.¹⁰

Noncombustible waste has potentially significant resource recovery value--not for recovery of the actinide material, but rather for the recovery of the metals. Typically, the metals include the materials used during construction and processing, and in shielding. Further, contaminated material waste also results from the nuclear fuel cycle fabrication and in particular the cladding hulls. Various programs are in the process of developing technologies to treat contaminated metal wastes. These programs include decontamination by either chemical or physical means (such as smelting) as well as aqueous and molten salt decontamination and melt slugging processes.¹⁰

2.4 RADIOACTIVE WASTE CLASSIFICATION¹⁹

As part of the regulations governing the management and disposal of radioactive waste, the NRC is developing a radioactive waste classification system. The classification system is not intended to replace existing practices, criteria, or regulations relating to the generation, packaging, handling, or transport of radioactive material; but rather, it will provide guidelines regarding the ultimate disposition of waste containing specific concentrations of individual radionuclides including transuranic radionuclides. As stated previously, the current regulatory position is based upon a requirement for retrievable storage of all waste with a TRU content of 10 nanocuries or more per gram.

During the regulatory process, issue was taken with some practical considerations in implementation of the 1974 AEC rule—particularly the 10 nanocurie per gram guideline. The general opinion was that the 10 nanocuries per gram limit was not justified and that the proposed rule should be supported by an economic impact analysis demonstrating a positive cost-benefit ratio. Further, it was noted that no practicable nondestructive assay method existed for the guideline. Other factors identified included the difficulty, expense, and personnel exposures in performing assays. Additionally, it was felt that the forms, volumes and categories of wastes subject to federal management under the proposed rule posed significant logistical problems. A number of modifications or alternatives to the 10 nanocurie per gram guideline were also suggested.

Upon reviewing the proposed rule and the comments received, the NRC staff determined that the proposed rule was unworkable and initiated development of regulations which would govern the disposal of all radioactive waste—not just TRU-contaminated waste. The staff initiated a study to provide a broad analytic base for a waste disposal classification system and a foundation for the forthcoming regulations and accompanying environmental impact statements.¹⁹

The objectives of the radioactive waste classification system are:

- To classify radioactive wastes according to their requirements for safe disposal
- To address the concerns of the public
- To implement the system without undue burden on those directly affected by it.

The NRC concluded that the objectives could be best realized by categorizing waste according to the type and duration of containment required for safe disposal.¹⁹

3.0 TRANSURANIC WASTE CLASSIFICATION SCHEMES

The purpose of this section is to identify regulations, previous classification schemes, and important factors which should be considered in the development and implementation of a TRU waste classification system.

3.1 EXISTING REGULATIONS

As a first step in establishing TRU waste classification criteria, the existing regulations were reviewed. Some aspects of these regulations could be interpreted as establishing concentrations of radioactive materials for disposal.

3.1.1 FEDERAL REGULATIONS, TITLE 10, PART 20

The maximum exposure permitted by 10 CFR Part 20.105 in unrestricted areas is 500 mrem per year to the whole body of any individual. For a population group, the exposure from radioactive materials in effluents may not exceed that which would occur if the group were continuously exposed to air or water concentrations containing one-third of the unrestricted Maximum Permissible Concentration (MPC) (10 CFR Part 20.106). These limitations are subject to the further constraint that the exposure must be "as low as reasonably achievable" (ALARA) (10 CFR Part 20.01).

Part 20 also restricts the method of waste disposal (10 CFR Part 20.301.305). Disposal into a sanitary sewage system is not allowed unless:

- 1) The waste is readily soluble or dispersible in water
- 2) The daily discharge is less than the larger of:
 - a) The quantity which if diluted by the average daily quantity of sewage would result in an average concentration equal to the unrestricted MPC in water, or
 - b) Ten times the quantity of such material specified in Appendix C of 10 CFR Part 20.

- 3) The monthly average discharge concentration is below the unrestricted MPC in water
- 4) The gross discharge is less than 1 curie per year.

Burial of waste in soil is restricted by 10 CFR Part 20.304 to 12 or less burials per year at a minimum depth of 4 feet with successive burials separated by distances of at least 6 feet. The total quantity buried at any one location and time may not exceed, at the time of burial, 1000 times the amount specified in Appendix C of 10 CFR Part 20.

There are no specific guidelines in 10 CFR Part 20 pertaining to disposal at sea or to incineration. These are handled on a case by case basis as provided for in Parts 20.302 and 20.305.

3.1.2 FEDERAL REGULATIONS, TITLE 10, PART 30

A person may receive, possess, use, transfer, own, or acquire materials containing byproduct radioactive material and be exempt from the requirements for a license, providing the activity concentrations of byproduct material do not exceed those listed in 10 CFR Part 30.70, Schedule A (see 10 CFR Part 30.14). However, the instruction of byproduct material in exempt concentrations into materials and transfer of ownership or possession of it does require a license in accordance with 10 CFR Part 32.11. Some limitations are stated in Part 32.11(c).

3.1.3 FEDERAL REGULATIONS, TITLE 10, PART 50 APPENDIX I

Appendix I to 10 CFR Part 50 provides numerical guides for reactor design objectives and for limiting conditions of operation. The applicant must provide reasonable assurance that the following design objectives will be met for each reactor. Total annual radioactive releases in liquid and gaseous effluents above background from a single light-water-cooled nuclear reactor must not cause the estimate of annual dose or dose commitment to any person in an unrestricted area to exceed:

- 1) 3 mrem to the total body or 10 mrem to any organ as a result of activity in liquid effluent
- 2) 5 mrem to the total body or 15 mrem to the skin due to activity in gaseous effluent
- 3) 15 mrem to any organ from radioactive iodine and radioactive material in particulate form released to the atmosphere.

In addition to meeting these design objectives, the radwaste system must include all items of reasonably demonstrated technology which can (when added to the system sequentially and in order of diminishing cost-benefit return), for a favorable cost-benefit ratio, effect reductions in dose to the population reasonably expected to be within 50 miles of the reactor. The interim value of \$1000 per total body man-rem and per man-thyroid-rem is currently accepted in the cost-benefit analysis.

Operating reactor guidelines are set at one-half of the design objective annual exposure based on actual releases in effluents during any calendar quarter. They represent design objectives for releases to the environment which are controlled and monitored prior to release and are the object of environmental monitoring after release. These requirements apply to liquid and gaseous effluents of a single light-water reactor, but they are not directly applicable to solid wastes.

3.1.4 FEDERAL REGULATIONS, TITLE 10, PART 71

Because it is likely that nearly all TRU contaminated waste will have to be transported, it is important to recognize the requirements of 10 CFR Part 71 for special packaging. Compliance may be guaranteed if the activity concentration is less than 2 nanocuries per gram or if each package contains less than 50 millicuries (the exempt quantity for mixed fission products).

3.1.5 FEDERAL REGULATIONS, TITLE 40, PART 190

The maximum annual exposure allowed by 40 CFR Part 190 to a member of the public as the result of planned discharges of radioactive material to the general environment from uranium fuel cycle operations is 25 mrem to the whole body, 75 mrem to the thyroid, and 25 mrem to any other organ. These limitations exclude operations at waste disposal sites, but do not specifically exclude waste itself.

3.1.6 PROPOSED FEDERAL GUIDANCE ON TRANSURANIUM ELEMENTS IN THE ENVIRONMENT

The Environmental Protection Agency has proposed (42 FR 60956) federal radiation protection guidance on limits of dose to persons exposed to transuranics in the environment as a result of existing or possible future unplanned contamination. The text of the proposed guidance follows.

- "1. The annual alpha radiation dose rate to members of the critical segment of the exposed population as the result of exposure to transuranium elements in the general environment should not exceed either:
 - a. 1 millirad per year to the pulmonary lung, or
 - b. 3 millirad per year to the bone.
2. For newly contaminated areas, control measures should be taken to minimize both residual levels and radiation exposures of the general public. The control measures are expected to result in levels well below those specified in paragraph one. Compliance with the guidance recommendations should be achieved within a reasonable period of time.
3. The recommendations are to be used only for guidance on possible remedial actions for the protection of the public health in instances of presently existing contamination or of possible future unplanned releases of transuranium elements. They are not to be used by Federal agencies as limits for planned releases of transuranium elements into the general environment."

One "millirad per year to the pulmonary lung" is meant to be the equilibrium dose rate resulting from chronic inhalation. The corresponding dose equivalent rate for alpha emitting transuranics is 20 millirem per year.

3.2 WASTE CLASSIFICATION CRITERIA AND SCHEMES

3.2.1 PREVIOUS PROPOSED WASTE CLASSIFICATIONS

As stated, the purpose of this evaluation is to determine a functional waste classification and definition for TRU waste. The effort to date has included an extensive review and evaluation of numerous classification schemes and criteria. These included:

- The Battelle Pacific Northwest Laboratories report of June, 1974, "The Chemical Toxicity of Elements" (BNWL-1815) was used to develop the listing of chemical toxicity data for TRU radioisotopes and review the potential of this criteria as a waste classification scheme or element of a classification system. The use of chemical toxicity was found to be less restrictive than current radiotoxicity limits for TRU wastes.
- The National Academy of Sciences' report, "An Evaluation of the Concept of Storing Radioactive Wastes in Bedrock below the Savannah River Plant Site," considered "relative toxicities" of the major waste constituents. Appendix F of this report addresses the evaluation approach. This approach is similar to others discussed below and illustrates the applicability of relative toxicities to a specific site. This is an appropriate consideration for the TRU waste classification system development.
- The November 1967 IAEA technical report, "Standardization of Radioactive Waste Categories,"³ tabulated the information submitted by 11 countries concerning their systems of radioactive waste classification. The findings were that no two countries have the same classification system and that even within some countries the systems were different. The IAEA classifications first categorized radioactive wastes as liquid, solid or gaseous. Each of these was then categorized according to activity level and radiation dose, as appropriate. A modification of this approach would be appropriate for TRU waste

classification as it applies to handling, i.e., identification of shielding requirements for handling and disposal.

- The American Standards Institute—AIChE Radioactive Waste Categories was formulated for use by the American Institute of Chemical Engineers in 1967 but has been withdrawn. The system divided wastes into five (5) major categories, Classes A, B, C, D and E in ascending order of radionuclide concentration. This system does not readily address a simple approach for "disposal" but rather covers a broader spectrum of concerns. The approach would seem appropriate for a particular waste disposal scenario where "numerical" criteria for applications are desired. Thus, actual limits could be identified for each of the classes of waste at a TRU waste generating facility.
- Gera's Classification of Radioactive Waste.^{3,4} In the 1968 work by Gera, a rigorous waste classification system based on MPC's, activity concentrations, half-lives and exposure rates was proposed. In 1973, a different and more practical classification system was proposed which considered source of waste, dominant radiation and general operation information. Gera's system took into consideration high-level wastes, low-level wastes and alpha-bearing waste and is generally acceptable for a TRU waste classification system.
- The American Standards Institute issued a draft standard (ANSI-N525) in order to set forth definite meanings for terms used to describe broad categories of radioactive wastes. The waste categories specifically exclude:
 - Materials stored for possible future recovery of radioactive contents of value
 - 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).^{3,4} The waste classes are: high-level solid or liquid waste; low-level liquid waste; intermediate-level liquid waste; low-level gaseous waste; and high-level gaseous waste. The system does not provide guidance for disposition of TRU waste.

- The classifications specified by the DOE (Part I, DOE Manual, Chapter 0511, "Radioactive Waste Management,"

Appendix 0511, are for use as definitions of wastes and terminology for DOE-assigned responsibilities, authorities and procedures for radioactive waste management.⁶ The definitions do not represent a rigorous, comprehensive classification system, but they did provide groundwork for DOE classification efforts. This classification system has a definite category for TRU wastes; however, it uses the present arbitrary 10 nCi/g limit which makes it over-restrictive when considering potential hazards and long-term disposal.

- Blomeke and Kee^{20,21} 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
- Non-transuranium wastes
- Ore tailings

This system is based upon the 10 nCi/g limit for TRU waste and is unacceptable.

- Lawrence Livermore Laboratory concluded a study ("Determination of a Radioactive Waste Classification System," Cohen, and W. C. King, Prelim. Draft 1977) for the NRC in order that a meaningful waste classification system could be established. This study reviewed existing classification systems, optimized combinations of these systems and, most importantly, provided guidance for the disposition of the waste per the specific categories:
- Innocuous waste (direct discharge)

- Low-level waste (active containment)
- High-level waste (isolation)

Alpha-emitting material (TRU) is not classified separately but should follow essentially the same disposal criteria as other radioactive waste material.

- In DOE's Generic Environmental Impact Statement (GEIS), wastes were classified into categories based on the treatment requirements; i.e., all waste requiring ²⁵ similar treatment were included in one category. The 10 nCi/g limit was used to define TRU waste.
- In addition to these various formal classification schemes, the AGNS Barnwell facility was examined. At this facility solid waste generated at the reprocessing plant is divided into three major categories:
 - Spent fuel cladding hulls
 - High-level general process trash (over 50 mr/hr)
 - Low-level general process trash (0-50 mr/hr)

There are two categories which require on-site storage but are not considered waste:

- Failed process equipment
- Recoverable uranium scrap
- The actual acceptance criteria for disposal experiments in the Asse Salt Mine (Federal Republic of Germany) utilizes the following categories:
 - < 10 nCi/g

These wastes are considered as non α -waste; they do not need to meet special requirements

- 10 nCi - 5 μ Ci/g

These wastes are considered slightly α -contaminated; they have to be incorporated into a matrix material such as concrete, bitumen etc. They are stored like other low-or intermediate-level wastes depending on their content on β/γ emitters and their dose rate. Large amounts of these wastes

have already been disposed of in field experiments in the Asse Mine.

The 5 $\mu\text{Ci/g}$ values have been established by comparison of the radiotoxicity potential (ingestion) of α -bearing wastes with that of a 3% uranium ore. Such ores are found in nature, often in rather shallow formations, sometimes even in contact with water. Radioactive wastes in comparison to this are disposed of in deep geologic formations, well isolated from any circulating water. The wastes themselves are embedded into hard soluble matrix materials which form an additional barrier against the spread of radionuclides.

- > 5 $\mu\text{Ci/g}$

These wastes are considered as real α -wastes. Product specifications and storage techniques have not been fixed yet. No wastes of this category have been disposed of at Asse.

- The EPA's proposed criteria for radioactive waste deal with criteria for storage and disposal of all forms of radioactive wastes.¹⁵ (The actual criteria are included as Appendix C to this report). Though these criteria are not presently implemented, they are important since they would serve as a basis for developing detailed standards for radioactive wastes. Thus, these criteria directly impact both the NRC and DOE. The proposed criteria address six general waste management issues:

- Materials considered to be radioactive waste
- Control of radioactive waste
- Risk assessment
- Unacceptability of risk
- Location and waste isolation
- Supplementary protection goals

These proposed criteria directly impact TRU waste management. While the proposed criteria do not provide any quantitative criteria for specific handling of a TRU waste stream, the proposed criteria do generally direct the approach taken in the development of such quantita-

tive criteria. "EPA is developing environmental protection standards for the various types of radioactive wastes. The proposed criteria will be used by all agencies in their respective programs."¹⁵

The major impact of the proposed criteria is the explicit exclusion of a general "de minimus" level below which waste would not be considered radioactive. The implication of this position with regard to contaminated or potentially contaminated TRU waste, could be very severe since it will be the responsibility of the waste generator to certify that a waste is not contaminated with a TRU radionuclide. This at least implies that an absolute zero contamination level may be required before uncontrolled disposal activities could occur.

3.2.2 NRC WASTE CLASSIFICATION SYSTEMS^{19, 35}

The NRC waste classification system, currently in development as related to 10 CFR Part 60, identifies five different categories of waste. These are Classes A through E.

The Class A radioactive waste requires isolation in a repository or other disposal facility providing a high degree of containment and isolation, and includes those wastes which: a) because of their initial radiotoxicity require special emplacement procedures to prevent even small accidental releases, or b) will not decay to specified levels during the period of administrative control. Class A waste (the "default" class), has no upper concentration limits.

The Class B radioactive waste includes those wastes which require licensed confinement in intermediate-depth burial which will decay to specified levels during the period (150 years) of administrative control.* Class B wastes are classified as those wastes which are disposed at facilities where no contamination of a potable aquifer occurs during an administrative control period of 150 years. Thus, a 150-year decay period is assumed for these wastes.

* The EPA proposed criteria (Appendix C) assumes 100 years.

Class C radioactive waste includes those wastes which can be disposed of in such a manner that ready access by an unsuspecting reclaimer is unlikely; however, no administrative control is applied.

The Class D radioactive waste category includes those wastes which can be disposed in a controlled disposal site with a period of administrative control. This is similar to the present shallow land burial practices.

The Class E radioactive wastes are those innocuous wastes which require an unlicensed confinement (in a similar manner to non-radioactive trash), and include those materials which, because of their very low (essentially non-radioactive) hazard potential, may be disposed of at a regular solid waste disposal facility as non-radioactive wastes. It should be noted that this class of waste appears to conflict with the proposed EPA criteria mentioned above and reproduced in Appendix C.

This five-category classification scheme evolved from an earlier three-class system¹⁹ which, basically, delineated wastes as those disposed of in sanitary land fills, shallow land burial sites or deep geologic repositories.

A quantitative basis for delineating the waste classes was determined for various exposure events. The approach was to determine, through reasonably conservative calculations, a Class A/Class B interface level which would not exceed radiological exposure guidelines under the predicted disposal conditions. Interface levels between Class B and Class C and the other waste categories would be evaluated similarly. The exposure guidelines for the interfaces are assumed to be 500 mrem/yr (whole body or critical organ equivalent dose rate) where potential exposure of a few individuals (10's of individuals) is involved; 100 mrem/yr to many individuals (100's of individuals). Two additional dose guidelines, though not related to the final classification schemes, should be applied to specific site impact analyses. These include (where large population groups might be involved) the dose rate assumed to be equivalent to 1 mrem/yr during the disposal of radioactive waste produced during the generation of one GWe-yr of energy, and the "as low as reasonable achievable" ("ALARA") philosophy (when

population doses should not exceed those which could be achieved at a reasonable cost). These, plus the requirements for administrative control (for certain facilities) of a 150-year period, establish the present guidelines for the five-class system.³⁵ Relationships between the various class interface levels and maximum exposure were determined. If other radiation exposure criteria are applied, altered interface levels may readily be determined based upon these relationships.

Since the concern in this report is waste classification with emphasis upon that waste requiring deep geologic repository, the application of the modeling approach must consider the interface between Class A (deep geologic repository) and Class B (administratively controlled intermediate-depth land burial).

The procedure for determining this interface involves examination of the environmental impacts from waste disposed in an intermediate-depth land containment facility. Concentration or inventory limitations for low-level wastes are then determined by comparing of the impacts with the radiological dose guidelines presented above. Similarly, the interface between other waste classes is evaluated.

The radiological pathways (environmental exposure events) considered included the following analytical procedures:

- Identifying a set of reasonably conservative exposure events
- Describing man's encounter with the waste either by intrusion or by the transport of the radioactive materials through the environment to man
- 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 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 presented in Figure 3-1³⁵.

Included in the set are the mechanisms through which individuals contact the waste, such as:

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

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

- Groundwater migration to a resource waterway
- 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.

While numerous other pathways may be identified, it was determined that these pathways are either not restricting or are highly improbable.³⁵

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 was performed for the generic facilities, the pathway analysis was also performed for several specific waste disposal facilities in order to test the applicability of the generic models. 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.

