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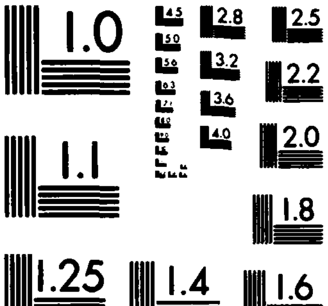

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Low-Level Radioactive Waste Vitrification (LLWV) is a technically feasible and cost competitive alternative to the traditional immobilization options, i.e., cementation or bituminization. This thesis analyzes cementation, bituminizatio and vitrification, reviews the impact of the Low-Level Waste stream composition on the vitrification process, then proposes and discusses several techniques to control the votile radionuclides in a Process Improved LLWV system (PILLWV). The techniques that control the volatile radionuclides include chemical precipitation, electrodialysis, and ion exchange. Ion exchange is preferred. A com-

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parison of the technical sppecifications, of the regulatory compliance, and of the cost considerations shows the PILLWV to be the superiorLLW immobilization option.

An Improvement to Low-Level Radioactive Waste Vitrification Processes

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May 86

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A thesis submitted to the University of Illinois, Urbana , IL in partial fulfillment of the requirements for the degree of Master of Science in Nuclear Engineering.

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AN IMPROVEMENT
TO
LOW-LEVEL RADIOACTIVE WASTE
VITRIFICATION PROCESSES

BY

WALTER SAN HORTON

B.S., Clemson University, 1973

Thesis

Submitted in partial fulfillment of the requirements
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APPENDIX

LIST OF ABBREVIATIONS

AEIC	Annual Equivalent Installation Cost
AIOC	Annual Installation and Operation Cost
AGD	Above Ground Disposal
A_e	Activity of Effluent
A_i	Activity of Influent
BWR	Boiling Water Reactor
CFR	Code of Federal Regulations
Ci	Curie
Conc	Concentration
DBA	Design Basis Accident
DF	Decontamination Factor
DOE	United States Department of the Energy
DOT	United States Department of Transportation
DWPF	Defense Waste Processing Facility
E-1	$1*10^{-1} = 0.1$
EIE	Electrodialysis-Ion Exchange
EPA	United States Environmental Protection Agency
ELECD	Electrodialysis
ESLB	Enhanced Shallow Land Burial
ft^3	Cubic Foot
HLW	High Level Waste
hr	Hour

IAEA	International Atomic Energy Agency
L	Liter
LLWV	Low-Level Waste Vitrification
LWR	Light Water Reactor
m^3	Cubic Meter
mrem	Millirem
MWe	Mega Watt Electric
nCi	NanoCurie
NRC	United States Nuclear Regulatory Commission
PILLWV	Process Improved Low-Level Waste Vitrification
PVC	Polyvinyl Chloride
PWR	Pressurized Water Reactor
rem	Unit Dose Equivalent in cgs system
SLB	Shallow Land Burial
Soln	Solution
TMI	Three Mile Island
VR	Volume Reduction

CHAPTER 1

INTRODUCTION

1.1 Introduction

The operation of nuclear reactors generates radioactive wastes that require effective, and economical immobilization and disposal.

The traditional Low-Level Radioactive Waste (LLW) immobilization options are cementation or bituminization. Either of these options could be followed by Shallow Land Burial (SLB) or Above Ground Disposal. These rather simple LLW procedures appeared to be readily available, to meet regulatory requirements, and to satisfy cost constraints. The authorization of State Compacts, the forced closure of half of the six SLB disposal facilities of the U.S., and the escalation of transportation/disposal fees diminish the viability of these immobilization options. The synergetic combination of these factors led to a reassessment of traditional methods and to an investigation of other techniques. Low Level Radioactive Waste Vitrification (LLWV) is a technically feasible, and cost competitive alternative to the existing LLW immobilization options.[1] This thesis proposes several techniques to control the volatile radionuclides in LLWV.

1.2 Scope of this Thesis

The purpose of this thesis is to analyze the traditional LLW immobilization options, to review the impact of the LLW stream composition on LLWV, then to propose and discuss several techniques to control the volatile radionuclides in a Process Improved LLWV system (PILLWV). This chapter contains the introduction and background information. The background section of this chapter clarifies for the reader the radioactive waste management terminology. Chapter 2 analyzes the most common LLW immobilization options. The next chapter proposes several improvements to the LLWV process which is described in Ref.1. These improvements are applications of existing technology to the LLWV system and are aimed at controlling the volatile radionuclides. Chapter 4 illustrates the regulatory compliance of the PILLWV waste form and provides a cost estimation of an ion exchange PILLWV. The final chapter summarizes the thesis results and presents recommendations for further work. The general results of chapter 3 and chapter 4 were presented at the Waste Management '86 conference and are to be published.[2]

1.3 Terminology Review

The terminology of the Radioactive Waste Management is both dynamic and confusing even for an expert. This dismal state of affairs results from the lack of a single controlling agency that is responsible for terminology standardization, and from the interdisciplinary nature of Radioactive Waste Management. This section reviews and clarifies the currently accepted terminology.

Radioactive Wastes[3] (Radwaste) is:

> the generic term for gases, liquids, solids, and equipment produced or used in nuclear operations of negligible economic value that contain radionuclides in excess of threshold quantities except for radioactive material from post weapons test activities.

In the U.S. Radwaste is subdivided into three categories: High-level Radioactive Wastes (HLW), Transuranic Radioactive Wastes (TRU), and Low-Level Radioactive Wastes (LLW). The Nuclear Regulatory Commission defines[4,5] HLW as:

> (1) Irradiated reactor fuel, (2) liquid wastes resulting from the first-cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel, and (3) solids into which liquid wastes have been converted.

TRU's were originally defined as those wastes contaminated with U-233 or transuranic radionuclides. This was changed when 10 CFR 61 was adopted. The currently accepted definition[6] of TRU waste is:

> material of no economic value which at the end of the institutional control periods contains alpha emitters of atomic number greater than 92 (but including U-233), with half-lives of greater than 20 years and in concentrations greater than 100 nCi/g.

Finally, LLW is defined[7] as:

> radioactive wastes not classified as HLW, TRU, spent fuel, or by-product material as defined in section 11e.(2) of the Atomic Energy Act (uranium or thorium mill tailings and waste).

This broad definition of LLW includes wastes which vary greatly in radionuclide content, in physical and chemical form, and/or in specific activity.

Various Federal and State regulations prescribe the maximum Radwaste concentrations that are safe to release to the environment. Waste concentrations above these maxima require immobilization prior to disposal. Here, immobilization means the conditioning processes that yield a waste form which minimizes the migration or leaching of the Radwaste. Disposal is defined[8] as

> the isolation of radioactive wastes from the biosphere inhabited by man and containing his food chains by emplacement in a land disposal facility.

Various Radwaste immobilization and disposal schemes are used or are in development (Table 1.1).

TABLE 1.1

Radwaste Immobilization and Disposal Schemes

Waste	Immobilization Form	Disposal Technique
HLW	Clays	Geologic Burial
	Concretes	
	Calcines	
	Glasses	
	Crystalline Ceramics	
LLW	Urea-formaldehyde	Above Ground
	Cement	Enhanced Shallow Land Burial
	Bitumen (asphalt)	
	Glass	Shallow Land Burial
TRU	All of the Above (Activity Dictated)	All of the Above

Geologic Burial means disposal of Radwaste in an excavated geologic formation[9], whereas Shallow Land Burial (SLB) is Radwaste disposal in or within the upper 30 meters of the earth's surface.[10] Above Ground Disposal (AGD) is as its name implies Radwaste disposal in a structure above the earth's surface. Enhanced Shallow Land Burial (ESLB) is SLB that has been improved by incorporating engineered confinement schemes.[11]

The last term that the reader should be familiar with is the Decontamination Factor (DF). The DF is an efficiency figure of merit for processes (filters, ion exchange columns, etc.) that partition or decontaminate Radwaste streams.[12]

CHAPTER 2

LLW IMMOBILIZATION OPTIONS ANALYSIS

2.1 Introduction

The traditional LLW immobilization techniques include cementation and bituminization. Cementation incorporates the LLW into a cement matrix, while bituminization encapsulates the LLW with bitumen (asphalt). The proposed HLW immobilization process in the U.S., vitrification, incorporates the Radwaste into a glass matrix. This process is technically complex and expensive, and it initially received little consideration as an LLW immobilization alternative.

2.2 Traditional Immobilization Methods Assessment

Cementation and bituminization have been reported to present serious technical and economic disadvantages. Technical disadvantages of cementation include low waste loading, high cesium and sodium leachability, and the inherent volume increase of the waste form.[1,13] In this thesis, waste loading means the percent concentration of the radwaste in the waste form, rather than the percent of radionuclides or the percent of fission products in the waste.[14] Leaching refers to the degradation of the chemical durability of waste forms by the resultant, overall chemical reaction between radioactive waste forms and water.[15] Table

2.1 summarizes waste loadings and leachabilities of cement and glass, and shows the immobilization advantage of glass.

TABLE 2.1

Comparison of Waste Loading and Leachability[13*]

Waste Form	Waste Loading(%)	Cesium Leaching(%)
Cement	10 to 5	47.5
Glass	33	0.1
Glass Increase(Decrease)	3 to 6 times	(475) times

* Reference 13 does not specify the glass advantage.

