PNRI-E(NM)--94003

MANAGEMENT OF LIQUID RADIOACTIVE WASTES AT PNRI

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Date Submitted: October 1994

ABSTRACT

Liquid wastes accepted at PNRI waste management facility are generated by hospitals and research institutions from all over the country including those generated from the research laboratories within the PNRI. The operation of the Philippine TRIGA Research Reactor is also a potential source of liquid waste to be handled and managed by the facility in the future.

This technical report is a result of the study of the present status and development of the management of liquid wastes at PNRI.

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1.0 INTRODUCTION

1.1 Description

Radioactive wastes are the leftovers of any activity involving the use of radioactive materials. Radioactivity is a natural and spontaneous process of atomic decay in which the nucleus of an unstable atom breaks apart. As it breaks apart it releases energy called radiation. When the unstable atoms are naturally dispersed and diluted throughout the earth, the released energy from their decay is also dispersed and diluted. It is part of our natural background radioactivity.

Nuclear or radioactive waste comes in various forms from many peaceful uses of nuclear energy: electricity generation, research, and medical, agricultural, and industrial applications.

1.2 Hazards of Radioactive Wastes

The hazards from wastes arise when they are not properly processed. All wastes must be disposed of in ways that do not disturb the environment or harm living things now or in the future. For some of the wastes, effective disposal solutions have not yet been found.

Exposure to high levels of radiation can harm human beings. However, the effects of low levels of radiation on the body are less certain. The evidence so far indicates that any hazard is too small to be found.

There are conservative assumptions, however, that any activity involving exposure to radiation must be considered to involve some risk. The risk may be very small, but there is no point in taking that risk if it may easily be avoided.

1.3 Sources and Description of Liquid Radioactive Wastes

Wastes generated from hospitals and research institutions are in the form of chemical substances which are labelled with radioactive isotope. Aside from the radiological hazard, if not properly treated, these wastes can contribute to chemical and biological contamination in the environment.

The Philippine Nuclear Research Institute (PNRI) is operating and maintaining an interim low level radioactive waste storage and treatment facility. The Institute, through its Radiation Protection Section renders wastes management services to both government and private institution all over the country. The wastes which are brought to PNRI for safe management are generated from the use of both sealed and unsealed radioactive materials and substances in industry, medicine, research institutions, as well as from the day to day operations of PNRI laboratories. (Refer to Figures 1 of Appendix A.)

The liquid wastes accepted by PNRI for processing and interim storage come in different chemical composition. Most of them were generated from research laboratories both on-site and off-site. The anticipated operation of the Philippine TRIGA Research Reactor is also a potential source of liquid waste. Table 1 of Appendix B shows the inventory of liquid radioactive wastes accepted by PNRI Radwaste Management Facility from 1989 to 1992.

2.0 PROCESS DESCRIPTION

In the management of radioactive wastes, the wastes are classified and segregated by the client themselves according to the guidelines setforth in the Wastes Management Acceptance Criteria issued by the PNRI to the off-site wastes generators and in the PNRI Safety Manual for the on-site laboratories, stipulating criteria to be satisfied prior to transporting of radioactive waste/spent sealed sources to PNRI waste management facility. It may be mentioned that the Institute is exempted from Code of PNRI regulations since it has the responsibility of regulating and implementing functions for waste management. Safety inside the Institute is taken cared of by an overall Safety Committee (with specific subcommittees) which are responsible in the enforcing of the rules provided in the official Safety Manual.

The classification and segregation of wastes depend upon the type of treatment necessary. The final stage in the processing of liquid wastes is the conditioning process intended to immobilize the wastes for interim storage or transport to a final repository site. Presently, the method of conditioning applied is cementation of packaged treated wastes in 200 liter drums. The conditioned wastes in drums are stored in 2 trenches within the radioactive wastes management facility, which has a total capacity of 100 m^3 volume. Three additional trenches were constructed which

will accommodate a total volume of 300 m^3, expected to be generated within a period of ten years. This will give the Institute a lead time of ten years after which a final disposal site will have been decided upon. The flow diagram of the process of liquid waste management at PNRI is shown in Figure 3, Appendix A.

2.1 Waste Identification, Documentation, and Record Keeping

A coding system is adopted to identify radioactive waste packages accepted for waste management. All information pertaining to each waste package and its content, including all the processes that the wastes have undergone are entered into a computer data base. All conditioned wastes in drums bear identification using a code system. Records and data are maintained and are made available for retrieval any time.

2.2 Waste Segregation

Liquid wastes vary extensively in both chemical and radionuclide content, with each nuclear operation generally producing a primary type of liquid waste depending upon the particular operation being conducted. Most operations produce a variety of miscellaneous radioactive liquid wastes from support facilities such as showers, laundries, analytical laboratories, and decontamination services.

Each waste stream is examined at its source for both volume and concentration reduction and possible pretreatment before combination with other streams. In some cases, pretreatment of waste streams may produce an effluent suitable for combination with other waste streams for final treatment by one process. Many combinations of treatment are possible, and an analysis of all options may be time consuming. Computer modelling is being considered to be very useful in helping to identify the optimum conditions for chemical treatment of waste streams. In addition, the deliberate mixing of certain waste streams from multistep operations may bring about desirable precipitation formation without the need for any additional chemical reagents.

In the selection of waste treatment method, the materials that may interfere with the process are identified, and although it is neither practicable nor economic to

absolutely prevent these materials from entering the collection system, it is necessary to ensure that only minimal amounts are allowed. This is done in two ways:

(a) by segragating, as far as possible, liquids containing these materials;
(b) by co-operating with the waste generator to ensure that minimal amounts are used, and if possible, alternative materials which will not affect the treatment process be used.

The following materials can adversely affect plant operation or the decontamination process during liquid waste treatment:

(a) miscellaneous solid wastes such as paper and fibrous materials which can cause blockages and clog filters;
(b) oil, greases and solvents which form scums that may attack plastic components, introduce a fire or explosion risk and merkedly affect the decontamination factors;
(c) chemicals not compatible with materials of construction;
(d) detergent at a level of a few parts per million which can interfere with flocculation process; higher levels can cause foaming and completely ruin the process;
(e) complexing and other reagents that are used in decontamination procedures.