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FIGURE 3-1

SET OF ENVIRONMENTAL EXPOSURE EVENTS
 USED IN NRC WASTE
 CLASSIFICATION ANALYSIS³⁵

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.³⁵

The results of this evaluation (waste classification, Table 3-1) for selected TRU isotopes are presented in Table 3-2.

As an example that obtaining the disposal concentration guide (DCG) from the maximum average concentration (MAC), the provisions of Class E are that no administrative control is utilized and easy access is allowed to the waste by a reclaimer. Therefore, 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 3-2.

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 MACs for this category are given under the Class D column in Table 3-2. The provisions of Class C are similar to those of Class D, except that 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 (intermediate-depth land burial).

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 DCGs given in the Class B column of Table 3-2 are obtained by correcting the DCGs of Class C by the radioactive decay factor.

TABLE 3-1
NRC PROPOSED WASTE DISPOSAL CLASSIFICATION SYSTEM³⁵

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)

TABLE 3-2
DISPOSAL CONCENTRATION GUIDES (DCG) OF SELECTED TRU ISOTOPES
FOR WASTE CLASSES ($\mu\text{Ci}/\text{cm}^3$)

Isotope	WASTE CLASS				
	E	D	C	B	A ²
U-235 ¹	0.015	0.03	11	11	
U-238	0.015	0.03	*	*	
Np-237	5.4 E-4	0.02	0.3	0.3	
Pu-238	3.4 E-4	0.4	*	*	
Pu-239	3.0 E-4	0.1	90	90	
Pu-240	3.0 E-4	0.1	810	810	
Pu-241	0.015	5.9 E+3	*	*	
Pu-242	3.1 E-4	0.1	13	13	
Am-241	9.2 E-4	0.4	*	*	
Am-243	9.2 E-4	0.3	600	*	
Cm-242	0.024	*	*	*	
Cm-244	1.5 E-3	13	*	*	

* Particular entries are omitted if the DCG for that class exceeds the Class A DCG (specific activity of isotope) for that isotope.

¹ U-235 and U-238 included for reference.

² All concentrations greater than Class B.

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 must be analyzed in a specified manner. A repository and Class A waste should be considered as a system. Thus, the DCGs 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.

It is proposed that the classification of TRU-contaminated waste, or potentially contaminated waste, be handled as a subset of present NRC efforts in the area of general radioactive waste classification. In this manner, much of the work and rationale developed can be utilized in the present task. For practical purposes the Class D guidelines serve as a realistic breakpoint for defining waste concentrations which require geologic disposition. Whether Class B or C facilities are ever developed is subject to further analysis, licensing, etc. It is known that Class D facilities are in existence today and a federal repository is planned for wastes with TRU concentrations greater than those allowed in shallow land burial sites.

Any practical application of a classification of "TRU-contaminated waste" involves the capabilities of radiation instruments for measuring the amounts of these materials in the various containers packaged and shipped for storage and retrieval or ultimate disposal. The following sections outline the present state of the art and the possibilities of improvements in the near future.

4.0 TRANSURANIC RADIOISOTOPE DETECTION^{27,28,31,33,34}

The accurate measurement and analysis of TRU contaminated wastes in a routine manner is important in the practical implementation of a TRU contaminated waste classification system. The following section provides a brief review of the techniques and types of analyses which have been identified as possibly applicable for low-level TRU concentration measurements. Since nondestructive assay (NDA) methodology and applications of the associated instrumentation are discussed extensively in the open literature, emphasis in this part of the report is placed only on the factors affecting NDA measurement accuracies and the selection of the appropriate NDA techniques for TRU waste measurements based on these factors.

4.1 ANALYTICAL METHODS AND TECHNIQUES²⁸

Nondestructive analytical methods for TRU isotopes in solid waste fall into two categories: passive and active analyses. Passive methods use the natural radiation emissions to identify and quantify the isotopes that are present. In active analyses, external radiation is used to induce a measured response or change in the TRU emissions.

The sensitivity for detection, i.e., measuring the nature and amount of radioactivity present, depends primarily on the following factors:

- The specific activity, i.e., radioactivity per unit measure of the radiation to be detected
- The nature of the exsiccated or matrix solidification material
- The package size or form in which material is available at the time of measurement
- The external background from the facility's environment
- The time allotted and accuracy required for the individual measurement

Sophisticated instrumentation will be required to measure the events, and skilled personnel will be needed to operate and maintain the equipment as well as to analyze the resulting data.

4.1.1 PASSIVE ANALYSIS TECHNIQUES²⁸

NEUTRON EMISSION FROM SPONTANEOUS FISSION

Two groups of neutrons are considered: those that are emitted at the time of fission (prompt or fission neutrons) and those that are emitted at some time after fission (delayed neutrons). On an average, more than two prompt neutrons are emitted per fission. Those prompt neutrons cover a broad energy spectrum, ranging from less than 0.05 MeV to greater than 15 MeV with the average prompt-neutron energy between 1 and 2 MeV. Delayed neutrons, however, are emitted from several of the fission product isotopes and are emitted individually as single particles. Average energies of these delayed neutrons are generally less than 0.5 MeV. Because more than two prompt neutrons are emitted simultaneously during fission, coincidence counting may be used to discriminate against the neutron background that is caused by the delayed neutrons and the (α ,n) reactions.

PROMPT GAMMA-RAY EMISSION FROM SPONTANEOUS FISSION

About three times more prompt gammas than prompt neutrons are emitted during fission. These gamma rays are emitted simultaneously and have energies in the range of 0.3 to 10.5 MeV. Counting the prompt gammas in coincidence with the prompt neutrons is a possible technique for measuring the quantity of TRUs present in the solid waste.

NEUTRON EMISSION FROM (α , n) EMISSIONS

Many light elements yield neutrons when bombarded with energetic alpha particles. The emitted neutron energy depends on the energy of the bombarding alpha particle, the binding energy of the neutron, and the energy excitation of

the residual nucleus. A rather broad continuous energy spectrum results with a maximum energy from 1 MeV for lithium to 10 MeV for beryllium. The neutron yield depends on the energies of the bombarding alpha-particles and on the composition of the target nucleus. For example, the alpha particles of Pu-238 bombarding the oxygen atoms in PuO_2 -238 will yield about 1.4×10^4 n/sec-g whereas PuO_2 -239 will yield only 45 n/sec-g. Thus, a measurement of the neutron yield from the (α , n) reaction can perhaps be used to measure TRU isotopes in waste.

PRODUCTION OF HELIUM FROM α -DECAY

Alpha particles are helium nuclei. Measuring the production of helium from alpha decay in the TRU-laden waste may provide a method of determining the amount of TRUs in a container.

PRODUCTION OF KRYPTON AND XENON BY SPONTANEOUS FISSION

Many isotopes of krypton and xenon are TRU fission products and most are radioactive. Thus, measuring the production of these gases through the spontaneous fission of the TRUs may be used as a method for detecting the TRU isotopes in a waste container.

GAMMA AND X-RAY EMISSION

Almost all of the TRU isotopes emit gamma rays and fluorescent X-rays during decay. These characteristic emissions can also be used to identify and quantify the TRU isotopes in solid waste.

A gamma-ray spectroscopy system complements the potential of other assay methods by providing the capability to nondestructively determine the content and the isotopic composition of various TRU isotopes. High-resolution gamma-ray systems are capable of extracting the maximum amount of information (isotopic composition, isotopic content, presence of extraneous gamma-ray

sources) from an assay, but content density severely affects the accuracy of quantitative predictions based on this assay method.

4.1.2 ACTIVE ANALYSIS TECHNIQUES²⁸

NEUTRON EMISSION FROM INDUCED FISSION

For most of the TRU isotopes with odd mass numbers, the spontaneous-fission rate is so low that the fission neutrons, particularly in quantities as small as 10 nCi/g, cannot be detected above the (α , n) background. Introducing neutrons or high-energy photons from an external source increases the fission rate. If a sufficient neutron or photon flux can be applied to the internal volume of the waste, it is possible to detect the induced fission neutrons. Counting the fission neutrons individually and in coincidence pairs yields the quantity of TRU isotopes present. Also, with increased fissioning, the yield of delayed neutrons is increased. Thus, the quantity of TRU isotopes present perhaps can be determined by counting the delayed neutrons following a specified irradiation time.

If neutrons are used as the irradiation source, the neutron energy should be in the thermal or epithermal range for greatest sensitivity; if photons are used as an irradiation source, the energy of the photons must be greater than 8 MeV to induce fission in the TRU isotopes.

PROMPT GAMMA-RAY EMISSION FROM INDUCED FISSION

The techniques used to count the prompt gammas from induced fission are the same as those used to measure spontaneous-fission gamma rays.

PRODUCTION OF GASEOUS KRYPTON AND XENON BY INDUCED FISSION

Increasing the fission rate by irradiation with neutrons or with high-energy photons results in an increased production of the fission-product gases. Because the fission yields differ for the isotopes of krypton or xenon for different TRU

isotopes, identification of the fissioning TRU nuclei may be possible by determining the ratios of the fission-gas isotopes.

NEUTRON ACTIVATION²⁸

It may be possible to transmute the TRU isotopes that are difficult to detect into isotopes that are easily detectable. Transmutation is accomplished by irradiating the atoms with thermal neutrons.

4.2 FACTORS AFFECTING MEASUREMENT ACCURACY³¹

Certain sample characteristics and measurement practices can affect the response of NDA systems. If these are not controlled or properly accounted for in determining the quantity of TRU from the measured activity, errors will be introduced into the final results.

The technical factors (excluding personnel related factors) contributing to the overall uncertainty associated with an NDA measurement are identified in the following four areas:

- The operational characteristics of the NDA systems
- The isotopic composition of the TRU waste
- The TRU waste and matrix materials
- The composition and dimensions of the waste container

4.2.1 OPERATIONAL CHARACTERISTICS

The operational characteristics of the NDA system, together with the ability of the system to resolve the desired response from a composite signal, determine the ultimate usefulness of the system. These operational characteristics include: operational stability, geometric effects, stimulating radiation uniformity, and energy of the stimulating radiation.

OPERATIONAL STABILITY

The ability of an NDA system to reproduce a given measurement may be sensitive to fluctuations in the operational environment. Temperature, humidity, and line voltage variations affect NDA systems to some extent. These effects may be manifested through the introduction of spurious electronic noise or changes in the high-voltage applied to the detectors or amplifiers, thereby changing the detection efficiency.

The environment must be controlled if such fluctuations result in severe NDA response variations that cannot be eliminated through calibration and operational procedures.

GEOMETRIC EFFECTS

The concern in the geometry of counting is: What portion of the radiation emitted by a TRU waste package actually enters the sensitive volume of the detector? This portion ranges from a very small fraction, when the distance from package to detector is large, to 100% for some 4π -detectors, when the TRU waste package being counted is completely inside the detector.

Also, for some detectors such as the well-type gamma and neutron counters, the response of the gross count rate is a function of the position of a point source within the well. This implies that the size and distribution of the sample being counted within the well may have an important bearing on the detector response. To make the necessary error corrections, therefore, it is important to predetermine the geometry effect of a counting system.

STIMULATING RADIATION UNIFORMITY

It is important that the stimulating radiation field (i.e., interrogating neutron or gamma-ray flux) in active NDA systems be designed to be uniform in intensity and energy spectrum throughout the volume of the irradiation chamber. The residual effect can be measured by using a TRU waste package that is small in

comparison with the dimensions of the irradiation chamber. The response can then be measured with the TRU waste positioned in different locations within the irradiation chamber.

Various methods, including rotating and scanning the container, scanning the source, distributing sources, and combinations of these methods, must be investigated to reduce the response uncertainty attributable to a nonuniform stimulating radiation field. Scanning a rotating container while the detector and source positions are fixed appears to offer an advantage in response uniformity.

ENERGY OF THE STIMULATING RADIATION

If the energy of the stimulating radiation is as high as practicable but below the threshold of any interfering reactions (such as the neutron-induced fission in U-238), the penetration of the stimulating radiation will be enhanced throughout the volume of the irradiation chamber.

The presence of extraneous materials, particularly those of low atomic number, lowers the energy spectrum of the interrogating neutron flux in active neutron NDA systems. Incorporating a thermal neutron detector to monitor this effect, thereby providing a basis for a correction to reduce the response uncertainty caused by this effect, is probably feasible.

4.3 ISOTOPIC COMPOSITION OF TRU WASTES

The TRU waste analysis response observed by an NDA system is usually a composite of contributions from more than a single isotope of plutonium or other TRU element. These sources of radiation are described briefly below.

4.3.1 MULTIPLE GAMMA-RAY SOURCES

The plutonium isotopes Pu-238 through Pu-241, as well as other TRU isotopes, are spontaneous gamma-ray emitters. The observed spontaneous gamma-ray spectrum, from a TRU sample must recognize the contribution of gamma rays

from these TRU isotopes. The uranium isotopes U-233 and U-238 spontaneously emit a gamma-ray spectrum and one gamma ray from U-238 (~766 keV, which is really from the Pa-234 daughter nuclide) is nearly of the same energy as one emitted by Pu-238. Uranium-232, occurring in combination with U-238, has a series of prolific gamma-ray-emitting daughter products, including Th-228. These and other sources must be recognized in accurately assessing the TRU contribution from a particular container.

4.3.2 MULTIPLE SPONTANEOUSLY FISSIONING ISOTOPES

Plutonium-240 is the principal spontaneously fissioning isotope in the plutonium fuel now used in the nuclear fuel cycle. A small percentage of the total fission signal observed is due to Pu-238 and Pu-242.

Uranium has a much lower spontaneous fission rate than plutonium, but in mixed-oxide fuels the spontaneous fission yield from U-238, which is the predominant isotope present, may approach one percent of the Pu-240 yield.

4.3.3 MULTIPLE FISSILE AND FERTILE ISOTOPES

In active NDA assay systems, the observed fission response may come from more than one radioisotope. When a sample of plutonium or uranium mixed-oxide fuel is actively interrogated, the measured response will include contributions from the plutonium, uranium, and other fissile isotopes and, if the energy of the interrogating neutrons is high enough, the response will include contributions from both the fissile and fertile isotopes of plutonium and uranium.

4.4 ANALYSIS RESPONSE DEPENDENCE ON THE TRU AND MATRIX MATERIALS ³¹

If an NDA system is sensitive to the geometry of the detection system and the field of interrogating radiation, variations in the observed response may be attributed to the attenuation of emitted gamma rays, neutron multiplication,

alpha-neutron reactions, attenuation of the interrogating radiation, and isotopic equilibrium.

4.4.1 ATTENUATION OF EMITTED GAMMA RAYS

The intensity of gamma rays is attenuated as they pass through matter. The magnitude of this attenuation depends on the energy of the gamma rays, as well as the thickness, density, and atomic number of the absorbing material. Low-energy gamma rays are much more severely attenuated than those of high energy. Measuring gamma rays of energies below approximately 80 keV is difficult and usually impractical because of severe attenuation problems.

Plutonium and other TRU isotopes have high mass absorption coefficients; therefore, self-absorption of gamma rays by these two elements can severely limit the application of passive gamma-ray spectrometry of relatively dense samples.

4.4.2 NEUTRON MULTIPLICATION

Neutrons from spontaneous or induced fission reactions can be absorbed by other nuclei, subsequently causing these nuclei to fission and release additional neutrons. This multiplication results in an increased sample response and therefore should be considered in all active and passive NDA systems.

4.4.3 ALPHA-NEUTRON (α, n) REACTIONS

Neutrons are randomly generated through interaction of alpha particles with light elements such as oxygen, fluorine, nitrogen, carbon, and beryllium. Isotopes of TRU elements emit large quantities of alpha particles, which can cause (α, n) reactions and produce neutrons that increase the response of fission measurements.

4.4.4 SAMPLE SELF-SHIELDING

When performing an active assay of dense TRU contaminated metals or heterogeneous samples containing lumps of TRU elements, self-shielding of these isotopes against the interrogating neutrons will occur to varying degrees. Penetrability of the interrogating neutrons into a waste package is dependent on the energies of these neutrons, the density of the waste, and the type and amount of matrix material present. Matrix materials containing neutron moderators such as hydrogen will attenuate the interrogating neutrons to lower energy levels and increase the sample self-shielding effect.

4.4.5 ISOTOPIC EQUILIBRIUM

Some gamma-ray signatures involve gamma rays emitted from a daughter product of the fissioning isotope in the waste. These signatures can be accurately measured only when the isotopes in the waste and its daughter are in equilibrium.

4.4.6 EFFECT OF MATRIX MATERIALS

Matrix materials, which can be considered as all materials present in the sample other than the TRU isotopes, can have various effects on the NDA results. Matrix materials of low atomic number, particularly hydrogenous materials, reduce the energy of neutrons by elastic collision. The lower-energy neutrons are more likely to interact with other nuclei in the sample and thus affect the observed spontaneous fission response.

Matrix materials of high atomic number cause attenuation of gamma rays, particularly gamma rays of low energies. This can cause decreased response during an NDA measurement.

4.5 COMPOSITION AND DIMENSION OF THE CONTAINER

Variations in thickness of the waste container walls and structural composition can significantly affect the accuracy of NDA measurements. Therefore, the same type of container should be used, if possible, for the standard and the

unknown waste package. Otherwise, a calculated or measured correction must be applied to the measured data to take into account the difference in container wall thickness and structural composition.

4.6 TRU DETECTION STATUS^{28,27,31,33,34}

The NDA techniques selected should reflect a consideration of the accuracy requirements for the assay and the type of TRU isotopes and containers in the inventory. No single NDA method is capable of universal application, and frequently more than one NDA technique is required to perform the job.

The above-mentioned nondestructive analytical methods for measuring low-level TRU contamination can be grouped into four basic detection schemes: neutron counting, photon counting, fission-gas production measurements, and helium production measurements.

Table 4-1 is a summary of the minimum theoretical detection limits that are possible for each alpha-emitting TRU isotope ($T_{1/2} > 100$ d) for each of the detection methods. Where blank spaces exist, insufficient data were available on the isotope to calculate a detection level. A conservative approach was taken for the calculations. Therefore, these levels should be achievable with instrumentation and techniques presently available.²⁸

Three of the eight methods presented in this report involve irradiating the waste material with thermal or epithermal neutrons at a flux density around 10^6 n/cm²-sec. Computer neutron diffusion codes have shown that a reasonably uniform flux (within $\pm 20\%$) can be obtained over the volume of a 208-liter (55-gal) waste container.