Cement is incapable of immobilizing cesium without additional processing. Zeolite absorption schemes are used to minimize the cesium leaching in cement at defense waste treatment facilities.[16]

Bituminization, which is used extensively outside the U.S., yields a waste form that is flammable[1] and very leachable.[17] Reference 17 explicitly states that bituminization is ill-advised for immobilization of cesium. Table 2.2 summarizes the results of Ref. 17.

TABLE 2.2

Bitumen Immobilization Constraints[17]

- Cesium insolubilization
- No metals, glass, rubbish, filters, PVC
- No solvents with Boiling Points $\leq$ 140°C
- Water content $\leq$ 5%

Finally, disposal fees at the three operating SLB sites have escalated by up to 300% since 1983.[18,19] Appendix A provides the 1983 and the 1985 commercial LLW disposal rate schedules for the three SLB sites. For illustrative purposes, Table 2.3 shows the curie surcharge rate increase at Barnwell, S. C. from 1983 to 1985.

TABLE 2.3

Comparison of Curie Surcharge Fees (Barnwell,SC)

Content per Shipment (Ci)	1985 Surcharge[18] ($)	1983 Surcharge[19] ($)	Increase (%)
1.2-5	1500	500	300
75.1-100	7450	2500	298
250-500	15000	5000	300
1000.1-5000	24000	8000	300

These technical and economic problems warrant the search for an alternative to the traditional LLW immobilization options.

2.3 LLWV Immobilization Assessment

Reference 1 describes in detail a proposed LLWV process which is summarized in Fig. 1.1. Vitrification produces smaller waste volumes.[1] This advantage is a significant factor for SLB, ESLB, and/or AGD, when one considers available disposal space and disposal costs that are based upon waste volumes. Vitrification also produces a waste form with leaching resistance[13] superior to the previously reviewed methods (Table 2.1). The LLWV waste form was shown to be in compliance with the proposed regulation 10 CFR 61.[1] Since the publication of Ref.1., 10 CFR 61 was approved, and an updated assessment of the regulatory compliance of the LLWV waste form is provided in Table 2.4. Reference 1 also shows that the process is cost competitive with the traditional LLW immobilization options (Table 2.5).

2.4 LLW Stream Composition Impact on LLWV

The glass waste form of the vitrification process is produced by heating the Radwaste and glass formers to approximately 1150-1500°C. This high temperature heat treatment requires modifications to control the volatile radionuclides of LLW streams.

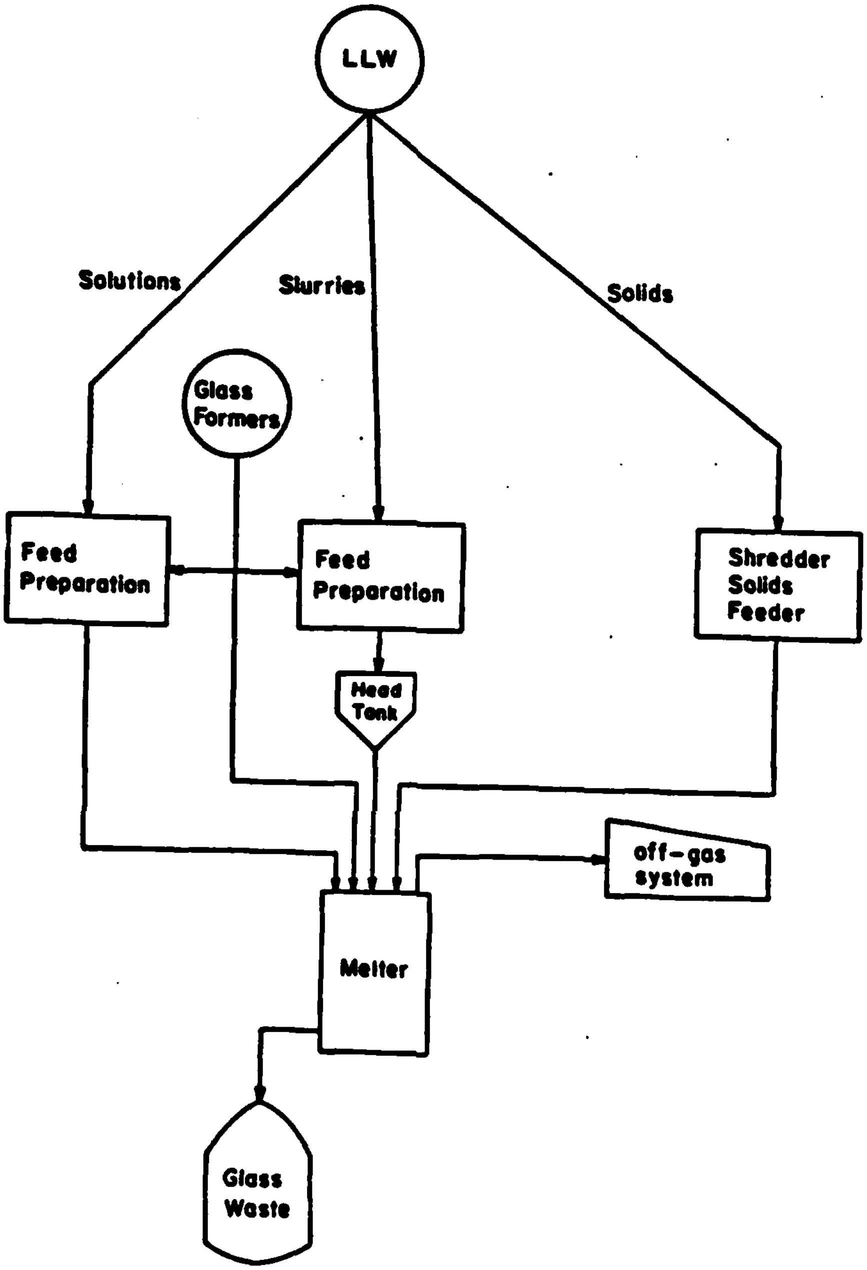

Fig. 1.1. Proposed LLWV Process[1]

TABLE 2.4

FEDERAL REGULATIONS COMPLIANCE

10 CFR 61 Part 61.56: Waste Characteristics	Properties of Waste Glass
(a) The following requirements are minimum requirements for all classes of waste and are intended to facilitate handling at the disposal site and provide protection of health and safety of personnel at the disposal site.	
(1) Wastes must not be packaged for disposal in cardboard or fiber board boxes.	(1) Waste glass is packaged in metal containers.
(2) Liquid waste must be solidified or packaged in sufficient absorbent material to absorb twice the volume of the liquid.	(2) Waste glass processing eliminates any liquid water in the waste form.
(3) Solid waste containing liquid shall contain as little free standing and noncorrosive liquid as is reasonably achievable, but in no case shall the liquid exceed 1% of the volume.	(3) Waste glass processing eliminates any liquid water in the waste form.
(4) Waste must not be readily capable of detonation or of explosive decomposition or reaction at normal pressures and temperatures, or of explosive reaction with water.	(4) Waste is chemically stable because any chemically reactive wastes are stabilized in the glass forming process.
(5) Waste must not contain, or be capable of generating quantities of toxic gases, vapors, or fumes harmful to persons transporting, handling, or disposing of the waste. This does not apply to radioactive gaseous waste packaged in accordance with paragraph (a)(7) of this section.	(5) Waste is stable and does not generate toxic gases, vapors, or fumes.
(6) Wastes must not be pyrophoric. Pyrophoric materials contained in the wastes shall be treated, prepared, and packaged to be nonflammable.	(6) Waste is not pyrophoric.
(7) Wastes in gaseous form must be packaged at a pressure that does not exceed 1.5 atmospheres at 20 degrees centigrade. Total activity must not exceed 100 curies per container.	(7) Does not apply.
(8) Wastes containing biological, pathogenic, or infectious material must be treated to reduce to the maximum extent practicable the potential hazard from the nonradiological	(8) These wastes are decomposed to nontoxic form by thermal degradation and oxidation in the glass forming process.

TABLE 2.4
(CONTINUED)

10 CFR 61 Part 61.56: Waste Characteristics	Properties of Waste Glass
(b) The requirements in this section are intended to provide stability of the waste. Stability is intended to ensure that the waste does not structurally degrade and affect overall stability of the site through slumping, collapse, or other failure of the disposal unit and thereby lead to water infiltration. Stability is also a factor in limiting exposure to an inadvertent intruder, since it provides a recognizable and nondispersible waste.	
(1) Waste must have structual stability. A structurally stable waste form will generally maintain its physical dimensions and its form, under the expected disposal conditions such as weight of overburden and compaction equipment, the presence of moisture, and microbial activity, and internal factors such as radiation effects and chemical changes. Structural stability can be provided by the waste form itself, processing the waste to a stable form, or placing the waste in a disposal container or structure that provides stability after disposal.	(1) (a) Waste glass demension change with a 100 degree centigrade temperature change is 0.1%. (b) Compressive strength of the waste glass is 6.9 to 140 MPa. (1 to 20 ksi) (c) Waste glass is chemically, thermally, and radiolytically stable.
(2) Not withstanding the provisions in Part 61.56(a)(2)and (3), liquid wastes, or wastes containing liquid, must be converted into a form that contains as little free-standing and noncorrosive liquid as is reasonably achievable, but in no case shall the liquid exceed 1% of the volume of the waste when the waste is in a disposal container designed to ensure stability, or 5% of the volume of the waste for waste processed to a a stable form.	(2) Vitrification eliminates liquid water from the waste form.
(3) Void spaces within the waste and between the waste and its package must be reduced to the extent practicable.	(3) The waste glass product is a solid monolith within its container with the exception of some cracks in the glass structure.