With some waste streams, the removal of non-radioactive contaminants as well as the radioactive ones is necessary, particularly where effluents are discharged into fresh or estuarine waters. It may be necessary to adjust some of the chemical properties such as pH or concentration of specific ions. There may be a need for waste to be segregated from the main waste collection system for pre-treatment before entering the main stream.

Generally, liquid wastes collected at PNRI have been segregated by the waste generator during the stage of waste collection, following instructions provided in the PNRI Waste Acceptance Criteria. Currently, liquid wastes are segregated based on the applicable treatment method that the batch of waste may possibly undergo considering

the available treatment facility already in operation or considered for operation in the near future. Liquid wastes are be segregated as follows:

(a)	aqueous waste	-	composed of materials dissolved/dispersed or mixed with wwater
(b)	organic mixture	-	composed of carbon containing substances and materials derived from living matter

(Refer to Fig. 2 Appendix A for the breakdown of liquid wastes collection from 1989 to 1992 based on current waste characterization system.

2.3 Waste Characterization

The selection of a treatment process for liquid waste is, to a large extent, determined by the physical, chemical, and radiological properties of the waste.

2.3.1 Chemical Properties

The chemical properties of aqueous wastes that have to be taken into account in considering the treatment process to be adopted includes:

- pH value
- chemical bonds
- characteristic chemical reactions
- toxicity
- thermal properties
- chemical oxygen demand (COD)
- biological oxygen demand (BOD)

The chemical composition of a liquid is, in principle, the decisive factor in selecting a certain decontamination procedure. The ionic species present in the waste will be determined by the redox potential and the stability constants of the possible species and may be anionic, cationic, or neutral. Organic componds which may be present in either a separate phase or in solutions could interfere with conventional treatment process for aqueous mixtures.

2.3.2 Physical Properties

Some of the important physical properties of a waste stream considered in the choice of treatment method are the folloing:

- electrical conductivity
- turbidity
- emulsifying ability
- density
- surface tension
- viscosity

The electrical conductivity of an aqueous liquid gives some measure of its dissolved salt content and will indicate whether or not electrochemical treatment can be considered. Turbidity indicates the presence of colloidal particles which may be removed by some separation process.

Emulsion formation can possibly occur due to the presence of organic substances in an effluent. This could adversely affect the efficiency or effectivity of flocculation and filtration.

The density and viscosity may have some bearing on the pumping and mixing performance of the liquors, while surface tension affects incorporation of powdered reagents.

2.3.3 Radiological Properties

The composition of radioactive waste streams covers a very wide range regarding the levels alpha, and beta-gamma emitting nuclides. The specific acivity of the wastes determines whether it is classified as low-activity or high-activity level. The half-life of the radionuclide content of the waste liquor determines whether it can be classified as long-lived or short-lived. Table 2 in Appendix B shows the method of waste categorization in PNRI based on the radiological properties.

The radiological properties of a given waste stream affect the choice of treatment process, the safety of its operation, and the radiological effect on the operators and on the environment.

In precipitation process, the high sorption capacity of some flocs may result in high radionuclide concentrations in the sludge. High loadings of beta-gamma emitters will increase the radiation doses to equipment and may require increased biological shielding.

The radiation stability of separated sludges and any immobilization matrices has to be taken into account. Considerations have to include radiolysis which generates flammable or toxic gases, degrades organic materials to products that may interfere with the treatment process or can catalyse reactions leading to a rapid or violent release of energy.

2.3.4 Biological Characteristics

Liquid wastes arising from medical diagnostic/research laboratories are examined on the basis of the waste generators' activities reported to the Nuclear Regulations, Licensing, and Safeguards Division (NRLSD). This is to determine the presence of biological/pathological contamination which may be present in the waste stream. The PNRI Waste Acceptance Criteria requires such kind of wastes to undergo treatment at the source in order to destroy the harmful microorganisms present prior to the shipment of the wastes to PNRI. This is to protect the health and safety of the facility operators and the environment as well.

The presence of harmful microorganisms such as M. Leprae and Mycobacterium Tuberculosis bacteria in C-14 liquid wastes from pathological laboratories which may be undestroyed by pre-treatment is also being considered in the choice of waste treatment. Incineration is a means of waste treatment/disposal which can destroy both organic materials and harmful microorganisms.

2.4 Liquid Waste Treatment

Liquid waste treatment are performed prior to disposal or conditioning for the following reasons:

a. to meet the required permissible concentration limit prior to discharge;
b. to adjust physical properties to the level setforth by laws;
c. to change the volume and form for more effective waste immobilization and waste minimization.

The liquid wastes treatment methods are as follows:

2.4.1 Delay/Decay Storage

Liquid wastes containing short-lived radionuclide (half-lives of less than 2 years) are stored in a designated decay room until the time that the activity has gone down to a level which is within the limit for discharge. (Refer to Table 3 Appendix A for Derived Water Concentration Limit.)

2.4.2 pH Adjustment

Aqueous liquid wastes which are either acidic or basic and have undergone radioactive decay are treated in order to adjust the pH to neutral level prior to its discharge.

2.4.3 Dilution to Permissible Concentration Limit

Aqueous liquid wastes after undergoing chemical treatment are diluted by water prior to discharge. The Code of PAEC Regulations (CPR) contains a section providing the limit for permissible discharge , both for controlled and uncontrolled areas.

2.4.4 Precipitation

Precipitation is being considered and studied for the treatment of aqueous liquid wastes containing Co-60, Co-58, Cr-51, Fe-59, Mn-54, Cs-134, Cs-137, Sr-89, and Sr-90.

Generally, precipitation may be carried out by the following process:

- lime-soda process
- phosphate precipitation
- hydroxide process
- oxalate precipitation

Table 4 of Appendix B provides a list of simple process treatment which can be applied for liquid waste treatment.

For the existing long-lived aqueous liquid wastes at PNRI, the following precipitation processes may be efficient as well as simple:

For Co-60, and also Co-58, Cr-51, Mn-54, and Fe-59:

- precipitation by $Fe(NO_3)_3.9H_2O$ and NaOH at initial pH of 7-9 followed by co-precipitation with $Fe(OH)_3$.

