**STATUS AND PRACTICALITY OF DETRITIATION
AND TRITIUM REDUCTION STRATEGIES FOR
ENVIRONMENTAL REMEDIATION**

University of South Carolina
Columbia, SC 29208

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

STATUS AND PRACTICALITY OF DETRITIATION AND TRITIUM REDUCTION STRATEGIES FOR ENVIRONMENTAL REMEDIATION

H. H. Fulbright¹, A. L. Schwirian-Spann¹, K. M. Jerome², B. B. Looney², V. Van Brunt¹

¹University of South Carolina
Columbia, SC 29208

²Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P. O. Box 62, Oak Ridge, TN 37831; prices available from (423) 576-8401.

Available to the public from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161

TABLE OF CONTENTS

EXECUTIVE SUMMARY		xi
I.0 INTRODUCTION		I-1
II.0 OBJECTIVES		II-1
III.0 CONCEPTUAL APPROACH		III-1
III.A Introduction of Evaluation Matrix		III-1
III.B Summary Indicators		III-2
III.C Costing Method		III-4
<i>III.C.1 Capital Investment Cost</i>		III-5
<i>III.C.2 Production Costs</i>		III-5
IV.0 BACKGROUND		IV-1
IV.A Basic Concepts of Detritiation Technologies		IV-1
IV.B Previous Hydrogen Isotope Separation Technology Assessments		IV-2
V.0 SCENARIO DEVELOPMENT AND ASSUMPTIONS		V-1
V.A GSA Plume Background		V-1
V.B Scenario Development		V-2
V.C Water Quality Parameters		V-2
VI.0 TECHNOLOGY IDENTIFICATION AND DESCRIPTION		VI-1
VIA Introduction of the Technology Classes		VI-1
VLB Technology Class Descriptions and Selected Technology for Evaluation		VI-3
VI.B.1 Evaporation/Distillation and Related Processes		VI-3
VI.B.1.a Evaporation by Heating		VI-3
VI.B.1.b Evaporation by Humidification		VI-3
VI.B.1.c Distillation		VI-4
VI.B.2 Mass Transfer Based Equilibrium Processes		VI-5
VI.B.2.a Stripping		VI-5
VI.B.2.b Sparging		VI-5
VI.B.2.c Extraction		VI-6
VI.B.2.d Adsorption		VI-7
VI.B.2.e Homogeneous Exchange Reactions - Girdler-Sulfide (GS)		VI-8
VI.B.2.f Heterogeneous Ion Exchange - Liquid Phase Catalytic Exchange and Dual Temperature Liquid Phase Catalytic Exchange (LPCE and DTLPCE)		VI-9
VI.B.2.g Heterogeneous Ion Exchange - Combined Electrolysis/Catalytic Exchange (CECE)		VI-10
VI.B.3 Membrane Processes		VI-11
VI.B.4 Direct Onsite Immobilization or Storage		VI-12
VI.B.4.a Ground Freezing		VI-13
VI.B.4.b Storage Tanks		VI-14
VI.B.4.c Infiltration Deduction		VI-14
VI.B.5 Frequency Based Separation - Lasers		VI-15
VI.B.6 Electrolysis Plus		VI-16

VII.0 RESULTS	VII-1
VII.A Summary	VII-1
VII.B Cost Results	VII-1
VII.C Evaluation Matrix	VII-3
VIII.0 CONCLUSIONS	VIII-1
RELEVANT LITERATURE / REFERENCES	REF-1
APPENDIX A COST EVALUATION DETAILED INFORMATION	A-1
TAB A1: Evaporation by Direct Heating	
TAB A2: Evaporation by Humidification	
TAB A3: Stripping and Sparging	
TAB A4: Girdler Sulfide	
TAB A5: Dual Temperature Liquid Phase Catalytic Exchange	
TAB A6: Combined Electrolysis/Catalytic Exchange	
TAB A7: Ground Freezing	
TAB A8: Storage Tanks (Carbon Steel)	
TAB A9: Storage Tanks (Stainless Steel)	
TAB A10: Infiltration Reduction	
TAB A11: Electrolysis	
APPENDIX B ECONOMIC DEFINITIONS	B-1

LIST OF TABLES

Table III-1	Summary Evaluation Matrix of Detritiation Technologies for Treatment of Groundwater	III-6
Table III-2	Values used for Capital Investment Parameters for the Cost Evaluation of Detritiation Technologies	III-7
Table III-3	Values used for Production Cost Parameters for the Cost Evaluation of Detritiation Technologies	III-8
Table V-1	Tritium Plume Treatment Scenarios for Study of Detritiation Technologies	V-3
Table V-2	Potential Water Quality Parameters Present in the Groundwater Plume Defined for the Detritiation Technology Evaluation	V-4
Table VI-1	Guide to Identification of the Technology Classes and Specific Processes Evaluated	VI-18
Table VII-1	Overwhelming Cost Factors	VII-4
Table VII-2	Summary of Aqueous Detritiation Technology Cost Evaluation	VII-5
Table VII-3	Evaluation Matrix for Aqueous Detritiation Technologies and Strategies	VII-6

LIST OF FIGURES

Figure IV-1	Summary Graph of Previous Economic Comparison of Heavy Water Purification Technologies [62]	IV-3
Figure V-1	Tritium concentration profile to Fourmile Branch from the F & H Area Seepage Basins and the Solid Waste Disposal Facility [45]	V-5
Figure V-2	Location of the F & H Area Seepage Basins and the Solid Waste Disposal Facility at SRS	V-6
Figure V-3	Tritium plume map for the F & H Area Seepage Basins and the Solid Waste Disposal Facility [45]	V-7
Figure V-4	Example plume trajectory showing vertical distribution of tritium in groundwater downgradient of the F-Area Seepage Basins [45]	V-8
Figure VI-1	Simplified Subsurface Water Balance Diagram Used to Scope Potential Performance of In-Place Immobilization Options	VI-20
Figure VII-1	Summary of cost evaluation for the low flow scenario: cost per 1000 gallons treated versus the cost per Ci averted.	VII-7
Figure VII-2	Summary of cost evaluation for the high flow scenario: cost per 1000 gallons treated versus the cost per Ci averted.	VII-8
Figure VII-3	Summary of cost evaluation for the low flow scenario: cost per Ci averted versus the total capitalized cost	VII-9
Figure VII-4	Summary of cost evaluation for the high flow scenario: cost per Ci averted versus the total capitalized cost.	VII-10
Figure VII-5	Summary of cost evaluation for the low flow scenario: cost per 1000 gallons treated versus the total capitalized cost.	VII-11
Figure VII-6	Summary of cost evaluation for the high flow scenario: cost per 1000 gallons treated versus the total capitalized cost.	VII-12
Figure VII-7	Summary of cost evaluation for the low flow scenario: annual projected cost over the 20 year projected action (all costs are in present \$ and sum to the total capitalized cost)	VII-13
Figure VII-8	Summary of cost evaluation for the high flow scenario: annual projected cost over the 20 year projected action (all costs are in present \$ and sum to the total capitalized cost)	VII-14

LIST OF ACRONYMS

ACE	adsorption and catalytic exchange
AECL	Atomic Energy of Canada
ALARA	As Low As Reasonably Achievable
CECE	combined electrolysis catalytic exchange
CFC	chlorofluorocarbons
Ci	Curie
CRNL	Chalk River Nuclear Laboratories
D	Deuterium
DOE	Department of Energy
DTLPCE	dual temperature liquid phase catalytic exchange
ELEX	Electrolysis Chemical Exchange
EPA	Environmental Protection Agency
Et	Evapotranspiration
FEI	Facility Effectiveness Index
GS	Girdler-Sulfide
GSA	General Separations Area
H	Hydrogen
HETP	height of an effective theoretical plate (a parameter that describes the performance of a separator).
HT	form of tritium gas
HTO	form of tritiated water
ICRP	International Commission on Radiological Protection
IR	infra-red
L	liter
LLNL	Lawrence Livermore National Laboratory
LPCE	liquid phase catalytic exchange
ml	milliliter
mrem	millirem
NRC	Nuclear Regulatory Commission
OHRD	Ontario Hydro Research Division
OMB	Office of Management and Budget
PNNL	Pacific Northwest National Laboratories
ppQd	parts per quadrillion
RIKEN	Institute of Physical and Chemical Research
ROD	Record of Decision
RTF	Replacement Tritium Facility
SEG	Scientific Ecology Group
SPFA	Steel Plate Fabricators Association
SRS	Savannah River Site
SWDF	Solid Waste Disposal Facility
T	Tritium
T ₁	form of tritium gas
T ₂ O	form of tritiated water
VPCE	Vapor Phase Catalytic Exchange

EXECUTIVE SUMMARY

Operation of nuclear facilities throughout the world generates wastewater, groundwater and surface water contaminated with tritium. Because of a commitment to minimize radiation exposures to "levels as low as reasonably achievable," the U.S. Department of Energy (DOE) supports development of tritium isotope separation technologies. Also, DOE periodically documents the status and potential viability of alternative tritium treatment technologies and management strategies. The specific objectives of the current effort are to evaluate practical engineering issues, technology acceptability issues, and costs for realistic tritium treatment scenarios. A unique feature of the assessment is that the portfolio of options was expanded to include various management strategies rather than only evaluating detritiation (i.e., isotope separation) technologies.

The evaluation was performed through the development of a comparison matrix. The matrix provided an assessment of key issues including effectiveness, cost, maturity, potential fatal flaws, regulatory acceptability and public acceptability. Substantial effort was invested in developing the approach, or ground rules, for generating the information in the matrix. The resulting ground rules carefully balance simplicity and necessary sophistication to permit fair and robust comparisons to be generated rapidly. For example, a Facility Effectiveness Index was defined to account for the various pathways and chemical forms of tritium and allow reasonable comparison of technology performance. Important practical considerations were emphasized in developing the ground rules. One key decision was defining an upper limit on the tritium in the concentrate stream based on realistic occupational and radiation handling guidelines. Finally, the technologies in the matrix were grouped according to similarities in mechanism, or theory, of tritium isolation. This classification approach will facilitate future use. The performance of new technologies can be "scoped" by appropriately modifying the results for the appropriate class.

In aqueous waste, tritium contamination is typically in the form of HTO (one of the hydrogen atoms in water is replaced by tritium). Since the properties of the tritium in this form are similar to water, decontamination is challenging. As a result, the projected treatment costs for the various technologies/strategies were higher than traditional water and wastewater treatment costs -- ranging from about \$50/1000 gallons to greater than \$10000/1000 gallons. In terms of costs, three distinct groups were identified ranging from "low" to "high."