TABLE 2.5

ANNUAL RADWASTE MANAGEMENT COSTS[a1] (1984 $1000)

Cost Item	No Volume Reduction	Vitrification	Calcination/ Incineration	Bituminization	Evaporator/ Crystallizer	Shredding/ Compaction	Incineration
Total materials and burial	1,954	353	707	1,200	1,545	1,822	1,722
Solidification labor cost	535	37	102	128	354	535	549
VR operating cost	--	895	355	833	85	-44	229
VR amortized capital cost	--	500	902	712	203	7	289
Drum storage cost credit	--	-90	-84	-67	-27	-10	-17
Transportation to burial	2,011	694	997	2,696	1,962	1,990	1,976
Total	4,500	2,389	2,979	5,503	4,123	4,300	4,738

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[a] Case is for 1100-MWe BWR, 1250 miles transportation, Barnwell burial.

2.4.1 LLW Stream Composition

Reference 20 gives typical radionuclide compositions of LLW streams. Cesium is a predominant radionuclide in the LLW streams of Light Water Reactors.[20,21] Appendix B shows the concentrations of radionuclides in these waste streams. Table 2.6 gives the relative content of cesium activity in each these LLW streams.

TABLE 2.6

LLW Radionuclide Composition

LLW Stream	Total[20] (Ci/MWe)	Cesium[20] (Ci/MWe)	Cesium (%)
BWR	2.142	1.232	57.5
PWR	0.771	0.313	40.6

2.4.2 LLWV Safety Assessment

A Safety Assessment and Major Radionuclides in the Source Terms were reported in Ref. 1. An analysis (Table 2.7) of this Safety Assessment shows that cesium is the major contributor to the source term for LLWV Design Basis Accidents (DBA).

TABLE 2.7

Source Term Analysis

Design Basis Accident	% Cs in Source Term
Glass Leakage	100
Thermal Shock Wave	100
Inoperative Scrubber	50
Venturi Leak	50
Full Container Drop	100
Cell Cover Dropped	50
Melter Pressurization	50
Plenum Leakage	50
Regeneration Solution Spill	50

2.4.3 Cesium Test Facility Effects

Predominance in the LWR LLW stream and in the DBA source term initially identified cesium as the radionuclide to be controlled. The need for cesium control is further supported by LLLWV pilot experiments.

LLWV test results at Mound Laboratory show that cesium is sorbed in the walls of the glass melter and in the components of the off-gas system. Furthermore, the cesium can be randomly desorbed. LLW streams of 1 mCi to 5.2 mCi of cesium were vitrified. It was found that between 11% and 28% of the cesium was unaccounted for.[22]

Analysis of the experimental data reported in Ref. 22 shows significant cesium retention when ion exchange resins are vitrified. For a large number of experiments, the unaccounted cesium percentage, in average, for ion exchange resins is 12.5, whereas the unaccounted cesium percentage, in average, for dry solid wastes is 20.1.

The adsorption of cesium produces an unacceptable system mass balance.[22] The sorption and random desorption of cesium would seriously hinder the licensing process of a commercial LLWV facility.

2.5 Conclusion

Waste Loading and leachability of the LLWV waste form is superior to both cementation and bituminization.[10] Further, the LLWV glass exceeds all standards of stability as prescribed in 10CFR61.[1] The escalation of SLB disposal fees requires the use of an immobilization process which optimizes volume reduction.

Cesium is shown to be the predominant radionuclide in LLW streams,[20] to be the principal source term in DBA's,[1] and to be randomly sorbed/desorbed by the melter and off-gas components during vitrification.[22] The foregoing analysis identifies cesium as the critical volatile radionuclide that must be controlled in order to improve the proposed LLWV processes. In the next chapters, process improvements are proposed and discussed.

CHAPTER 3

PROCESS IMPROVED LLWV

3.1 Introduction

The Process Improved LLWV (PILLWV) controls the volatility of cesium by selectively incorporating the radionuclide into a vitrifiable form. In essence, the initial LLW stream is partitioned prior to the feed preparation step of Fig. 1.1. Numerous processes that selectively separate and fix cesium are reported in the literature and are in various stages of development both in the U.S. and elsewhere. These processes include ion exchange,[23,24] chemical precipitation,[25] and electrodialysis.[26] Each process in turn will be reviewed.

3.2 Ion Exchange

Ion exchange is a well developed industrial application and is currently used in the management of High-Level Wastes (HLW) at Defense Waste Processing Facilities.[16,23,24] Adaptation of the ion exchange process to wastes other than HLW is novel in this country, but it has received moderate study in Sweden,[27] Japan,[28] and the USSR.[29,30,31] The ion exchange process described in Ref. 27 transfers the activity of spent organic ion exchange resins to inorganic ion exchange media. Reference 28 reports fundamental data on cesium ion exchange with a hexacynaoferrate (II) impregnated zeolite. Soviet researchers (Refs. 29, 30, 31) recommend decontamination of Low- and Medium-Level radioactive wastes by ion exchange prior to bituminization or cementation. These processes were meant to reduce the volume of the waste prior to immobilization by the traditional techniques.

An ion exchange process using heat resistant and cesium specific media will control cesium's volatility during vitrification. Recall from section 2.4.3 that the unaccounted cesium is less even when general purpose bead resins are vitrified. In Fig. 3.1 the conceptual design of a possible ion exchange PILLWV is shown.

A continuous ion exchange system is recommended due to its demonstrated efficiency and economy for nuclear[30] and non-nuclear[32] applications (Table 3.1 and Table 3.2).

TABLE 3.1

ION EXCHANGE EFFICIENCY[30+]

ION EXCHANGE SYSTEM	Volume of Exchanger(L)	DF[+]
Continuous	30	700
Fixed	600	200

[+] Decontamination Factor

Table 3.1 shows that continuous ion exchangers are 2.5 times more efficient and require 20 times less volume than fixed bed exchangers. In addition, Table 3.2 shows that continuous ion exchangers are approximately 25% cheaper than fixed bed ion exchangers.

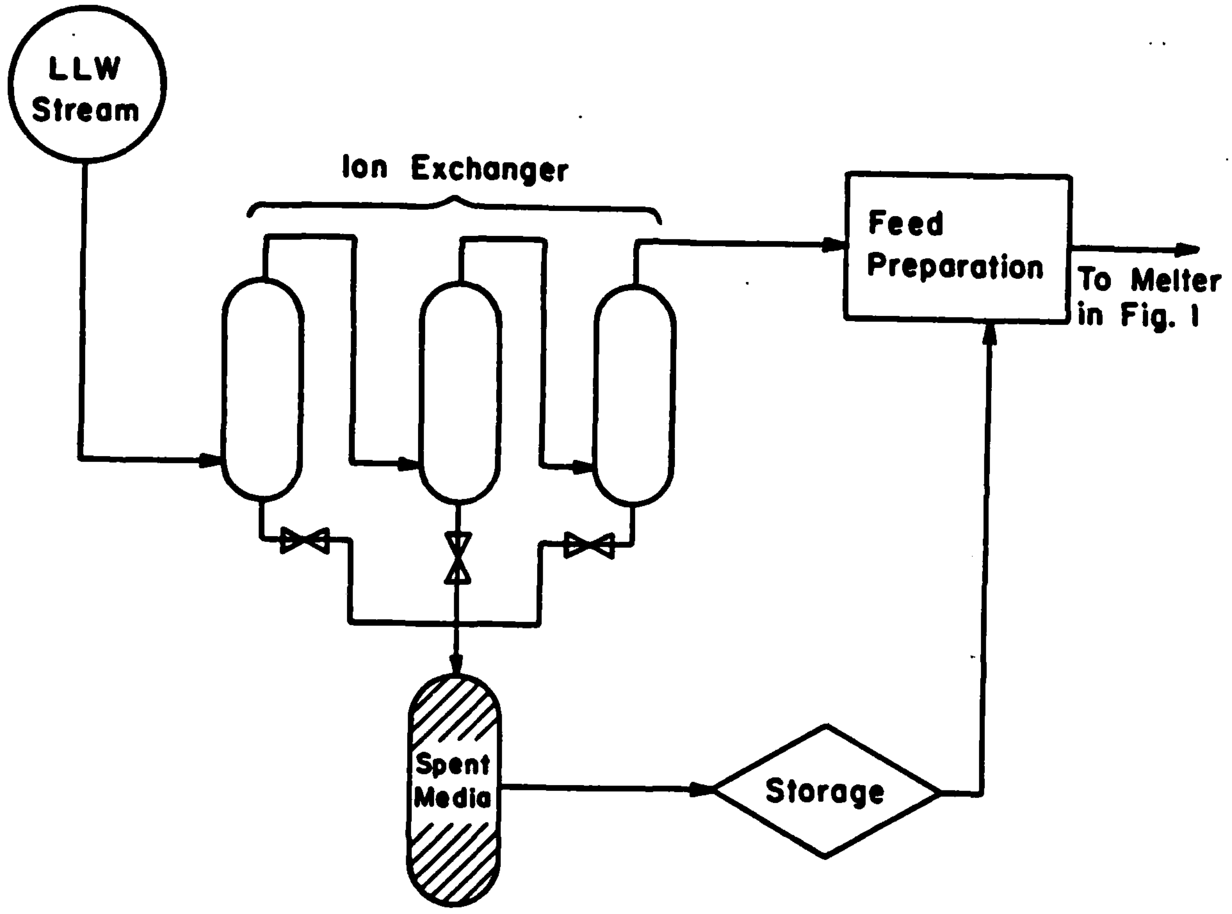


Fig. 3.1. Ion Exchange PILLWV

TABLE 3.2

Cost Comparison
Continuous Versus Fixed Bed Ion Exchange

Type	Cost[32] ($1000)	Continuous Ion Exchange Advantage
General		
Continuous	2164	
Fixed	2773	
		22%
Softening		
Continuous	206	
Fixed	284	
		27%
NaH BLEND		
Continuous	1038	
Fixed	1410	
		26%

The technical criteria used to determine the ion exchange media include high cesium selectivity, high radiation resistivity, and good thermal stability. The selection of the ion exchange medium should be tailored to a particular LLW stream, however several effective candidates are given in Table 3.3.