For Cs-137 and Sr-90:

- precipitation by $Ni_2[Fe(CN)_6]$, $Ca(NO_3)_2$, and $Na_3PO4.12H_2O.12H_2O$ at initially adjusted pH of 10-11.5. Cs-137 will coagulate with Nickel salt while Sr-90 will co-precipitate with $Ca_3(PO_4)_2$.

If the process is efficient enough, the supernatant liquid can be released for discharge.

2.4.5 Incineration

Incineration is already implemented in the Institute for disposal of background level and non-radioactive wastes. The process, however, if properly designed can be applicable for the disposal of combustible organic liquid wastes containing only C-14 and H-3. (Refer to references 2 and 3.) Organic liquid wastes containing C-14 and H-3 may be absorbed or sprayed in a batch of combustible solid non-radioactive wastes and incinerated. The process will eventually result to the dispersion of C-14 and H-3 which have been converted

to CO_2 and H_2O, respectively in the stack gases. The use of excess oxygen supply will minimize incomplete combustion and minimize the presence of unconverted C-14 and H-3 in the ash.

In the adoption of the above method, the following should be taken into account:

- the ratio of the C-14 and/or H-3 in the waste to the total non-radioactive combustible wastes/fuel to be used so as not to exceed the Derived Air Concentration Limit (DAC) provided in IAEA Safety Series No.9 (Refer to reference No. 5);

- the flume of the stack gases should not allow direct exposure of any building within fifty (50) feet of radius around the facility;

- re-charging of ashes should be carried out in case test results show presence of unburned carbon.

- the total amount of radionuclide subjected to incineration should be less than the Annual Limit Intake (ALI) provided in IAEA Safety Series No. 9.

2.4.6 Burial

PNRI presently has not adopted burial as means of radioactive wastes disposal. Considering C-14/H-3 containing wastes generated by biological/pathological research laboratories which are primarily fatty acid substrate or amino acids, microbiological decay by burial is considered applicable and subjected to study.

2.5 Waste Conditioning

Conditioning is the last stage in the processing of wastes intended to immobilize wastes prior to interim storage or shipment to a designated final repository site.

Cementation technology was the first yet still the most widely applied technique

for the conditioning of radioactive wastes. Compared with other methods, it is relative simple and inexpensive. The quality of the final cemented waste form depends very much on the composition of wastes and the geometry of the arrangement of packages included and also on the type of cement used. The compatibility of the type of cement with the type of waste should also be considered.

Aqueous liquid wastes containing long-lived beta-gamma emitters are immobilized by mixing with cement slurry in a 100 liter steel drum. When dried, the immobilized waste in 100 liter drum is then over-packed with cement in a 200 liter steel drum. When dried, and coded, this conditioned waste package is brought to the trench for interim storage.

In the cementation process, transport regulations of radioactive wastes are taken into consideration because of the anticipated future shipment of the package to the designated radioactive waste final repository site.

3.0 CONCLUSION/RECOMMENDATIONS

In the country's stage of industrial and technical growth, it is expected that the use of radioactive materials will also grow a wide range resulting to generation of varied type/composition of liquid wastes. For such reason, it is recommended that more extensive studies be carried out in improving PNRI waste characterization. Assessment on the design and applicability of proposed new processes should be taken with more serious consideration in order to improve waste minimization technique and to be able to have more extensive life expectancy of proposed final radwaste repository site.

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4. IAEA Safety Series No. 9, Basic Safety Standards for Radiation Protection, 1982 Edition

5. IAEA Technical Report Series 337, Chemical Precipitation Process for the Treatment of Radioactive Wastes, 1992 Edition

6. IAEA Technical Report Series 349, Report on Radioactive Wastes Disposal, 1993 Edition

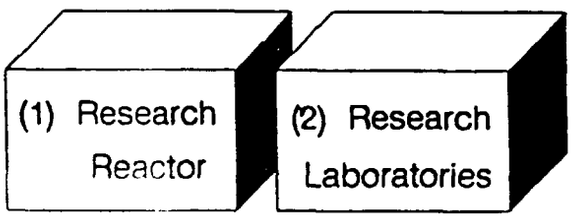
7. IAEA Technical Report Series 350, Improved Cement Solidification of Low and Intermediate Level Radioactive Wastes, 1993 Edition