A suggested test procedure for neutron counting and krypton or xenon sampling required that five separate neutron counts be made on each waste container. The neutron-count data yield the spontaneous-fission rate of the material in the container, the delayed-neutron count rate decay, and the effect of the waste

TABLE 4-1

SUMMARY OF MINIMUM-DETECTION LEVELS^{a *}
FOR ALL TRU ISOTOPES BY NON-DESTRUCTIVE
ASSAY AT A PACKING DENSITY OF 50 KG/M³

TRU	SF Neutron ^b (Ci/g)	Kr-Xe(SF) ^c (Ci/g)	Kr-Xe(IF) ^d (Ci/g)	X Ray or Gamma Ray ^e (Ci/g)	Delayed ^f Neutrons (Ci/g)	He ^g (Ci/g)	Prompt Gamma (SF) ^h (Ci/g)	Prompt Gamma (IF) ⁱ (Ci/g)
U-233	-	-	1×10^{-9}	9×10^{-9}	5×10^{-9}	-	-	1×10^{-8}
Np-237	$>3 \times 10^{-1}$	$>3 \times 10^2$	2×10^{-6}	5×10^{-10}	1×10^{-5}	-	4×10^{-1}	3×10^{-5}
Pu-236	9×10^{-4}	8×10^{-1}	2×10^{-4}	7×10^{-7}	9×10^{-4}	-	1×10^{-1}	3×10^{-3}
Pu-238	4×10^{-4}	4×10^{-1}	7×10^{-5}	1×10^{-6}	3×10^{-4}	-	5×10^{-2}	9×10^{-4}
Pu-239	2×10^{-1}	2×10^2	5×10^{-9}	3×10^{-7}	2×10^{-8}	-	2×10^{-1}	7×10^{-8}
Pu-240	2×10^{-5}	2×10^{-2}	$>2 \times 10^{-4}$	9×10^{-2}	$>9 \times 10^{-4}$	-	2×10^{-3}	$>2 \times 10^{-3}$
Pu-242	1×10^{-7}	1×10^{-4}	$>1 \times 10^{-6}$	-	$>8 \times 10^{-6}$	-	2×10^{-5}	$>2 \times 10^{-5}$
Pu-244	2×10^{-10}	2×10^{-7}	-	4×10^{-10}	-	-	3×10^{-8}	-
Am-241	3×10^{-1}	3×10^2	7×10^{-5}	1×10^{-10}	3×10^{-4}	$>10^{-8}$	4×10^1	9×10^{-4}
Am-242	-	-	1×10^{-7}	8×10^{-8}	5×10^{-7}	but	-	1×10^{-6}
Am-243	-	-	$>2 \times 10^{-4}$	1×10^{-10}	$>8 \times 10^{-4}$	probably	-	$>2 \times 10^{-3}$
Cm-242	1×10^{-5}	1×10^{-2}	$>4 \times 10^{-2}$	2×10^{-7}	$>2 \times 10^{-1}$	$<10^{-6}$	1×10^{-3}	$>6 \times 10^{-1}$
Cm-243	-	-	5×10^{-6}	3×10^{-9}	2×10^{-5}	for all [*]	-	6×10^{-5}
Cm-244	5×10^{-7}	5×10^{-4}	-	6×10^{-6}	-	isotopes	6×10^{-5}	-
Cm-245	-	-	5×10^{-9}	1×10^{-9}	3×10^{-8}	-	-	7×10^{-8}
Cm-246	2×10^{-9}	2×10^{-6}	-	-	-	-	3×10^{-7}	-
Cm-247	-	-	-	-	-	-	-	-
Cm-248	7×10^{-12}	7×10^{-9}	-	$<10^{-8}$ SF γ	-	-	8×10^{-10}	-
Cm-250	3×10^{-13}	3×10^{-10}	-	$<10^{-8}$ SF γ	-	-	8×10^{-11}	-
Bk-247	-	-	-	2×10^{-9}	-	-	-	-
Cf-248	1×10^{-8}	1×10^{-5}	-	-	-	-	1×10^{-6}	-
Cf-249	3×10^{-6}	3×10^{-3}	2×10^{-7}	6×10^{-10}	7×10^{-7}	-	3×10^{-4}	2×10^{-6}
Cf-250	9×10^{-10}	9×10^{-7}	$>2 \times 10^{-5}$	-	$>1 \times 10^{-4}$	-	1×10^{-7}	$>3 \times 10^{-4}$
Cf-251	-	-	4×10^{-8}	-	2×10^{-7}	-	-	5×10^{-7}
Cf-252	1×10^{-11}	2×10^{-8}	-	$<10^{-8}$ SF γ	-	-	3×10^{-9}	-
Es-252	-	-	-	4×10^{-8}	-	-	-	-
Es-254	6×10^{-7}	6×10^{-4}	-	2×10^{-9}	-	-	8×10^{-5}	-

* To convert these minimum-detection levels to Ci/cm³, multiply by 0.05.

TABLE 4-1

(CONT.)

SUMMARY OF MINIMUM-DETECTION LEVELS^a
FOR ALL TRU ISOTOPES BY NON-DESTRUCTIVE
ASSAY AT A PACKING DENSITY OF 50 KG/M³

Notes

- ^a Minimum-detection levels are used here as the minimum levels that appear to be obtainable with reasonable effort. Because none of the methods (except gamma-ray analysis) has been demonstrated, these values are calculated estimates. A conservative approach was taken in the calculations and in most cases, these values are expected to be bettered.
- ^b Determined by coincidence counting of spontaneous-fission prompt neutrons.
- ^c Determined by measurement of the buildup of noble-fission-gas concentration as spontaneous fission takes place in a sealed container. Analysis is made of Kr-88 concentration after equilibrium has been established.
- ^d Determined by measurement of the amount of noble fission gases produced from induced fission by an irradiating neutron flux of 10^6 n/cm²-sec. An irradiation time of 30 minutes and a decay time of two hours are assumed; Kr-88 is the chosen isotope.
- ^e Determined by gamma-ray analysis of one selected photon energy in presence of a natural background of 20 μ R/h. Count time is taken as 1,000 seconds in each case.
- ^f Determined by counting delayed neutrons after container is subjected to a neutron irradiation-flux density of 10^6 n/cm²-sec until equilibrium is established for Br-87 (~10 min). Delayed-neutron yield data for thermal fissions are not available for isotopes other than U-233 and Pu-239. Values for other isotopes are calculated from estimated yield values.
- ^g Determined after sealing drum for 10 d followed by purging with nitrogen and measuring the helium concentration.
- ^h Determined by counting prompt gammas from spontaneous fission. Only photons of > 3 MeV are counted after passing through a collimator and 2-cm thick lead window.
- ⁱ Determined by counting prompt gammas from induced fission by thermal or epithermal neutrons with a flux density of 10^6 n/cm²-sec. Only photons with energies of > 3 MeV are counted after they pass through a collimator and 2-cm thick lead window.

matrix on the neutrons. The total time for the count analysis for each waste container was approximately 60 minutes.

Krypton and xenon sampling take about two hours, but sampling can be conducted in parallel with several containers sampled simultaneously. The average production rate is then approximately six containers per 8-hr shift or 80 minutes per container. A minimum crew consists of one trained technician (to operate the neutron generators, take the counts, and collect the samples) and one scientist to calibrate the systems as well as analyze and interpret the data. Because of the hazard associated with the neutron generators, elaborate safety procedures and interlocks are needed to prevent occupational radiation injury.

Ten of the twenty-seven TRU isotopes can be detected at a 10 nCi/g level using these neutron methods. The main uncertainty with neutron counting arises from the effect of the neutron background (e.g., from the (α, n) reactions) on the detection sensitivity. The added analytical complexity from the presence of several TRU isotopes in the waste can be handled with a computer program. The ratios of the various isotopes must be determined by other means; neutron counting cannot identify the specific isotopes present.

The helium production measurement method is not as sensitive as neutron or gamma counting but it appears to have considerable potential. It was estimated that one trained technician could test six to eight containers by 8-hr shift after the containers have been prepared, sealed, and stored for > 10 d to permit helium buildup. The major uncertainty involved with this method is whether the waste container can be sealed tightly enough to contain the helium. Any leak of helium will cause the calculated amount of TRU in the container to be less than what was actually present.

If Pu-239 or U-233 alone are the major TRU isotopes to be tested, the production of krypton or xenon by induced fission appears to be an attractive method. As an estimate, one technician can test about four containers per 8-hr shift. The major problem with this method is the complexity of interpreting the gas-analysis data.

In the absence of a gamma-ray background, photon counting is a feasible method. One trained technician can count ten to twelve containers per 8-hr shift. Scientific support is required to calibrate the equipment and to review the analysis methods. The major uncertainty with this method arises from the effect of the waste matrix as it attenuates the low-energy photons before they are counted. The non-uniform distribution of TRU in the waste also causes problems.

The remaining three methods (krypton and xenon production for spontaneous fission, prompt-gamma counting from spontaneous, and from induced fission) are not attractive, mainly because of low sensitivity. If the minimum detection level is raised to $1 \mu\text{Ci/g}$ (1000 nCi/g), prompt-gamma counting from induced fission provides a method for measuring U-233 and Pu-239.

The following observations were made concerning the measurement of small quantities of TRU in waste material using nondestructive testing techniques:²⁸

- No simple method exists for measuring the quantity of a TRU in a package of waste in the presence of a gamma-ray background greater than a few milliRoentgen/hr.
- When an interfering background is not present, gamma-ray spectroscopy provides the best method for identifying and quantifying the TRU present in the waste. Several such systems have been developed and are in use today. Major research efforts will continue toward the development of greater sensitivity and better resolution. However, improvements within the next few years are not expected to provide an increase in sensitivity to reduce the detection level of TRU by tenfold.
- Monitoring the production of helium from the alpha decay of the TRU is an untried method that has the potential to measure all TRU isotopes present in waste. The major technical difficulty with this method involves the naturally occurring helium in the air. However, detection sensitivity of the technique appears to be close to the 10 nCi/g level.
- The only other viable measurement method at the 10 nCi/g level involves complex procedure of spontaneous-fission

neutron counting, and krypton-xenon sampling and analysis. The delayed-neutron counting is not required because it does not add new data. However, it does provide a confirmation of the krypton-xenon sampling results. Ten TRU isotopes can be measured at the 10 nCi/g level including Pu-239. Elaborate counting and electronic circuits are required to operate the system as well as to collect and analyze the data. This method has not yet been demonstrated experimentally on small quantities of TRU and technical difficulties are more pronounced with this technique than with the other practical methods.

- Including the gamma-analysis method, neither of the other two proposed methods will identify the TRU isotopes present. In the neutron irradiation and counting as well as in the krypton-xenon sampling methods, a foreknowledge of the TRU isotopes present and their relative abundance is required even to quantify the amount of TRU present. If this foreknowledge is unattainable, these methods are useless.
- Counting prompt neutrons from induced fission is not feasible, even when counting in coincidence pairs, because interference from the source neutrons completely masks the prompt-neutron count. No technique has been discovered to overcome this difficulty.
- Raising the minimum detection level to 1 μ Ci/g (1000 nCi/g) will permit the detection of all 27 TRU isotopes by the helium detection method and 19 of the isotopes by gamma-ray spectroscopy (in the absence of an interfering background).
- If the minimum-detection level were raised to 1 μ Ci/g (1000 nCi/g), measurement of the prompt fission gammas would be feasible, even in the presence of a 1-R/hr gamma background; additional energy discrimination could be accomplished with shields. However, the isotopes thus detected can be measured at lower activity levels by other methods.
- Lowering the minimum-detection level to 1 nCi/g will make it impossible to measure all TRUs except the five isotopes having the highest spontaneous-fission rates (i.e., Pu-244, Cm-248, Cm-250, Cf-250 and Cf-252).

4.7 TRU WASTE ASSAY FACILITY

Given a particular regulatory criterion for TRU waste classification (and consequential disposition), a nuclear facility would design and operate a waste assay facility to implement such criteria. The following description is for a prototypical facility at a commercial 1500 MTU reprocessing plant.³⁰ The purpose of this section is to describe an approach which has been designed to implement present regulations with emphasis upon control of Special Nuclear Material (SNM).³³

The proposed assay system design has been dictated by the requirement of a minimum throughput of 65 drums (total for both 208-L and 303-L (55- and 80-gallon) drums per 24-hour day, with fission product activity varying from very low ($< 40 \mu\text{Ci}$ per drum) to very high ($> 1 \text{ Ci}$ per drum). The type and number of detectors, i.e., two neutron systems and one gamma-ray system, have been determined by the throughput requirements for a 1500 MTU/yr reprocessing plant. It should be noted that this includes 10,425 drums of an expected 23,200 drums annually. It was presumed that some waste would be defined non-TRU and no assay would be performed.

4.7.1 OVERALL PROCESS DESCRIPTION

4.7.1.1 NONDESTRUCTIVE ASSAY (NDA) METHODS

No single NDA approach is able to provide all the required information because of the wide variety of waste categories, the projected concentration of uranium, plutonium, and fission products, the large container sizes, etc., which are generated at a fuel processing center. A system combining passive gamma and neutron detection with active neutron interrogation is required. Table 4-2 provides a summary of nondestructive assay techniques evaluated for SNM.

TABLE 4-2
SUMMARY OF NONDESTRUCTIVE ASSAY TECHNIQUES FOR SNM

#	Technique	Quantity Measured	Major Advantages	Major Disadvantages
1	Passive Gamma Ray-NaI	% U-235	Relatively simple and inexpensive.	Possible interference from U-237 decay. Non-uniform sensitivity due to heterogeneity.
2	Passive Gamma Rays-Ge(Li)	% U-235	Relative simple and inexpensive	Non-uniform sensitivity due to heterogeneity. Cost of Ge(Li) detector. Length of time required for assay.
3	Neutron source interrogation-detect prompt neutrons and gamma rays.	Fissile Content	Fairly uniform sensitivity to fissile.	Sensitive to moisture content of material. Possible interference γ from activities present.
4	Neutron source (e.g., Cf-252) interrogation-detect delayed neutrons (and possibly delayed gamma)	Fissile Content	Fairly uniform sensitivity to fissile. Low sensitivity to activity of material.	Sensitive to moisture content of material. Complete removal of source required during counting period.
5	14-MeV neutron generator interrogation-detect delayed neutrons (and possibly delayed gamma)	Fissile and Total U	Same as neutron source interrogation - also measures total uranium.	Sensitive to moisture content of material. Relatively complex and expensive. Shielded facility required.
6	Linac γ -ray Interrogation-detect prompt and delayed neutron.	Total U	Good uniform sensitivity to uranium.	Relatively complex and expensive. Shield required. Same as Linac γ -ray interrogation. Sensitive to moisture content of material.
	Linac sub-MeV neutron interrogation-detect delayed neutrons	Fissile	Same as neutron source interrogation.

4.7.1.2 GENERAL DESCRIPTION OF THE NDA SYSTEM

The passive gamma system consists of a Ge(Li) detector optimized for measuring Pu-239 natural activity in the presence of extraneous gamma activity. The main function of this detector is to measure the activity due to U-235, Pu-239, and possibly Pu-241. A fast-slow electronic system is provided, which is compatible with both the Ge(Li) or NaI detector. This allows extension of the measurement especially for U-238, into situations where the background due to lower energy gamma radiation is relatively high.

The neutron detection system consists of a large (approximately 4π) neutron detector. The neutrons emitted by either the spontaneous fissions of plutonium or by (α , n) reactions are thermalized in a hydrogenous moderator and are detected by a large number of thermal neutron proportional counters. The neutron detector is shielded with a layer of lead to minimize adverse effects from high-radiation fields.

Active neutron interrogation is achieved by oscillating a neutron source (Cf-252) which avoids possible reliability problems associated with a neutron generator. The measured signal is derived from the delayed neutrons detected when the source is out.

The data accumulated by the Ge(Li) and NaI(Tl) detectors are analyzed by a mini-computer which will compute the waste package contents based on previously prepared calibration curves. Similarly, at the end of the passive and active neutron counting, the computer will determine the amount of Pu-240 and total fissile material.

4.7.1.3 NDA SYSTEM COMPONENTS AND FEATURES

The system is composed of the following components:

- A Ge(Li) detector, cryostat, dewar, and liquid nitrogen level monitor and all of its associated electronics

- Appropriate shielding and collimation for the Ge(Li) detector
- A NaI (Tl) detector and its associated electronics
- Appropriate shielding and collimation for the NaI (Tl) systems
- Interface electronics compatible with both Ge(Li) and NaI (Tl) systems
- A radioactive source and collimator for matrix transmission measurements
- "4 π " thermalized neutron detector complete with appropriate neutron shielding
- "4 π " gamma-ray shielding for the neutron detector
- A complete scanning system for continuous vertical scanning of the barrels for passive gamma activities. The barrel is continuously lifted and rotated while being scanned. Piecewise, discontinuous scanning can be done manually (the measurement within the neutron detector does not require vertical scanning, since the effective volume of the detector is larger than the barrel).
- An oscillating Cf-252 neutron source, with provisions for underground storage
- Multichannel analyzer-computer system for measurement and analysis of the data generated by the Ge(Li), and NaI (Tl), and neutron detectors.
- At least four standard barrels containing encapsulated fissile materials and any other special material as required for calibration

4.7.2 DETECTION REQUIREMENTS

The purpose of the 208-L drum scanner is to determine the total fissile content, total plutonium, and total uranium in solid wastes which originate at one of four plant locations. In general, the waste is heterogeneously distributed nuclear material randomly mixed throughout both low and high atomic number matrix material. Listed below are design parameters and requirements for the waste originating from the four locations.

4.7.2.1 SEPARATIONS FACILITY WASTE

The design parameters and requirements for the Separations Facility's waste are as follows:

- < 3.5 g Pu/drum (expected concentration)
- < 350 g U/drum (expected concentration)
- Fission product activity (Zr-95, Nb-95, Ru-106, Rh-106, Ru-103, Rh-103): 1-50 curies/drum
- Desired measurements: plutonium, total fissile content
- Detection method for total fissile content: active neutron
- Detection method for plutonium content: passive neutron (assuming no (α, n) contribution)
- Desired accuracy: $\pm$ 25-50% (depends upon limitation of standards used)
- Desired precision: $\pm$ 50% (reproducibility of repeated measurements)
- Minimum detection limit (sensitivity) per drum: $\sim$ 0.25 g fissile material, $\sim$ 0.05 g Pu-240
- Expected counting time per drum: 15-20 minutes

4.7.2.2 URANIUM HEXAFLUORIDE FACILITY WASTE

The design parameters and requirements for the UF₆ Facility's waste are as follows:

- $\leq$ 1.0 g Pu/drum (expected concentration)
- 32-1600 g U/drum (expected range)
- Fission product activity (Zr-95, Nb-95, Ru-106, Rh-106, Ru-103, Rh-103): $\leq$ 2 μ Ci/drum

- Desired measurements: U-235, Pu-239, U-238, Pu-240, total fissile content, and total plutonium
- Detection method for total fissile content: active neutron
- Detection method for Pu-240: passive neutron (may require coincidence circuit due to (α , n) contribution from fluorine)
- Detection method for U-238, Pu-239, U-235: passive gamma
- Minimum detection limit (sensitivity) per drum: 0.25 g fissile material, 0.12 g Pu-240, 250 g U-238, 0.5 g Pu-239, 2.5 g U-235
- Desired accuracy: $\pm 25-50\%$
- Desired precision $\pm 50\%$
- Expected counting time per drum: 15-20 minutes

4.7.2.3 ANALYTICAL LABORATORY SERVICES WASTE

The design parameters and requirements for the Analytical Laboratory Services' waste are as follows:

- ≥ 0.02 g Pu/drum (expected concentration)
- ≥ 0.5 g U/drum (expected concentration)
- Fission product activity (Zr-95, Nb-95, Ru-106, Rh-106, Ru-103, Rh-103): ≤ 2 μ Ci/drum
- Desired measurement: U-235, Pu-239, U-238, Pu-240, and total fissile content
- Detection method for total fissile content: active neutron
- Detection method for Pu-240: passive neutron
- Detection method for U-238, Pu-239 and U-235: passive gamma

- Minimum detection limit (sensitivity) per drum: 0.25 g fissile material, 0.05 g Pu-240, 100 g U-238, 0.25 Pu-239, 0.5 g U-235
- Desired accuracy: $\pm 25-50\%$
- Desired precision $\pm 50\%$
- Expected counting time per drum: 15-20 minutes

4.7.2.4 PLUTONIUM OXIDE FACILITY WASTE

The design parameters and requirements for the Plutonium Oxide Facility's waste are as follows:

- ≥ 0.5 g Pu/drum (expected concentration)
- ≤ 2000 ppm U/g Pu/drum
- Fission product activity (Zr-95, Nb-95, Ru-106, Rh-106): $\leq 2 \mu$ Ci/drum, Am-241 growth
- Desired measurements: Pu-239, Pu-240, and total fissile content
- Detection method for total fissile content: active neutron
- Detection method for Pu-240: passive neutron
- Detection method for Pu-239: passive gamma
- Minimum detection limit (sensitivity) per drum: 0.25 g fissile content, 0.05 g Pu-240, 0.25 g Pu-239
- Desired accuracy: $\pm 25-50\%$
- Desired precision: $\pm 50\%$
- Expected counting time per drum: 15-20 minutes

4.7.3 CONCEPTUAL DESIGN

The Waste Assay Facility may be divided into two general areas: the office area and the assay area.