TABLE 3.3

Ion Exchange Media Candidates

Medium	Waste Stream	DF+
Duolite CS-100++[33,34]	HLW	10000
Titanates[27]	HLW	10000
Duolite ARC-359++[16]	HLW	10000
γ-Zirconium Phosphate[35.36]	TMI Accident	10000

+ Decontamination Factor

++ Duolite CS-100 and Duolite ARC-359 are manufactured by Diamond Shamrock Corporation

All of the candidate media have high cesium selectivity and radiation resistance. In addition, these ion exchange media retain cesium during heat treatment which is a crucial requirement for vitrification. The first three media of Table 3.3 have been vitrified at HLW facilities, and γ-Zirconium Phosphate has successfully been sintered.[33,27,35]

Preprocessing the LLWV stream with an ion exchange system provides a significant reduction of the amount of cesium in the melter feed (Table 3.4).

TABLE 3.4

Melter Feed Cesium Concentration

	Untreated[20] Cs Concentration (1000 MWe-yr)	Predicted Cs Concentration
BWR LLW	8.640E-1 Ci/m^3	8.64E-5 Ci/m^3
PWR LLW	4.074E-1 Ci/m^3	4.07E-5 Ci/m^3

The reduction, shown in Table 3.4, is calculated with the reported DF's of Table 3.3 and the Decontamination Factor (DF) formula[37], DF = A_i / A_e:

where

DF = Decontamination Factor
A_i = Influent Activity
A_e = Effluent Activity

In summary, a continuous ion exchange treatment system uses fully developed and proven technology that could be easily integrated into the LLWV process. An ion exchange PILLWV effectively controls the volatility of cesium during vitrification and the partitioned waste stream may be also processed into a waste glass. The ion exchange PILLWV capitalizes on the effectiveness of ion exchange and vitrification to produce a superior waste form in a superior LLW treatment system.

3.3 Chemical Precipitation

A chemical precipitation system would be integrated in the LLWV process in the same way as an ion exchange process (Fig. 2). This technique (precipitation) is used to remove cesium from low-level waste salts prior to cementation and disposal at the Defense Waste Processing Facility (DWPF) at the Savannah River Plant (SRP).[24] SRP has underground waste storage tanks containing large inventories of cesium in solution. Chemical precipitation of the cesium decontaminates these solutions and is easily integrated into SRP's existing process. While chemical precipitation has been adopted by SRP, it appears that the process is not as effective as anticipated.[38]

West Valley also investigated chemical precipitation as a potential cesium removal and volume reduction process. The efficiency of chemical precipitation to remove cesium from the waste streams of West Valley was found to be lower than ion exchange. The unacceptably low efficiency for the precipitation process at West Valley is due to the difference in pH and radionuclide concentration of the waste stream.[39]

Sodium and Potassium tetraphenyl borates are both cited in the literature as having high cesium selectivity.[23,25,39] The thermal properties of the precipitates that they produce have not been reported. These properties must be established prior to vitrification. Furthermore, as seen above the individual waste stream characteristics (pH of the solution, presence and/or concentration of competing ions) can greatly impact the effectiveness of a chemical precipitation system.

3.4 Electrodialysis

Reference 40 defines electrodialysis as a process in which a selectively permeable membrane separates a specific substance from a solution of numerous substances. Two other membrane processes are dialysis and reverse osmosis.[40] Table 3.5 provides a comparison of these membrane processes.

TABLE 3.5

Membrane Processes

Process	Driving Force	Range (Micron)
Electrodialysis	Electric Potential	E-2 to E-4
Dialysis	Concentration	E-1 to E-3
Reverse Osmosis	Pressure	E-2 to E-3

Electrodialysis (ELECD) has received limited application within the nuclear industry in the U.S.,[41] the UK,[42] and the USSR.[29] Reference 41 reports the preliminary development of several promising membranes for cesium separation. Researchers in the UK report effective and economical membrane separation of cesium in Low- and Medium-

Level Radwastes.[42] Reference 29 reports successful volume reduction of LLW streams by ELECD prior to immobilization in bitumen or cement. The concept of a combined electrodialysis-ion exchange (EIE) system is shown in Fig. 3.2.

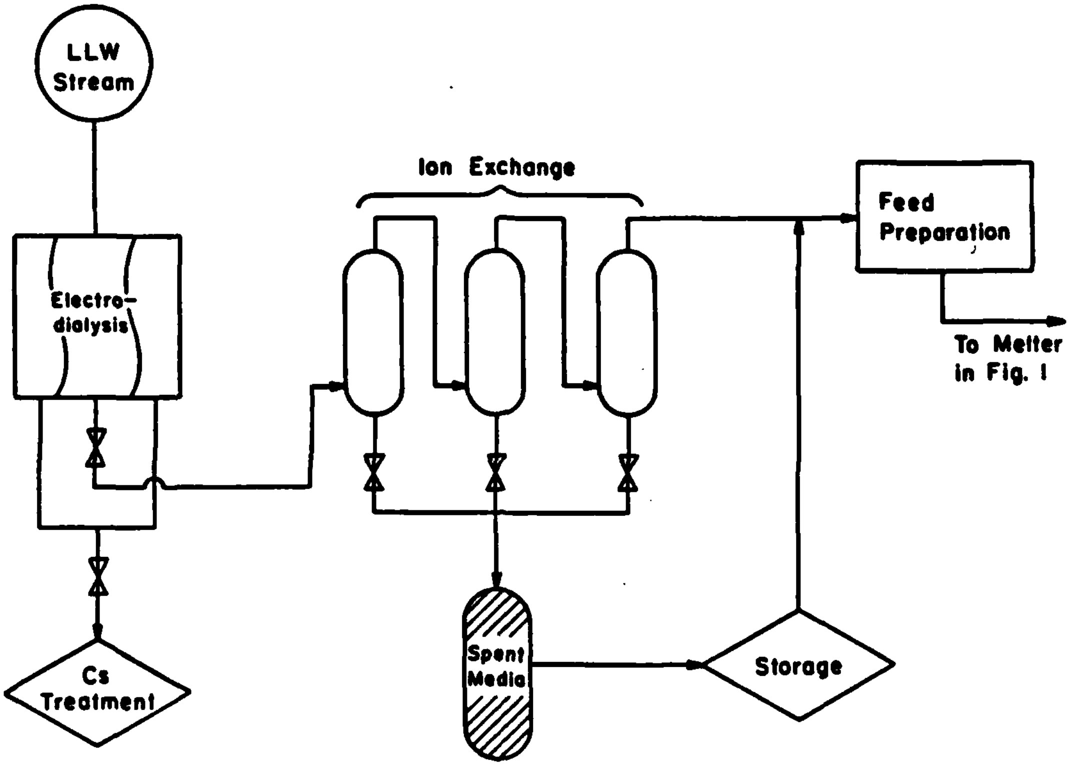


Fig. 3.2. Electrodialysis-Ion Exchange PILLWV

ELECD has been shown to efficiently and economically separate cesium,[42] but a follow-on immobilization process must be utilized to obtain a waste form acceptable for disposal. This follow-on treatment decreases in part the volume reduction capability of the process, but significant overall system effectiveness is attainable.[42]

Cesium decontamination factors of 2000 for ELECD are reported.[42] Table 3.6 summarizes the melter feed concentrations of an EIE. These values are calculated by the sequential use of the DF formula and the respective process DF's.

TABLE 3.6

EIE Melter Feed Cesium Concentration
(1000 MWe-yr)

	Initial Cs Conc[20] (Ci/m3)	ELECD[42] DF	ELECD Treated Cs Conc (Ci/m3)	Ion Exchange[34] DF	EIE Treated Cs Conc (Ci/m3)
BWR LLW	8.640E-1	2000	4.320E-4	10000	4.320E-8
PWR LLW	4.074E-1	2000	2.037E-4	10000	2.037E-8

Comparison of the melter feed concentrations of Table 3.4 and 3.6 shows an improvement of 3 orders in magnitude for a proposed EIE process versus an ion exchange process.

In addition, Table 3.6 shows that ELECD can initially decrease the cesium concentration of the LLW stream fed to ion exchange columns, which increases the life of the ion exchange media. ELECD alone effectively removes specific ions from LLW streams, however the requirement of a follow-on immobilization step for the concentrated waste stream is a significant disadvantage. Possible follow-on immobilization steps include ion exchange, chemical precipitation, or solidification in either a thermosetting resin or a DOW polymer. Reference 29 briefly indicates preliminary success in a combined electrodialysis-ion exchange technique in preparation for bituminization or cementation. This combined technique provides the desired cesium partitioning, however an effective immobilization technique for the partitioned cesium waste stream must be determined.