8. WAMAP Mission Report, 1989

Appendix A

Fig. 1. RADIOACTIVE WASTES GENERATORS

A. PNRI On-Site Generators



B. Licensed Radioactive Material Users

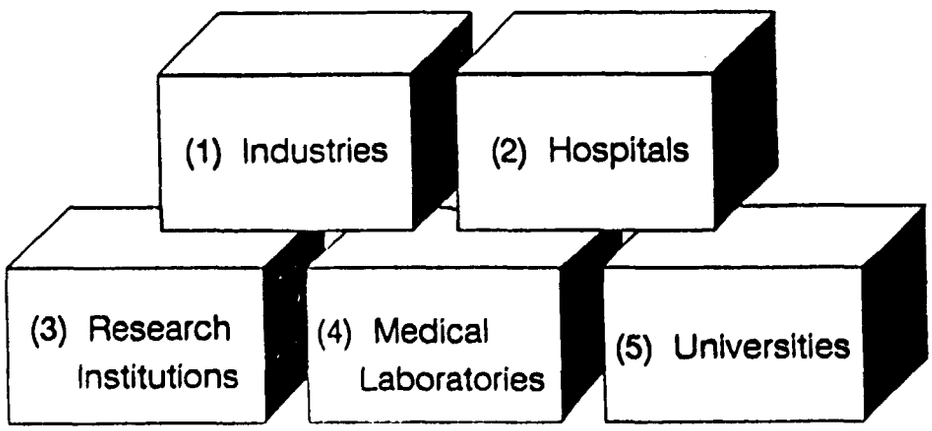


Fig. 2. Breakdown of Liquid Wastes Managed in PNRI

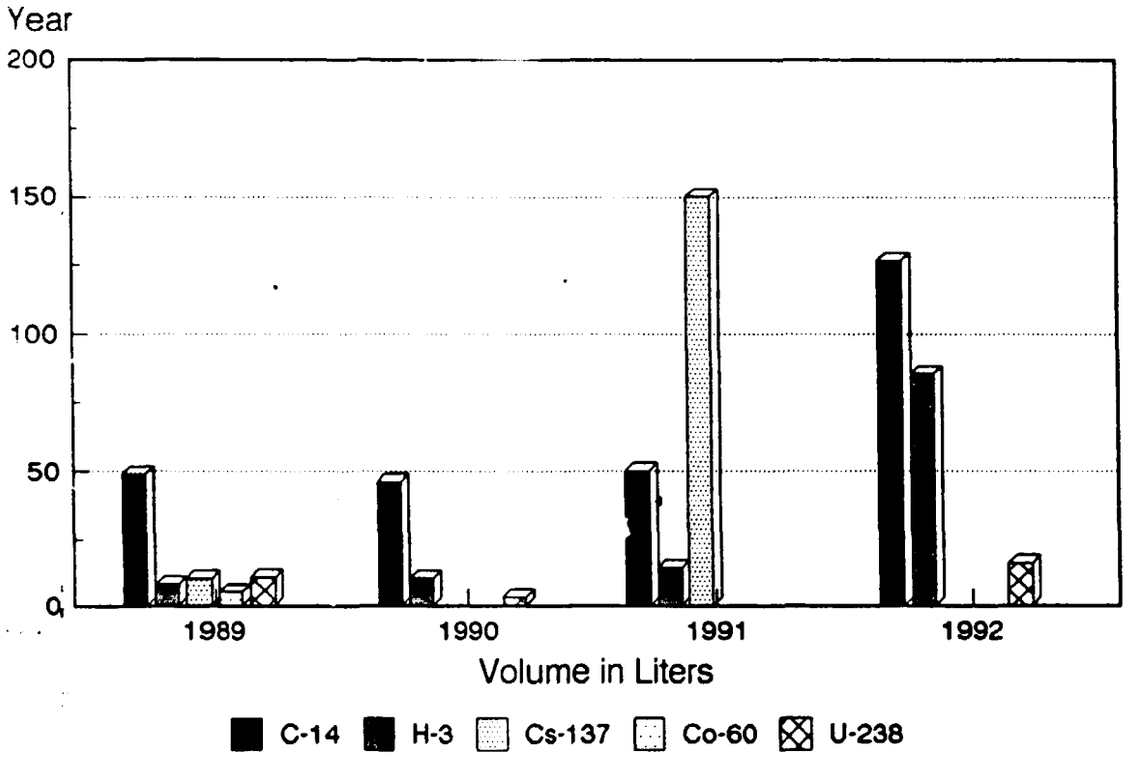
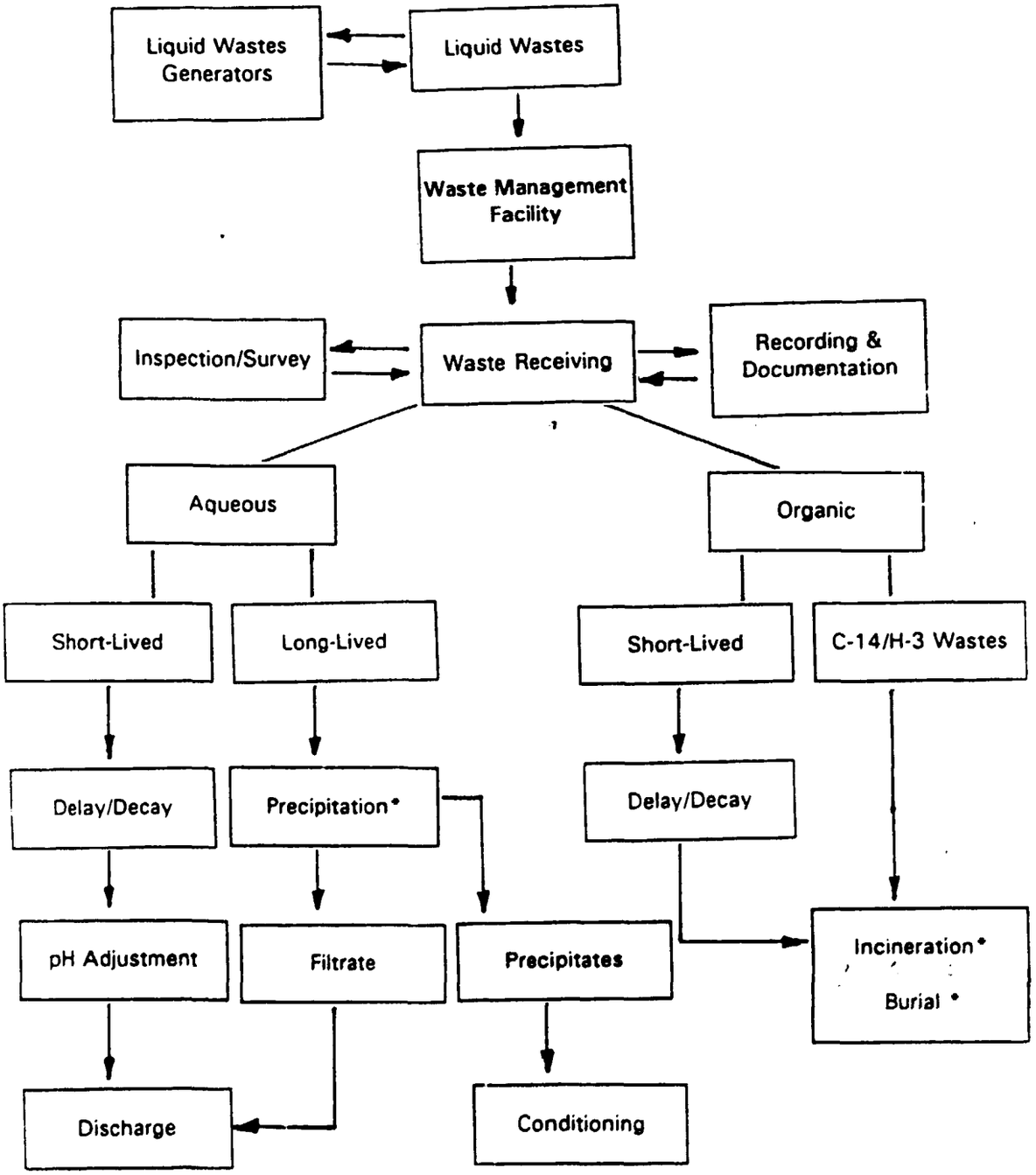


Fig. 3. FLOW DIAGRAM OF LIQUID WASTE MANAGEMENT AT PNRI



Note: * Still under evaluation.