The results of the evaluation clearly indicated that optimization of the activities upstream of any detritiation process can significantly improve cost effectiveness. The scenario where groundwater pump and treat was designed to "surgically" remove the highest concentration water resulted in costs per Ci averted that were about 10 times lower than a traditional pump and treat design that attempts complete capture.

Based on the various considerations in the matrix, the technologies were classified as either potentially viable or not viable.

Key findings for potentially viable technologies:

- Girdler-Sulfide (GS) costs were relatively "low". GS is the least expensive process that actually performs isotope separation and provides a high degree of performance. GS would require many years to deploy and GS processes pose extremely high potential risks because of the large inventory of high pressure hydrogen sulfide needed.
- Dual Temperature Liquid Phase Catalytic Exchange (DTLPCE) performs isotope separation and has a high degree of performance. This technology was in the "intermediate" cost group but eliminates the process hazards associated with GS. DTLPCE is earlier in the development cycle and would require several years of work for deployment. New catalysts currently in development are expected to improve the performance of DTLPCE (and LPCE), making these technologies more competitive with GS.

- Storage tanks provide a high degree of confidence and isolation of tritium from the environment. Tanks were in the "intermediate" cost group. Tanks are most cost effective (and environmentally justified) for the low volume high concentration scenario. Deployment of tanks would require much less time than construction of isotope separation facilities. Alternate uses of tritium contaminated water for certain types of site needs, such as decontamination and decommissioning, make direct collection and onsite immobilization more economical and attractive. For example, contaminated water could be used to produce the concrete needed to decommission waste tanks, fill disposal vaults or to make saltstone. Finding a productive use for contaminated water would lower the costs for tanks by reducing the storage volume needed.
- Other types of onsite immobilization were also promising -- infiltration reduction and ground freezing were evaluated as representative of this class. Infiltration reduction as described was relatively inexpensive, rapid to deploy, and sensitive to the local ecology. This strategy only modestly reduced tritium release, however. Ground freezing is in the "intermediate" cost group and shows promise, especially if extremely high concentration zones can be targeted. Ground freezing would require several years to deploy. Infiltration reduction (in combination with other actions) and ground freezing are potentially viable.

Key findings for technologies determined to be not viable at this time:

- The two evaporation technologies are in the lowest cost group. These technologies do not perform any isotope separation -- they simply change liquid water into gaseous water that is released to the atmosphere. While this would result in a lower overall population dose, the total tritium (HTO) release is unchanged. As a result, these processes were considered potentially unacceptable to the regulators and the public.
- Stripping and sparging, technologies in the "intermediate" cost range, are based on the same basic strategy (converting liquid HTO into gaseous HTO) as evaporation. Assuming the viability of the basic strategy, it is clear from the analysis that there is no reason to consider stripping or sparging versus simple evaporation.
- The "highest" cost group consisted of electrolysis and CECE. While both of these technologies provided a high level of performance with regard to reducing environmental tritium release, they were not clearly superior to GS, DTLPCE, or tanks. Both technologies had very high capital/equipment costs and high energy and operating costs. Both technologies would require many years for deployment.
- An earlier cost evaluation of the membrane separation process currently operating at a bench scale at PNNL projected relatively high costs. Significant improvements in economics are needed for the membrane process to be competitive with some of the "promising" alternatives identified above. The ongoing research is targeted at refining and optimizing the design and operation. Another lab scale technology, laser frequency isotope separation, has been shown to be theoretically possible. Unfortunately, current economic evaluations and process issues associated with halogenated organics suggest that the technology may not be viable.

This evaluation was supported by the DOE Office of Technology Development and the DOE Environmental Restoration Programs.

I.0 INTRODUCTION

The Savannah River Site (SRS) and other Department of Energy (DOE) facilities are in the process of characterization and clean up of former waste disposal sites. Many of these sites received water or wastewater containing tritium. Treatment of environmental tritium contamination is challenging because properties of the contaminant are similar to those of bulk water. Understanding behavior/treatment options for tritium is an important component of prudent environmental management across the DOE complex.

Current activities of the DOE emphasize environmental protection. DOE has also made an organizational and fiscal commitment to environmental restoration. Specifically, DOE is committed to identification and appropriate use of new (faster and/or better) technologies to improve its environmental clean up efforts and to make them more efficient (reduce costs). Supporting these efforts is a specific objective of our evaluation.

A large percentage of radioactivity released to the environment as a result of SRS operations is in various forms of tritium, a radioactive isotope of hydrogen. Tritium is generated as a product or byproduct of a number of specifically-identified SRS processes. Over the years, tritium has accumulated in various wastes/products, or has entered the environment via the atmosphere or wastewater releases. The releases have been carefully measured and documented. Typically, tritium is the greatest contributor (> 90%) to the total dose from radionuclides to downstream Savannah River water users. Importantly, the maximum dose commitment to this population is well below (< 2%) of the EPA drinking water standard of 4 mrem/yr. Despite the low doses, DOE has maintained a commitment to periodically document the status of tritium handling and releases at SRS and to reevaluate the technical and process options for tritium reduction and aqueous detritiation. The objectives of this program are to support the sitewide mission by:

- 1) evaluating the status of current and emerging aqueous detritiation methods in relationship to levels of tritium found at environmental restoration waste sites,
- 2) developing a practical assessment of potential viability,
- 3) identifying promising methods for aqueous detritiation at levels found at environmental restoration waste sites, and
- 4) developing recommendations to assist Environmental Restoration and its support organizations in determining an appropriate target or technology portfolio for investment or development.

The evaluation of options for detritiation was performed through the development of a comparison matrix. In the matrix, the key attributes of the various options are summarized to allow qualitative and semiquantitative comparison. Substantial effort was invested in developing the approach, or ground rules, for generating the information in the matrix. The resulting ground rules carefully balance simplicity and necessary sophistication to permit fair and robust comparisons to be generated rapidly. Finally, in performing the evaluation it is important to distinguish between detritiation technologies and tritium reduction strategies. A detritiation technology actually performs a separation of water containing tritium atoms from normal water (isotope separation). A tritium reduction strategy is an overall concept to reduce the tritium related exposure or risk to the public. While many tritium reduction strategies include a detritiation technology, some do not (e.g., storage or immobilization with radioactive decay). Furthermore, even for cases where a detritiation technology is used, front end and back end decisions will be extremely important determinative factors for costs and benefits. By using a scenario based evaluation, the comparison matrix captures some of the more important decisions in developing a tritium reduction strategy along with the actual detritiation technology issues. In particular, the scenario development allows comparison of alternative groundwater pump and treat design concepts (low volume versus high volume) and includes secondary waste considerations and other important factors.

WSRC-RP-96-0075
Rev 0
February 26, 1996

II.0 OBJECTIVES

The objective of this report is to evaluate the status of current and emerging aqueous detritiation methods and develop a practical assessment of potential viability. The ultimate purpose of this effort is to assist Environmental Restoration and its support organizations in allocating future investments by identifying the most promising strategies for reducing tritium releases and the resulting exposure. The specific goal of the effort is to develop an assessment of existing and emerging technologies in practical engineering terms.

III.0 CONCEPTUAL APPROACH

III.A Introduction of Evaluation Matrix

The assessment matrix identifies and evaluates tritium reduction strategies for groundwater remediation. Each technology identified is summarized and the best possible estimates of cost in traditional engineering units (e.g., \$ per 1,000 gallons) are tabulated. Additionally, the table identifies development needs so that possible cost reductions (as a function of breakthroughs in key items) can be qualitatively evaluated. The assessment matrix and cost evaluation are based on specific treatment scenarios; the scenarios (activity range, flow rates, other water quality information, etc.) are relevant to existing conditions at a known site. In this form, the report will support reasonable and justifiable decision making. For example, a technology might be considered unattractive if costs significantly exceed the range of \$100/1,000 gallons; this is about 10 to 100 times the cost of most common water treatment methods for metals, organics, etc. The cost estimation assumptions and methods are discussed in detail below.

An evaluation of the technologies in use or under development for detritiation of groundwater should include more than just an evaluation of cost. Areas included in this evaluation cover the current status of the technology; advantages, disadvantages and potential fatal flaws in the technology; key ideas for further development of the technology; and acceptability by the regulators and the public. A summary matrix is provided as table III-1. The technologies were broken into technology classes based on chemical processes except for the immobilization/storage class. The current status of each technology was determined based on the criteria of being commercially available, pilot-scale tested, bench-scale tested or being laboratory-scale/conceptual model. The key advantages and disadvantages of the technologies were identified. Where improvements in the processes could potentially lead to improved operation and decreased cost these were noted. "Potential Fatal Flaws in the Technology" were identified where they existed. This topic encompasses a wide variety of problems that can occur with processes that might make them unacceptable for application. Examples of potential fatal flaws include the possibility of catastrophic exposures to workers and/or the public associated with the technology. Such flaws might include a possible release of a highly toxic substance into the environment. Safety hazards such as high pressures and temperatures, explosive, toxic or corrosive chemicals were considered in evaluating potential fatal flaws. Other types of potential fatal flaws include excessive energy requirements and/or chemical inventories.

It was recognized that because many of these technologies are new in the eyes of the regulatory and public communities, the evaluation of acceptability would be subjective. Three different criteria were set for both the regulator and public acceptability. The three criteria for regulator acceptability are: 1) the technology is currently accepted by the EPA or state regulators (RODs have been signed and/or the technology is currently in use for environmental remediation of tritiated surface/groundwater); 2) the technology is likely to be accepted (demonstrations have been conducted and/or approval to conduct such has been granted or no major flaws are connected with the technology that would likely make the regulator agencies hesitant to approve); and 3) significant regulatory issues may be associated with the technology. Potential fatal flaws in the technologies were noted where they existed. For the most part, these flaws identified additional exposures to workers and/or the public associated with the technologies. It was assumed that flaws in the technology that could lead to increased exposure to the public would be impediments to approval for the regulator agencies. Levels of exposure were also the focus of the criteria developed for acceptability by the public. The three criteria for public acceptability are: 1) no tritium exposure to the public from implementation of the technology; 2) implementation of the technology significantly reduces exposure to the public; and 3) implementation of the technology minimally reduces the tritium exposure to the public or shifts the exposure to a new population.

Two scenarios based on volumes of water treated and activity levels of tritium in the water were evaluated. The column of the table labeled "Activity Level Treated" distinguishes the two scenarios which were evaluated for all technologies undergoing the full cost evaluation. The last three columns of the table

report the findings of the cost evaluation. The items reported in this portion of the table are described in detail in the following sections of this chapter.