3.5 Conclusion

Of the three identified processes that selectively partition cesium from LLWV streams, ion exchange is the preferred method. Ion exchange technology is well developed and may be easily integrated into the LLWV process. Ion exchange media of high cesium selectivity in LLW streams and high cesium retention when vitrified are commercially available. Apparently, the effectiveness of chemical precipitation is questionable. In addition, the process is waste stream specific, and the thermal stability of the precipitate is to be determined. Electrodialysis has potential, but its volume reduction capability is degraded by the follow-on immobilization techniques, and industrial development of the process is still to be completed.

CHAPTER 4

PILLWV REGULATORY COMPLIANCE AND COST ESTIMATION

4.1 Introduction

Any immobilized waste form must conform to all State and Federal regulatory requirements. These requirements set specific standards for stability, transportation, radiation protection, and final disposal of Radwaste. The Radwaste regulatory environment is very dynamic and is further complicated at the Federal level by the existence of four separate agencies with partially overlapping authority, i.e. the Environmental Protection Agency (EPA), the Nuclear Regulatory Commission (NRC), the Department of Transportation (DOT), and the Department of Energy (DOE). These agencies are autonomous and often issue conflicting regulatory requirements. Tables 4.1 and 4.2 show the applicable regulations and their interrelationships.

LLWV is an unconventional LLW immobilization method. Therefore, it must not only comply with the regulatory requirements and be technically superior to conventional methods, but it must also be cost competitive. Regulatory aspects and cost estimations of the PILLWV waste form will be discussed in turn.

TABLE 4.1

Federal Regulations Applicable to Waste Management[43]

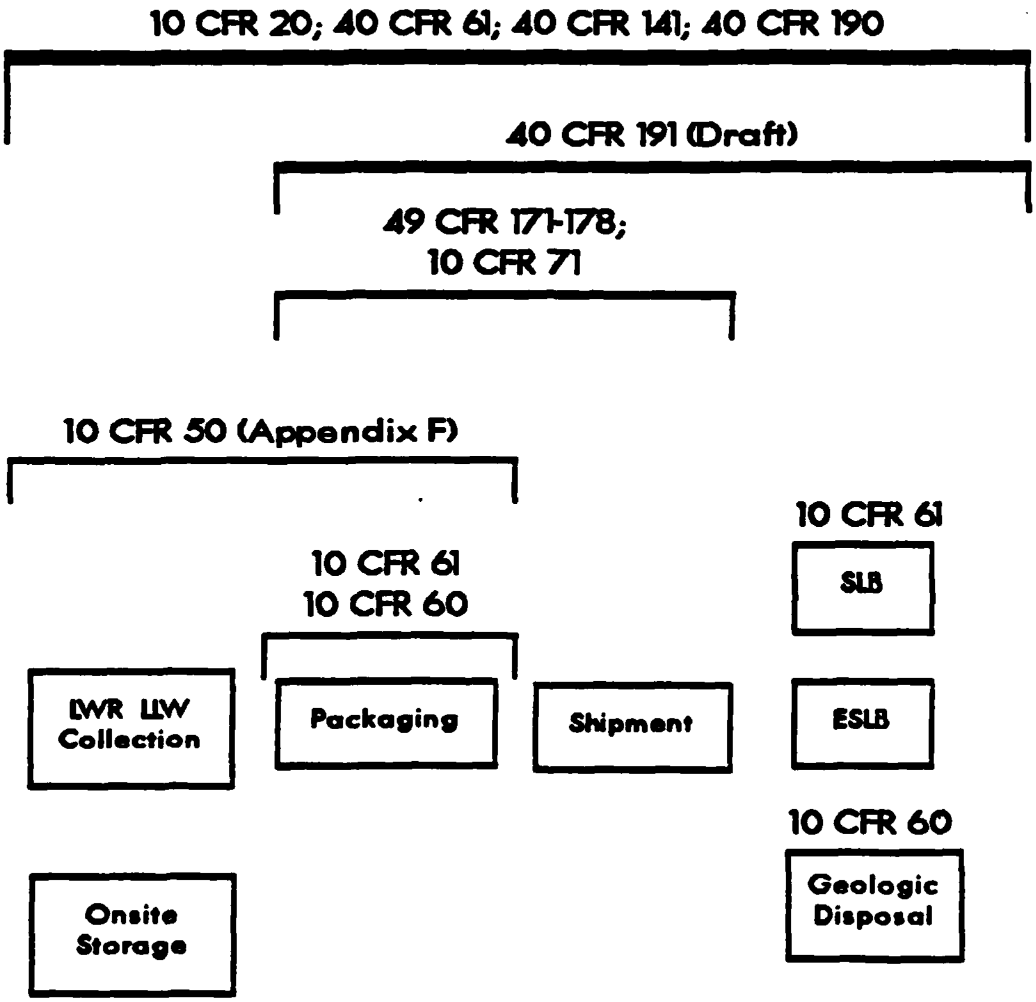
Regulation	Federal Agency	Title
10 CFR 20	NRC	Standards for Protection Against Radiation
10 CFR 50	NRC	Policy Relating to the Siting of Fuel Reprocessing Plants and Related Waste Management Facilities
10 CFR 60	NRC	Disposal of High-Level Radioactive Wastes in Geologic Repositories
10 CFR 61	NRC	Licensing Requirements for Land Disposal of Radioactive Wastes
10 CFR 71	NRC	Packaging of Radioactive Material for Transport and Transportation of Radioactive Material Under Certain Conditions
40 CFR 61	EPA	Clean Air Act, Section 112
40 CFR 141	EPA	Drinking Water Regulations
40 CFR 190	EPA	Environmental Radiation Protection Standards
40 CFR 191 (DRAFT)	EPA	Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes

TABLE 4.1
(Continued)

40 CFR 192	EPA	Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings
49 CFR 171-178	DOT	Requirements for Transportation of Radioactive Materials
Order 5480,XI	DOE	Standards and Requirements for Radiation Protection
Order 5820	DOE	Radioactive Waste Management

TABLE 4.2

Regulatory Interrelationships



• Adapted from Ref. 43.

4.2 Regulatory Compliance

The glass of the reported LLWV process[1] meets all of the regulatory requirements for stability stated in 10 CFR 61 (Table 2.4) and for transport stated in 49 CFR 173 (Table 4.3). The PILLWV glass will also meet these regulatory requirements. In additional, Table 4.3 shows that the concentrated cesium PILLWV waste forms do not exceed Class C waste limits as defined in 10 CFR 61.

The methodology for LLW classification is provided in 10 CFR 61.55. The waste class, A, B, or C, is determined by comparing the specific activity of the waste for selected radionuclide(s) to the regulatory standards. Cesium has the most stringent overall standards of the selected radionuclides in 10 CFR 61 (Table 4.4).

In this work, cesium is selected for the determination of the vitrified waste product classification due to its impact on LLWV as described in chapter 2 and to the stringent classification previously discussed standards . A cesium dose rate to specific activity conversion factor for low level waste solid material is 1 rem/hr per 200 Ci/m^3.[45] Conversion of the drummed product dose rates gives specific activities that may be compared to the regulatory standards (Table 4.5).

TABLE 4.3

Annual Vitrified Product 1100-MWe BWR[1*]

Waste	Volume (m^3)	Activity (Ci)	Drummed Products Number	mrem/hr	Shipping Container[+]	Class
Resin	82	1,170				
			10.3	1.08	A	B
			31	10.8	B	B
			10.3	108	B	C
Conc liquid	226	362				
			38	0.095	Unshielded	A
			114	0.95	Shielded	B
			38	9.5	B	B
Filter Sludge	152	1,364				
			34	2.08	A	B
			102	20.8	B	B
			34	208	B	C

[*] Waste Classification in accordance with Federal Regulation 10 CFR 61 not included in Ref. 1.

[+] Shipping Container Type in accordance with Federal Regulation 49 CFR 173. The dose limits of Ref. 1 are correctly shown as mrem/hr instead of rem/hr.

Table 4.4

Classification Standards for LLW[44]

Radionuclide	Class* A	Class* B	Class* C
All nuclides with half-life < 5 yrs	700	+	+
H-3	40	+	+
Co-60	700	+	+
Ni-63	3.5	70	700
Sr-90	0.04	150	7000
Cs-137	1	40	4600

* If the concentration (Ci/m^3) < value given.
\+ No limits set.

Table 4.5

Annual Vitrified Product Classification
1100-MWe BWR

Waste[1]	Dose Rate[1] (mrem/hr)	Calculated Activity(Ci/M^3)	Calculated Class
Resin			
	1.08	0.22	A
	10.8	2.2	B
	108	21	B
Conc Liquid			
	0.095	0.019	A
	0.95	0.19	A
	9.5	1.9	B
Filter Sludge			
	2.08	0.42	A
	20.8	4.2	B
	208	42	C

The waste classifications of Table 4.3 are conservative adjustments of the calculated values of Table 4.4. These conservative adjustments are made to account for variance of cesium concentrations in individual waste streams, and for unusually high concentrations of the other regulated radionuclides.

4.3 Cost Estimation

Reference 1 gives an installation and operation cost comparison for LLW volume reduction techniques. Vitrification was reported to be the cheapest volume reduction technique.[1] (Table 2.5)

Firm cost estimation figures for installation and operation of nuclear grade ion exchange systems are not available in the open literature, but an estimated 1984 annual installation and operation cost (AIOC) is $108,000.