Appendix B

Table 1. INVENTORY OF LIQUID WASTES ACCEPTED BY PNRI FOR MANAGEMENT

		1989	1990	1991	1992
A. Long-Lived Radioisotopes					
C-14	Aqueous	8.55	9.3	31.736	3
	Organic	40	37	18.5	123.544
H-3	Aqueous	0.028		1	19.5
	Organic	8	10	13	66
Cs-137	Aqueous	10.05		150	
Co-60	Aqueous	5.05			
U-238	Aqueous	10.5	3		16
B. Short-Lived Radioisotopes					
Tc-99m	Aqueous				8
S-35	Aqueous				
	Organic				2.5
I-125	Aqueous				9
	Organic				2
P-32	Aqueous				
	Organic				4
I-131	Aqueous		3		17
	Organic				
Cs-134	Aqueous			140	

Note: Quantities of liquid wastes are in liters.

Table 2.

RADIOACTIVE WASTE MATERIAL CATEGORIES

Waste Category	Content (Single radionuclide or combination of what are listed in a specific category)
A-1	radionuclides with half-lives ≤ one month ex. I-131
A-2	radionuclides with half-lives > one month and ≤ one year
B-1	radionuclides with half-lives > one year but ≤ five years ex. Cs-134, Co-60
B-2	radionuclides with half-lives > five years ≤ 20 years ex. H-3
B-3	radionuclides with half-lives > 20 years but ≤ 100 years ex. Cs-137
C-1	radionuclides with half-lives > 100 years but ≤ 500 years ex. Am-241
C-2	radionuclides with half-lives > 500 years ex. C-14, U-238, Pu-239, Th-230

Table 3. DERIVED WATER CONCENTRATIONS (DWC) OF RADIONUCLIDES

Element (Atomic Number)	Isotope[1]		Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Actinium (89)	Ac 227	S	2E0	8E-2
		I	3E2	1E1
	Ac 228	S	1E2	4E0
		I	1E2	4E0
Americium (95)	Am 241	S	4E0	2E-1
		I	3E1	8E-1
	Am 242m	S	4E0	2E-1
		I	1E2	4E0
	Am 242	S	2E2	4E0
		I	2E2	4E0
	Am 243	S	4E0	2E-1
		I	3E1	1E0
	Am 244	S	4E3	2E2
		I	4E3	2E2
Antimony (51)	Sb 122	S	3E1	1E0
		I	3E1	1E0
	Sb 124	S	3E1	8E-1
		I	3E1	8E-1
	Sb 125	S	1E2	4E0
		I	1E2	4E0
Argon (18)	A 37	Sub[2]	...	...
	A 41	Sub	...	...
Arsenic (33)	As 73	S	4E2	2E1
		I	4E2	2E1
	As 74	S	8E1	2E0
		I	8E1	2E0
	As 76	S	2E1	8E-1
		I	2E1	8E-1
	As 77	S	8E1	3E0
		I	8E1	3E0
Astatine (85)	At 211	S	2E0	8E-2
		I	8E1	3E0

Element (Atomic Number)	Isotope[1]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Barium (56)	Ba	131	S	2E2	8E0
			I	2E2	8E0
	Ba	140	S	3E1	1E0
			I	3E1	8E-1
Berkelium (97)	Bk	249	S	8E2	2E1
			I	8E2	2E1
	Bk	250	S	2E3	8E0
			I	2E2	8E0
Beryllium (4)	Be	7	S	2E3	8E1
			I	2E3	8E1
Bismuth (83)	Bi	206	S	4E1	2E0
			I	4E1	2E0
	Bi	207	S	8E1	2E0
			I	8E1	2E0
	Bi	210	S	4E1	2E0
			I	4E1	2E0
	Bi	212	S	4E2	2E1
			I	4E2	2E1
Bromine (35)	Br	82	S	3E2	1E1
			I	4E1	2E0
Cadmium (48)	Cd	109	S	2E2	8E0
			I	2E2	8E0
	Cd	115m	S	3E1	1E0
			I	3E1	1E0
	Cd	115	S	4E1	1E0
			I	4E1	2E0
Calcium (20)	Ca	45	S	1E1	4E-1
			I	2E2	8E0
	Ca	47	S	4E1	2E0
			I	4E1	1E0
Californium (98)	Cf	249	S	4E0	2E0
			I	3E1	8E-1
	Cf	250	S	2E1	4E-1
			I	3E1	1E0
	Cf	251	S	4E0	2E-1
			I	3E1	1E0
	Cf	252	S	3E1	8E-1
			I	3E1	8E-1
	Cf	253	S	2E2	4E0
			I	2E2	4E0
	Cf	254	S	2E-1	4E-3
			I	2E-1	4E-3

Element (Atomic Number)	Isotope[1]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Carbon	C	14	S	8E2	3E1
(6)	(CO_2)		Sub	...	...
Cerium	Ce	141	S	1E2	4E0
(58)			I	1E2	4E0
	Ce	144	S	1E1	4E-1
			I	1E1	4E-1
Cesium	Cs	131	S	3E3	8E1
(55)			I	1E3	4E1
	Cs	134m	S	8E3	2E2
			I	1E3	4E1
	Cs	134	S	1E1	4E-1
			I	4E1	2E0
	Cs	135	S	1E2	4E0
			I	3E2	8E0
	Cs	136	S	8E1	4E0
			I	8E1	2E0
	Cs	137	S	2E1	8E-1
			I	4E1	2E0
Chlorine	Cl	36	S	8E1	3E0
(17)			I	8E1	3E0
	Cl	38	S	4E2	2E1
			I	4E2	2E1
Chromium	Cr	51	S	2E3	8E1
(24)			I	2E3	8E1
Cobalt	Co	57	S	8E2	2E1
(27)			I	4E2	2E1
	Co	58m	S	3E3	1E2
			I	2E3	8E1
	Co	58	S	2E2	4E0
			I	1E2	4E0
	Co	60	S	4E1	2E0
			I	4E1	1E0
Copper	Cu	64	S	4E2	1E1
(29)			I	2E2	8E0