III.B Summary Indicators

Since tritium is not destroyed by the various detritiation processes, rational comparison must track the tritium as it is concentrated, sequestered or transferred to a new phase. The most important result of a tritium reduction strategy is lowering the tritium flux and/or exposure associated with releases from SRS. Thus, a technology that removes all of the tritium from water by completely transferring it to the air is not 100% effective. Such a technology may be determined to be beneficial, because each curie released to surface water results in a higher population dose than each curie released to the air. The process efficiency based on only eliminating the water pathway must be modified to equitably compare a wide range of strategies. Fair credit should be available for reducing tritium release through any mechanism (e.g., volume reduction, concentration reduction, storage, etc.). To allow comparison, we have defined a Facility Effectiveness Index (FEI). This index accounts for the secondary effluent streams and allows estimation of overall performance using the original aqueous tritium content. In the discussion below, the index is defined, each term is considered and the behavior of the index is demonstrated for a few interesting bounding cases.

$$FEI = 1 - (F_{w,out} / F_{w,in}) - \beta_i (F_{i,out} / F_{w,in})$$

where:

$F_{w,in}$	=	influent or target aqueous tritium (Ci/yr or Ci)
$F_{w,out}$	=	effluent or residual aqueous tritium (Ci/yr or Ci)
β_i	=	i:aqueous release impact ratio (dimensionless)
$F_{i,out}$	=	secondary effluent tritium (Ci/yr) (e.g., HTO release to air)

The index will range from 0 (no effectiveness) to 1 (100% effectiveness). The index is composed of three terms: a baseline term (= 1), an aqueous effectiveness modifier, and an air/other secondary release penalty factor. The middle term addresses effectiveness in reducing aqueous concentrations. If the effluent flux from a process is zero, this term is zero, the baseline term is not modified and the overall FEI is 1. As expected, if all of the tritium remains in the effluent (i.e., $F_{w,out} = F_{w,in}$), the middle term is 1 and the FEI is 0. The final term(s), the air/other secondary release penalty factor, is a modifier similar to the middle term, but adjusted for the relative impacts of the tritium form released – for example release of tritiated water (HTO) to the air versus HTO released to surface streams. The term is defined in a general manner and multiple penalty factors can be added if needed to account for all the possible secondary effluent streams. The impact ratio (β_i) is facility specific and is a function of the number and location of receptors and transport issues (chemical form, stack height flow rate, meteorology, etc.). For SRS, the most significant β_i can be calculated relatively accurately, because the quantity and chemical form of tritium released to air and water and the resulting population doses are reported each year. For purposes of our scoping calculation, the primary secondary waste stream is air release of HTO. Based on these reports, the $\beta_{air,HTO}$ for SRS is approximately 0.4. This value would be influenced somewhat by the specific system design and operation. The historical estimate, however, provides an appropriate tool for our scoping study. A sample calculation for 1992 is shown below:

$$\beta_{air,HTO} = \frac{\text{population dose from air releases} / \text{HTO releases to air}}{\text{population dose from water releases} / \text{tritium releases to water}}$$

$$\beta_{air,HTO} = \frac{5.76 \text{ person-rem} / 100000 \text{ curies}}{2.05 \text{ person-rem} / 13800 \text{ curies}} \approx 0.4$$

Thus, each curie of HTO released to the air results in only 40% of the population dose compared to each curie of HTO released to the water. From a practical perspective, this means that a technology that is 100% effective in transferring HTO from water to air is only 60% effective at eliminating offsite impacts. Consistent with this conceptual model, such a hypothetical technology would generate a FEI of 0.6. Note that SRS also releases tritium gas (primarily HT) to the air (e.g., 56,000 Ci in 1992). This form of tritium results in much less dose, however, and the $\beta_{w,HT}$ can be assumed to be 0 for purposes of scoping analysis. Definition of the FEI allows consideration of two additional control strategies -- reduce or eliminate air emissions or convert HTO to HT if tritium is released to the air (100% water to air transfer and conversion to HT would generate a FEI = 1). If other secondary effluent streams are identified for any specific technology, a β_i can be estimated to facilitate appropriate evaluation of performance.

The index must be flexible to allow comparison of traditional aqueous detritiation processing with subsurface barriers, and onsite trapping/storage/use options. For many proposed tritium reduction strategies, the $F_{w,in}$ and $F_{w,out}$ equal the respective concentrations times the respective flows. Interestingly, the $F_{w,out}$ can be reduced by lowering concentration (through actual aqueous detritiation), by reducing volume (through storage, trapping or use of tritium onsite), or both. For subsurface processes, equivalent performance can be determined based on defining a target plume (total curies) equivalent to the defined pump and treat scenarios. These underlying parameters become the basis of the various tritium reduction strategies. Thus, the index provides an important tool to allow equitable comparison of disparate strategies. A process with an FEI of 0.5 is equivalent to removing half of the curies from the influent water -- the FEI allows the greatest possible flexibility and creativity in reaching this performance.

Overall, each tritium reduction strategy will be evaluated for representative scenarios using several quantitative and qualitative factors in a matrix. Three summary indicators are included in the matrix: the FEI discussed above, $cost_w$ (\$/1,000 gallons), and $cost_h$ (\$/Ci). The $cost_w$, water basis, allows comparison of the performance to traditional water and wastewater engineering treatment costs and provides a means for gross estimation of lifetime costs. The $cost_h$, tritium basis, defines performance in terms of the contaminant activity and provides a means for gross estimation of the cost for potential risk reduction. In calculating $cost_h$ the FEI will be incorporated (i.e., $cost_h = \$/ (FEI * F_{w,in})$, where the terms are defined similar to above in consistent units). Because of the basis of the FEI, this calculation provides an evenhanded manner to adjust costs for air releases. In other words, the $cost_h$ is the cost per Ci averted rather than \$ per Ci removed.

Note that for balancing costs and risks, this approach is similar (but not identical to) the traditional calculations used in commercial and federal nuclear programs to reduce doses to levels that are "as low as reasonably achievable" (ALARA). Documentation of ALARA guidelines has been published by the International Commission on Radiological Protection [34,35], the Nuclear Regulatory Commission [9,29], the International Atomic Energy Agency [49,81], DOE [54], and others [10,11,83]. In summary, the costs and the total population dose reduction of an action in person-rem are calculated and combined into the cost per person-rem reduction. Actions with resulting costs of less than \$1000 per person-rem reduction are typically considered "reasonable" [9]. While this traditional ALARA approach is widely accepted, the results depend directly on dose calculations that are subject to revision. Also, direct acceptance by the public, through a participation process, of the quantitative "value judgment" (i.e., acceptable \$/person-rem) for an action has never been explicitly recognized.

For this work, we developed an approach that is more loosely tied to the dose calculations through the FEI; dose calculations are only used for relative scaling rather than directly as the primary basis for conclusions. Actual, or effective, "curie" reductions are simple to calculate and can be directly compared with all of the public reports of tritium releases from the various sites (because they are in the same units). Finally, a process based on the use of the FEI and normalizations to volume and curies lends itself to both engineering objectives and straightforward policy objectives (i.e., what percentage of tritium release can be eliminated). Importantly, however, the scoping calculations suggest that ALARA evaluation of tritium

reduction strategies from groundwater results in costs much greater than traditional "reasonable" ALARA actions. In ALARA units, costs much greater than \$1,000,000 per person-rem were typical of our analyses. Implementation of such actions would represent a policy shift and a societal cost-risk revaluation. We have specifically chosen to use an alternative approach for evaluating cost versus risk to emphasize technology descriptions and performance rather than to debate such value judgments and dose calculations. Resolution and public acceptance of ALARA issues would assist in final decisionmaking.

III.C Costing Method

An important component of the evaluation is calculating costs in a manner to allow fair and direct comparison of costs for the various options. The total (life cycle) cost for an action in consistent units is the principal investment measure. This information, combined with early costs (designated "year 0" costs) and the spending profile over the life of the action, provide decisionmakers with important information to assist in their planning. Further, the life cycle costs are used as the basis for calculating the summary costs that are normalized to the amount of water treated or to the curies averted. An important consideration when calculating the life cycle costs is the time value of money. Actions that result in large early expenditures are penalized versus actions that spend the money in a more even fashion. The methods for calculating lifecycle costs for programmatic decisionmaking in federal agencies are identical to the approach used in industry, and consists of estimating costs in constant dollars using a reference year [71]. A factor known as the discount rate is used to perform the necessary calculations; the discount rate is a function of interest rates and expected inflation. This approach is described in detail [58] in the Office of Management and Budget Circular A-94, "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs." Each year, a new Appendix C containing updated discount rates are published concurrent with the President's budget and the rates "are considered valid" for use by federal agencies through the end of February the following year [58,59].

OMB circular A-94 prescribes a standard approach to be used in evaluating costs and/or benefits of programs or projects when they are distributed over time. DOE has specified use of the referenced methods for comparative analysis of actions in Showalter, et al., 1995 [71] and in DOE Order 1360.8A [14]. Of particular interest is Showalter, et al., 1995, which provides specific examples and results using the recommended methods for DOE environmental technologies. All of the scoping costs used in this study were generated using the referenced approach and the most current available discount rate of 4.9% for project life cycles of about 20 years. Note that the discount rate has varied over a relatively narrow range since 1992 and the scoping analysis should be relatively insensitive to expected changes.

Year 0 of each implementation is assumed to be a construction and start up year (costs are capital, construction, engineering, etc.). The annual operations and maintenance costs during the 20 years of operation (year 1 through year 20) are all modified to constant dollars (reference to year 0) and summed with the year 0 costs for the life cycle costs. To aid the decisionmaker, the spending profile in constant dollars for each action is graphed and the year 0 and typical annual costs are tabulated. This provides a modest additional sophistication to the decisionmaker because large start up or future individual expenditures will be identified -- for example if a catalyst bed is assumed to have a 10 year lifetime. The resulting large deviations in the spending profile are discussed for such cases. The summary cost indicators divide the total life cycle costs in constant dollars by the volume treated or contamination averted, as appropriate.

The overall approach allows fair comparison of the widely varying actions that are possible for tritium reduction. Such actions can have large up-front costs (e.g., construction of a large complex facility for isotope separation) or can spread costs relatively evenly over the project lifetime (e.g., construction of tanks as needed for holding water to allow natural decay). The resulting costs are one part of the overall matrix of information needed for responsible decisionmaking.

The centerpiece of the costing effort is a standard engineering evaluation of the selected technologies. The scenario costs were determined based on tables 26 and 27 (pp. 210-211) in Peters and Timmerhaus [60]. The tables in Peters and Timmerhaus are based on "ordinary" chemical processing plants. Because the systems being evaluated treat radioactive materials, they would not be considered "ordinary". Therefore, the individual percentages for each component may vary from the percentage ranges listed in the tables of standard engineering costing references. In all cases the technologies described have never been used for treatment of environmental levels of tritium on a full-scale basis.