4.7.3.1 THE OFFICE AREA

The office area consists of an office, a guard room, a lunchroom, first aid, health physics, electrical supply, locker rooms, and some storage space. This area is radioactively uncontaminated. The materials and methods used in the construction of this area are similar to standard office construction, except the outer wall is concrete, 0.15 to 0.3 meters thick.

4.7.3.2 THE ASSAY AREA

The assay area consists of a drum surge gallery, mechanical area (filters), a gamma assay gallery, and a neutron assay cell. The outside walls of the assay area are 0.4 meters thick concrete and the neutron assay cell walls are 0.75 meters thick concrete. The assay area has only one floor level (except the mechanical filter room which has two floors) but is quite high (about six meters) due to the bridge crane coverage in the neutron assay cell and the drum surge gallery.

DRUM SURGE GALLERY

The drum surge gallery will have space for the temporary storage of about 200-400 drums. The prescanner will be located in this area to determine the necessity of subsequent assay for gamma and/or neutron radiation.

GAMMA ASSAY GALLERY

The gamma assay gallery is a relatively small area that is used to measure the gamma radiation emitted from waste in 210-L and 303-L drums.

NEUTRON ASSAY CELL

The neutron assay cell is used to measure the neutron radiation emitted from waste in drums. The cell is occupied by personnel and consists of two identical stations for neutron measurement. Two stations are required to maintain throughput.

The sources used in the measurement of neutron radiation consist of small (milligram) quantities of Cf-252. These sources emit large quantities of neutrons.

4.7.4 OPERATING DESCRIPTION

Waste drums are received from various parts of the reprocessing plant. Drums are first removed from the solid waste assay facility's storage area and taken to a prescanner, which measures the radiation level and weighs the drum prior to the beginning of the measurement sequence. The prescanner measures both the gross fission product activity emanating from the drum and the neutron yield through the use of slab counters. The data from the prescanning operation is used to determine the initial measurements required for assay of the drum. In some cases the prescanner may be the only measurement mode for very low-level radioactive drums.

The drums are stored in pits in the assay galleries prior to assay. After completion of a particular assay, they are removed to the storage location or on to another type of assay station as the data require. Movement of the drums is accomplished by using overhead cranes.

The operation of the passive gamma analysis station is essentially computer controlled. After loading a drum, the scanning operation, the acquisition spectra in a time differential mode, and the source transmission experiments are all controlled by data acquisition and analysis software. The computer interprets the data as compared to "standard" drum calibrations. The program "flags" any drum that has a high density anomaly for analysis by neutron assay.

Drums requiring neutron assay are tagged and either stored temporarily, or taken to the neutron assay cell. Drum movement is done with overhead cranes. Administrative controls and tamper resistant lids on all the drums prevent unauthorized access and movement of drums. Drums are taken into the neutron assay cell and are either placed in pits in the floor for temporary storage, or placed directly into a neutron assay station.

The neutron assay station(s) is interfaced into an analysis computer for automatic readout of neutron event. The operation of the active neutron interrogation source is controlled by computer. This control consists of determining the location to place the source, the time in that location, and the number of cycles between source locations. The flux monitor output is also read directly by computer.

Active neutron interrogation requires (for measurement reliability) that a minimum of three regions of the drum be irradiated repetitively with subsequent delayed neutron counting. The analysis software computes the amount of SNM compared to calibration drum data. The neutron assay of one drum takes about 30-45 minutes.

In all cases, the data are stored in computer compatible form (magnetic tape, paper tape, or computer discs) for future reference. The status of a drum is attached (labels, tags, etc.) by operating personnel before leaving the assay station. The drum is lifted out of an assay station by crane and transported to either temporary storage or directly out of the facility for disposal.

5.0 TRU CONTAMINATED WASTE FUNCTIONAL DEFINITION

The purpose of this section is to develop a functional definition for the radioactive wastes which have been contaminated with TRU radioisotopes. This definition is based upon an evaluation which has been briefly addressed in Sections 2 and 3 and reflects the large and diverse inventory of DOE generated TRU waste and relatively unknown commercial TRU contaminated waste presently buried at five shallow land burial sites.⁵

5.1 STATUS OF RADIOACTIVE WASTE CLASSIFICATION

In Section 3, various waste classification schemes were briefly reviewed and their potential application to the present TRU contaminated-waste problem was briefly addressed.

At present, EPA is developing general environmental protection criteria applicable to all radioactive wastes, which will provide basic criteria to be satisfied by waste systems. These will provide an interim basis upon which NRC can proceed with the final development and implementation of regulations, and DOE can continue ongoing operations. EPA will issue specific, numerical environmental standards for disposal of stable TRU form and other forms in 1979 and 1982, respectively. NRC is developing and will propose a waste classification system which will include a limit on the concentrations of TRU wastes that can be disposed of by shallow land burial. NRC will issue TRU disposal regulations in 1980.³²

DOE will continue to package and retrievably store TRU wastes in conformance with internal DOE standards until the required capability for processing and disposal is established. As formal EPA and NRC criteria and standards are promulgated, DOE operations will be modified to achieve compliance or conformance. Commercial practices are expected to continue with only Richland, Washington accepting commercial waste with TRU content above 10 nCi/g.

The purpose of this TRU functional definition is to provide an interpretation of the basic criteria for waste management in terms of requirements for TRU waste to be satisfied. The objectives of this classification system are:

- To classify wastes according to their requirements for safe disposal
- To address the concerns of the public, and
- To implement the system without undue burden on those directly affected by it.

5.1.1 DOSE GUIDELINES

The present NRC waste classification efforts are not based upon EPA proposed criteria or standards (see Appendix C) but rather have been based upon "...a reasonable set of study guidelines" proposed by the NRC.^{19,35}

The guidelines^{19,35}, which are presented below, were derived from the ICRP recommendations:

1. 500 millirem/yr to a few individuals (10's of individuals).
2. 100 millirem/yr to many individuals (100's of individuals).
3. Exposures to the general population will be as low as reasonably achievable, economic and social factors being taken into account - (not directly applicable to a TRU waste classification system as discussed in Section 3.2.2).
4. Population exposures are to be justified by resulting benefit: One millirem/year/gW_{yr} for many individuals as the result of the disposal of the waste generated per gigaWatt-yr of electrical energy (8.8×10^{12} kilowatt hours)-(not directly applicable to a TRU waste classification system as discussed in Section 3.2.2).

These dose limitations apply to either the whole body or critical organs, whichever event is the most restrictive.

5.1.2 TRU WASTE DISPOSAL CLASSIFICATION METHODOLOGY 19,35

Given a set of dose guidelines, it is necessary to develop a methodology to evaluate proposed waste disposal alternatives. For the NRC evaluation it was determined that the classification system should contain five categories of actions in handling radioactive waste:

- Class A - Isolate the waste (non-Class B) from the biosphere so that biologically significant releases or inadvertent re-entry by mankind into the disposal area is highly unlikely
- Class B - Waste disposal in a facility with additional cover, e.g. 10 m (intermediate depth burial) and where there is no present potential for contaminating a potable aquifer during a 150 year post-closure period
- Class C - Dispose of waste in such a manner that ready access by a reclaimer is unlikely; however, no period of administrative control is assumed
- Class D - Confine the waste (low-level waste) for an administrative control period of time in a controlled disposal site (similar to present shallow land burial)
- Class E - Discharge the waste directly to the biosphere in a manner similar to the handling of routine trash (innocuous waste) i.e., no administrative control and early access by worker/reclaimer

With the NRC system, classification of the wastes according to the nature of the 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. In the classification system, the method governing the disposition of waste is based primarily on the hazard potential and is expressed in terms of radioactivity per unit volume at the time of disposal. For the purpose of this review, emphasis will be given to this system's applicability to TRU waste.

5.1.3 ENVIRONMENTAL EXPOSURE EVENTS

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

The analytical procedures for determining the quantitative values of the TRU waste-class interfaces addressed above employed three basic steps:

- Identifying a set of reasonably conservative exposure events
- Describing the transport of the TRU isotopes through the environment to man or man's encounter into the TRU waste
- Calculating the concentrations or inventories of TRU isotopes 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 mechanisms included in the analysis by which individuals contact the TRU waste are:

- Inhalation of dust by a reclaimer digging in the waste or by residents on the reclaiming site
- Ingestion of water from a well dug by a reclaimer
- Consumption of food grown in a garden containing contaminated soil
- Direct exposure to workers or residents from gamma radiation

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

- Erosion/corrosion events depending upon waste cover or containment
- Groundwater migration to a resource waterway

Using these given exposure mechanisms, it is necessary to establish appropriate data bases for each of the disposal methods. The procedure for determining the Class B (intermediate depth burial)/Class A (repository storage) interface is to examine the environmental impacts from waste disposal in reference containment facilities for each class.¹⁹ Concentration or inventory limitations for low-level wastes are then determined by comparison of the impacts with the dose guidelines given previously. The interface between other waste classes is determined similarly. Appendix D presents the mathematical models and numerical values utilized to perform the exposure event analyses.

For this study the major area of interest involves the Class D interface, i.e., what waste cannot be buried in present shallow land burial facilities and which will or may require deep geologic disposal.

5.1.4 DISPOSAL CONCENTRATION GUIDES (DCG) FOR TRU WASTE MIXTURES³⁵

The DCG presented in Table 3-2 is 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.

$$\frac{1}{\text{DCG}_m} = \sum_{i=1}^n \frac{f_i}{(\text{DCG})_i}$$

where,

- n = number of isotopes in the mixture
- f_i = radioactivity fraction of i^{th} isotope in the mixture
- $(\text{DCG})_i$ = DCG for i^{th} isotope
- DCG_m = DCG for the waste mixture

It is worth noting that this evaluation must consider not only TRU isotopes, but all radioisotopes present since each will contribute at different levels to the potential dose exposure.

5.2 TRU WASTE FUNCTIONAL DEFINITION

The methodology discussed above provides an acceptable means of determining levels of TRU concentration which require deep geologic disposal (Class A waste), engineered containment (Class B waste) and other disposal schemes (Classes C, D and E). However, the exact interface points have not yet been established except to the extent that waste at a 10 nCi/g level will obviously not require deep geologic disposal while a value of $\sim 0.1 \mu\text{Ci}/\text{cm}^3$ ($\sim 100\text{-nCi}/\text{cm}^3$) appears a more likely interface range. The exact values are subject to further modeling refinement, analysis and review, as well as evaluation of compliance with EPA criteria, DOE practices, and other regulatory considerations.

Based upon the present evaluation the limits of Table 3-2 appear appropriate as guides for future work. These limits, when compared with the TRU isotope detection capability (Section 4), appear within the working range for various methods or combinations of detection methods. Given this ability to monitor generated waste, it is necessary to determine potential areas of uncertainty or controversy.

The most important question, which directly impacts TRU waste functional definition, is "where does a waste generator measure his waste?" It would appear that it is a simple question to answer — in the waste container. However, this does not adequately address the factor of waste form, use of best available technology, costs and other factors which might influence the handling and disposal of a waste stream. The as-generated "raw" (untreated) TRU waste may be at a concentration at which it would be readily handled as a Class B low-level waste requiring shallow land burial, but, if the waste is processed and the volume reduced, it would be classified as a Class A waste requiring the substantially more expensive deep geologic disposal. Thus, a functional definition must address this type of potential problem.

An obvious solution is to mandate a final waste form and allow the waste generator to meet such requirements via the "licensing" process. This would require completion of the waste form evaluation prior to implementation of a TRU waste classification system. Another solution is to require that the waste generator utilize state-of-the-art waste processing technology and that the NRC identify such acceptable technology for generic TRU waste classes. This approach is similar to the philosophy utilized in licensing nuclear power plants.

Numerous questions arise concerning not only new facilities, but also operating facilities. Further, the huge backlog of waste presently buried in shallow land sites and stored retrievably must also be addressed. However, the present limits in Table 3-2, when expanded to all TRU isotopes, provide a reasonable functional definition of TRU waste requiring deep geologic disposal.

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APPENDIX A
GLOSSARY OF
TERMS AND DEFINITIONS

TERA CORPORATION

Actinide Series: The series of elements beginning with actinium, element No. 89, and continuing through lawrencium, element No. 103, which together occupy one position in the periodic table. The series includes uranium, element No. 92, and all the man-made transuranium elements. The group is also referred to as the "actinides."

Activation: The process of making a material radioactive by bombardment with neutrons, protons, or other nuclear particles. Also called radio-activation. The resultant radioactive materials are commonly called activation products.

Activity: A measure of the rate at which a material is emitting nuclear radiations; usually given in terms of the number of nuclear disintegrations occurring in a given quantity of material over a unit of time; the standard unit of activity is the curie (Ci).

Alpha Particle (α): A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons; hence it is identical with the nucleus of a helium atom.

Alpha Waste: Waste material that is contaminated by radionuclides that emit alpha particles, particularly (in this text) the transuranium elements.

Anion: A negatively charged ion.

Aqueous Phase: The liquid phase in solvent extraction which consists of dilute of nitric acid.

Back End of the Fuel Cycle: Includes reactors, spent fuel storage, fuel reprocessing, mixed-oxide fuel fabrication, and waste management.

Beta Particle (β): An elementary particle emitted from a nucleus during radioactive decay. It has a single electrical charge and a mass equal to $1/1837$ that of a proton. A negatively charged beta particle is physically identical to the electron. If the beta particle is positively charged, it is called a positron (β^+).

Burial Grounds: Areas designated for storage of containers of radioactive wastes by near-surface burial in geologic media.

Calcination: A process of solidifying high level liquid waste by evaporating to dryness on a granule and converting from the nitrate form to the oxide form.

Calcine: Material heated to a temperature below its melting point to bring about loss of moisture and oxidation to a chemically stable form.

Cask: A container that provides shielding and containment for transportation of retrievable storage of solid waste. The shielding is normally steel or concrete, and the waste is contained in a canister within the cask.

Cation: A positively charged ion.

Cermet: Ceramic-metal systems suitable for use at high temperatures. They have some of the desirable properties of both ceramics and metals, e.g., high melting point, high oxidation resistance, high thermal conductivity, and shock resistance.

Cladding Waste (hulls): Fuel rods in most nuclear reactors today are made up of fissionable materials clad in a protective alloy sheathing that is relatively resistant to radiation and the physical and chemical conditions that prevail in a reactor core. The spent fuel rods, after removal from the reactor and storage to permit radioactive decay of the short-lived fission products, are removed and in certain fuel cycle processing systems are chopped up, and the residues of the fissionable materials are leached out chemically. The remaining residues, principally the now radioactivated cladding material (zirconium alloys, stainless steel, etc.) and insoluble residues of nuclear fuel, fission products, activation products and transuranium nuclides, are left behind as cladding waste, which is a special category of transuranium radioactive waste.

Combustible: A "material capable of being burned, except that if the only combustible content of a package is plastic lining or wrapping used for contamination control purposes around incombustible objects or materials, the contents of the package as a whole may be considered noncombustible." (DOE Manual 0511—Radioactive Waste Management)

A precise definition of the term "combustible" is difficult, if not impossible, to prepare. This difficulty arises because the combustible nature of a given material is dependent not only upon the form of the material but also on the conditions of ignition which must be considered. It is the intent of this definition that emphasis be placed on combustion. However, one should not ignore the long-term phenomena of pyrolysis and thermal decomposition.

This definition of "combustible" is applied to a material under the conditions existing (or possibly foreseen) in the disposal facility. Thus, extreme conditions and the method of packaging need not be included as factors in the determination of combustibility of the package. Further, the production of flammable gases need not be a consideration in determining combustibility of the waste material if the control of such gases can be accomplished by separate means. The overall intent of the definition is to consider those materials that may burn in the common sense of the word and that could lead to or add to a fire if not properly protected. The principal type of material considered as combustible should be the organics, which are composed mostly of hydrogen, carbon and oxygen. Those materials classed as fire-retardant, either by nature of the composition or because of treatment, should also be included since they will release heat and flammable gases if exposed to fire from other sources and can, therefore, add to the overall intensity of a fire.

Combustion: The rapid and self-propagating oxidation of materials in air, with the evolution of significant quantities of heat.

Concrete Matrix: A process to fix calcine in a monolithic form by mixing with a concrete slurry.

Contamination: The deposition of radioactive material on a surface or the presence of fission products in a process stream

Contamination-Free: "A condition of the outer surfaces of stored containers, as determined by appropriate swipe surveys or direct radiation instrument surveys, sufficiently free of contamination so that under standard radiation work procedures for the site in question respiratory protection will not be required during container handling." (ERDAM 0511--Radioactive Waste Management)

Countercurrent: The opposed flow of the aqueous phase and organic phase in an extraction column.

Crib: A back-filled burial trench into which intermediate-level liquid waste is distributed through a perforated pipe.

Critical: The condition in which a material is undergoing nuclear fission at a self-sustaining rate; the critical mass of a material is the amount that will self-sustain nuclear fission when placed in an optimum arrangement in its present form.

Curie (Ci): A unit of radioactivity defined as the amount of a radioactive material that has an activity of 3.7×10^{10} disintegrations per second (d/s); millicurie (mCi) = 10^{-3} curie; microcurie (μ Ci) = 10^{-6} curie; nanocurie (nCi) = 10^{-9} curie; picocurie (pCi) = 10^{-12} curie; femtocurie (fCi) = 10^{-15} curie.

Decay: The spontaneous radioactive transformation of one nuclide into a different nuclide or into a different energy state of the same nuclide. Every decay process has a definite half-life.

Decommissioning: The process of removing a facility or area from operation and decontaminating and/or disposing of it or placing it in a condition of standby with appropriate administrative and physical controls and safeguards.

Decontamination: The selective removal of radioactive material from a surface or from within another material.

Deep Geologic Formations: Geologic media beneath the continents and isolated from biologic species and phenomena. Distinguished from ice sheets and sea floor geologic media.

Defense Waste: Nuclear waste generated from government defense programs as opposed to commercial waste which is generated from civilian reactor programs.

Denitrations: The chemical process of converting uranyl nitrates ($\text{UO}_2(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) to uranium trioxide (UO_3).

Diluent: An organic compound used to dilute the solvent in a solvent extraction process. It is usually nonreacting.

Disposal: The planned release or placement of waste in a manner that precludes recovery.

Dose: The energy imparted to matter by ionizing radiation per unit mass or irradiated material at a specific location. The unit of absorbed dose is the rad.

Engineered Storage: The storage of radioactive wastes, usually in suitable sealed containers, into any of a variety of structures especially designed to protect them from water and weather and to help keep them from leaking to the biosphere by accident or sabotage.

Enriched Uranium: Uranium in which the percentage of the fissionable isotope uranium-235 has been increased above the 0.7% contained in natural uranium.

Extraction Column: A piece of process equipment which intimately mixes the organic phase and the aqueous phase in the solvent extraction process. Material is transported between the phases.

Extraction Cycle: The use of several extraction columns to separate a wanted product by solvent extraction from other constituents of the feed stream.

Federal Repository: A DOE-controlled facility to be used for the disposal of nuclear waste.

Fertile Material: A material, not itself fissionable by thermal neutrons, that can be converted into a fissile material by irradiation in a reactor. There are two basic fertile materials, uranium-238 and thorium-232. When these fertile materials capture neutrons, they are partially converted into fissile plutonium-239 and uranium-233, respectively.