Element (Atomic Number)	Isotope[1]		Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Curium (96)	Cm 242	S	3E1	8E-1
		I	3E1	1E0
	Cm 243	S	4E0	2E-1
		I	3E1	8E-1
	Cm 244	S	8E0	3E-1
		I	3E1	1E0
	Cm 245	S	4E0	2E-1
		I	3E1	1E0
	Cm 246	S	4E0	2E-1
		I	3E1	1E0
	Cm 247	S	4E0	2E-1
		I	2E1	8E-1
	Cm 248	S	4E-1	2E-2
		I	2E0	4E-2
	Cm 249	S	2E3	8E1
		I	2E3	8E1
Dysprosium (66)	Dy 165	S	4E2	2E1
		I	4E2	2E1
	Dy 166	S	4E1	2E0
		I	4E1	2E0
Einsteinium (99)	Es 253	S	3E1	8E-1
		I	3E1	8E-1
	Es 254m	S	2E1	8E-1
		I	2E1	8E-1
	Es 254	S	2E1	4E-1
		I	2E1	4E-1
	Es 255	S	3E1	1E0
		I	3E1	1E0
Erbium (68)	Er 169	S	1E2	4E0
		I	1E2	4E0
	Er 171	S	1E2	4E0
		I	1E2	4E0
Europium (63)	Eu 152 (T/2 - 9.2 hrs)	S	8E1	2E0
		I	8E1	2E0
	Eu 152 (T/2 - 13 yrs)	S	8E1	3E0
		I	8E1	3E0
	Eu 154	S	2E1	8E-1
		I	2E1	8E-1
	Eu 155	S	2E2	8E0
		I	2E2	8E0
Fermium (100)	Fm 254	S	2E2	4E0
		I	2E2	4E0
	Fm 255	S	4E1	1E0
		I	4E1	1E0
	Fm 256	S	1E0	4E-2
		I	1E0	4E-2

Element (Atomic Number)	Isotope[a]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Fluorine	F	18	S	8E2	3E1
(9)			I	4E2	2E1
Gadolinium	Gd	153	S	2E2	8E0
(64)			I	2E2	8E0
	Gd	159	S	8E1	3E0
			I	8E1	3E0
Gallium	Ga	72	S	4E1	1E0
(31)			I	4E1	1E0
Germanium	Ge	71	S	2E3	8E1
(32)			I	2E3	8E1
Gold	Au	196	S	2E2	8E0
(79)			I	2E2	4E0
	Au	198	S	8E1	2E0
			I	4E1	2E0
	Au	199	S	2E2	8E0
			I	2E2	8E0
Hafnium	Hf	181	S	8E1	3E0
(72)			I	8E1	3E0
Holmium	Ho	166	S	4E1	1E0
(67)			I	4E1	1E0
Hydrogen	H	3	S	4E3	1E2
(1)			I	4E3	1E2
			Sub	...	...
Indium	In	113m	S	2E3	4E1
(49)			I	2E3	4E1
	In	114m	S	2E1	8E-1
			I	2E1	8E-1
	In	115m	S	4E2	2E1
			I	4E2	2E1
	In	115	S	1E2	4E0
			I	1E2	4E0
Iodine	I	125	S	2E0	8E-3
(53)			I	2E2	8E0
	I	126	S	2E0	1E-2
			I	1E2	4E0
	I	129	S	4E-1	2E-3
			I	2E2	8E0
	I	131	S	2E0	1E-2
			I	8E1	2E0
	I	132	S	8E1	3E-1
			I	2E2	8E0

Element (Atomic Number)	Isotope[1]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
	I	133	S	8E0	4E-2
			I	4E1	2E0
	I	134	S	2E2	8E-1
			I	8E2	2E1
	I	135	S	3E1	2E-1
			I	8E1	3E0
Iridium	Ir	190	S	2E2	8E0
(77)			I	2E2	8E0
	Ir	192	S	4E1	2E0
			I	4E1	2E0
	Ir	194	S	4E1	1E0
			I	4E1	1E0
Iron	Fe	55	S	8E2	3E1
(26)			I	3E3	8E1
	Fe	59	S	8E1	2E0
			I	8E1	2E0
Krypton	Kr	85m	Sub	...	...
(36)	Kr	85	Sub	...	...
	Kr	87	Sub	...	...
	Kr	88	Sub	...	...
Lanthanum	La	140	S	3E1	8E-1
(57)			I	3E1	8E-1
Lead	Pb	203	S	4E2	2E1
(82)			I	4E2	2E1
	Pb	210	S	2E-1	4E-3
			I	2E3	8E0
	Pb	212	S	2E1	8E-1
			I	2E1	8E-1
Lutetium	Lu	177	S	1E2	4E0
(71)			I	1E2	4E0
Manganese	Mn	52	S	4E1	1E0
(25)			I	4E1	1E0
	Mn	54	S	2E2	4E0
			I	1E2	4E0
	Mn	56	S	1E2	4E0
			I	1E2	4E0
Mercury	Hg	197m	S	2E2	8E0
(80)			I	2E2	8E0
	Hg	197	S	4E2	1E1
			I	4E2	2E1
	Hg	203	S	2E1	8E-1
			I	1E2	4E0