This cost was calculated in the following manner. The 1970 installation and yearly operation costs for an 800 gallon per minute, continuous, zeolite ion exchanger (to selectively remove cesium) are $95,000 and $11,100, respectively.[46] An annual equivalent installation cost

(AEIC) was calculated with the standard interest formula[47]

$$\text{AEIC} = P * (A/P)_n^i \ ,$$

where

AEIC = Annual Equivalent Installation Cost
P = Present Value ($95,000)
(A/P) = Capital Recovery Factor
i = Interest Rate
n = Number of Years

The assumed interest rate is 15% and the life expectancy of the zeolite ion exchanger of Ref. 46 is 10 years. The capital recovery factor, 0.19925, is determined from the tabulated data of Ref. 47. The AEIC is $19,000.

This AEIC and the operation cost are evaluated in 1970 dollars, therefore a 1984 dollar adjustment is required for comparison with costs of Ref.1. Producer price indexes are used for such adjustments. The 1970 and 1984 nonfood, excluding fuel, producer price indexes for manufacturing are 109.6 and 395.7, respectively.[48] The 1970 AEIC and operation cost are multiplied by the 1984 producer price index then divided by the 1970 index to give a 1984 estimated AEIC of $108,000 and an operation cost of $40,000. The AEIC and the operation cost are summed to give the AIOC ($108,000). Table 4.6 shows that the Ion Exchange PILLWV is cost competitive with the LLWV system costs of Ref. 1.

TABLE 4.6

Ion Exchange PILLWV and LLWV Costs[1a*]
(1984 $1,000,000)

Item	PILLWV	LLWV
Total materials and burial	0.353	0.353
Solidification labor	0.037	0.037
VR operating costs	0.935	0.895
VR amortized capital cost	0.568	0.500
Drum credit	-0.090	-0.090
Transportation	0.694	0.694
Total	2.597	2.389

[a] Case is for 1100-BWR, 1250 miles transportation, Barnwell,SC.
[*] Ion Exchange PILLWV costs not included in Ref.1.

A 1986 installation cost of an ion exchange system that selectively removes cesium is $71,000.[49] This figure shows that the 1984 estimated AEIC is very conservative, therefore an ion exchange LLWV system would appear to be even more attractive when compared to the installation cost of Ref.45. It is assumed that the 1986 installation cost reflects considerable technological and economic improvement in the process.

Table 4.7 summarizes the cost of volume reduction techniques of Table 2.5 and shows that the Ion Exchange PILLWV is cost competitive.

TABLE 4.7

Volume Reduction Cost Comparison[1+]
($1,000,000)

PROCESS	COST
Vitrification	2.4
Vitrification with Ion Exchange*	2.6
Incineration/ Calcination	3.0
Evaporation	4.1
Incineration	4.7
Bituminization	5.5

[+] Costs are for a 1100-MWe BWR, 1250 miles transportation to Barnwell, S.C.

[*] Vitrification with Ion Exchange not Included in Ref.1. Incineration/calcination, evaporation, and incineration all use cementation as the immobilization technique.

Table 4.7 shows that the ion exchange PILLWV is cheaper than the traditional immobilization methods and the cost of the ion exchange improvement is only 4.5% of the LLWV cost of Ref. 1.

A comparison of the base disposal charges (cubic foot) is shown in Table 4.8.

TABLE 4.8

Comparison of Base Disposal Charges
Barnwell, S. C.
(1100-MWe BWR)

Process	Volume (Ft^3)	Total Charges (@ $25.112/$ft^3$)
Vitrification	3000	$75,000
Cementation	26000	$650,000

This base disposal cost estimate is made by converting the total number of 55-gallon drums of PILLWV (Table 4.3) into cubic feet and multiplying this figure by the Barnwell standard waste charge of Table A-1. Cementation has a volume increase factor of 1.6.[50] The cementation cost estimate was calculated by multiplying the total waste volume (Table 4.3) by the volume increase factor and by the standard charge of Table A-1. Due to insufficient data, weight and curie surcharges are not included in this cost estimate.

4.4 Conclusion

The PILLWV waste form meets all regulatory standards for stability, transport, radiation protection, and disposal as LLW. The highest waste classification of the drummed products is class C. The volume reduction cost comparisons show that the PILLWV is cost competitive with the LLWV process of Ref. 1. The basic cubic foot disposal charges for vitrification are 9 times cheaper than cementation.

CHAPTER 5

SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDY

5.1 Summary of Results

The objective of this thesis, as stated in section 1.2 was to analyze the traditional LLW immobilization options, to review the impact of the LLW stream composition on LLWV, then to propose and discuss several techniques to control the volatile radionuclides in a Process Improved LLWV system (PILLWV).

The analysis, in chapter 2, showed several technological and cost disadvantages of the traditional LLW immobilization options. Cementation and bituminization have high cesium leachability and low waste loading in comparison with glass.[13] The 300% escalation of SLB disposal fees dictates the use of an immobilization process which optimizes volume reduction. The LLWV process of Ref. 1 is also analyzed in chapter 2. Cesium is identified as the key volatile radionuclide to be controlled in order for vitrification to be a viable LLW immobilization option. The analysis shows cesium to be the predominant radionuclide in LLW streams,[20] to be the principal source term in LLWV DBA's,[1] and to be randomly sorbed/desorbed by the melter and offgas components during vitrification.[22]

In chapter 3, an improvement to LLWV was proposed which relies on partitioning, and virtually eliminates the loss of cesium from the LLWV process. Ion exchange is the preferred method of the three identified processes that selectively partition cesium from the LLWV stream. Ion exchange technology is fully developed and may be easily integrated into the vitrification process. In addition, ion exchange media of high cesium selectivity and high cesium retention when vitrified are commercially available. The other possible process improvements have serious technological obstacles which must be first studied, understood, and overcome before industrial applications may be considered. The major obstacles of chemical precipitation and electrodialysis include the questionable thermal stability of precipitates, process applicability to specific waste streams and selection of a follow-on immobilization process.

The following chapter showed that the PILLWV waste form complies with all regulatory standards for stability, transportation, and disposal as LLW. The highest waste classification of PILLWV process is class C. The volume reduction cost comparisons of chapter 4 show that the PILLWV is cost competitive with the LLWV process of Ref. 1. Finally, the standard disposal charges (cubic foot) for the vitrification waste forms are significantly lower than for the cementation waste forms.

High disposal costs and technical limitations of the traditional LLW immobilization techniques necessitated investigation of alternative methods. The PILLWV yields an improved waste product and effectively controls cesium volatility which should facilitate the licensing procedure of a prospective LLWV facility. The comparison of the technical specifications, of the regulatory compliance, and of the cost considerations shows the PILLWV to be the superior immobilization option.

5.2 Recommendations for Future Study

Further work is recommended in the following areas:

(1) A design study, and pilot testing of the ion exchange PILLWV to verify the type of ion exchange column, and the optimum exchange media. In addition, the study should include an economic assessment of a large scale commercial LLW immobilization facility.

(2) An experimental investigation to determine the properties of the precipitates identified in chapter 3. The emphasis of the study should be on the thermal stability of the precipitates during vitrification, and the elimination of the process constraints imposed by specific waste streams.

(3) A design study and experimental test of an electrodialysis PILLWV to determine specific membrane (s), and the optimum follow-on immobilization technique.

(4) A design study, and experimental testing of the ion exchange PILLWV to produce partitioned radiation sources for medical, industrial, or institutional uses. The study should include media selection, and an economic assessment.

APPENDIX A

LLW DISPOSAL RATE SCHEDULES

The 1983 and 1985 commercial LLW disposal fees are shown in Table A1, Table A2, Table A3, and Table A4. Tables A1, A2, and A3 show the 1985 LLW disposal charges for the Barnwell Low-Level Radioactive Waste Disposal Facility, the Washington Nuclear Center, and the Nevada Nuclear Center, respectively. Table A4 provides the 1983 LLW disposal charges for each of these facilities.

TABLE A1

BARNWELL RATE SCHEDULES[18]
(DECEMBER 9, 1985)

1. BASE DISPOSAL CHARGES: (Not including Surcharges and Barnwell County Business License Tax)

A.	Standard Waste	\$ 25.112/ft.^{3}
B.	Biological Waste	\$ 26.112/ft.^{3}
C.	Special Nuclear Material (SNM) plus \$1.75 per Gram SNM	\$ 25.112/ft.^{3}

Note: Minimum charge per shipment, excluding Surcharges and specific Other Charges is \$500.00

2. SURCHARGES:

A. Weight Surcharges (Crane Loads Only)

Weight of Container	Surcharge Per Container
0 - 1,000 lbs.	No Surcharge
1,001 - 5,000 lbs.	\$ 275.00
5,001 - 10,000 lbs.	\$ 550.00
10,001 - 20,000 lbs.	\$ 825.00
20,001 - 30,000 lbs.	\$1,100.00
30,001 - 40,000 lbs.	\$1,650.00
40,001 - 50,000 lbs.	\$2,200.00
greater than 50,000 lbs.	By Special Request

B. Curie Surcharges:

Curie Content Per Shipment	Surcharge Per Shipment
0 - 1	No Surcharge
1.1 - 5	\$ 1,500.00
5.1 - 15	\$ 2 250.00
15.1 - 25	\$ 3,000.00
25.1 - 50	\$ 4,500.00
50.1 - 75	\$ 5,500.00
75.1 - 100	\$ 7,450.00
100.1 - 150	\$ 8,900.00
150.1 - 250	\$12,000.00
250.1 - 500	\$15,000.00
500.1 - 1,000	\$18,000.00
1,000.1 - 5,000	\$24,000.00
Greater than 5,000	By Special Request

TABLE A1 (CONTINUED)

C. Special Handling Surcharge may apply on unusually large or bulky containers. These type containers are acceptable upon approval of prior request.