Fines: Calcine dust having the consistency and flow properties of talcum powder.

Fissile Materials: While sometimes used as a synonym for fissionable material, this term has also acquired a more restricted meaning, namely, any material fissionable by neutrons of all energies, including (and especially) thermal (slow) neutrons as well as fast neutrons; for example, uranium-235 and plutonium-239.

Fission: The splitting of a heavy nucleus into two approximately equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy and generally one or more neutrons. Fission can occur spontaneously, but usually is caused by nuclear absorption of gamma rays, neutrons, or other particles.

Fissionable Material: Commonly used as a synonym for fissile material. The meaning of this term also has been extended to include material that can be fissioned by fast neutrons only, such as uranium-238. Used in reactor operations to mean fuel.

Fission Products (F.P.): The nuclei (fission fragments) formed by the fission of heavy elements, plus the nuclides formed by the fission fragments' radioactive decay.

Fluidized Bed: A bed of granular material expanded and agitated by an upflow of gas.

Fuel (nuclear, reactor): Fissionable material used as the source of power when placed in a critical arrangement in a nuclear reactor.

Fuel Assembly: An assembly of fuel elements.

Fuel Cycle: The complete series of steps involved in supplying fuel for nuclear power reactors. It includes mining, refining, the original fabrication of fuel elements, their use in a reactor, chemical processing to recover the fissionable material remaining in the spent fuel, re-enrichment of the fuel material, refabrication into new fuel elements, and management of radioactive waste.

Fuel Element: A tube, rod, or other form into which fissionable material is fabricated for use in a reactor.

Fuel Separation (fuel reprocessing): Processing of irradiated (spent) nuclear reactor fuel to recover useful materials as separate products, usually separation into plutonium, uranium, and fission products.

Gamma Rays (γ): High-energy, short-wavelength electromagnetic radiation emitted by a nucleus. Gamma radiation usually accompanies alpha and beta emissions and always accompanies fission.

Glass-ceramic: A fine-grained, crystalline material created by the controlled heating of a glass.

Half-life ($T_{1/2}$): The time in which half the atoms of a particular radioactive substance disintegrate to another nuclear form. Measured half-lives vary from millionths of a second to billions of years.

Half-life, Biological: The time required for a living organism to eliminate, by natural processes, half the amount of substance that has entered it.

Health Physics: The science concerned with recognition, evaluation, and control of health hazards from ionizing and nuclear radiations.

HEPA: High efficiency particulate air filter. A type of filter designed to remove 99.9% of particles down to 0.3 μ m in diameter from a flowing air stream.

High-Level Liquid Waste (HLLW): The aqueous waste resulting from the operation of the first-cycle extraction system (Purex Process), 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.

Immobilization: Treatment and/or emplacement of the wastes so as to impede their movement.

Interim Storage: The storage of wastes in a protected area while awaiting transfer to a deep geologic repository for extended storage or for disposal.

Ion Exchange: A chemical process involving the reversible interchange of various ions between a solution and a solid material, usually a resin. It is used to separate and purify chemicals, such as fission products, rare earths, in solution.

Ionizing Radiation: Any radiation displacing electrons from atoms or molecules, thereby producing ions. Examples: alpha, beta, and gamma radiation.

Isolation: A term encompassing both final storage and/or disposal in geologic formations.

Isotope: One of two or more atoms with the same atomic number (the same chemical element) but with different atomic weights. An equivalent statement is that the nuclei of isotopes have the same number of protons but different numbers of neutrons. Isotopes usually have very nearly the same chemical properties, but somewhat different physical properties.

Licensed Material: Source material, special nuclear material, or by-product material received, possessed, used, or transferred under a general or special license issued by the U.S. Nuclear Regulatory Commission or an Agreement State.

Long-lived Isotope: A radioactive nuclide that decays at such a slow rate that a quantity of it will exist for an extended period.

Long-lived Nuclides: Radioactive isotopes with half-lives greater than about 30 years. Most long-lived nuclides of interest to waste management have half-lives on the order of thousands to millions of years (Pu-239 - 24,400 years; Tc-99 - 2.1×10^5 years; I-12 - 1.6×10^7 years).

Man-rem: A unit in health physics to compare the effects of different amounts of radiation on groups of people. It is obtained by multiplying the average dose equivalent to a given organ or tissue (measured in rems) by the number of persons in that population.

Metal-Matrix: A process to fix calcine in a monolithic form by filling the void spaces with molten metal (either aluminum or lead).

Monolith: A dense, solid material incorporating nuclear waste.

Natural (Normal) Uranium: Uranium as found in nature. It is a mixture of the fertile uranium-238 isotope (99.3%), the fissionable uranium-235 isotope (0.7%), and a minute percentage of uranium-234.

Nonretrievable Solid Transuranic Waste: Any solid transuranic waste that contains, or is judged to contain, less than a specified quantity or concentration of transuranic elements (currently 10 nCi/g) and that may be disposed of in a nonretrievable manner, but still under conditions that will permit control in a disposal area and minimization of any migration of the transuranic elements. Included in this category are wastes contaminated with high beta-gamma emitters.

Normal Retrievable Waste: Wastes containing more than 10 nCi/g of transuranic isotopes and less than the recovery limit for that type of material as determined by the site.

Nuclide: A species of atom having a specific mass, atomic number, and nuclear energy state. These factors determine the other properties of the element, including its radioactivity.

Off-gas: Gas released by any process in fuel reprocessing or nuclear waste management.

Organic-Phase: The liquid phase in solvent extraction which consists of the organic solvent and the organic diluent.

Overpack: Secondary (or additional) external containment for packaged nuclear waste.

Partition: The chemical separation of actinides from other fission products.

pH: A measure of the hydrogen ion concentration in aqueous solutions. Acidic solutions have a pH from zero to 7. Basic solutions have a pH from 7 to 14.

Pit: An excavation for the disposal of miscellaneous aqueous and organic wastes, some of which may be contaminated with tritium, fission products, or activation products.

Plutonium (Pu): A heavy, radioactive, man-made, metallic element with atomic number 94. Its most important isotope is fissionable plutonium-239, produced by neutron irradiation of uranium-238. It is used for reactor fuel and in weapons.

Primary Wastes: As-generated forms and quantities of wastes.

Production Reactor: A nuclear reactor designed primarily for large-scale production of plutonium, tritium, and other radionuclides by neutron irradiation.

Process-Generated Wastes: Those wastes that are generated by, or are the result of, process operations in the enclosure defining the process lines and related equipment. In general, the TRU contamination levels will be significant.

Purex: A solvent extraction process in which uranium and plutonium are selectively separated from each other and from fission products by extraction from nitric acid solutions with tributylphosphate in a hydrocarbon diluent.

Rad (acronym for radiation absorbed dose): The basic unit of absorbed dose of ionizing radiation.

Radiation: The emission and propagation of energy through matter or space by means of electromagnetic disturbances, which display both wave-like and particle-like behavior; in this context the "particles" are known as photons. Also, the energy so propagated. The term has been extended to include streams of fast-moving particles (alpha and beta particles, neutrons, cosmic radiation, etc.). Nuclear radiation is that emitted from atomic nuclei in various nuclear reactions, including alpha, beta, and gamma radiation and neutrons.

Radioactive Contamination: Deposition of radioactive material in any place where it may harm persons, spoil experiments, or make products or equipment unsuitable or unsafe for some specific use. The presence of unwanted radioactive matter. Also radioactive material found on the walls of vessels in used-fuel processing plants, or radioactive material that has leaked into a reactor coolant. Often referred to only as contamination.

Radioactive Waste: Materials of no value consisting of, including, or contaminated with radioactive material in excess of the levels or concentrations permitted for unconditional release of such materials.

Radioactivity (often shortened to "activity"): The spontaneous decay or disintegration of an unstable atomic nucleus, usually accompanied by the emission of ionizing radiation. The word radioactivity is often used to refer to radioactive materials or radioactive nuclides, but this usage is not, strictly speaking, correct. Radioactivity is a process, not a substance.

Radioisotope: A radioactive isotope. An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation. More than 1,300 natural and artificial radioisotopes have been identified.

Radionuclide: An unstable nuclide of an element that decays or disintegrates spontaneously, emitting radiation.

Radwaste: See Radioactive Waste above.

Raffinate: The waste stream containing fission products from an extraction column.

Reactor: A device by means of which a fission chain reaction can be initiated, maintained, and controlled.

Recovery: The reprocessing of TRU contaminated materials for the purpose of reclaiming and reusing the transuranic elements which they contain.

Rem: A unit of measure for the dose of ionizing radiation that gives the same biological effect as 1 roentgen of x rays; 1 rem equals approximately 1 rad for X, gamma, or beta radiation.

Repository: A federally owned and operated facility for storage or disposal of specific types of radioactive waste from DOE sites and/or NRC licensees.

Resins: A synthetic organic polymer that can act as an ion exchanger.

Retrievable Solid Transuranic Waste: Any solid transuranic waste that contains, or is judged to contain, more than a specified quantity or concentration of transuranic elements (currently 10 nCi/g) and must, as a result, be placed into interim storage for eventual disposition.

Retrievable Storage: "Solid waste generated at DOE sites and containing significant U-233 or transuranium nuclide contamination shall be stored at DOE sites, segregated from other radioactively contaminated solid waste and with combustible and noncombustible transuranium-contaminated waste packaged separately. The packaging and storage conditions shall be such that the packages can be readily retrieved in an intact, contamination-free condition for 20 years. The packages shall be suitably labeled so the waste they contain can be identified by cross reference to permanent records." (DOE Manual 0511--Radioactive Waste Management)

Roentgen (abbreviation r): A unit of exposure to ionizing radiation. It is that amount of gamma or X rays required to produce ions carrying one (1) electrostatic unit of electrical charge (either positive or negative) in one (1) cubic centimeter of dry air under standard conditions. Named after Wilhelm Roentgen, German scientist who discovered X rays in 1895.

Room-Generated Wastes: Those wastes that are generated by, or are the result of, support operations in the room or area containing the transuranic processing facilities. These materials are usually of considerably lower contamination level than wastes generated in process lines.

Salt Cake: The remaining product of high-level liquid waste when evaporated to dryness without agitation.

Scrap: The feed materials for a TRU recovery process, that is, the transuranic-contaminated materials which are discarded from a process but which contain sufficient transuranic elements to warrant recovery.

Secondary Wastes: Forms and quantities of all wastes that result from applying waste treatment technologies to primary wastes.

Separations: Chemical processes used to separate nuclear products from by-products and from each other.

Short-lived Isotope: A radioactive nuclide that decays so rapidly that a given quantity is transformed into its daughter products within a short period (usually those with a half-life of days or less).

Short-lived Nuclides: Radioactive isotopes with half-lives no greater than about 30 years, e.g., Cs-137 and Sr-90.

Solidification: Conversion of radioactive waste to a dry, stable solid.

Solid Radioactive Waste: Radioactive waste material that is essentially dry but may contain sorbed radioactive fluid in sufficiently small amounts to be immobile when buried in dry soil.

Solvent Extraction: A process in which materials are selectively removed from an aqueous solution by contact with an immiscible organic solvent.

Special Nuclear Material (SNM): Plutonium, uranium-233, uranium-235, or uranium enriched to a higher percentage than normal of the -233 or -235 isotopes.

Storage: Retention of radioactive waste in some type of man-made engineered device (e. g., tank) in a manner permitting retrieval.

Storage Area: The area in which the storage facility is located (i.e., the site of the storage facility).

Storage Facility: The actual place of storage of wastes. This may be an engineered structure such as a building or vault or a protected area in any other type of facility.

Tanks: A large metal container located above ground or underground for storage of liquid wastes.

Tank Farm: An installation of interconnected underground containers (tanks) for storage of high-level waste.

Transmutation: Conversion of a radioactive nucleus to another isotope by bombarding it with radiation or nuclear particles.

Transportation: Movement of materials between sites. Intrasite movement is not considered. Includes alternative methods for packaging, handling, and transport of waste materials. Concepts include all conventional methods of land and water transport required by the waste management system.

Transuranic Waste: Any waste material measured or assumed to contain more than a specified concentration (e.g., presently 10 nanocuries of trans-uranium activity per gram of waste) of transuranic elements.

Transuranium: Nuclides having an atomic number greater than that of uranium (i.e., greater than 92). The principal transuranic radionuclides of concern in radioactive waste management are tabulated below with their half-lives:

<u>Nuclide</u>	<u>Half-Life (Years)</u>	<u>Principal Decay Modes</u>
neptunium-237	2,140,000	alpha
plutonium-238	86	alpha, spontaneous fission
plutonium-239	24,390	alpha, spontaneous fission
plutonium-240	6,580	alpha, spontaneous fission
plutonium-242	379,000	alpha
americium-241	458	alpha
americium-243	7,950	alpha
curium-245	9,300	alpha
curium-246	5,500	alpha, spontaneous fission

The transuranium nuclide produced in largest amounts is plutonium-239; americium-241 is also produced in significant amounts. One system of classification used at Oak Ridge includes U-235 (162,000 year half-life, alpha decay) among the transuranium isotopes, although strictly speaking this is not accurate. For further discussion see Appendix B.

Treatment: Operations intended to benefit safety or economy by changing the waste characteristics. Four basic treatment concepts are defined:

- Volume reduction
- Immobilization of radioactivity
- Change of composition
- Removal of radioactivity from the waste

Trench: A long and narrow excavation in the ground for solid waste. Unless qualifying descriptions are given, a trench is unlined, and its walls are unsupported. After the solid wastes are placed in position, the trench is filled to grade level with some of the removed soil.

Uranium: A radioactive element with the atomic number 92 and, as found in natural ores, an average atomic weight of approximately 238. The two principal natural isotopes are U-235 (0.7 percent of natural uranium), which is fissionable, and U-238 (99.3 percent of natural uranium), which is fertile. Natural uranium also includes a minute amount of U-234.

Vitrification: The process of forming an amorphous as opposed to crystalline structure--a glassing process.

Waste Container: The device or devices, including liners and closures, used in the packaging of wastes.

Waste Package: The final configuration of the waste in its container as it is ready to be placed into interim storage or final geologic disposal.

ABBREVIATIONS

AEC	United States Atomic Energy Commission
ALARA	As low as reasonably achievable
DOE	United States Department of Energy
DF	Decontamination factor
ERDA	United States Energy Research and Development Administration
HLLW	High level liquid waste
ICPP	Idaho Chemical Processing Plant
ICRP	International Commission of Radiological Protection
ILLW	Intermediate level liquid waste
INEL	Idaho National Engineering Laboratory
MU	Metric ton uranium
NRC	United States Nuclear Regulatory Commission
TBP	Tributyl phosphate
WCF	Waste Calcining Facility

APPENDIX B

TRANSURANIUM RADIONUCLIDES²

AN OVERVIEW OF CHEMICAL, PHYSICAL AND RADIOLOGICAL PROPERTIES

TERA CORPORATION

INTRODUCTION

The transuranium radionuclides are those nuclides with atomic numbers 93 to 103, inclusive. Table B-1 gives the atomic numbers, names and chemical symbols of this group of elements. Table B-2 presents various physical characteristics of alpha-emitting TRU isotopes with half-lives greater than 100 days.

No known nuclides of the transuranium elements are stable. In general, the higher the atomic number of the element, the shorter the half-life.

Plutonium is the best known of the transuranium radionuclides and it is common to compare the properties of this group of radionuclides to plutonium. This group of radionuclides is highly radioactive and has a high specific activity, i.e. there are many curies, Ci, of radioactivity for each gram of nuclide.

The relatively high energy release per each nuclear decay and the general tendency of these nuclides to concentrate in bone tissue leads to a highly toxic effect when these nuclides are present within the human body. On a Ci or radioactivity basis, the transuranium radionuclides are not greatly different from plutonium in their toxicity. On a mass or gram basis, however, some of these radionuclides are a factor of 10^4 times more toxic than plutonium. Their extremely high toxicity per unit mass requires that extraordinary precautions and care need to be taken when working with these materials. These radionuclides require a skill and a specially designed complement of equipment for handling that far exceeds that required for the more common fission product radionuclides. It is necessary to plan diligently with expert knowledge to design and operate safe transuranium processing and handling facilities.

Experience in working with fission products or uranium is helpful in planning transuranium radionuclide work and activities, but such experience cannot be translated to working with these high specific activity materials. The contamination control requirements are 10^3 to 10^6 times more rigid for the transuranium radionuclides than for the typical fission product radionuclides.

TABLE B-1
TRANSURANIUM ELEMENTS

<u>Atomic Number</u>	<u>Element Name</u>	<u>Chemical Symbol</u>
93	Neptunium	Np
94	Plutonium	Pu
95	Americium	Am
96	Curium	Cm
97	Berkelium	Bk
98	Californium	Cf
99	Einsteinium	Es
100	Fermium	Fm
101	Mendelevium	Md
102	Nobelium	No
103	Lawrencium	Lw

TABLE B-2
ALPHA-EMITTING TRU ISOTOPES
WITH HALF-LIFE GREATER THAN 100 DAYS²⁸

Isotope	T _{1/2} (yr)	T(SF) _{1/2} (yr)	Thermal Neutron Cross Sections (barn)	Specific Activity (g/Ci)	(SF) Activity (fission/ sec-g)	ν (SF)	Parent	Daughter
²³³ ₉₂ U	1.62 × 10 ⁵		σ _c = 49 σ _f = 524	1.05 × 10 ²	~ 0		²³³ Pa ²³³ Np	²²⁹ Th
²³⁷ ₉₃ Np	2.14 × 10 ⁶	>10 ¹⁸	σ _c = 170 σ _f = 0.019	1.42 × 10 ³	<5.6 × 10 ⁻⁵		²³⁷ U ²⁴¹ Am ²³⁷ Pu	²³³ Pa
²³⁶ ₉₄ Pu	2.85 × 10 ⁰	3.5 × 10 ⁹	σ _f = 170	1.88 × 10 ⁻³	1.6 × 10 ⁴		²⁴⁰ Cm ²³⁶ Np	²³² U
²³⁸ ₉₄ Pu	8.64 × 10 ²	4.9 × 10 ¹⁰	σ _c = 500 σ _f = 16.8	5.75 × 10 ⁻²	1.13 × 10 ³	2.26	²³⁸ Np ²³⁸ Am ²⁴² Cm	²³⁴ U
²³⁹ ₉₄ Pu	2.44 × 10 ⁴	5.5 × 10 ¹⁵	σ _c = 274 σ _f = 741	1.63 × 10 ¹	1.00 × 10 ⁻²	2.2	²³⁹ Np ²⁴³ Cm ²³⁹ Am	²³⁵ U
²⁴⁰ ₉₆ Pu	6.58 × 10 ³	1.34 × 10 ¹¹	σ _c = 286 σ _f = <0.08	4.4 × 10 ⁰	4.1 × 10 ⁻²	2.17	²⁴⁴ Cm ²⁴⁰ Np ²⁴⁰ Am	²³⁶ U
²⁴² ₉₆ Pu	3.79 × 10 ⁵	7.1 × 10 ¹⁰	σ _c = 19 σ _f = <0.2	2.57 × 10 ²	7.7 × 10 ²	2.16	²⁴⁶ Cm ²⁴² Am	²³⁸ U
²⁴⁴ ₉₆ Pu	~7.6 × 10 ⁷	2.5 × 10 ¹⁰	σ _c = 1.8	~5.2 × 10 ⁴	2.7 × 10 ³		²⁴⁸ Cm	²⁴⁰ U F.P.
²⁴¹ ₉₅ Am	4.58 × 10 ²	2 × 10 ¹⁴	σ _c = 700 σ _c = 100 σ _f = 3.0	²⁴² Am 3.08 × 10 ⁻³ ^{242m} Am	2.7 × 10 ⁻¹	2.3	²⁴¹ Pu ²⁴³ Bk ²⁴¹ Cm	²³⁷ Np
^{242m} ₉₅ Am	1.52 × 10 ²		σ _c = 2000 σ _f = 6000	1.03 × 10 ⁻¹			-	²⁴² Am ²³⁸ Np
²⁴³ ₉₅ Am	7.95 × 10 ³		σ _c = 74 σ _f = <0.07	5.40 × 10 ⁰			²⁴³ Pu ²⁴⁷ Bk	²³⁹ Np
²⁴² ₉₆ Cm	4.43 × 10 ⁻¹	7.2 × 10 ⁶	σ _c = 20 σ _f = < 5	3.01 × 10 ⁻⁴	7.58 × 10 ⁶		²⁴² Am ²⁴⁶ Cf	²³⁸ Pu F.P.
²⁴³ ₉₆ Cm	3.2 × 10 ¹		σ _c = 250 σ _f = 662	2.2 × 10 ⁻²			²⁴³ Bk	²³⁹ Pu

TABLE B-2

(CONT.)