Element (Atomic Number)	Isotope[1]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Molybdenum (42)	Mo	99	S	2E2	8E0
			I	4E1	2E0
Neodymium (60)	Nd	144	S	8E1	3E0
			I	8E1	3E0
	Nd	147	S	8E1	2E0
			I	8E1	2E0
	Nd	149	S	3E2	1E1
			I	3E2	1E1
Neptunium (93)	Np	237	S	4E0	1E-1
			I	4E1	1E0
	Np	239	S	2E2	4E0
			I	2E2	4E0
Nickel (28)	Ni	59	S	2E2	8E0
			I	2E3	8E1
	Ni	63	S	3E1	1E0
			I	8E2	3E1
	Ni	65	S	2E2	4E0
			I	1E2	4E0
Niobium (41)	Nb	93m	S	4E2	2E1
			I	4E2	2E1
	Nb	95	S	1E2	4E0
			I	1E2	4E0
	Nb	97	S	1E3	4E1
			I	1E3	4E1
Osmium (76)	Os	185	S	8E1	3E0
			I	8E1	3E0
	Os	191m	S	3E3	1E2
			I	3E3	8E1
	Os	191	S	2E2	8E0
			I	2E2	8E0
	Os	193	S	8E1	2E0
			I	8E1	2E0
Palladium (46)	Pd	103	S	4E2	1E1
			I	3E2	1E1
	Pd	109	S	1E2	4E0
			I	8E1	3E0
Phosphorus (15)	P	32	S	2E1	8E-1
			I	3E1	8E-1

Element (Atomic Number)	Isotope[1]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Platinum	Pt	191	S	2E2	4E0
(78)			I	1E2	4E0
	Pt	193m	S	1E3	4E1
			I	1E3	4E1
	Pt	193	S	1E3	4E1
			I	2E3	8E1
	Pt	197m	S	1E3	4E1
			I	1E3	4E1
	Pt	197	S	2E2	4E0
			I	1E2	4E0
Plutonium	Pu	238	S	4E0	2E-1
(94)			I	3E1	1E0
	Pu	239	S	4E0	2E-1
			I	3E1	1E0
	Pu	240	S	4E0	2E-1
			I	3E1	1E0
	Pu	241	S	3E2	8E0
			I	2E3	4E1
	Pu	242	S	4E0	2E-1
			I	4E1	1E0
	Pu	243	S	4E2	1E1
			I	4E2	1E1
	Pu	244	S	4E0	2E-1
			I	1E1	4E-1
Polonium	Po	210	S	8E-1	3E-2
(84)			I	3E1	1E0
Potassium	K	42	S	4E2	1E1
(19)			I	2E1	8E-1
Praseodymium	Pr	142	S	4E1	1E0
(59)			I	4E1	1E0
	Pr	143	S	4E1	2E0
			I	4E1	2E0
Promethium	Pm	147	S	2E2	8E0
(61)			I	2E2	8E0
	Pm	149	S	4E1	2E0
			I	4E1	2E0
Protoactinium	Pa	230	S	3E2	8E0
(91)			I	3E2	4E-2
	Pa	231	S	1E0	8E-1
			I	3E1	4E0
	Pa	233	S	2E2	4E0
			I	1E2	8E0

Element (Atomic Number)	Isotope[1]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Radium (88)	Ra	223	S	8E-1	3E-2
			I	4E0	2E-1
	Ra	224	S	3E0	8E-2
			I	8E0	2E-1
	Ra	226	S	2E-2	1E-3
			I	4E1	1E0
	Ra	228	S	3E-2	1E-3
			I	3E1	1E0
Radon (86)	Rn	220	S	...	...
			I	...	...
	Rn	222	S	...	...
Rhenium (75)	Re	183	S	8E2	2E1
			I	3E2	1E1
	Re	186	S	1E2	4E0
			I	4E1	2E0
	Re	187	S	3E3	1E2
			I	2E3	8E1
	Re	188	S	8E1	2E0
			I	4E1	1E0
Rhodium (45)	Rh	103m	S	2E4	4E2
			I	1E4	4E2
	Rh	105	S	2E2	4E0
			I	1E2	4E0
Rubidium (37)	Rb	86	S	8E1	3E0
			I	3E1	8E-1
	Rb	87	S	1E2	4E0
			I	2E2	8E0
Ruthenium (44)	Ru	97	S	4E2	2E1
			I	4E2	1E1
	Ru	103	S	8E1	3E0
			I	8E1	3E0
	Ru	105	S	1E2	4E0
			I	1E2	4E0
	Ru	106	S	2E1	4E-1
			I	2E1	4E-1
Samarium (62)	Sm	147	S	8E1	2E0
			I	8E1	3E0
	Sm	151	S	4E2	2E1
			I	4E2	2E1
	Sm	153	S	8E1	3E0
			I	8E1	3E0

Element (Atomic Number)	Isotope[1]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Scandium	Sc	46	S	4E1	2E0
(21)			I	4E1	2E0
	Sc	47	S	1E2	4E0
			I	1E2	4E0
	Sc	48	S	3E1	1E0
			I	3E1	1E0
Selenium	Se	75	S	4E2	1E1
(34)			I	3E2	1E1
Silicon	Si	31	S	1E3	4E1
(14)			I	2E2	8E0
Silver	Ag	105	S	1E2	4E0
(47)			I	1E2	4E0
	Ag	110m	S	4E1	1E0
			I	4E1	1E0
	Ag	111	S	4E1	2E0
			I	4E1	2E0
Sodium	Na	22	S	4E1	2E0
(11)			I	4E1	1E0
	Na	24	S	2E2	8E0
			I	3E1	1E0
Strontium	Sr	85m	S	8E3	3E2
(38)			I	8E3	3E2
	Sr	85	S	1E2	4E0
			I	2E2	8E0
	Sr	89	S	1E1	1E-1
			I	3E1	1E0
	Sr	90	S	4E-1	1E-2
			I	4E1	2E0
	Sr	91	S	8E1	3E0
			I	4E1	2E0
	Sr	92	S	8E1	3E0
			I	8E1	2E0
Sulfur	S	35	S	8E1	2E0
(16)			I	3E2	1E1
Tantalum	Ta	182	S	4E1	2E0
(73)			I	4E1	2E0
Technetium	Tc	96m	S	2E4	4E2
(43)			I	1E4	4E2
	Tc	96	S	1E2	4E0
			I	4E1	2E0
	Tc	97m	S	4E2	2E1
			I	2E2	8E0