III.C.1 Capital Investment Cost

The total capital investment cost estimate includes direct costs, indirect costs, and working capital. In the cases presented, the only known cost is an estimate of the purchased equipment cost. All other capital investment cost components were determined from this cost based on the percentage ranges listed in the following table based on Peters and Timmerhaus. Approximate percentages for each category were estimated for each scenario based on the complexity of the treatment system. Deviations from standard percentages provided in tables III-2 and III-3 are discussed in the section specific to each technology and detailed in the assumption list in Appendix A.

Table III-2 shows the standard percentages used by the Peters and Timmerhaus text in parentheses and the standard percentages used for these calculations in the far right column.

III.C.2 Production Costs

The total yearly product costs were similarly determined based on the utility cost for each scenario based on the Peters and Timmerhaus data as presented in table III-3.

Table III-1 Summary Evaluation Matrix of Detritiation Technologies for Treatment of Groundwater

Technology Class	Current Status of Technology ¹	Advantages of Technology	Disadvantages of Technology	Development Needs	Potential Fatal Flaws in Technology	Acceptability by Regulators ²	Public Acceptability ³	Activity Level Treated ⁴	Operating/Maintenance Costs \$	Total Project Cost \$	Summary Indicators FEI \$/1000 gallons \$/Ci
Tech. 1											
Tech. 2											
Tech. 3											
Tech. 4											

Notes:

- 1) The current status of the technologies is described as one of the following four definitions: 1. commercially available, 2. pilot-scale tested, 3. bench-scale tested, 4. laboratory, conceptual model
- 2) The acceptability by the regulators is described by one of the following three definitions: 1. currently accepted by EPA or state regulators, 2. likely to be accepted, 3. significant regulatory issues.
- 3) The public acceptability is described by one of the following three definitions: 1. no tritium exposure to the public, 2. significantly reduces exposure to the public, 3. minimal reduction of tritium exposure or shifting of exposure to new populations.
- 4) The activity levels treated are defined as follows: A. high volume of liquid at a low concentration, B. low volume of liquid at a high concentration.

Table III-2 Values used for Capital Investment Parameters for the Cost Evaluation of Detritiation Technologies

Peters and Timmerhaus information	Estimated Percentages
I. Direct Costs (70-85% of fixed-capital investment)	
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	(calculated)
1. Purchased equipment (15-40% of fixed capital investment)	(calculated)
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	50%
4. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	25%
5. Piping, installed (10-80% of purchased-equipment cost)	75%
6. Electrical, installed (10-40% of purchased-equipment cost)	40%
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%
Total Direct Cost	
II. Indirect Costs (15-30% of fixed-capital investment)	(calculated)
A. Engineering and supervision (5-30% of direct cost)	30%
B. Construction expense and contractor's fee (6-30% of direct cost)	30%
C. Contingency (5-15% of fixed-capital investment)	15%
Total Indirect Costs	
III. Fixed-capital Investment (Direct + Indirect Costs)	
IV. Working capital (10-20% of total capital investment)	15%
V. Total capital investment (Fixed-capital Investment + Working capital)	

Table III-3 Values used for Production Cost Parameters for the Cost Evaluation of Detritiation Technologies

Peters and Timmerhaus information	Estimated Percentages
I. Manufacturing Cost	
A. Direct production costs (about 60% of total product cost)	(calculated)
1. Raw materials (10-50% of total product cost)	0%
2. Operating labor (10-20% of total product cost)	20%
3. Direct Supervisory and clerical labor (10-25% of total product cost)	15%
4. Utilities (10-20% of total product cost)	(calculated)
5. Maintenance and Repairs (2-10% of fixed-capital investment)	10%
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of fixed capital investment)	1.0%
7. Laboratory charges (10-20% of operating labor)	1%
8. Patents and royalties (0-6% of total product cost)	6%
B. Fixed Charges (10-20% of total product cost)	(calculated)
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of fixed capital investment for machinery and equipment and 2-3% of building value for buildings)	10%
2. Local taxes (1-4% of fixed-capital investment)	1%
3. Insurance (0.4-1% of fixed-capital investment)	0.4%
4. Rent (8-12% of value of rented land and buildings)	0%
C. Plant-overhead costs (50-70% of cost for operating labor, supervision, and maintenance, or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%
II. General expenses = administrative costs + distribution and selling costs + research and development costs	
A. Administrative costs (about 15% of costs for operating labor, supervision, and maintenance, or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%
C. Research and development costs (2-5% of every sales dollar or about 5% of total product cost)	2%
D. Financing (interest) (0-10% of total capital investment)	0%
III. Total Product cost = manufacturing cost + general expenses	
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income- tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).	

IV.0 BACKGROUND

Discharge of water and wastewater containing tritium is regulated worldwide. Differences exist in discharge limits and regulatory philosophies from country to country and from state to state in the U.S. Despite the attention and concern throughout the world, however, there is no operating facility for treatment of large volumes of water at levels typical of "contaminated" environments. Tritium (T) is a radioactive isotope of hydrogen (H). T can substitute for H in and can exist in aqueous forms (**HTO** and **T₂O**), gaseous forms (**HT** and **T₂**), and to a much lower extent other compounds. Those compounds identified by boldface type are the predominant forms of tritium in most environmental situations. Tritium has a half life of about 12 years; thus, approximately 5.5% of any tritium released to the environment decays each year. The properties of tritium are very similar to other forms of hydrogen. As a result, the isotopic separation needed for detritiation is challenging. DOE and the commercial nuclear industry have periodically evaluated the status of detritiation technologies to determine their potential viability for environmental clean up and dilute wastewater applications [1]. Our work builds on these previous studies with an emphasis on practical engineering issues, cost considerations and expanding the portfolio of options to include related aspects of tritium reduction strategy (e.g., alternatives to detritiation, pretreatment volume reduction, etc.).

IV.A Basic Concepts of Detritiation Technologies

Assessment of detritiation technologies for environmental remediation begins with an understanding of the isotopic separation methods that have been proposed/used for hydrogen-tritium separations, and an assessment of their current state of development. This assessment, combined with an understanding of the complexities of performing isotopic separation for dilute solutions, and practical engineering and cost considerations are needed to address environmental clean up objectives. The diluteness of environmental remediation applications of aqueous detritiation can be shown by comparing target concentrations. Environmental levels, even at contaminated sites are typically more than five orders of magnitude below levels encountered in tritium production and moderator purification applications. Thus, the difficulty of performing an isotope separation is further compounded by its application to an extremely dilute separation.

Historically, methods for separating the isotopes of hydrogen in aqueous systems have been based on the purification of and the production of heavy water. The need for pure heavy water free from both tritiated and light water has prompted the development of commercial production facilities for D₂O. Heavy water is recovered and purified from light water for use in heavy-water moderated reactors. Fission of the heavy water moderator results in a buildup of tritiated water in the moderator. Technologies devoted to removing the tritiated water contaminant from the heavy water have also been commercialized.

In the case of heavy water purification the recovery of heavy water from light water is accomplished by concentrating a product without regard to the fraction of the heavy water recovered from the light water. For heavy water applications, alternative separations technologies have been proposed since the Manhattan Project. For moderator water extraction, the fractional recovery from the light water is limited in the design of the commercial technologies. The same is true with the heavy water detritiation for reactor applications. In these cases too, the fractional recovery of the heavy water is restricted. Thus, the reactor applications technologies are concerned with obtaining a pure heavy water process stream without placing a restriction on the fractional recovery of the tritiated water. This is distinctly different than applying isotope separations technology to recover a fixed fraction of tritiated water from either a light water or heavy water source. In the purification case one obtains a very pure product consisting of a small fraction of the product in the feed. In the second case, one obtains a relatively impure product that contains most of the product contained in the feed. In fact, for aqueous detritiation the product composition is restricted to concentrations below that requiring special handling for radioactive materials.

In general, the ease of separation can be characterized using a separation factor which is a measure of the ability of a technology or chemistry to effect a separation. The larger the separation factor the easier a separation. The separation factor provides a shortcut tool for assessing the capital costs as well as the operating and energy costs for a separation. However, as a separation factor approaches 1.0 a separation becomes more costly and less viable because both the capital and operating costs approach infinity. A separation factor of 1.0 implies that a separation is not possible. For most technologies, a separation factor can be related to the difference in physical or chemical properties used as technical basis for the technology. Thus for distillation, the separation factor is a measure of the relative volatility of the chemicals being separated; for extraction, it is a measure of relative solubility in a solvent. The primary difficulty for practical isotope separations is that the difference in the properties associated with the different isotopes is small and thus the separation factor for most technologies approaches 1.0.

The effects of diluteness on the costs for detritiation for environmental applications are associated with the large volume of material handled per unit volume of tritiated water. The high concentration of tritiated water that can be handled without special occupational considerations (eg. highly protective suits and air supply) is 1.0×10^{-9} mole fraction, the low concentration required to meet the drinking water standard is 1.0×10^{-15} mole fraction. Thus, the concentration range of interest is between 1 ppb and 1 ppQd (parts per quadrillion). The effect of these numbers on the technologies for comparison is to increase the volumes and the energy requirements for processing. These "orders of magnitude" concentration issues are the primary challenge in developing and evaluating detritiation schemes.

IV.B Previous Hydrogen Isotope Separation Technology Assessments

In 1978 Rae performed a preliminary process comparison of heavy water production methods [62]. He compared different technologies by plotting separation factor vs. energy cost (see figure IV-1). The separation factor being proportional to capital costs and the energy consumption being a measure of operating costs. In his evaluation, economically favored processes had higher separation factors and lower energy consumption than uneconomic ones. Rae recognized that the factors plotted on the x and y axes were rough estimators (surrogates) for capital and operating costs. Rae stated that a detailed process design may influence the precise costs; however, the effect of changes would not substantially change each technology position on figure IV-1 due to the log-log scale coordinates. Only six of the technologies on the chart represent isotopic separation starting as an aqueous system. The Sulzer Process (H_2O/H_2 exchange), Girdler-Sulfide (GS), H_2O crystallization, H_2O distillation, combined electrolysis catalytic exchange (CECE), and electrolysis. All of the other technologies on the chart start with hydrogen and are not relevant to our study (i.e., the economics for these processes would require electrolysis as a preparation step!). [62]

According to Rae, the only economic processes starting from a water source were the Sulzer Process (Water-Hydrogen Exchange) and the GS Process. The Water-Hydrogen Exchange is a heterogeneous catalyzed exchange reaction that requires a catalyst that degrades. The GS process uses hydrogen sulfide which acts as a homogeneous exchange reaction medium. Although the Sulzer process has a higher separation factor than the GS process the catalyst costs raise its capital cost and this is not reflected in either the figure or the text. The GS process was shown to be the most economical. Those aqueous technologies classified by Rae as "uneconomic" fell into two categories. Electrolysis and CECE (in the upper right corner of the graph) would be expected to have reasonable capital costs but very high operating costs. If a large scale source of hydrogen is available, CECE becomes economic in a "parasitic" mode. Distillation and crystallization have separation factors very near "1" indicating extremely high capital costs. [62]

Rae performed his technology comparison of hydrogen isotope separation processes based on heavy water purification and production. It provides a guide for hydrogen isotope production technology. In contrast, this report shifts focus and provides detailed economic process comparison of technologies based on fractional recovery of tritiated water from dilute solutions (i.e., treatment of tritium contaminated water).