Isotope	$T_{1/2}$ (yr)	$T(SF)_{1/2}$ (yr)	Thermal Neutron Cross Sections (barn)	Specific Activity (μ /Ci)	(SF) Activity (fission/ sec-g)	ν (SF)	Parent	Daughter
$^{244}_{96}\text{Cm}$	1.76×10^{-1}	1.31×10^7	$\sigma_c = 15$	1.2×10^{-2}	4.14×10^6		$^{248}_{98}\text{Cf}$ $^{244}_{98}\text{Am}$ $^{244}_{96}\text{Bk}$	$^{240}_{94}\text{Pu}$ F.P.
$^{245}_{96}\text{Cm}$	9.3×10^3		$\sigma_c = 200$ $\sigma_f = 1900$	6.4×10^0			$^{249}_{98}\text{Cf}$ $^{245}_{98}\text{Am}$ $^{245}_{96}\text{Bk}$	$^{241}_{94}\text{Pu}$
$^{246}_{96}\text{Cm}$	5.5×10^3	1.7×10^7	$\sigma_c = 15$	3.8×10^0	3.2×10^6		$^{250}_{98}\text{Cf}$ $^{246}_{98}\text{Am}$ $^{246}_{96}\text{Bk}$	$^{242}_{94}\text{Pu}$ F.P.
$^{96}\text{Cm}^{247}$	1.6×10^7		$\sigma_c = 180$	1.1×10^4			$^{247}_{98}\text{Cf}$	$^{243}_{94}\text{Pu}$
$^{96}\text{Cm}^{248}$	4.7×10^5	4.6×10^6	$\sigma_c = 6$	3.27×10^2	1.16×10^7		$^{252}_{98}\text{Cf}$ $^{248}_{96}\text{Bk}$	$^{244}_{94}\text{Pu}$ F.P.
$^{96}\text{Cm}^{250}$		1.7×10^4			3.1×10^9		$^{245}_{98}\text{Cf}$	F.P.
$^{247}_{97}\text{Bk}$	1.4×10^3			9.66×10^{-1}			$^{247}_{98}\text{Cf}$	$^{243}_{94}\text{Am}$
$^{248}_{98}\text{Cf}$	9.59×10^{-1}	$\geq 1.5 \times 10^4$		6.64×10^{-4}	$\geq 3.6 \times 10^9$		$^{252}_{98}\text{Fm}$ $^{248}_{96}\text{Bk}$	$^{244}_{94}\text{Cm}$ F.P.
$^{249}_{98}\text{Cf}$	3.60×10^2	1.5×10^9	$\sigma_c = 270$ $\sigma_f = 1735$	2.51×10^{-1}	2.5×10^4		$^{249}_{96}\text{Bk}$ $^{249}_{95}\text{Es}$	$^{245}_{94}\text{Cm}$ F.P.
$^{250}_{98}\text{Cf}$	1.32×10^1	1.7×10^4	$\sigma_c = 1500$ $\sigma_f = < 350$	9.24×10^{-3}	3.1×10^9		$^{254}_{98}\text{Fm}$ $^{250}_{96}\text{Bk}$ $^{250}_{95}\text{Es}$	$^{246}_{94}\text{Cm}$ F.P.
$^{251}_{98}\text{Cf}$	$\sim 8 \times 10^2$		$\sigma_c = 3000$ $\sigma_f = 3000$	$\sim 6 \times 10^{-1}$			$^{255}_{98}\text{Fm}$ $^{251}_{95}\text{Es}$	$^{247}_{94}\text{Cm}$
$^{252}_{98}\text{Cf}$	2.65×10^0	8.5×10^1	$\sigma_c = 30$	1.86×10^{-3}	6.2×10^{11}	3.8	$^{256}_{98}\text{Fm}$	$^{248}_{94}\text{Cm}$ F.P.
$^{252}_{99}\text{Es}$	$\sim 1.84 \times 10^{-1}$			$\sim 2.7 \times 10^{-4}$			$^{256}_{100}\text{Fm}$	$^{248}_{96}\text{Bk}$
$^{254}_{99}\text{Es}$	7.56×10^{-1}	7×10^5	$\sigma_c < 40$	5.4×10^{-4}	7.4×10^7		$^{258}_{100}\text{Fm}$	$^{250}_{96}\text{Bk}$ F.P.

^a Has no parent isotope but is produced by a (n, γ) reaction.

The transuranium elements are normally produced by neutron irradiation of uranium or higher atomic number elements in a nuclear reactor. The transuranium radionuclides are also produced in thermonuclear explosions and by accelerators. Reactor irradiation is usually the preferred method of production when more than trace quantities of a nuclide are desired.

The major differences between the transuranium radionuclides and uranium are the greater specific activity, shorter spontaneous fission half-lives, and the larger number of X-ray and gamma-ray photons emitted per disintegration of the transuranium radionuclides. In handling or processing these nuclides one is confronted not only with dose rates that may require extensive shielding, but also with the problem of ensuring that radionuclides do not escape into the work environment and enter the body by inhalation, ingestion or other methods. Table B-3 presents maximum permissible concentration (MPC) values for the major TRU isotopes.

The high specific activities require an exceptional degree of diligence in all manipulations to assure control and absolute containment. The loss of control over even the slightest amount, by any normal standards of measurement, of a transuranium radionuclide can lead to serious hazards and timely and costly decontamination requirements. The potential for difficulties in handling and working with transuranium radionuclides depends upon the type of operation to be performed as well as the physical properties of the particular nuclide being used.

PHYSICAL PROPERTIES

Modes of Decay

Most transuranium radionuclides emit alpha particles. Many also emit neutrons and some emit beta particles. Most particle emissions are accompanied by X-ray or gamma-ray emissions of relatively low energy, usually a few tens of kilovolts.

TABLE B-3

CONCENTRATIONS IN AIR AND WATER ABOVE NATURAL BACKGROUND

TRU ELEMENT	ISOTOPE ¹		RESTRICTED AREAS ²		UNRESTRICTED AREAS ³	
			AIR (μ Ci/ml)	WATER (μ Ci/ml)	AIR (μ Ci/ml)	WATER (μ Ci/ml)
Americium	Am 241	S	6×10^{-12}	1×10^{-4}	2×10^{-13}	4×10^{-6}
		I	1×10^{-10}	8×10^{-4}	4×10^{-12}	3×10^{-5}
	Am 242m	S	6×10^{-12}	1×10^{-4}	2×10^{-13}	4×10^{-6}
		I	3×10^{-10}	3×10^{-3}	9×10^{-12}	9×10^{-5}
	Am 242	S	4×10^{-8}	4×10^{-3}	1×10^{-9}	1×10^{-4}
		I	5×10^{-8}	4×10^{-3}	1×10^{-9}	1×10^{-4}
	Am 243	S	6×10^{-12}	1×10^{-4}	2×10^{-13}	4×10^{-6}
		I	1×10^{-10}	8×10^{-4}	4×10^{-12}	3×10^{-5}
	Am 244	S	4×10^{-6}	1×10^{-1}	1×10^{-7}	5×10^{-3}
		I	2×10^{-5}	1×10^{-1}	8×10^{-7}	5×10^{-3}
Berkelium	Bk 249	S	9×10^{-10}	2×10^{-2}	3×10^{-11}	6×10^{-4}
		I	1×10^{-7}	2×10^{-2}	4×10^{-9}	6×10^{-4}
	Bk 250	S	1×10^{-7}	6×10^{-3}	5×10^{-9}	2×10^{-4}
		I	1×10^{-6}	6×10^{-3}	4×10^{-8}	2×10^{-4}
californium	Cf 249	S	2×10^{-12}	1×10^{-4}	5×10^{-14}	4×10^{-6}
		I	1×10^{-10}	7×10^{-4}	3×10^{-12}	2×10^{-5}
	Cf 250	S	5×10^{-12}	4×10^{-4}	2×10^{-13}	1×10^{-5}
		I	1×10^{-10}	7×10^{-4}	3×10^{-12}	3×10^{-5}
	Cf 251	S	2×10^{-12}	1×10^{-4}	6×10^{-14}	4×10^{-6}
		I	1×10^{-10}	8×10^{-4}	3×10^{-12}	3×10^{-5}

TABLE B-3

(CONT.)

			RESTRICTED AREAS ²		UNRESTRICTED AREAS ³	
TRU ELEMENT	ISOTOPE ¹		AIR ($\mu\text{Ci/ml}$)	WATER ($\mu\text{Ci/ml}$)	AIR ($\mu\text{Ci/ml}$)	WATER ($\mu\text{Ci/ml}$)
Curium	Cf 252	S	6×10^{-12}	2×10^{-4}	2×10^{-13}	7×10^{-6}
		I	3×10^{-11}	2×10^{-4}	1×10^{-12}	7×10^{-6}
	Cf 253	S	8×10^{-10}	4×10^{-3}	3×10^{-11}	1×10^{-4}
		I	8×10^{-10}	4×10^{-3}	3×10^{-11}	1×10^{-4}
	Cf 254	S	5×10^{-12}	4×10^{-6}	2×10^{-13}	1×10^{-7}
		I	5×10^{-12}	4×10^{-6}	2×10^{-13}	1×10^{-7}
	Cm 242	S	1×10^{-10}	7×10^{-4}	4×10^{-12}	2×10^{-5}
		I	2×10^{-10}	7×10^{-4}	6×10^{-12}	2×10^{-5}
	Cm 243	S	6×10^{-12}	1×10^{-4}	2×10^{-13}	5×10^{-6}
		I	1×10^{-10}	7×10^{-4}	3×10^{-12}	2×10^{-5}
	Cm 244	S	9×10^{-12}	2×10^{-4}	3×10^{-13}	7×10^{-6}
		I	1×10^{-10}	8×10^{-4}	3×10^{-12}	3×10^{-5}
	Cm 245	S	5×10^{-12}	1×10^{-4}	2×10^{-13}	4×10^{-6}
		I	1×10^{-10}	8×10^{-4}	4×10^{-12}	3×10^{-5}
	Cm 246	S	5×10^{-12}	1×10^{-4}	2×10^{-13}	4×10^{-6}
		I	1×10^{-10}	8×10^{-4}	4×10^{-12}	3×10^{-5}
	Cm 247	S	5×10^{-12}	1×10^{-4}	2×10^{-13}	4×10^{-6}
		I	1×10^{-10}	6×10^{-4}	4×10^{-12}	2×10^{-5}
	Cm 248	S	6×10^{-13}	1×10^{-5}	2×10^{-14}	4×10^{-7}
		I	1×10^{-11}	4×10^{-5}	4×10^{-13}	1×10^{-6}
	Cm 249	S	1×10^{-5}	6×10^{-2}	4×10^{-7}	2×10^{-3}
		I	1×10^{-5}	6×10^{-2}	4×10^{-7}	2×10^{-3}

TABLE B-3

(CONT.)

TRU ELEMENT	ISOTOPE ¹		RESTRICTED AREAS ²		UNRESTRICTED AREAS ³	
			AIR (μ Ci/ml)	WATER (μ Ci/ml)	AIR (μ Ci/ml)	WATER (μ Ci/ml)
Einsteinium	Es 253	S	8×10^{-10}	7×10^{-4}	3×10^{-11}	2×10^{-5}
		I	6×10^{-10}	7×10^{-4}	2×10^{-11}	2×10^{-5}
	Es 254m	S	5×10^{-9}	5×10^{-4}	2×10^{-10}	2×10^{-5}
		I	6×10^{-9}	5×10^{-4}	2×10^{-10}	2×10^{-5}
	Es 254	S	2×10^{-11}	4×10^{-4}	6×10^{-13}	1×10^{-5}
		I	1×10^{-10}	4×10^{-4}	4×10^{-12}	1×10^{-5}
	Es 255	S	5×10^{-10}	8×10^{-4}	2×10^{-11}	3×10^{-5}
		I	4×10^{-10}	8×10^{-4}	1×10^{-11}	3×10^{-5}
Fermium	Fm 254	S	6×10^{-8}	4×10^{-3}	2×10^{-9}	1×10^{-4}
		I	7×10^{-8}	4×10^{-3}	2×10^{-9}	1×10^{-4}
	Fm 255	S	2×10^{-8}	1×10^{-3}	6×10^{-10}	3×10^{-5}
		I	1×10^{-8}	1×10^{-3}	4×10^{-10}	3×10^{-5}
	Fm 256	S	3×10^{-9}	3×10^{-5}	1×10^{-10}	9×10^{-7}
		I	2×10^{-9}	3×10^{-5}	6×10^{-11}	9×10^{-7}
Neptunium	Np 237	S	4×10^{-12}	9×10^{-5}	1×10^{-13}	3×10^{-6}
		I	1×10^{-10}	9×10^{-4}	4×10^{-12}	3×10^{-5}
	Np 239	S	8×10^{-7}	4×10^{-3}	3×10^{-8}	1×10^{-4}
		I	7×10^{-7}	4×10^{-3}	2×10^{-8}	1×10^{-4}

TABLE B-3

(CONT.)

			RESTRICTED AREAS ²		UNRESTRICTED AREAS ³	
TRU ELEMENT	ISOTOPE ¹		AIR ($\mu\text{Ci/ml}$)	WATER ($\mu\text{Ci/ml}$)	AIR ($\mu\text{Ci/ml}$)	WATER ($\mu\text{Ci/ml}$)
Plutonium	Pu 238	S	2×10^{-12}	1×10^{-4}	7×10^{-14}	5×10^{-6}
		I	3×10^{-11}	8×10^{-4}	1×10^{-12}	3×10^{-5}
	Pu 239	S	2×10^{-12}	1×10^{-4}	6×10^{-14}	5×10^{-6}
		I	4×10^{-11}	8×10^{-4}	1×10^{-12}	3×10^{-5}
	Pu 240	S	2×10^{-12}	1×10^{-4}	6×10^{-14}	5×10^{-6}
		I	4×10^{-11}	8×10^{-4}	1×10^{-12}	3×10^{-5}
	Pu 241	S	9×10^{-11}	7×10^{-3}	3×10^{-12}	2×10^{-4}
		I	4×10^{-8}	4×10^{-2}	1×10^{-9}	1×10^{-3}
	Pu 242	S	2×10^{-12}	1×10^{-4}	6×10^{-14}	5×10^{-6}
		I	4×10^{-11}	9×10^{-4}	1×10^{-12}	3×10^{-5}
	Pu 243	S	2×10^{-6}	1×10^{-2}	6×10^{-8}	3×10^{-4}
		I	2×10^{-6}	1×10^{-2}	8×10^{-8}	3×10^{-4}
	Pu 244	S	2×10^{-12}	1×10^{-4}	6×10^{-14}	4×10^{-6}
		I	3×10^{-11}	3×10^{-4}	1×10^{-12}	1×10^{-5}

¹ S = Soluble; I = Insoluble

² Restricted area is discussed in 10CFR Part 20.103

³ Unrestricted area is discussed in 10CFR Part 20.105

Of the 46 known isotopes of elements 93 (Np) through 99 (Es) with half-lives greater than one day, 30 are alpha emitters, nine decay by beta emission, five capture orbital electrons, and two undergo spontaneous fission as the primary modes of decay. Several of these radionuclides, however, are parents of decay chains whose various decay products have half-lives which cause a complicated pattern of growth and decay of daughter products after the initial preparation of an isolated and essentially pure radionuclide. The precursors from irradiation may also exist in a given sample, as a result of incomplete separation, and add to the complex decay chain.

If the half-life of the "parent" transuranic radionuclide is much longer than that of the "daughter" (e.g. Am-243-Np-239, Cm-245-Pu-241, or Es-254-Bk-250), the activity of the material handled will approach the state of secular equilibrium in which the number of daughter atoms formed per unit time is equal to the number which decay. The rate of approach to this steady state is governed by the half-life of the daughter as $(1 - e^{-\lambda t})$. No equilibrium exists if the daughter is longer lived than the parent (e.g. Am-241-Np-237, Cm-244-Pu-240 or Cf-252-Cm-248). These two conditions—secular and no equilibrium—prevail; transient equilibrium, which requires the parent and daughter to have approximately equal half-lives, seldom occurs in the transuranium decay schemes.

Specific Activity

The relatively short half-lives of many of these radionuclides leads to a high specific activity, i.e. a large number of curies per gram of nuclide. The half-life, specific activity and an activity comparison normalized to Pu-239 are shown in Table B-4.

When one recalls that Pu-239 has a specific activity some 10^5 times that of natural uranium, the rapid decay rates for the transuranium radionuclides are clear. The radius of spherical particles of the more common transuranium radionuclides that would decay at the rate of 1000 d/m—a contamination level at which it is necessary to consider the need for decontamination, ranges from about 10^{-4} to about 10^{-5} cm. It is necessary to consider the degree of control

TABLE B-4
RADIOACTIVE DECAY
AND SPONTANEOUS FISSION HALF-LIVES
OF SELECTED NUCLIDES

Isotope	Radioactive half-life (yr)	Specific activity (Ci/g)	Normalized to Pu-239	Spontaneous fission half-life (yr)	Calculated neutron emission rate (n/sec/g)
Pu-239	24,400	0.062	1	5.5×10^{15}	0.03
Am-243	7,950	0.185	3	--	--
Am-241	458	3.24	52	2×10^{14}	0.06
Pu-238	86.4	17.6	280	4.9×10^{10}	3.4×10^3
Cm-244	17.6	83.3	1,300	1.3×10^7	1.2×10^7
Pu-241*	13.2	113	1,800	--	--
Cf-252	2.646	536	8,600	85	2.3×10^{12}
Bk-249*	0.86	1,680	27,000	6×10^8	2.7×10^5
Es-254	0.756	1,870	30,000	7×10^5	2.9×10^8

*Beta emitters; all others decay by alpha emission.

required to avoid the loss of control of even one particle of these small sizes and the containment problems for handling these radionuclides.

The high specific activities also lead to higher dose rates for small quantities of materials if one is measuring quantity in units of weight. For all of these nuclides it is necessary to be alert to the potential for X-ray and gamma-ray radiations as well as neutron and beta radiations, even though the primary mode of decay may be by alpha particle emission.

Spontaneous Fission

Spontaneous fission of transuranium radionuclides results in the emission of many neutrons in addition to the build-up of fission products that emit both beta and gamma rays. Some of the transuranium radionuclides have relatively short spontaneous fission half-lives corresponding to high spontaneous fission decay rates. In fact, the very high spontaneous fission rate of Cf-252 has provided a most useful application of this radionuclide as a neutron source. It has unique potentials because it provides a small source of an intense neutron flux. Table B-2 summarizes the spontaneous fission half-lives and neutron emission rates for some of these radionuclides.