Element (Atomic Number)	Isotope[1]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
	Tc	97	S	2E3	8E1
			I	8E2	3E1
	Tc	99m	S	8E3	2E2
			I	3E3	1E2
	Tc	99	S	4E2	1E1
			I	2E2	8E0
Tellurium (52)	Te	125m	S	2E2	8E0
			I	1E2	4E0
	Te	127m	S	8E1	2E0
			I	8E1	2E0
	Te	127	S	3E2	1E1
			I	2E2	8E0
	Te	129m	S	4E1	1E0
			I	2E1	8E-1
	Te	129	S	8E2	3E1
			I	8E2	3E1
	Te	131m	S	8E1	2E0
			I	4E1	2E-4
	Te	132	S	4E1	1E0
			I	2E1	8E-1
Terbium (65)	Tb	160	S	4E1	2E0
			I	4E1	2E0
Thallium (81)	Tl	200	S	4E2	2E1
			I	3E2	8E0
	Tl	201	S	4E2	1E1
			I	2E2	8E0
	Tl	202	S	2E2	4E0
			I	8E1	3E0
	Tl	204	S	1E2	4E0
			I	8E1	2E0
Thorium (90)	Th	227	S	2E1	8E-1
			I	2E1	8E-1
	Th	228	S	8E0	3E-1
			I	2E1	4E-1
	Th	230	S	2E0	8E-2
			I	4E1	1E0
	Th	231	S	3E2	8E0
			I	3E2	8E0
	Th	232	S	2E0	8E-2
			I	4E1	2E0
	Th	Natural	S	2E0	8E-2
			I	2E1	8E-1
	Th	234	S	2E1	8E-1
			I	2E1	8E-1

Element (Atomic Number)	Isotope[a]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Thulium	Tm	170	S	4E1	2E0
(69)			I	4E1	2E0
	Tm	171	S	4E2	2E1
			I	4E2	2E1
Tin	Sn	113	S	8E1	4E0
			I	8E1	3E0
	Sn	125	S	2E1	8E-1
			I	2E1	8E-1
Tungsten	W	181	S	4E2	2E1
(Wolfram)			I	4E2	1E1
	W	185	S	2E2	4E0
			I	1E2	4E0
	W	187	S	8E1	3E0
			I	8E1	2E0
Uranium	U	230	S	4E0	2E-1
(92)			I	4E0	2E-1
	U	232	S	3E1	1E0
			I	3E1	1E0
	U	233	S	4E1	1E0
			I	4E1	1E0
	U	234	S	4E1	1E0
			I	4E1	1E0
	U	235	S	3E1	1E0
			I	3E1	1E0
	U	236	S	4E1	1E0
			I	4E1	1E0
	U	238	S	4E1	2E0
			I	4E1	2E0
	U	240	S	4E1	1E0
			I	4E1	1E-1
	U-Natural		S	2E1	8E-1
			I	2E1	8E-1
Vanadium	V	48	S	4E1	1E0
(23)			I	3E1	1E0
Xenon	Xe	131m	Sub	...	...
(54)	Xe	133	Sub	...	...
	Xe	133m	Sub	...	...
	Xe	135	Sub	...	...
Ytterbium	Yb	175	S	1E2	4E0
(70)			I	1E2	4E0

Element (Atomic Number)	Isotope[1]			Restricted Areas Bq/ml	Unrestricted Areas Bq/ml
Yttrium	Y	90	S	2E1	8E-1
(39)			I	2E1	8E-1
	Y	91m	S	4E3	1E2
			I	4E3	1E2
	Y	91	S	3E1	1E0
			I	3E1	1E0
	Y	92	S	8E1	2E0
			I	8E1	2E0
	Y	93	S	3E1	1E0
			I	3E1	1E0
Zinc	Zn	65	S	1E2	4E0
(30)			I	2E2	8E0
	Zn	69m	S	8E1	3E0
			I	8E1	2E0
	Zn	69	S	2E3	8E1
			I	2E3	8E1
Zirconium	Zr	93	S	8E2	3E1
(40)			I	8E2	3E1
	Zr	95	S	8E1	2E0
			I	8E1	2E0
	Zr	97	S	2E1	8E-1
			I	2E1	8E-1
Any single radionuclide not listed above with decay mode other than alpha emission or spontaneous fission and with radioactive half-life less than 2 hours			Sub	...	...
Any single radionuclide not listed above with decay mode other than alpha emission or spontaneous fission and with radioactive half-life greater than 2 hours				4E0	1E-1
Any single radionuclide not listed above, which decays by alpha emission or spontaneous fission.....				2E-2	1E-3

[1] Soluble (S); Insoluble (I).

[2] "Sub" means that values given for submersion in a semispherical infinite cloud of air-borne material.

Table 4. TREATMENT PROCESS

Nuclides	Simple processes	pH	Expected DF
Pu, Am	Hydroxides (especially ferric), oxalates	7–12 1	>1000
^{51}Cr	Ferrous hydroxide	>8.5	>100
^{54}Mn	Manganese hydroxide, manganese dioxide	>8.5	>100
^{58}Co, ^{60}Co, ^{59}Fe	Ferrous or ferric hydroxides	>8.5	>100
^{90}Sr	Ferrous hydroxides	7–13	pH dependent
	Calcium or iron phosphate	>11	>100
	Calcium carbonate	10.5	>100
	Manganese dioxide	>11	>100
	Barium sulphate	>8.5	>100
	Polyantimonic acid	≈1	>100
Zr, Nb, Ce	Hydroxides (especially ferric)	>8.5	100–1000
Sb	Ferrous hydroxides	5–8.5	5–10
	Titanium hydroxide	5–8.5	10–100
	Polyantimonic acid and manganese dioxide	≈1	20–40
	Diuranate	8.5–10.5	20–30
Ru	Ferrous hydroxide	5–8.5	5–10
	Copper + ferrous hydroxides	8.5	10–25
	Cobalt sulphide	1–8.5	30–150
	Sodium borohydride	8.5	50
Cs	Ferrocyanide	6–10	>100
	Zeolite	7–11	10
	Tetraphenylborate	1–13	100–1000
	Phosphotungstic acid	≈1	>100
	Ammonium phosphomolybdate	0–9.5	>10