Since 1994, DOE Hanford has prepared an annual summary of potential processes for the mitigation of tritium in process effluent, groundwater, and similar aqueous waste [1, 13]. The reports, prepared as part of the Hanford Federal Facility and Consent Order (Tri-Party Agreement), discuss national and international policies related to tritium regulation, concentrations and exposures throughout the world, and the available tritium isotope separation methods. In the most recent report, a group of relatively mature candidate technologies were identified as potentially applicable for "environmental" tritium. These included: CECE, dual temperature liquid phase catalytic exchange (DTLPCE), laser isotope separation, and membrane separation. The authors noted that research was "progressing" on some of these technologies, notably membrane separation. A separate group of less mature technologies was also discussed. These included: sparging ("isotope exchange"), nickel adsorption, Metanetix adsorption, and organic chemical exchange. Following their assessment of both groups of technologies, the authors concluded: "At present there continues to be no known commercially available process for practical reduction of the tritium burden in process effluent."

Figure IV-1. Summary Graph of Previous Economic Comparison of Heavy Water Purification Technologies [62]

V.0 SCENARIO DEVELOPMENT AND ASSUMPTIONS

This study was prompted by the need to evaluate potential detritiation technologies for use on groundwater contamination or aqueous releases at DOE facilities such as the Savannah River Site (SRS). Groundwater plumes in the General Separations Area (GSA) are used as the basis for defining the scenarios in this study in terms of volume, size, concentration, and water quality. In developing the scenarios two issues were identified: pretreatment needs and posttreatment handling. These issues are impacted by volume of groundwater handled. The plumes in the GSA were the starting point for developing two options for the volume of groundwater to be treated based on alternate conceptual design strategies.

V.A GSA Plume Background

A large percentage of the radioactivity released to surface water by operations at SRS is tritium in the form HTO. In 1994, for example, tritium was the greatest contributor (83%) to the total dose for users of downstream Savannah River public water supplies. Importantly, the maximum 1994 dose commitment for all radionuclides at Beaufort-Jasper SC and Port Wentworth GA was 0.06 mrem, only 1.5 % of the EPA standard for drinking water (4 mrem/year). The entire release of tritium in 1994 to the Savannah River was about 10900 Ci; 62% of this total was from groundwater flow to Fourmile Branch in the vicinity of the GSA which is comprised of the F & H Area Seepage Basins and the nearby Solid Waste Disposal Facilities (SWDF). Based on previously conducted studies future tritium releases from the GSA to Fourmile Branch will be dominated by plumes originating in the SWDF [45]. With the closure of the F & H Area Seepage Basins in 1988, tritium releases from prior seepage basin operations are decreasing over time, figure V-1. Tritium releases from the SWDF have been relatively stable over the past 10 years. Recent studies indicate the tritium release associated with the SWDF will decline in the future, over a period of approximately 20 years [16]. As a scoping evaluation based on the operational history of the facility, and the geology and hydrology of the site, we have assumed that, with no corrective action, SWDF tritium releases to Fourmile Branch will remain approximately at current levels for at least 10-20 years [45].

As shown on figure V-2, the F & H Area Seepage Basins and the SWDF are located in the center of SRS between two streams, Upper Three Runs to the north and Fourmile Branch to the south. Recharge to the groundwater in this area is primarily due to infiltration of rainwater (rainfall minus runoff and evapotranspiration). Groundwater moves downward and laterally, draining to the nearby streams.

Measurements (e.g., flow and contaminant concentrations) in surface waters and in groundwater downgradient of these facilities have been performed from the 1950s through the present. Additionally, examination of cores from drilling and boring and geological descriptions of the area have been performed during this period. Most of the flow to Fourmile Branch occurs in the upper two water-bearing layers, a water table zone and a semi-confined zone. A leaky aquitard (clayey zone) is present between these zones. Within these zones, there are areas with higher and lower permeability. This structure controls the water flow rates, the contaminant plume shape, and the contaminant arrival times and locations in the downgradient surface water. Figure V-3, a map of the tritium plume in the vicinity of the basins and SWDF, shows the tritium flux to Fourmile Branch in this area results from the seepage basins and flow exiting the southwest corner of the SWDF. As expected, vertical water flow in these plumes follows a curved path downward near the source and then upward into the draining surface water, figure V-4. With the closure of the F & H Area Seepage Basins, the contribution from these sources to the tritium plume in the GSA is steadily decreasing. This is evident in the samples collected from the Fourmile Branch Seepine quarterly monitoring program [12]. Thus, the contamination from the southwest corner of the SWDF is the primary continuing source of tritium in the GSA.

Also important to scenario development and target plume selection is bulk water quality. The F&H Area Seepage Basins received low pH wastewater with high specific conductance (salt content). Composition of the resulting groundwater plume reflects the source. The SWDF plume has neutral pH with a natural

level of dissolved salts. Thus, the F&H Area Seepage Basins' plumes would require significantly more pretreatment for most of the detritiation technologies than would the SWDF plume.

Based on the expected future tritium contributions, the nature of the groundwater, and the regulatory status, the characteristics of the SWDF plume were selected for the bounding scenarios to evaluate detritiation of groundwater at a hypothetical site.

V.B Scenario Development

Plume concentration and geometry data from the southwest corner of the SWDF were used as the basis for developing the scenarios for this study. Data show the example trajectory as depicted in figure V-4 represents the flow paths from the SWDF to Fourmile Branch. Latest data reported for tritium levels from the SWDF show a large plume bounded by concentrations measured at the detection limit of 50 pCi/ml. One scenario is based on the removal and/or treatment of the bulk plume. This will require treating low concentrations at a high volume. A smaller, localized volume of groundwater emanating from the source having concentrations greater than 10,000 pCi/ml has been identified. The presence of the localized higher concentration zone within the plume lends itself to the concept of removal and/or treatment of this smaller volume of groundwater with a higher concentration of the contaminant. Thus, the second scenario is of a high concentration plume pumped at a low volume.

Sizing the plumes for the two scenarios was based on the above data along with an examination of the vertical migration of the tritium. An examination of the vertical migration reveals tritium does not appear to breach the confining unit into the underlying aquifer. The depth of the watertable aquifer was used to define the vertical component of the plume for scenario one (large volume, low concentration). Based on available information, the depth of the vertical component of the plume in scenario two (small volume, high concentration) was selected to be one-half the total depth (30 ft).

The two scenarios to be used in this study are described in table V-1. The scenarios are a high concentration plume pumped and/or treated at a low volume and a low concentration plume pumped and/or treated at a high volume. It is assumed the treatment will occur for a 20 year period. Both scenarios are realistic approaches to lowering the amount of tritium being released to the environment. Scenario one opts for source control through strategic or surgical pump and treat. Such source control should theoretically provide maximum benefit per dollar invested. Closure and capping of the F&H Area Seepage Basins, another type of source control applicable to some sites, has been seen to be very effective in decreasing tritium releases. Scenario two is the more classic approach of removing and/or treating the entire plume of contamination. Scenario two, a complete capture goal, is the approach typically specified by regulators in implementing hazardous waste cleanup.

V.C Water Quality Parameters

Treatment of tritium in groundwater may be affected by water quality parameters. The effect will vary depending on the technology and the exact water quality matrix. Potential effects are discussed in relative terms below. In an effort to determine, in a definitive manner, the effects of the water quality matrix on the remediation of the tritium, treatability studies should be conducted for each water source to be treated/remediated. The water quality matrix will have little to no effect on treatments such as longterm storage of the tritiated water in tanks. Water quality parameters may impact the evaporation/distillation technologies and other technologies that are sensitive to dissolved salts.

Water quality parameters that may be present in the groundwater plume at the SWDF have been provided in table V-2. These parameters are potential contaminants of concern in the SWDF groundwater.

Table V-1: Tritium Plume Treatment Scenarios for Study of Detritiation Technologies

Scenario 1: (High Concentration Plume, Low Volume Pumping) Volume to be treated: 3.24 E+07 ft ³ (9.69 E+07 gallons) 1200 ft width 900 ft length 30 ft thickness <i>Average Tritium Activity during operation period: 25,000 pCi/ml</i> Total Tritium in Plume: 9452 Ci * <i>Pumping Rate: 25 gpm flow for 20 years</i> Total Volume Pumped during operation period: 2.63 E+8 gallons Tritium Removal: 1282 Ci/yr *
Scenario 2: (Low Concentration Plume, High Volume Pumping) Volume to be treated: 3.456 E+08 ft ³ (1.03 E+09 gallons) 2400 ft width 2400 ft length 60 ft thickness <i>Average Tritium Activity during operation period: 3,000 pCi/ml</i> Total Tritium in Plume: 12098 Ci * <i>Pumping Rate: 250 gpm flow for 20 years</i> Total Volume Pumped during operation period: 2.63 E+9 gallons Tritium Removal: 1538 Ci/yr *

* Note that the total volume of the plume and the tritium present in the plume is less than water removed and tritium removed by 20 years of active pumping. This difference is due to assumed future releases during the 20 years of operation.

Table V-2: Potential Water Quality Parameters Present in the Groundwater Plume Defined for the Detritiation Technology Evaluation

Bulk Parameters:		
Specific Conductance		20 - 200 $\mu\text{S}/\text{cm}$
pH		5 - 7
Total Dissolved Solids		13,000 - 175,000 $\mu\text{g}/\text{L}$
Major Ions:		
Aluminum		50 - 800 $\mu\text{g}/\text{L}$
Iron		10 - 500 $\mu\text{g}/\text{L}$
Sodium		1,000 - 8,000 $\mu\text{g}/\text{L}$
Calcium		400 - 45,000 $\mu\text{g}/\text{L}$
Nitrate-nitrite as Nitrogen		100 - 3,000 $\mu\text{g}/\text{L}$
Chloride		1,000 - 10,000 $\mu\text{g}/\text{L}$
Sulfate		1,500 - 8,000 $\mu\text{g}/\text{L}$
Key Trace Constituents:		
Lead		10 - 70 $\mu\text{g}/\text{L}$
Trichloroethylene		2 - 200 $\mu\text{g}/\text{L}$
Total Organic Halogens		25 - 150 $\mu\text{g}/\text{L}$

Figure V-1. Tritium concentration profile to Fourmile Branch from the F & H Area Seepage Basins and the Solid Waste Disposal Facility [45]

Figure V-2. Location of the F & H Area Seepage Basins and the Solid Waste Disposal Facility at SRS

Figure V-3. Tritium plume map for the F & H Area Seepage Basins and the Solid Waste Disposal Facility [45]

Figure V-4. Example plume trajectory showing vertical distribution of tritium in groundwater downgradient of the F-Area Seepage Basins [45]

VI.0 TECHNOLOGY IDENTIFICATION AND DESCRIPTION

The technologies under development or in use in the detritiation of water can be combined into technology classes. The classes are based on chemical processes except for the immobilization/storage class. Use of these classes will enable the reader to determine if one of the classes has been or appears to be more promising than other classes. One or more specific technologies under each class were evaluated. All technologies identified are discussed in this chapter. The technologies selected for full cost evaluation were chosen based on level of development, availability of design/process information. In most cases, the technologies evaluated should be approximately representative of the best performance of each class.