CHEMICAL PROPERTIES

The chemical reactions of the transuranium radionuclides are similar to and may be expected to generally parallel the reactions of plutonium; there are, of course, many specific exceptions to their plutonium-like chemical behavior. The chemical reactions of plutonium have been extensively studied and several good reviews and handbooks summarizing these properties are readily available. For example, the two volume Plutonium Handbook edited by Wick details the chemical as well as physical properties of plutonium.

The transuranium radionuclides are metals, although with the exception of plutonium, americium and neptunium, they are seldom available in quantities sufficient for visual recognition as metals. These radionuclides, as finely divided

metals, are pyrophoric—reacting rapidly with oxygen to form oxides. They are best stored and handled in inert atmospheres until reacted to form some stable compound. In many of their chemical compounds they may be in a powder form and easily dispersed. The minute particles that may break or be rubbed off of even large crystal forms lead to challenging handling and containment programs if rigid control over these materials is to be established and maintained.

The high specific activity of the transuranium radionuclides leads to handling difficulties other than contamination control. Self-heating, radiolytic decomposition actions in aqueous solution, and spontaneous ignition when exposed to air (oxygen) constitute the bulk of these problems. A kilogram of plutonium metal is warm to the touch, emitting ~2 watts of thermal energy, while Cm-244 and Cm-242, potential thermoelectric power sources, emit approximately 3 and 120 watts/g of thermal energy, respectively. In most applications only Pu-238, Cm-242, Cm-244 and Cf-252 produce sufficient heat to be of concern. Table B-5 summarizes the decay heat production of some transuranium radionuclides.

The chemical form of a transuranium radionuclide can change the magnitude and nature of the radiation hazards encountered. The high energy alpha emissions can result in an alpha particle nuclear reaction which can result in significant neutron emissions (e.g. beryllium, oxygen, chlorine, fluorine and nitrogen chemical reactions involving transuranium radionuclides may transform a safely shielded facility designed for alpha and low-energy photon radiations into a poorly shielded facility where neutron radiation becomes of primary concern).

CRITICALITY CONSIDERATIONS

The potential for a self-sustaining nuclear chain reaction of criticality accident is currently not as significant for the transplutonium elements as for Pu-239 or U-235 because of the limited (generally less than 100 g) amounts of these materials available at any given facility. If quantities of any transuranium radionuclide greater than 300 grams are available, a careful and detailed review of criticality control provision is mandatory. Only a few transplutonic nuclides appear to be capable of supporting a chain reaction with thermal neutrons; the

TABLE B-5
DECAY HEAT PRODUCTION

<u>Nuclide</u>	<u>Decay Heat, Watts/g</u>
Pu-238	0.57
Pu-239	0.0019
Pu-240	0.014
Pu-241	0.00011
Am-241	0.11
Am-243	0.0061
Cm-242	120
Cm-244	2.8
Bk-249	0.4
Cf-252	39

remainder are fissionable by fast neutrons only (as metals or alloys). The fissile nuclides in solution present the most serious criticality control problems since the amount of material in solution is difficult to inventory and the critical mass is usually lower for solutions than for metals.

Table B-6 compares the neutron cross-sections and the number of neutrons emitted per fission event of several transplutonic nuclides with those of the more familiar fissile materials, U-233, U-235, and Pu-239.

TABLE B-6
NEUTRON CRITICALITY PARAMETERS

<u>Nuclide</u>	<u>σ_c (barn)</u>	<u>σ_c (barn)</u>	<u>neutrons/ fission</u>	<u>Minimum critical mass* (g)</u>
U-233	49	524	2.50	590
U-235	99	579	2.43	820
Pu-239	254	754	2.89	510
Am-242m	5500	6390	~3.0	1000
Cm-243	250	590	~3.2	500-1000
Cm-245	335	1900	~3.2	500
Cm-247	180	1026	~3.3	500
Cf-249	270	630	~3.7	500-1000
Cf-251	1100	3000	~3.7	500-1000
Es-254	40	2000	~3.9	500

* Minimum critical mass for fully reflected solutions.

APPENDIX C

**ENVIRONMENTAL PROTECTION AGENCY
CRITERIA FOR RADIOACTIVE WASTES¹⁵**

TERA CORPORATION

[6540-01-M]

ENVIRONMENTAL PROTECTION AGENCY

(FRL 963-2)

CRITERIA FOR RADIOACTIVE WASTES

Invitation for Comment: Environmental Protection.

AGENCY: U.S. Environmental Protection Agency.

ACTION: Recommendations for Federal radiation guidance.

SUMMARY: The Environmental Protection Agency seeks public comment on environmental protection criteria for storage and disposal of all forms of radioactive wastes. All substantive comments will be considered in formulating final criteria which will be recommended to the President for approval as guidance to Federal agencies. The recommended criteria establish the basic principles which should be applied in the formulation of policies, plans, programs, and decisions involving management and disposal of radioactive waste. The recommended criteria also establish ground rules to be followed in the development of generally applicable standards for radioactive waste sources. These criteria: (a) Define radioactive wastes, indicate which types of wastes should be controlled, and give examples of where these wastes originate; (b) state the goal of radioactive waste control and define limitations on institutional and other controls over certain time periods; (c) discuss the factors to be considered in assessing risk to the general public and the general environment; (d) discuss the factors which would result in unacceptable risk for different methods of disposal; (e) require that the selection, design, and operation of a disposal site must enhance isolation of radioactive wastes; and (f) discuss the appropriateness of retrievability of waste and communication of waste disposal locations to future generations.

DATE: Comments should be received by January 15, 1979.

ADDRESS: Written comments to: Manager, Waste Environmental Standards Program (ANR-460), Office of Radiation Programs, U.S. Environmental Protection Agency, 401 M Street SW, Washington, D.C. 20460.

FOR FURTHER INFORMATION CONTACT:

Dr. Harry J. Pettengill, 703-557-8927.

SUPPLEMENTAL INFORMATION: EPA is required to recommend radiation protection guidance for Federal agencies (42 U.S.C. 2021(h)). Accord-

ingly, the Agency is developing environmental protection criteria which would be used by all Federal agencies that have responsibilities for managing or regulating radioactive wastes. This guidance, if approved by the President, will supersede any existing guidance concerning the disposal of radioactive wastes. Federal agencies would be required to comply with this guidance in carrying out their responsibilities.

Other agencies, besides EPA, which are actively involved in radioactive waste management, are the Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC). The DOE is conducting research for different control technologies to store and dispose of high-level and transuranic wastes and will operate such disposal facilities. The NRC is preparing specific regulations for licensing of storage and waste disposal facilities. EPA is developing environmental protection standards for the various types of radioactive wastes. The proposed criteria will be used by all agencies in their respective programs. The schedules of the interrelated activities of EPA and other Federal agencies are being addressed by the Interagency Nuclear Waste Management Task Force established by the President on March 15, 1978, to recommend a comprehensive Federal program for the long-term management of nuclear waste.

The Agency has received considerable assistance from the public in developing these proposed criteria through participation in two public workshops and in a public forum. The proposed criteria have also been reviewed by a working group on radioactive waste, composed of Federal agencies that would carry out the guidance once approved by the President. The basis for the proposed criteria were developed in a background report which was made available to all workshop and forum participants and others on January 18, 1978 (43 FR 2223). Copies of the report are still being provided upon request. The background report will be revised to reflect the comments received from the public forum participants and on the criteria proposed herein.

DEFINITIONS

The following terms are defined for use in this notice:

Acute (radiation exposure).—A term used in reference to a single large dose of ionizing radiation or to a series of substantial doses in a short interval of time, as differentiated from chronic exposure.

Barrier.—Any medium which stops or significantly retards the movement of, emplaced radioactive materials, such as a natural geologic medium or a

container or solidified waste matrix engineered by humans;

Chronic (radiation exposure).—Continuous or intermittent exposure to small amounts of ionizing radiation over a long period of time, as differentiated from acute exposure;

Diffuse (waste containing naturally-occurring radioactivity).—Waste material containing naturally-occurring radioactivity in concentrations similar to that of many natural ore bodies;

Discrete (waste containing naturally-occurring radioactivity).—Waste material containing naturally-occurring radioactivity which is substantially concentrated relative to that of the virgin natural material;

Disposal.—The placement of radioactive waste with no intent of recovery;

General environment.—The total terrestrial, atmospheric, and aquatic environments outside sites in which any radioactive waste management activities are conducted;

Institutional control.—Activities, devices, and combinations thereof which involve the performance of functions by human beings to limit contact between the waste and humans or the environment;

Isolation.—The placement of radioactive waste so that contact between the waste and humans or the environment will be highly unlikely for a chosen period of time;

Monitoring.—Measuring the quantity and type of discharges or migration of radioactive wastes from a waste management facility, or measuring changes in physical, chemical, or biological characteristics of the site and the surrounding site area;

Retrievability.—A designed capability to recover waste from an emplaced location, within a specified time;

Risk.—A general concept encompassing both the probability and the severity of adverse effects;

Site.—Any location under institutional control which has a boundary inside which radioactive wastes are handled, stored, or disposed of;

Storage.—Retention of radioactive waste at facilities with designed provisions for recovery within a defined time;

Waste management.—The range of activities for dealing with radioactive waste, including preparation, storage, and disposal.

BACKGROUND

Our responsibility to maintain environmental quality for future generations is well recognized. As enunciated in the National Environmental Policy Act of 1969 (NEPA), it is an important national goal to "fulfill the responsibilities of each generation as trustee of the environment for succeeding generations." In applying the above

NEPA principle, EPA notes that some radioactive waste materials are both long-lived and highly toxic. These materials may pose substantial health risks to both present and future generations. EPA believes that such materials should be properly controlled. Since no current waste management technology can be expected to be absolutely effective in isolating radioactive wastes from the biosphere (particularly over very long periods of time), decisions on radioactive waste management and control must assure that radioactive waste does not pose an unreasonable risk to human health and the environment.

Some of the issues which surfaced in EPA's deliberations about such waste control decisions were: (1) The types of materials to be categorized as radioactive wastes and subject to control; (2) the efficacy of engineered controls and natural barriers to isolate wastes; (3) the usefulness of social institutions in providing control, especially their viability over time; (4) the potential health risks of wastes (over various time intervals and with differing levels of control); (5) the unacceptability of various levels of risk; and (6) other considerations such as retrievability and communication of waste disposal sites to succeeding generations to assure continued isolation.

The Agency has developed a set of proposed criteria which address each of the above issue areas. The Agency intends to use the criteria as the basis for developing environmental standards for different radioactive waste sources. EPA will transmit the final criteria to the President for his approval and publication as Federal guidance. The promulgation of the criteria as Federal guides will foster continuity in Federal programs for the disposal of radioactive wastes. The Environmental Protection Agency has addressed the aforementioned issues in concert with other Federal and State agencies, radiation protection professionals, and the public. Thus, the proposed criteria which follow are designed to guide Federal agencies in making policy, programmatic operations, and standard setting decisions for radioactive wastes by setting forth in general terms those principles which should be applied in assuring protection of the public health.

The first criterion defines radioactive wastes, indicates which ones should be controlled, and gives source examples. The next criterion defines the fundamental goal of radioactive waste control and in that regard calls for the use of institutional and natural barriers to control wastes with long hazardous lifetimes. The third criterion states that risk is the primary basis for making radiation protection decisions for radioactive wastes and

discusses what factors should be taken into account in assessing the risks to individuals and populations. The fourth, and possibly the most complex criterion, addresses the difficult subject of determining when risks from the disposal of radioactive wastes are unacceptable. The fifth recommends conditions which disposal locations should satisfy. The final criterion specifies several relevant supplemental control considerations which should be used if a net improvement in environmental protection can be achieved.

The Agency recognizes that there is substantial public debate regarding the desirability of establishing a moratorium on the production of additional nuclear wastes until such time as a National Radioactive Waste Policy has been adopted. These proposed criteria do not attempt to resolve this issue. In the Agency's view the quantity or quality of radioactive material which may be produced in the future should not be permitted to influence decisions on what levels of risk associated with such materials are regarded as acceptable or unacceptable. Curtailment of the production of certain types of radioactive waste could be determined to be an appropriate waste management control concept under the proposed criteria in certain circumstances. For example, to avoid unacceptable risk, either for current or future generations, control measures requiring extraordinary precautions for waste disposal might be judged necessary. If such control measures are feasible only for limited quantities of waste then policies to limit the total amount of wastes which are generated would be an essential element of an effective control program.

ENVIRONMENTAL PROTECTION CRITERIA

The criteria proposed herein should be used as a complete set and each should be satisfied for any radioactive waste that becomes subject to control in accordance with the first criterion. Certain exceptions are recognized and these are specifically stated. Unless circumstances are such that a given criterion can be waived because prescribed conditions for exceptions are satisfied, all criteria are to be followed for any given waste.

The following proposed criteria are under consideration for the Guidance of Federal Agencies in providing environmental and radiological protection for all forms of radioactive wastes:

PROPOSED CRITERION NO. 1

Radioactive materials should be considered radioactive wastes requiring control for environmental and public health protection if they have no designated product or resource value and: (a) Are human-produced by nuclear fission or activation, fabricated from

naturally radioactive materials into discrete sources, or as a result of regulatory activities are prohibited from uncontrolled discharge to the environment; or (b) contain diffuse naturally-occurring radioactive materials that, if disposed into the biosphere, would increase exposure to humans above that which would occur normally in pathways due to the preexisting natural state of the area. Examples of radioactive waste materials that should be subject to environmental protection requirements are:

All radioactive materials associated with the operation and decommissioning of nuclear reactors for commercial, military, research, or other purposes and the supporting fuel cycles, including spent fuel if discarded, fuel reprocessing wastes, and radionuclides removed from process streams or effluents.

Artificially produced radiolabels, including discrete radium sources, for medical, industrial, and research use and waste materials contaminated with them.

The naturally-radioactive residues of mining, milling, and processing of uranium and phosphate ores.

PROPOSED CRITERION NO. 2

The fundamental goal for controlling any type of radioactive waste should be complete isolation over its hazardous lifetime. Controls which are based on institutional functions should not be relied upon for longer than 100 years to provide such isolation; radioactive wastes with a hazardous lifetime longer than 100 years should be controlled by as many engineered and natural barriers as are necessary.

PROPOSED CRITERION NO. 3

Radiation protection requirements for radioactive wastes should be based primarily on an assessment of risk to individuals and populations; such assessments should be based on predetermined models and should examine at least the following factors:

- The amount and concentration of radioactive waste in a location and its physical, chemical, and radiological properties;
- The projected effectiveness of alternative methods of control;
- The potential adverse health effects on individuals and populations for a reasonable range of future population sizes and distributions, and of uses of land, air, water, and mineral resources for 1,000 years, or any shorter period of hazard persistence;
- Estimates of environmental effects using general parameters or of health effects based on generalized assumptions for as long as the wastes pose a hazard to humans, when such

estimates could influence the choice of a control option;

e. The probabilities of releases of radioactive materials to the general environment due to failures of natural or engineered barriers, loss of institutional controls, or intrusion; and

f. The uncertainties in the risk assessments and the models used for determining them.

PROPOSED CRITERION NO. 4

Any risks due to radioactive waste management or disposal activities should be deemed unacceptable unless it has been justified that the further reduction in risk that could be achieved by more complete isolation is impracticable on the basis of technical and social considerations; in addition, risks associated with any given method of control should be considered unacceptable if:

a. Risks to a future generation are greater than those acceptable to the current generation;

b. Probable events could result in adverse consequences greater than those of a comparable nature generally accepted by society; or

c. The probabilities of highly adverse consequences are more than a small fraction of the probabilities of high consequence events associated with productive technologies which are accepted by society.

PROPOSED CRITERION NO. 5

Locations for radioactive waste disposal should be chosen so as to avoid adverse environmental and human health impacts and, wherever practicable, to enhance isolation over time.

PROPOSED CRITERION NO. 6

Certain additional procedures and techniques should also be applied to waste disposal systems which otherwise satisfy these criteria if use of these additional procedures and techniques provide a net improvement in environmental and public health protection. Among these are:

a. Procedures or techniques designed to enhance the retrievability of the waste; and

b. Passive methods of communicating to future people the potential hazards which could result from an accidental or intentional disturbance of disposed radioactive wastes.

DISCUSSION

ISSUE NO. 1: MATERIALS CONSIDERED RADIOACTIVE WASTES

The first issue that must be resolved in formulating criteria to govern the handling of radioactive wastes is just what materials are to be considered radioactive wastes within the scope of the criteria. For a given material, this judgment has two parts: Deciding that

it is a "waste", and determining whether its degree of radioactivity is great enough to require that the waste material be disposed of in a way that protects against that radioactive hazard.

The primary factor in deciding that a material is a "waste" is the material's residual value. If it has no designated remaining value as a resource or a product, the material should be considered a waste. Because these criteria are addressed to the treatment of radioactive wastes, as opposed to other radioactive materials with current or possible future uses, materials which may have such uses would not be considered wastes subject to the criteria. Depending on the circumstances, the judgment of the material's remaining value will be made by the person or organization possessing or controlling it, or by a Government agency on behalf of the society as a whole. Once a material has been designated as a waste, whether or not it should be disposed of under these criteria depends on its radiological hazard.

A view expressed in the criteria development process was that EPA should set a minimum level of radioactive content below which any material should not be considered a radioactive waste. The Agency does not believe that this would be an appropriate course, primarily because no safe level of exposure to radioactivity can be established from the available evidence. As a result, EPA and other agencies concerned with radiation protection have followed a policy of requiring exposures to be reduced as much as practicable. This approach requires consideration of the circumstances surrounding any particular exposure source, and thus, precludes the establishment of any general "de minimus" level.

It does not appear feasible to formulate a criterion generally identifying those radioactive materials or exposure levels which pose so little hazard under any circumstances that they should not be considered radioactive wastes. Therefore, EPA has formulated a criterion that cites three broad classes of materials that should be considered radioactive wastes for disposal purposes: the first class consists of those materials produced artificially, either by nuclear fission, activation, or by fabrication from naturally radioactive materials into discrete sources. These materials are easily identified and described, and directly controllable.

A second class of substances which would be considered radioactive wastes under the proposed criterion are those containing diffuse naturally occurring radioactive material. However, these materials would be subject to the criterion only if they could result in exposures greater than those which

would have occurred, through any pathway, if the material had not been disturbed by human activity.

The rationale underlying this distinction is that requiring the material to be treated as radioactive waste implies that its radioactivity is the decisive characteristic of the material. Yet if failure to treat the material as radioactive waste would not increase exposures over pre-existing levels, requiring disposal of the material as a radioactive waste seems unreasonable. If such an improvement is desirable, it should be for reasons other than that the material is a waste containing some natural radioactivity.

The final class of wastes which should be considered radioactive wastes for purposes of disposal under these criteria includes any retained waste materials which are prohibited by Government regulatory action from unrestricted discharge into the general environment due to their radioactive content. While this category of substances will obviously contain many wastes covered by the two previous classes, certain materials fall into neither category. Therefore, the Agency believes the restriction on discharge to the general environment is in itself sufficient basis for requiring any such material to be disposed of in accordance with these criteria. Examples of such materials could include those removed from effluent streams at nuclear reactors or phosphate fertilizer plants.