3. OTHER CHARGES

A.	Cask Handling Fee	$600.00 per cask, minimum

B. Taxes and Special Funds

1.	Perpetuity Escrow Fund	$ 2.80 per ft.^{3}
2.	South Carolina Low Level Radioactive Waste Disposal Tax	$ 4.00 per ft.^{3}
3.	Southeast Regional Compact Fee	46.2¢ per ft.^{3}
4.	Barnwell County Business License Tax:	

A 2.4% Barnwell County Business License Tax shall be added to the Total of all disposal fees.

NOTE: Items 3.B. 1, 2, and 3 are included in Item 1, Base Disposal Charges.

TABLE A2

NEVADA NUCLEAR CENTER RATE SCHEDULE[18]
(DECEMBER 9,1985)

1. DISPOSAL CHARGES

A. SOLID MATERIAL

Steel Drums, Wood Boxes:

R/HR AT CONTAINER SURFACE	PRICE PER CU. FT.
0.00 - 0.20	$ 20.61
0.201 - 1.00	22.34
1.01 - 2.00	25.09
2.01 - 5.00	30.02
5.01 - 10.00	35.43
10.01 - 20.00	45.82
20.01 - 40.00	56.77
40.01 - 60.00	86.29
60.01 - 80.00	103.55
80.01 - 100.00	114.19
Over 100.00	By Request

Disposal Liners Removed from Shield: (Greater than 12.0 cu.ft. each)

R/HR AT CONTAINER SURFACE	SURCHARGE PER LINER	PRICE PER CU. FT.
0.00 - 0.20	No Charge	$ 20.61
0.201 - 1.00	$ 271.72	20.61
1.01 - 2.00	668.54	20.61
2.01 - 5.00	940.98	20.61
5.01 - 10.00	1,360.17	20.61
10.01 - 20.00	1,735.76	20.61
20.01 - 40.00	2,156.95	20.61
40.01 - 60.00	2,557.19	20.61
60.01 - 80.00	2,951.60	20.61
80.01 - 100.00	3,351.84	20.61
Over 100.00	By Request	By Request

B. Biological Waste, Animal Carcasses $22.37/cu.ft.

TABLE A2
(CONTINUED)

2.	SURCHARGE FOR HEAVY OBJECTS:	
	Less than 10,000 pounds	No Charge
	10,001 pounds to Capacity of Site Equipment	$214.00 plus $.10 per lb. above 10,000 lbs.
3.	SURCHARGE FOR CURIES (Per Load):	
	Less than 100 curies	No Charge
	101 - 300 curies	$1,554.00 plus 20¢/Ci above 100 Ci.
	301 - License Limits	By Request
4.	MINIMUM CHARGE PER SHIPMENT	$483.00
5.	CASK HANDLING FEE:	$794.00 minimum each
6.	WASTE CONTAINING CHELATING AGENTS IN PACKAGES AMOUNT GREATER THAN 1% BY WEIGHT:	By Request
7.	SURCHARGE FOR NON-ROUTINE MAN-REM EXPOSURE (DUE TO DESIGN OR PHYSICAL DEFECT OF CONTAINER OR SHIELD):	$29.21 per man millirem
8.	DECONTAMINATION SERVICES (If Required)	$106.20 per man hour plus supplies at cost plus 15%
9.	CONTAINER VOLUMES:	

55 Gallon Drums - 7.50 cu. ft.
30 Gallon Drums - 4.01 cu. ft.
5 Gallon Drums - 0.67 cu. ft.

TABLE A3

WASHINGTON NUCLEAR CENTER RATE SCHEDULE[18]
(DECEMBER 9,1985)

1. DISPOSAL CHARGES

A. SOLID MATERIAL

Steel Drums, Wood Boxes:

R/HR AT CONTAINER SURFACE	PRICE PER CU. FT.
0.00 - 0.20	$ 24.90
0.201 - 1.00	26.76
1.01 - 2.00	29.66
2.01 - 5.00	31.00
5.01 - 10.00	36.08
10.01 - 20.00	45.99
20.01 - 40.00	56.34
40.01 - 60.00	80.24
60.01 - 80.00	95.75
80.01 - 100.00	105.37

Disposal Liners Removed from Shield: (Greater than 12.0 cu. ft. each)

R/HR AT CONTAINER SURFACE	SURCHARGE PER LINER	PRICE PER CU. FT.
0.00 - 0.20	No Charge	$24.90
0.201 - 1.00	$ 258.46	24.90
1.01 - 2.00	634.84	24.90
2.01 - 5.00	890.80	24.90
5.01 - 10.00	1,288.52	24.90
10.01 - 20.00	1,644.84	24.90
20.01 - 40.00	2,042.57	24.90
40.01 - 60.00	2,422.73	24.90
60.01 - 80.00	2,795.36	24.90
80.01 - 100.00	3,175.52	24.90

B. LIQUID WASTES

1. Aqueous liquids in vials, less than 50 ml. each	$31.84/cu.ft.
2. Aqueous liquids, absorbed	24.90/cu.ft.

C. BIOLOGICAL WASTE, ANIMAL CARCASSES	26.76/cu.ft.

TABLE A3
(CONTINUED)

2.	**SURCHARGE FOR HEAVY OBJECTS:**	
	Less than 10,000 pounds	No Charge
	10,000 pounds to Capacity of Site Equipment	$194.29 plus 10¢ per lb. above 10,000 lbs.
3.	**SURCHARGE FOR CURIES (Per Load)**	
	Less than 100 curies	No Charge
	100 - 300 curies	$1,414.46 plus 19¢/Ci above 100 Ci
	301 - License Limits	By Request
4.	**SURCHARGE FOR SPECIAL NUCLEAR MATERIAL (SNM)**	$2.55 per gram of Special Nuclear Material by Isotope Weight
5.	**MINIMUM CHARGE PER SHIPMENT**	$435.00
6.	**CASK HANDLING FEE:**	$718.00 minimum each
7.	**WASTE CONTAINING CHELATING AGENTS IN PACKAGES AMOUNT GREATER THAN 1% BY WEIGHT:**	By Request
8.	**SURCHARGE FOR NON-ROUTINE MAN-REM EXPOSURE (DUE TO DESIGN OR PHYSICAL DEFECT OF CONTAINER OR SHIELD)**	$26.67 per man millirem
9.	**DECONTAMINATION SERVICES (If Required)**	$96.92 per man hour plus supplies at cost plus 21%

10. **CONTAINER VOLUMES:**

55 Gallon Drums - 7.50 cu. ft.
30 Gallon Drums - 4.01 cu. ft.
5 Gallon Drums - 0.67 cu. ft.

TABLE A4

1983 COMMERCIAL LLW DISPOSAL RATES[19]

TABLE A4

1983 COMMERCIAL LLW DISPOSAL RATES[18]

Facility:	Barnwell Low-Level Radioactive Waste Disposal Facility[b]	Washington Nuclear Center[c]			Nevada Nuclear Center[d]		
Rate schedule effective date:	January 1, 1983	March 1, 1983			January 17, 1983		
Rate schedule/basic charges							
Container type:	All[e]	Drums and boxes[f]	Disposable liners in shielded casks[f]		Drums and boxes[g]	Disposable liners in shielded casks[g]	
Type of cost (unit):	Total ($/m³)	Total ($/m³)	Volume ($/m³)	Radiation surcharge ($/liner)	Total ($/m³)	Volume ($/m³)	Radiation surcharge ($/liner)
Radiation level surface of container (R/h)							
0-0.05	545	670	670	None	560	560	None
0.05-0.10	722	670	670	None	560	560	None
0.10-0.20	828	670	670	None	560	560	None
0.20-0.25	828	722	670	234	607	560	216
0.25-0.50	899	722	670	234	607	560	216
0.50-1.00	1,005	722	670	234	607	560	216
1.00-2.00	1,075	802	670	574	683	560	531
2.00-5.00	1,075	967	670	805	833	560	748
5.00-10.0	1,252	1,129	670	1,165	985	560	1,081
10.0-20.0	1,605	1,445	670	1,487	1,277	560	1,379
20.0-25.0	1,605	1,755	670	1,846	1,584	560	1,714
25.0-40.0	1,958	1,775	670	1,846	1,584	560	1,714
40.0-50.0	1,958	2,538	670	2,190	2,426	560	2,032
50.0-60.0	2,311	2,538	670	2,190	2,426	560	2,032
60.0-75.0	2,311	3,033	670	2,526	2,913	560	2,345
75.0-80.0	3,018	3,033	670	2,526	2,913	560	2,345
80.0-100.	3,018	3,340	670	2,870	3,214	560	2,663
100.-125.	3,371	By special request			By special request only		
125.-250.	4,077						
250.-500.	7,609						
500.-1000	11,140						
1000-5000	14,671						
>5000	By special request						

TABLE A4
(CONTINUED)

TABLE A4
(CONTINUED)