Table VI-1 provides a listing of the technology classes and various specific processes in each class. The table identifies key developers and/or organizations for the technologies. The mechanistic basis for each of the classes is described below, the processes are discussed in narrative form, and the specific technologies chosen for full analysis are noted along with key implementation assumptions. Use table VI-1 as a guide to navigate the detailed discussion.

VIA Introduction of the Technology Classes

The various classes of aqueous detritiation technologies are: a) Evaporation/Distillation and Related Processes, b) Mass Transfer Based Equilibrium Processes, c) Rate-Governed Processes, d) Membrane Processes, e) Direct onsite immobilization or storage, f) Frequency Based Separations, and g) Electrolysis plus. The first six categories operate principally as aqueous processes, while the last category separates the hydrogen and oxygen in the water molecules as an initial step. For each class, the operative separation process is identified and specific examples of the class are described. The descriptions serve as narrative flowsheets and provide clues regarding the possible applicability of the various processes to environmental applications. Since none of the technologies destroys tritium, the quantity, concentration and form of the final concentrate stream is critical to the technical success of the process. For example, processes that eliminate all releases to the biosphere (through onsite immobilization or through supplying the recovered tritium to existing tritium production facilities) would be more effective than those that simply transfer tritium from a water release to an air release. Similarly, careful design to reduce treatment volumes, through optimization of activities upstream of detritiation are critical to the potential for actual implementation or successful demonstration.

Evaporation/Distillation and related processes are energy based separation technologies. Simple use of energy is the driving force employed in these processes. These processes range from simple vaporization of the contaminated liquid water (evaporation) to isotopic separation of the influent based on differences in behavior in response to heat. The two specific processes included in the engineering evaluation are: both evaporation methods – evaporation by direct heating and evaporation by humidification. The isotopic separation methods in this category (simple distillation and crystallization) have separation factors very close to “1” and require excessive capital equipment to be economically feasible [62].

Mass Transfer Based Equilibrium Processes are primarily based on ordinary chemical (concentration gradient driven) separation. This is a particularly important class of technologies and several alternative implementations were fully evaluated. Mass transfer operations involve changes in compositions of solutions. All of these technologies involve a mass separating agent. The mass separating agent may be partially immiscible with the solution. Several simple processes such as stripping/sparging (air is the mass separating agent) and adsorption/extraction (a solid material in the mass separating agent) are included in this class. Stripping/sparging was evaluated as representative of the simple exchange concept. Ion exchange processes with homogeneous and heterogeneous catalysis are also included in this class. The homogeneous catalysis is built around dual temperature mass transfer exchange between water-hydrogen sulfide. The water-hydrogen sulfide exchange, known as Girdler-Sulfide (GS) is the most successful process for production of heavy water. Commercial experience provides a sound basis for design assumptions. To circumvent the high cost of reflux, a modified Girdler-Sulfide was assumed to

provide reflux by physical means. Heterogeneous ion exchange processes include: direct exchange, vapor phase catalytic exchange (VPCE, the Sulzer process used at Grenoble and Darlington), liquid phase catalytic exchange (LPCE, developed by AECL at Chalk River and modified for dual temperature operation, DTLPCE, at the University of South Carolina), and combined electrolysis catalytic exchange (CECE, developed by AECL at Chalk River with several small facilities in operation). Current applications of all these technologies are on low volume/high concentration process type influent streams. The heterogeneous processes chosen for evaluation were dual temperature liquid phase catalytic exchange (DTLPCE) and combined electrolysis catalytic exchange (CECE). These processes were chosen due to the success of pilot plant and plant facilities. Both processes have the advantages of lower gas and liquid flows than the Girdler Sulfide process. These low flows allow these processes to be carried out in smaller columns and there is no need to vaporize the feed like the VPCE process (Sulzer). There are also important safety advantages in keeping the tritiated aqueous feed in the liquid phase. The implementation of the liquid phase catalytic exchange selected for evaluation was the dual temperature approach, which targets environmental concentrations somewhat more efficiently than the original monothermal design.

Rate governed processes are primarily based on separation during the course of a reaction sequence. These processes are based on differences in transport rate through some medium under an applied force, resulting from a gradient in pressure, temperature, composition, or electric potential. These processes give product phases that would be fully miscible if mixed with each other. Biological processes are included in this class; however, there was not enough information available on this process for evaluation. The limited scientific literature on biological isotopic differentiation indicates separation factors near 1 (i.e., high capital costs). These processes would be expected to have low energy use. Any concentration of tritium in biomass would result in a relatively high quantity of water rich secondary waste.

Membrane processes are similar to rate governed processes but add the selective solubility in or rejection by a thin polymeric membrane. Transport through a membrane can occur via diffusion of individual molecules or convection induced by a concentration, pressure, temperature, electrical potential gradient or a combination of these potentials. This category was chosen due to the work at Pacific Northwest National Laboratory to develop a polyphosphazene membrane for the separation of tritium. A limited evaluation of this technology was performed due to limited data on costs and design (current studies are only at the bench scale).

Direct onsite immobilization or storage includes a variety of alternative technologies. Some of these technologies are standard industry methods (many currently used at Savannah River Site). A few are innovative processes that are under investigation or have been suggested by the public. The direct onsite immobilization or storage processes include freezing the plume in place, pumping the tritium contaminated water into tanks, and constructing barriers to reduce water flow and releases. Three approaches were selected in this class: 1) storage tanks (both carbon steel and stainless steel were evaluated), 2) ground freezing and 3) a coordinated set of drainage modifications and increased evapotranspiration using plants resulting in infiltration reduction.

Frequency based processes are based on chemical derivatization in which the components to be separated are subjected to some form of chemical reaction. Either some components react and others do not, or else all react, such that the products are more readily separable than the initial unreacted mixture. Lasers have been explored by Lawrence Livermore Laboratories and Ontario Hydro for isotope separation of tritium. The idea is to cause one of the isotopes to enter an activated state selectively, using a laser of carefully determined and controlled emission frequency. This technology has relatively high process risks and is not considered sufficiently mature to consider for full evaluation.

Electrolysis plus processes are based on initially splitting the hydrogen/tritium from the oxygen in the water molecules followed by gas phase processing. Traditionally, the electrolysis step is followed by gas phase separation processes such as cryodistillation, metal hydride collection, thermal diffusion, mass spectrometry, chromatography, and others. Since the result of the original electrolysis is hydrogen, HT

and oxygen, and the FEI for conversion of HTO to atmospheric HT is 1 (i.e., atmospheric HT has no substantive human health impact), there is no environmental reason to perform the traditional gas phase separation. Furthermore, the initial electrolysis is expected to be the practical limitation on this class. Thus, the only implementation in the electrolysis "plus" category analyzed is electrolysis followed by release. The performance of this implementation of the process represents the optimal application from this group.

VI.B Technology Class Descriptions and Selected Technology for Evaluation

VI.B.1 Evaporation/Distillation and Related Processes

VI.B.1.a Evaporation by Heating

Evaporation is a process involving the conversion of a liquid to a vapor by volatilization caused by heat transfer. In the overwhelming majority of evaporations the solvent is water. Heating of the evaporators is usually achieved by steam condensing on metal tubes. The material to be evaporated flows inside the tubes. The boiling liquid is often under vacuum and the steam is at a low pressure. The heat transfer rate in the evaporator can be increased by reducing the boiling temperature of the liquid, which increases the temperature difference between the steam and the boiling liquid. When a single evaporator is used, the vapor from the boiling liquid is condensed and discarded. This is called a single-effect evaporation. A multiple effect evaporation involves increasing the evaporation per pound of steam by using a series of evaporators between the steam supply and the condenser. The characteristics of the liquid affect the design of the evaporator. The concentration of the liquor fed may be dilute enough to have many of the physical properties of water.

An evaporator consists basically of a device to transfer heat to the solution and a device to separate the vapor and liquid phases. Heat transfer, vapor-liquid separation and energy utilization are the main parameters involved in design of an evaporator. The material of construction for evaporators is usually a steel. A high degree of separation for most radioactive materials is achievable with the coupling of evaporators to efficient deentrainment devices. The high operating costs of evaporation limits its application to liquids that have a high concentration of dissolved solids and require high decontamination factors.

This technology was selected for full evaluation.

VI.B.1.b Evaporation by Humidification

Humidification and evaporation are synonymous terms. The usage of the word humidification implies that one is intentionally adding or removing vapor to or from a gas. The major application of evaporation is humidification, the conditioning of air and cooling of water [30]. If the liquid phase is a pure liquid containing but one component while the gas contains two or more, the operation is humidification. Contact of dry air with liquid water results in evaporation of some water into the air. This process includes diffusion of water vapor through the air. Humidification is concerned with the interphase transfer of mass and energy which result when a gas is brought into contact with a pure liquid in which it is essentially insoluble [78].

This technology was selected for full evaluation.

VI.B.1.c Distillation

Distillation is a separation process based on the difference in composition between a liquid mixture and the vapor in equilibrium with it. The composition differences arise from different effective vapor pressures, or volatilities, of the components in the liquid. The most elementary form of the method is simple distillation in which liquid is brought to boiling and the vapor formed is separated and condensed to form a product. Most distillations conducted commercially operate continuously, with a more volatile fraction recovered as distillate and a less volatile fraction recovered as bottoms or residue. If a portion of the distillate is condensed and returned to the process to enrich the vapor, the liquid is called reflux [16,38]. Distillation requires energy in the form of heat, which can subsequently be removed from the system, this is an important advantage.