These principles have been used to formulate the following criterion for determining which materials are radioactive wastes requiring disposal under the remaining criteria. Proposed criterion No. 1 designates broad classes of materials that should be regarded as wastes whose radioactive content requires consideration in their disposal. Usual methods for control of waste materials may be used for radioactive wastes as well if such methods provide a degree of control consistent with these criteria. Other materials or classes of materials may be added to this criterion in accordance with the principles discussed above if information discovered in the future indicates a need for doing so. Therefore, the following criterion is recommended:

PROPOSED CRITERION NO. 1

Radioactive materials should be considered radioactive wastes requiring consideration for environmental and public health protection if they have no designated product or resource value and: (a) are human-produced by nuclear fission or activation, fabricated from naturally radioactive materials into discrete sources, or as a result of regulatory activities are prohibited from uncontrolled discharge to the environment; or (b) contain diffuse natu-

rally occurring radioactive materials that, if disposed into the biosphere, would increase exposure to humans above that which would normally occur in pathways (air, water, food) due to the pre-existing natural state of the area. Examples of radioactive waste materials that should be subject to environmental protection requirements are:

All radioactive materials associated with the operation and decommissioning of nuclear reactors for commercial, military, research, or other purposes and the supporting fuel cycles, including spent fuel if discarded, fuel reprocessing wastes, and radionuclides removed from process streams or effluents.

Artificially produced radioisotopes, including discrete radium sources, for medical, industrial, and research use, and waste materials contaminated with them.

The naturally-radioactive residues of mining, milling, and processing of uranium and phosphate ores.

ISSUE NO. 2: CONTROL OF RADIOACTIVE WASTE

The management of radioactive wastes represents potential exposure of individuals and populations and the possible contamination of the general environment. These potential impacts require definitive controls to be established. Further, because of the trustee responsibility each generation has to succeeding ones, contamination of the general environment should be avoided regardless of whether humans will actually contact the waste directly. It is important to prevent both human and environmental adverse impacts. Therefore, the fundamental goal for controlling any type of radioactive waste should be complete isolation over its hazardous lifetime.

Controls for radioactive wastes are of three general types: Engineered barriers, natural barriers, and institutional mechanisms. Engineered barriers such as containers or structures generally can be considered only as interim measures for containment, despite the fact that some structures have survived intact through the ages. Stable geologic media are an example of natural barriers. Institutional controls are those which depend on some social order to prevent humans from coming in contact with wastes, such as controlling site boundaries, guarding a structure, land use policies, record-keeping, monitoring, etc.

It generally is accepted that long-term isolation should depend on stable natural barriers. Institutional mechanisms, which are essential in the early stages of management of any waste, are short-term processes because of practical limitations. Institutional means can be very effective in isolat-

ing radioactive wastes from humans if they can be maintained. Since society's basic structure and concern about waste may change, it is reasonable to rely on such controls for only limited periods.

The choice of a time period for relying on institutional controls is completely a matter of judgment, but is basic to a determination of when use of such controls is proper. During the developmental stages of this criteria document, it was proposed that 100 years should be the maximum time period for such controls to be depended upon with any degree of assurance. The public forum participants recommended deleting the time period because it appeared to be arbitrary; however, they left the issue unaddressed in any other form.

Because there are a number of current mechanisms for disposing of various types of wastes which are based on institutional care, the Agency believes that guidance is required to assure that institutional controls are relied upon only to the extent they are appropriate. There are numerous types of radioactive wastes of such hazard potential that they will require the adoption of stricter control methods than currently practiced and will require the development of new disposal technologies which will assure better isolation that afforded by institutional control mechanisms. For this reason, when disposal decisions are made they should recognize that institutional controls are only of limited use, and if the wastes will be hazardous longer than 100 years, other means of control will need to be found.

This means that in selecting control options for wastes whose hazards extend beyond 100 years decisions makers cannot rely on restrictions on customary uses of land and of ground or surface waters. This does not mean that institutional controls are required for 100 years, or that they must stop at that point if society can still maintain them; only that people making the initial disposal decision should not plan on their use to maintain protection beyond 100 years. The judgment that 100 years is the most appropriate time interval will be further examined throughout the public comment period.

In order to assure that these principles are achieved in controlling radioactive wastes, it is recommended that:

PROPOSED CRITERION NO. 2

The fundamental goal for controlling any type of radioactive waste should be complete isolation over its hazardous lifetime. Controls which are based on institutional functions should not be relied upon for longer than 100 years to provide such isolation; radioactive wastes with a hazard-

ous lifetime longer than 100 years should be controlled by as many engineered and natural barriers as are necessary.

ISSUE NO. 3: RISK ASSESSMENT

Radioactive wastes pose a risk of potential exposure to people and to environmental contamination, both of which vary considerably with time. In a practical sense, risk considerations and control considerations are necessarily interrelated because each influences the other. Risks will be increased or decreased depending on the effectiveness of the control imposed, and controls to some extent will be chosen depending on the severity of the risk. Although the risks of different radioactive wastes ought to be ascertained at various levels of control, in the final analysis it is the risk a waste poses over time that primarily should determine the required controls. For this reason, risk determination is a pivotal part of any environmental and public health protection policy for radioactive wastes, and is the key consideration in deciding whether and how to store or dispose of the wastes.

Risk determinations rest on a number of factors, especially the total amount of waste material at a particular location, its persistence due to form and concentration, its potential to enter the biosphere and produce adverse effects on individuals and populations, the effectiveness of various controls, and the inherent uncertainties of many of the parameters. It is especially important that the period of time for which particular radioactive wastes remain hazardous be considered from two basic standpoints: how well the control alternatives will perform in reducing the risks over time and the probability of any containment being breached.

The factors discussed above have been generally recognized and accepted as essential to risk assessments, and there is some agreement about how to take them into account. The period over which such assessments should be performed is, however, more controversial. The main constraint on choosing a time period is the reliability of the results. Health effects estimates can be useful in making public policy decisions on radiation control; however, for many long-lived radioactive wastes, the models available are inadequate over very long intervals. Projections of population size, land use, and human factors beyond a few hundred years are suspect, but the physical parameters of source terms, environmental transport models, and geological conditions may be reasonably predictable for a few thousand years.

Because of the long duration of potential hazards from many of the

wastes. It is appropriate to use an extended time period for estimation of health effects. In our judgment, health effects estimates can reasonably be made for periods up to about 1,000 years. Such a time period would provide consideration of both acute exposure risks and chronic exposure risks represented in many types of wastes containing both short- and long-lived fission products. A shorter time period, though less subject to speculation, may have the result of focusing control only on short-term risks that will soon disappear, when it would be equally appropriate to control the risks of long-lived components of the waste.

Some materials decay rapidly enough that virtually all their radioactivity is gone long before 1,000 years, in which case the estimation process is considerably more simple. On the other hand, some very significant waste materials persist well beyond 1,000 years, so it is important to account for this potential risk in deciding a form of control. In this case, it is desirable to have some means of comparing the potential impact on public health and the environment in order to choose the best control alternative. This can be done by physical parameters related to risk potential such as the quantity of various radionuclides entering environmental exposure pathways, their physical distribution, or the doses they may produce. Such comparisons can also be made with health effects estimates based on very general assumptions beyond 1,000 years. Although health effects estimates are desirable for these very long time periods, reasonable comparison of control alternatives can be made by other parameters such as curies released, calculated doses to assumed individuals, etc.

Impact assessments and the time periods for which they should be performed were discussed in developing the criteria. The public forum participants generally agreed that there is a need for risk assessments and that assessments should include, at least, those basic elements presented in the background report (43 FR 2223). However, the participants expressed considerable confusion about the meaning of the relationship between time and risk assessment, and recommended deletion of the time periods presented. Although the time periods chosen are based on judgment, the Agency believes it essential that meaningful estimates be made for the periods over which wastes represent potential hazards. In order to assess risks properly, it is recommended:

PROPOSED CRITERION NO. 3

Radiation protection requirements for radioactive wastes should be based

primarily on an assessment of risk to individuals and populations; such assessments should be based on predetermined models and should examine at least the following factors:

a. The amount and concentration of radioactive waste in a location and its physical, chemical, and radiological properties;

b. The projected effectiveness of alternative methods of controls;

c. The potential adverse health effects on individuals and populations for a reasonable range of future population sizes and distributions, and of uses of land, air, water, and mineral resources for 1,000 years, or any shorter period of hazard persistence;

d. Estimates of environmental effects using general parameters or of health effects based on generalized assumptions for as long as the wastes pose a hazard to humans, when such estimates could influence the choice of controls;

e. The probabilities of releases of radioactive materials to the general environment due to failures of natural or engineered barriers, loss of institutional controls, or intrusion; and

f. The uncertainties in the risk assessments and the models used for determining them.

ISSUE NO. 4: UNACCEPTABILITY OF RISK

The term risk expresses a general concept encompassing both the probability of occurrence of adverse effects and their severity. Both aspects are basic to decisions on the adequacy of controls for radioactive waste. The most restrictive regulatory position to adopt would be to allow no additional risks whatever. No matter how desirable "zero risk" might be as a goal, it may not be technically or economically feasible. Moreover, society may have to forego some easily justified and beneficial activities to attain zero risk. Guidelines are required, therefore, for determining levels of risk other than zero that may be permitted. A difficulty in formulating such guidelines is that there is no generally accepted methodology for determining the risk that society would accept in a given set of circumstances.

Examination of risks for waste disposal systems in terms of the consequences of exposure and their probability of occurrence will result in values greater than zero which vary with the types of waste, the controls available, and the kinds and severity of events that can be postulated to disrupt isolation. Consequences may range over chronic and acute exposures of a few individuals or large groups, with probabilities ranging from very remote to near certainty over the long term for some waste types and controls.

All societies experience risks and have developed patterns of acceptance of various types of risks. For high-technology societies these patterns are difficult to discern, and they often change in relatively short time frames because such societies are continually creating new sources of risks. Thus, in the absence of established methodologies for determining acceptable risk, the Agency believes it is reasonable to state (in terms of consequence of exposure and probability of occurrence) certain unacceptable risks resulting from the disposal of radioactive wastes.

The apparent opinion regarding radioactive waste in the United States is that any risks resulting from the disposal of radioactive wastes now or in the future would not be acceptable unless more complete isolation were unreasonable. To be responsive to this public attitude, reasonable controls that are available and economically feasible should be applied. Also, because of the responsibility each generation has to succeeding ones, a key social consideration is that at a minimum the current generation should not pose larger risks to a future generation than it would be willing to accept for itself. This does not mean that the risk has to be the same in future generations, only that it would not be unacceptable to the current generation if imposed on it—even though the projected impact on the first few generations may be well below levels determined to be acceptable. Risk levels unacceptable to the current generation for a given set of circumstances would be generally precluded in formulating protection standards for the waste materials in question.

In general, risks are more readily acceptable to society if the consequences are common ones that are not highly dreaded, and are well understood situations which can be related to other common risks. On the other hand, generally beneficial circumstances which have high potential for harm appear to be acceptable to people if occurrence of the harm is virtually impossible; that is, the probability is very low. These interrelationships between probability of occurrence and consequence are not linear functions, and thus an unacceptable risk value cannot be chosen as a product of the two. Instead, one is compelled to state separately conditions of unacceptability for the consequence of quite likely adverse events, and for the probability of very harmful situations. Since a broad range of circumstances is possible for wastes, each of which has its own probability and consequence, one is dealing with a continuum of probability/consequence; thus, it is only possible to give general guidelines for

deciding when various degrees of risk would be unacceptable. These are rooted in the basic concepts discussed above: Events likely to occur will be acceptable only if adverse consequences are low and are of a common type; events with high adverse consequence potential must be virtually certain not to occur.

In order to apply these principles, as stated in the proposed criterion, the following steps are required: First, the probabilities and consequences of possible events should be determined for different types and levels of control, and secondly, the results compared to other socially determined values for similar circumstances, if possible. The following paragraphs illustrate the second step.

High consequence events resulting from waste disposal can be compared to those associated with productive, shorter term technologies such as dams, dikes, and large stores of toxic or explosive chemicals. It is well recognized that productivity is associated with the creation of radioactive wastes. However, once wastes are created there is no further productivity directly associated with them. It is also important to note that the hazards many radioactive wastes pose are often much longer-lived than the explicitly productive aspects of other technologies. For radioactive wastes which pose long-term hazards, it seems reasonable that high consequence events should be considered unacceptable unless their probability is only a small fraction of that deemed acceptable for shorter term productive technologies.

Exposure situations which are likely to occur for certain kinds of wastes would be unacceptable, under the proposed criterion, unless predicted effects would be of questionable significance, even on a statistical basis. This means that if acute exposure is projected as a likely result of waste disposal, it should affect no more than a very few individuals randomly. If large groups are likely to be chronically exposed, the projected risks should be small and no greater than comparable risks that society has already willingly accepted.

Each Federal agency that is involved in establishing policy for radioactive waste disposal will be responsible for estimating the consequences of likely radiation exposure circumstances for wastes, and for determining whether they are unacceptable based on an examination of their consistency with other established social values that have evolved for comparable circumstances. Therefore, it is recommended that:

PROPOSED CRITERION NO. 4

Any risks due to radioactive waste management or disposal activities should be deemed unacceptable unless it has been justified that the further reduction in risk that could be achieved by more complete isolation is impracticable on the basis of technical and social considerations; in addition risks associated with any given method of control should be considered unacceptable if:

- Risks to a future generation are greater than those acceptable to the current generation;
- Probable events could result in adverse consequences greater than those of a comparable nature generally accepted by society; or
- The probabilities of highly adverse consequences are more than a small fraction of the probabilities of high consequence events associated with productive technologies which are accepted by society.

ISSUE NO. 5 LOCATION AND WASTE ISOLATION

It is generally accepted that long-term isolation of radioactive wastes should depend on stable natural barriers to assure isolation from the biosphere over the period that a radiological hazard persists. Obviously, the site's effectiveness in attaining this goal is influenced by its location. Therefore, it is desirable to select sites if they are reasonably available where the action of natural forces over time such as erosion, sedimentation, and crystallization can be projected to improve, rather than reduce, isolation of the wastes over the time they may represent a potential hazard if they were to enter the biosphere. Similarly, if geological media are used, they should reduce the effect of potential interaction with water to the greatest extent possible. Therefore, it is recommended that:

PROPOSED CRITERIA NO. 5

Locations for radioactive waste disposal should be chosen so as to avoid adverse environmental and human health impacts and, whenever practicable, to enhance isolation over time.

ISSUE NO. 6 SUPPLEMENTARY PROTECTION GOALS

A number of other subjects pertinent to protection of the public from radioactive wastes were discussed in the development of the criteria. Among these, most attention centered on monitoring, provision of retrievability, and passive communication of the nature of the possible hazard to future generations. In general, it was determined that, while each has positive aspects for control of radiological hazards, their application might under-

mine the goal of providing permanent isolation for wastes. It is difficult to maintain retrievability or conduct a monitoring program without compromising the ability to provide isolation. Furthermore, in many disposal situations which will satisfy the five criteria discussed above, the residual risk will mainly be attributable to potential failure mechanisms involving eventual intrusion by humans. Passive methods of communicating the hazard, such as markers which call attention to the waste, may sometimes be judged to provide a net reduction of risk. Other passive methods, such as creating records describing the waste, or setting aside of the land title to the disposal site, have value in reducing the likelihood of intrusion for some limited time.

An example of a circumstance where land title transfer is reasonable is a current site that has been in use for some time where optimal environmental isolation is no longer a practicable alternative, such as an abandoned mill tailings site, a nuclear test facility site, etc. In these cases, Federal ownership of the land beyond the normal period of institutional control would be reasonable to minimize potential intrusion. Such decisions should be made on a case-by-case basis and provision for specifically treating such exceptions should be addressed in standards and regulations which are promulgated for these types of wastes.

It is not appropriate to depend upon methods such as these or other similar ones for long-term control; nonetheless, when such methods would enhance overall protection from wastes, it is prudent to use them. This is particularly the case for retrievability and passive communication. Monitoring was judged by the Public Forum participants to be generally a part of early institutional controls prior to completion of disposal, and thus it is not included in the following criterion for supplementary controls. Therefore, it is recommended:

PROPOSED CRITERION NO. 6

Certain additional procedures and techniques should also be applied to waste disposal systems which otherwise satisfy these criteria if use of these additional procedures and techniques would provide a net improvement in environmental and public health protection. Among these are:

- procedures or techniques designed to enhance the retrievability of the waste, and
- passive methods of communicating to future people the potential hazards which could result from an accidental or intentional disturbance of disposed radioactive wastes.

NOTICES

IMPLEMENTATION AND FOLLOW-UP

It is expected that Federal agencies would use these criteria as a basis for developing detailed standards for radioactive wastes which are consistent with its particular requirements. The Agency, in cooperation with other Federal agencies, will follow the implementation of these recommendations, and will promote the coordination necessary to achieve an effective Federal waste management program. Periodically, the Agency will interpret and expand upon each of the recommendations as required to assure effective implementation by Federal agencies in accordance with new and changing information.

DOUGLAS M. COSTLE,
Administrator.

NOVEMBER 7, 1978.

[PR Doc. 78-32023 Filed 11-14-78; 8:45 am]

APPENDIX D

PROPOSED NRC

RADIOACTIVE WASTE DISPOSAL CLASSIFICATION

SYSTEM METHODOLOGY³⁵

TERA CORPORATION

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)*

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:

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

where,

D_e = dose rate guideline (500 mrem/yr)

C_m = MAC of isotope m in the waste at the time of burial,
($\mu\text{Ci}/\text{cm}^3$)

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

* Reference provided on page D-14.

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 $(\text{DF})_m$ for ^{239}Pu and the other values as given, a MAC of $0.1 \mu\text{Ci}/\text{cm}^3$ 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 $40 \mu\text{g}/\text{m}^3$ in rural areas and about $150 \mu\text{g}/\text{m}^3$ in urban areas. Over 90 percent of all measurements are less than $300 \mu\text{g}/\text{m}^3$. 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

TABLE A.1

REFERENCE VALUES OF KEY PARAMETERS

<u>Parameter</u>	<u>Value With Administrative Control</u>	<u>No Administrative Control</u>
A_d , dust loading in air	$5 \times 10^{-4} \text{ g/m}^3$	$5 \times 10^{-4} \text{ g/m}^3$
U_a , breathing rate	$0.91 \text{ m}^3/\text{hr}$	$0.91 \text{ m}^3/\text{hr}$
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	$\exp (150 \lambda_m)$	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 disper- sion coefficient	$10 \text{ m}^2/\text{yr}$	$10 \text{ m}^2/\text{yr}$

TABLE 5.1

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

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

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

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

average dust loading from the wastes is $50 \mu\text{g}/\text{m}^3$, 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 $0.1 \mu\text{Ci}/\text{cm}^3$ 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:

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

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 m^{th} nuclide (mrem/pCi)

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

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

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

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:

$$C_m = \frac{D_e m_v}{\lambda_L f_o U_D (DF)_m} \quad (A.3)$$

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_D = 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 using a spatially dependent source and element dependent leach constants, λ_L , and retardation factors, K . For a one-region aquifer flow system, the following equation is used to obtain f_o :

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

where,

v = aquifer flow rate (m/yr)

$a_i = \sqrt{K/D} x_i$

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

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

D = aquifer dispersion coefficient (m²/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 ground-water 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:

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

where,

μ = effective gamma ray attenuation coefficient for soil (cm⁻¹)

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

$(\mu/\rho)_t$ = mass absorption coefficient for tissue (cm²/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 $500 \text{ m}^3/\text{sec}$. 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, dis-

tances 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/cm³, 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).

$$C_m = \frac{D \dot{m}_d dT_d}{F_e U_a (DF)_m V_w} \exp (120\lambda m) \quad (A.6)$$

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.

TABLE 6.1

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

Isotope	WASTE CLASS				
	E	D	C	B	A
^3H	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.

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