Facility:	Barnwell Low-Level Radioactive Waste Disposal Facility[b]		Washington Nuclear Center[c]		Nevada Nuclear Center[d]	
Surcharges (effective):						
Curies (per load):	Curie content (Ci)	Surcharge/shipment ($/shipment)				
	0-1	0.00	<100 Ci	No charge	<100 Ci	No charge
	1-5	500	100-300 Ci	$1,278 + 17¢/Ci above 100 Ci	100-300 Ci	$1,200 + 15¢/Ci above 100 Ci
	5-15	750				
	15-25	1,000	>300 Ci	By request	>300 Ci	By request
	25-50	1,500				
	50-75	2,000				
	75-100	2,500				
	100-150	3,000				
	150-250	4,000				
	250-500	5,000				
	500-1000	6,000				
	1000-5000	8,000				
	>5000	Special request				
Biological tissue ($/m^3):	35		52		48	
Liquid wastes ($/m^3):			In vials <50 mL size	192	Scintillation liquids adsorbed	178
			Scintillation liquids adsorbed	192		
			Aqueous liquids adsorbed	0.0		
Weight surcharges:	Weight (10^3 lb)	Surcharge ($/container)	<10,000 lb — no charge		<10,000 lb — no charge	
	0-1	None	>10,000 lb to equipment limits $176.00 + 9¢/lb above 10,000 lb wt		>10,000 lb to equipment limits $165.00 + 8¢/lb above 10,000 lb wt	
	1-5	250				
	5-10	500				
	10-20	750				
	20-30	1,000				
	30-40	1,500				
	40-50	2,000				
	>50	Special request				

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[a] In addition to listed charges, there are a variety of minimum fees and special charges. Data taken from rate schedules provided by burial ground operators. Certain sites will not accept certain types of LLW or accept only under special permit.

[b] Operated by Chem Nuclear Service Inc. In addition to the charges shown, there is a 2.4% Barnwell Co. business tax on the total of all fees. There is a surcharge of $17.66/m^3 for drummed radioactive waste weighing less than 600 lb per drum and NOT shipped palletized in an open-top van, or a flat bed trailer.

[c] Operated by U.S. Ecology. Surcharge for special nuclear materials (SNM) of $2.30/gram of special nuclear material by isotopic weight.

[d] Operated by U.S. Ecology.

[e] Includes State of South Carolina $79.46/m^3 *perpetuity escrow fund charge.*

[f] Includes State of Washington fees: $61.80/m^3 for perpetual care and maintenance, $0.83/m^3 site closure fund and $10.59/m^3 radioactive waste surveillance surcharge.

[g] Third-party inspection required at the shippers expense.

Appendix B

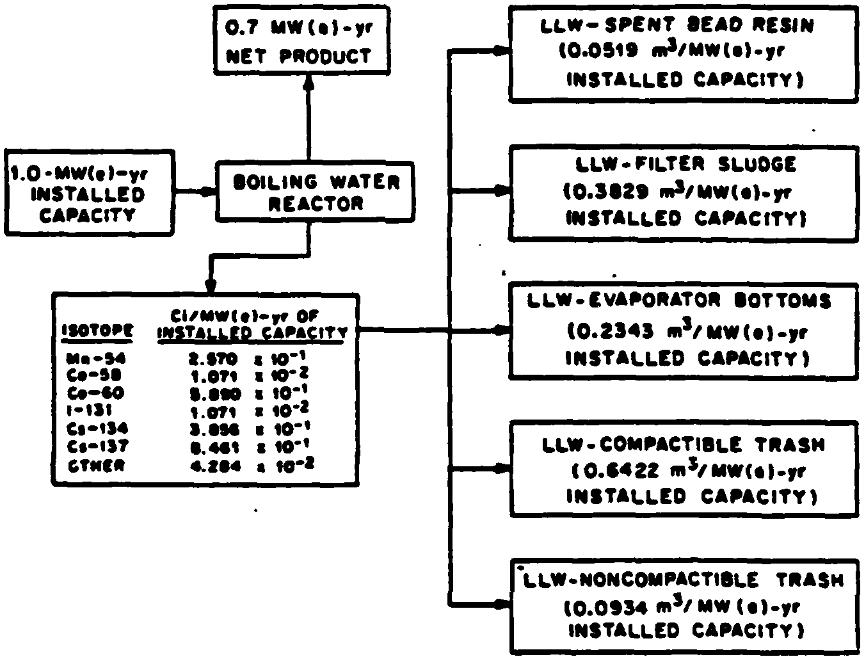
LWR WASTE STREAM CHARACTERISTICS

Tables B1 and Table B2 show the the LLW stream characteristics for both BWR's and PWR's.

TABLE B1

BWR WASTE STREAM CHARACTERISTICS[20]

ORNL DWG 83-494R2



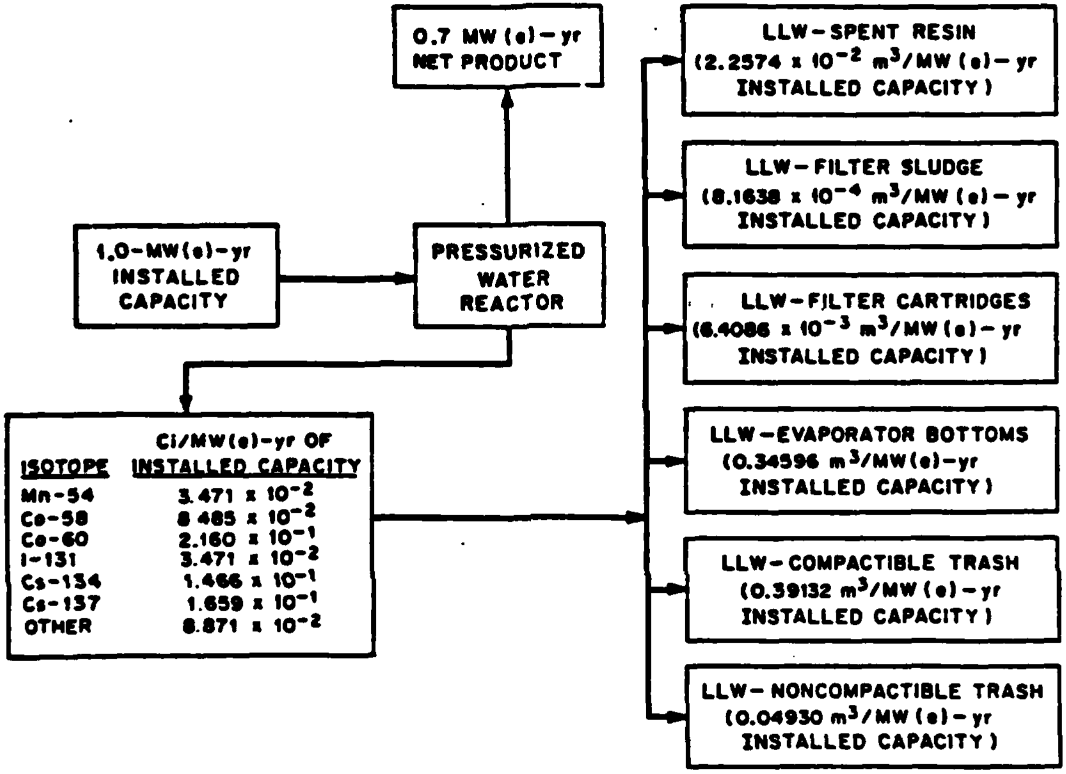
Fractions of elements from BWRs to waste streams

	Waste streams (LLW)				
Element	Spent resin	Filter sludge	Evaporator bottoms	Compactible trash	Noncompactible trash
Manganese	2.6354×10^{-2}	9.3917×10^{-1}	3.1183×10^{-2}	2.2344×10^{-3}	1.0599×10^{-3}
Cobalt	7.0285×10^{-2}	8.7092×10^{-1}	5.6058×10^{-2}	1.8539×10^{-3}	8.7941×10^{-4}
Cesium	7.5028×10^{-1}	1.6043×10^{-1}	8.6776×10^{-2}	3.4986×10^{-4}	1.6596×10^{-4}
Other	4.1677×10^{-2}	1.3814×10^{-1}	8.1222×10^{-1}	5.4041×10^{-3}	2.5635×10^{-3}

TABLE B2

PWR WASTE STREAM CHARACTERISTICS[20]

ORNL DWG 83-493R2



Fractions of elements from PWRs to waste streams

	Waste streams (LLW)					
Element	Spent resin	Filter sludge	Filter cartridges	Evaporator bottoms	Compactible trash	Noncompactible trash
Manganese	6.2466 x 10^{-1}	1.3035 x 10^{-2}	3.3891 x 10^{-1}	2.0335 x 10^{-2}	2.0202 x 10^{-3}	1.0367 x 10^{-3}
Cobalt	4.8884 x 10^{-1}	1.8298 x 10^{-2}	4.7574 x 10^{-1}	7.3118 x 10^{-3}	6.3433 x 10^{-3}	3.2551 x 10^{-3}
Cesium	9.0264 x 10^{-1}	3.1939 x 10^{-3}	8.3041 x 10^{-2}	4.8848 x 10^{-3}	4.1249 x 10^{-3}	2.1167 x 10^{-3}
Other	4.5348 x 10^{-1}	1.3360 x 10^{-3}	3.4735 x 10^{-2}	4.8484 x 10^{-1}	1.6922 x 10^{-2}	8.6837 x 10^{-3}

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