Water distillation exploits the vapor-liquid equilibrium:

by which tritium is enriched in the liquid phase. The separation factors are approximately the ratio of the vapor pressures. Operation parameters have normally been at 200 mbar and 60°C. Counterflow of the steam or liquid phase in a rectifying column, desired phase reversal by condensation at the top, and reevaporization at the bottom of the column leads to multiplication of the separation factor [79]. For isotopic enrichment of aqueous HTO and H₂O, the relative volatility of the H₂O over the HTO is approximately 1.07. This low value implies that a high reflux rate would be needed to concentrate or to deplete the tritium concentration in the liquid. The resulting effect of high reflux will be a very large column and radically increased operating costs over a simple evaporation process. Costs for distillation will far exceed costs for evaporation [3,24,30,75,79,83,84]. However, the process can be effective given a sufficient number of theoretical plates, and the separation factor can be increased by lowering both temperature and pressure.

The Manhattan Project used water distillation for the industrial production of heavy water. Three plants were built in 1943 in Morgantown, West Virginia, Childersburg, Alabama, and Dana, Indiana. The relative volatility for separating H₂O from HDO is only about 1.03 at atmospheric pressure; therefore, the size of equipment and the heat consumption of these plants was very high. Distillation of water was attractive because the process needed little development work and used standard equipment. After the plants were shut down in 1945, it was shown that distillation of water is one of the most satisfactory methods for final concentration of heavy water [44]. Water distillation can also be used for purifying D₂O that may have become contaminated in use by H₂O through dilution or DTO through neutron absorption [3].

Since 1953, Sulzer Brothers Ltd. (Switzerland) have built 35 plants for the vacuum distillation of H₂O/D₂O and two plants for low-temperature distillation of H₂/HD and HD/D₂/DT. [Note, these plants employ vacuum distillation, and are not the vapor phase catalytic exchange process developed later and known as the Sulzer Process.] When designing these plants it was noted the size of the plant is proportional to the tritium production and inversely proportional to the tritium concentration in the feed [79]. Some features of the Sulzer tritium extraction plants include small dimensions, low steam consumption and simple operation. The plants have small holdup, allowing for speedy restarting after interruptions. Environmental concerns are a minimum because most parts of the plant are under vacuum, which diminishes escape of tritium into the building.

The Heavy Water Group at Ontario Hydro Research Division in Canada has studied the feasibility of water distillation for heavy water production. For a heavy water system, the component to be recovered, HDO, is present in very low concentrations, so that large volumes of vapor must be passed through the separating system to extract sufficient HDO. The feasibility of performing heavy water separation by

distillation at low temperatures using a newly developed packing system was proven. It was predicted that a useful degree of separation could be achieved using simple parallel sheets carrying downward-moving water films, with upward moving vapor between them. The sheets were made of nylon fabric under tension, with a surface treatment to improve the uniformity of the water film [62].

Yamamoto and Kanagawa conducted preliminary experiments on the separation of tritium isotopes by water distillation at Nagoya University (Japan). This research led to a batch distillation of tritiated water at the university. Time variations of tritium activity were measured at the top of the column as well as at the distillate receiver by changing the vapor flow rate within the column. Results indicated the number of theoretical stages increased with decreasing vapor flow rate within the column in the ranges of the performed measurements [79]. Further studies were performed as a series of water distillations in a total reflux mode in a column in order to measure the HETP of various packings.

The advantages of this process are the robust construction of the equipment, high reliability, and leakage safety caused by the vacuum. There is no danger of a hydrogen explosion. Attractive advantages of this process are its simplicity and that the technology is known. Unlike the Girdler-Sulfide process, this process lacks any corrosive or toxic compounds. Other advantages of this method include the absence of water-hydrogen gas conversion by electrolysis and absence of a catalyst involved in chemical exchange processes. Therefore, water distillation has been applied to the detritiation of drainage from a nuclear fuel reprocessing plant. It has also been considered for volume reduction of tritiated water, based on tritium enrichment, from the cooling and safety systems of a nuclear fusion reactor [79]. Disadvantages of this process include the large size of the units, which results from the large number of exchange plates, and large power consumption [79]. In spite of the large heat requirements for stripping by distillation, only low grade energy is required and the process could utilize waste heat from a reactor.

This technology was not selected for full evaluation.

VI.B.2 Mass Transfer Based Equilibrium Processes

VI.B.2.a Stripping

Stripping is the opposite of absorption. One or more components of a liquid stream are removed by being vaporized into a sparingly soluble gas stream. While isotopic enrichment can occur by this process, its slow rate is increased by adding a reaction to radically enhance its performance efficiency. The separation usually occurs at elevated temperatures and ambient pressure. Here the gas stream is added as a separating agent. The separating agent eliminates the need to reboil the liquid at the bottom of the column, which is important if the liquid is not thermally stable. Stripping can be conducted in packed or plate towers. Stripping requires large liquid and vapor inventories for isotopic separation [30,84].

This technology was selected for full evaluation.

VI.B.2.b Sparging

This process, also known as bubble-mediated isotope exchange, consists of the diffusion of water vapor in air. Recent studies have suggested this process is a viable tritium treatment method [72,73]. Bubbling air through water is a dynamic process normally resulting in evaporation if the air is not saturated with humidity at the temperature of the water (similar to the evaporation humidification case above). The proposed sparge method humidifies the air with tritium free water to eliminate this evaporation. Under these conditions, transfer of molecules back and forth allows isotope exchange without a net loss or gain of water mass. Thus, the process slowly changes in the isotopic composition of the liquid without net additions or subtractions to the bulk water mass. Tritium transfer (liquid to vapor) is induced in the exchange vessel by a constant flux of water-saturated, zero-tritium air through the bulk liquid [72,73].

In 1994, a paper published by Slattery and Ingraham reported a study on the isotopic exchange between tritiated water and water vapor. The experiment involved bubbling air containing tritium free water vapor through a container of tritiated water. Tritium in the system reaches an equilibrium state between the vapor in the air and the water. This equilibrium state is in the same ratio as predicted by the liquid/vapor separation factor for tritium. Tritium in a 30 L container was depleted by about 80% after 50 days of continuous sparging. The sparging occurred at 35 L/min. The air remaining that contained the tritiated water vapor was vented to the atmosphere [1]. This is an environmental concern that was not addressed in this paper. On a larger scale, the same result could be obtained by distilling a body of water containing tritium. There is no difference whether the water vapor removed was from simple distillation or vapor sparging. This is due to the tritium being at equilibrium between the aqueous liquid and vapor phases.

This technology was selected for full evaluation.

VI.B.2.c Extraction

Extraction is a process in which one or more solutes are removed from a liquid by transferring the solute(s) into a second liquid phase. The two liquid phases must be immiscible (that is, insoluble in each other) or partially immiscible. The separation is based on different solubilities of the solute in the two phases. The key to an effective process lies with the discovery of a suitable solvent. In addition to being nontoxic, inexpensive, and easily recoverable, a good solvent should be relatively immiscible with feed components(s) other than the solute and have a different density. It must have a high affinity for the solute, from which it should be easily separated by distillation, crystallization, or other means. The complete extraction process includes the extraction unit and the solvent recovery process. In many applications, the downstream solvent recovery step is more expensive than the actual extraction step. For practical considerations of extraction as a viable separation alternative, the distribution coefficient for the solute between the phases will be at least 5, and perhaps as much as 50. Under these circumstances, an extraction column will not require many stages, and this indeed is usually the case [22,30,53,79,83,84].

A method of enriching deuterium using solvent extraction was explored by Augood. Liquid nitrogen was used as the solvent. Moderately low temperatures are involved in using nitrogen. Smaller gas volumes, greater hydrogen solubilities and better solubility differences can be achieved using liquid nitrogen. However, it was shown that the power consumption using this process is several times higher than for a hydrogen distillation plant. Augood also looked at using liquid neon as a solvent and achieved a very high separation factor [44].

The idea of host-guest chemistry has been proposed to simulate the ability of enzymes to catalyze organic reactions. Nishizawa from Osaka University explored this process by exchanging tritium between tritiated water and a primary amine salt. The amine salt is extracted into a chloroform layer containing a cyclic ether which strongly complexes the amine salt. Using tert-butyl-ammonium iodide a single stage separation factor of 50 was achieved using this extraction procedure. This large separation factor implies that the rate of exchange equilibrium could be sufficiently rapid for the industrial separation of hydrogen isotopes. The cost of the solvent and the disposal of the solvent are factors that must be considered when analyzing this process [1, 79]. The high separation factor obtained from this process seems unlikely. In 1993, Russian scientists ran similar tests with a system using carbon tetrachloride as the solvent and a substituted cyclic ether. The separation factor was determined to be 5. This is considerably different from the separation factor reported by Nishizawa [1].

Tritium labeling of organic substrates is thought to be radiation induced and to be catalyzed by super acid complexes. Detritiation of HTO oxide has been demonstrated in SRS laboratories by selective reaction of tritiated water at environmental levels of tritium with solid substrates of polystyrene. Approximately 10-15% of the tritium from environmental samples of tritiated water has been irreversibly removed or detritiated from HTO oxide. The aromatic rings of the polymer incorporate tritium from the oxide into the nonlabile hydrogen positions of the aromatic rings by direct hydrogen-tritium chemical isotope

exchange. The rate of the reaction is enhanced by Lewis acid catalysts [1, 40]. Tests on this process were conducted at the University of South Carolina using deuterated water that showed that substituted naphthalene displayed a capacity to exchange and preferentially hold deuterium over hydrogen. The exchange required an acid catalyst and a surfactant to disperse the naphthalene derivative in the deuterated water [1, 40].

This technology was not selected for full evaluation.

VI.B.2.d   Adsorption

Adsorption uses the tendency of molecules from an ambient fluid phase to adhere to the surface of a solid. Its origin is in the attractive forces between molecules. The force field creates a region of low potential energy near the solid surface and, as a result, the molecular density close to the surface is generally greater than in a bulk fluid. Adsorption may also occur from the liquid phase and is accompanied by a similar change in composition; although, in this case, there is generally little difference in molecular density between adsorbed and fluid phases. There are no known adsorbents that show isotopic enrichment from aqueous liquid solutions. Most of the important applications of adsorption depend on selectivity, or differences in the affinity of the surface for different components [23,48,83,84]. Partial pressure differences can be magnified by adsorption of molecules on an active solid surface. Typical adsorbents are charcoal, alumina, silica, and molecular sieves. Each has potential for use with hydrogen at low temperatures. The heavier isotope has a greater heat of adsorption, which leads to an enhancement of separation factors. Although this method is simple, there are many difficulties in designing a large plant.

Adsorption is studied by gas chromatography methods. One of the first studies used palladium black. Palladium catalyzes the exchange reactions so that only pure isotopic species are obtained, i.e., D_2 and T_2 . Excellent separations can be achieved using these packing materials because of a high separation factor value and large number of theoretical plates. The only extensive data has been on H_2 -palladium and water charcoal systems [79].

In 1984, Vieider [79] introduced a new concept for concentrating heavy water using a Lithium-ceramic blanket, which uses helium as a purge and to equalize pressure in the system. This concept requires a large helium flow for adequate control of water vapor and for the reduction of tritium permeation. A review of this process showed the cryogenic freezer method, which is used in several blanket designs for low-pressure purge-gas purification, becomes increasingly unattractive with increase in flow. Molecular sieves regenerated by conventional water desorption methods retain an unacceptable large quantity of tritium. The problem of high tritium inventories on the molecular sieves is resolved with a new process called adsorption and catalytic exchange (ACE) by AECL (Atomic Energy of Canada). This system consists of a catalytic recombiner, three molecular sieve drier columns, and an LPCE (Liquid Phase Catalytic Exchange) column. The solution to high tritium inventories is resolved using a regeneration procedure. This procedure involves pressure reduction, thermal desorption and isotopic exchange. Isotopic exchange is used for displacement of tritium with D_2O vapor. The D_2 and D_2O circulate in a closed loop as carriers of tritium and require no makeup. The total tritium inventory of the system was 208 g [79]. This process also uses established technology.

In Japan, the Rainey procedure is being used to prepare a finely divided nickel catalyst. This catalyst is used in many synthetic organic reductions. A 1:1 nickel/aluminum alloy is treated with aqueous sodium hydroxide, dissolving the aluminum and leaving a precipitate of finely divided nickel with hydrogen adsorbed to its surface. The initial hydrogen evolved in this procedure contained only a tenth of the tritium that was in the water. When the wet catalyst was heated from 100°C to 1000°C, the hydrogen evolved was enriched in tritium by a factor of 3.6 [1]. The nickel is no longer an active hydrogen adsorber after it is heated. This process cannot be operated continuously without a reversible substrate. This problem makes it difficult to design an operational system [1]. In 1940, a decision was made against the use of nickel. Platinum was then incorporated for D_2O production.

In other experiments, tritiated water was used as a tracer for determining the free volume of a separation column containing a medium that was proprietary. This work was presented by Dr. Irving DeVoe in 1995. Tritium stayed on the column until 12 bed volumes had been eluted. This media clearly has a stronger affinity for tritium than it does for normal hydrogen in water. It was proposed that coupling this technology with a steady-state reactor might provide an operation for tritium removal. A cationic species with a higher affinity can be used in desorption of tritium from the media. This is an advantage that would produce a concentrated stream. No further work has been conducted [1].

This technology was not selected for full evaluation.

VI.B.2.e Homogeneous Exchange Reactions - Girdler-Sulfide (GS)

The most successful process for production of heavy water is based on the exchange of hydrogen isotopes between hydrogen sulfide gas and liquid water according to the reaction:

To circumvent the high cost of reflux, Geib of Germany and Spevack in the United States conceived of using this exchange in a dual temperature system to provide reflux by physical means [3]. It is anticipated, by analogy, that for tritiated water the equilibrium reaction would be:

The reaction occurs rapidly in the liquid phase, without catalysis. Variation of the equilibrium constant with respect to temperature can be used as the basis for a separation process to produce a water stream enriched in HTO and a water stream depleted in HTO from a feed containing both HTO and H₂O. The GS process was only used for production of concentrated streams of heavy water [70]. This process consists of two towers, or two sections within a single tower, that operate at different temperatures. The equilibrium constant for the exchange reaction is temperature dependent. The separation factor is lower in the hot tower than in the cold tower. This lower separation factor makes possible transfer of tritium from water to hydrogen sulfide in the hot tower and thus converts the H₂S entering the hot tower into the HDS needed for refluxing in the cold tower. It is usual for countercurrent flows to be used, with the liquid falling down the tower and contacting a rising stream of gas. The chemical equilibrium in every case that has been considered favors transfer of the heavier isotope into the liquid, and so the liquid stream is progressively more enriched towards the bottom, and the gas stream is progressively depleted as it rises. Heat is conserved by heat exchange between hot and cold liquid and between hot and cold vapor. In principle, no materials other than feed water are consumed in the dual-temperature system. Energy consumption can be reduced by efficient heat exchange, with a lower bound set by the minimum required by the thermodynamics for the separation [3,39,40,67,70].

The exchange reaction between water and hydrogen sulfide was being investigated by Urey at Columbia University from 1940 to 1943 for possible use for heavy water production. Spevack, at this time, conceived and patented the dual temperature process. The first plant of this type was built at the Wabash Ordnance Plant at Dana, Indiana in 1952. This plant was designed by the Girdler Corporation and operated by E.I. du Pont de Nemours and Company. Three improved units were built by du Pont in Aiken, South Carolina in 1949 when a need for large amounts of heavy water for the reactors was recognized [3]. At both Dana and Savannah River the GS process was used for primary concentration of deuterium to 15%, with the remaining concentration being effected by distillation of water and electrolysis. By 1957, production rates decreased and the Dana plant was shut down and dismantled. Two thirds of the GS units at Savannah River were shut down and put into standby conditions [3]. In the mid 1960s, the GS process was adopted in Canada to supply the CANDU power reactor program [62].

The GS process uses an abundant feed and has fast mass transfer rates. Temperature which controls the GS process is moderate. Pressure for this process is not high enough to incur a large penalty in cost. The major reason for success of this process is the scale effect. The cost of this process is less than other processes due to the absence of a catalyst. A disadvantage of this process is restriction of temperature in the cold column due to formation of a solid hydrate. For a soluble gas like hydrogen sulfide the value of Henry's Law constant is small and gas phase resistance is important. Rates in the cold and hot towers are roughly similar, because both are by mass transfer in the gas phase [62]. This process has a low separation factor and a high energy consumption. Hydrogen sulfide is toxic, corrosive, and a potential safety hazard. Hydrogen sulfide is flammable and in certain mixtures of air it can be explosive. The major environmental considerations are H₂S emissions to water and to the atmosphere.

This technology was selected for full evaluation.

VI.B.2.f Heterogeneous Ion Exchange - Liquid Phase Catalytic Exchange and Dual Temperature Liquid Phase Catalytic Exchange (LPCE and DTLPCE)

Liquid Phase Catalytic Exchange (LPCE) relies on catalyzed phase transfer to enhance the separation. Reactions for this separation are shown below:

Reaction (1) proceeds in the presence of a wetproofed catalyst. The wetproofed catalyst is platinum supported on carbon, Pt-C. It is one of the most efficient catalysts for gas phase exchange of isotopes between hydrogen gas and water vapor. In the presence of liquid water, catalytic activity of these and many other platinized supports is severely impaired. When rendered hydrophobic, these catalyst powders give high catalytic activity. A wetproofing agent, such as Teflon, is used to render the catalyst hydrophobic. Reaction (2) represents the exchange occurring between bulk vapor and liquid. In its early development, LPCE was performed monothermally. Like the Girdler-Sulfide process, dual-temperature operation (DTLPCE) can be used to maximize the separation factor by taking advantage of the change in reaction equilibrium constants with temperature [1,40,67]. DTLPCE is more suited to environmental remediation objectives because it can achieve high decontamination factors (DF>100) and high volume reductions (>1000). DTLPCE consists of two packed towers each operating isothermally at different temperatures. Feedwater enters at the appropriate level in the cold tower and becomes progressively enriched by exchange with tritium-rich gas as it flows down the column. The liquid is then fed to the hot tower in which it is stripped by contact with gas of lower tritium content. The water is in contact with the same gas at the top of the cold tower and at the bottom of the hot tower. Flows and temperatures are controlled so the gas and water tend toward equilibrium at these two points. Therefore, tritium is transported down the cold tower and up the hot tower, providing enriched gas and liquid at the center pinch point. Equilibrium constants for isotopic exchange are significantly lower in the hot tower than in the cold tower, so the liquid at the bottom of the hot tower is depleted relative to the feed. This provides the low-activity feed for the top of the cold tower, except a small amount is fed back to the previous stage, at the top of the hot tower [40,67,70,79].

Chalk River Nuclear Laboratories (CRNL) in Canada discovered a simple method of wetproofing platinum catalysts and this has stimulated research for development of hydrogen isotope separations. One of the first applications was for separation of hydrogen isotopes for production of tritium and heavy water. Liquid phase catalytic exchange was chosen for a Chalk River Nuclear Laboratory demonstration because the process is simple and requires less energy than Vapor Phase Catalytic Exchange (VPCE). This plant was completed in 1985 and was for recovery of tritium from heavy water. Prior to this decision, a pilot plant was built in 1979 at CRNL to demonstrate the LPCE process, to measure catalyst activity for hydrogen isotope exchange and to demonstrate the lifetime performance of the catalyst [79].

Japanese workers also describe the use of liquid phase water/hydrogen catalytic exchange for concentration of tritiated water at environmental levels using electrolysis to generate the hydrogen gas stream containing HT. In 1988, the Japanese piloted the CECE concept at 3.6 L/day of liquid feed and reported enrichment factors of 300. Total separation factors of 10^4 were also reported as a comparison of HTO electrolytic concentration versus HT in the offgas. This was a monothermal LPCE demonstration [38].

A study was conducted at the Massachusetts Institute of Technology (MIT) using biological catalysts in place of precious metals for LPCE. The catalyst is the enzyme hydrogenase and it is effective without having to be purified. Whole bacterial cells, immobilized in a gel, were used. These are much less active than wet proofed platinum, but they may be much less expensive [70].

With water feed, the water-hydrogen exchange process has the advantages of lower gas and liquid flow rates and fewer stages than the Girdler-Sulfide process. Utility requirements would also be smaller. A disadvantage of this process is the expensive catalyst and the limited suppliers of the catalyst [3]. In comparison to VPCE this process can be carried out in a smaller column and there is no need to vaporize the feedwater. There are also important safety advantages in keeping the tritiated aqueous feed in the liquid phase [70].

This technology was selected for full evaluation.

VI.B.2.g Heterogeneous Ion Exchange - Combined Electrolysis Catalytic Exchange (CECE)

The Combined Electrolysis Catalytic Exchange (CECE) process, as is the liquid phase catalytic exchange process (LPCE), is based on the exchange reaction which occurs between HT and HTO:

In this case the heterogeneous exchange reaction process (LPCE) is coupled with electrolysis. Electrolysis provides a source of hydrogen as well as a further tritium enrichment step and also a method to convert high concentration tritiated liquid to a less toxic form. This is an equilibrium reaction which, at ambient temperatures, favors formation of HTO. When a tritiated gaseous hydrogen phase is brought into contact with a liquid water phase, there is a net transfer of tritium from gas to liquid phase. The rate of transfer is vastly improved by the presence of a precious metal catalyst. A stream of tritiated water is fed to a column packed with catalyst. In the column, the feed mixes with a liquid reflux stream flowing countercurrent to a gaseous steam-hydrogen stream. Tritium is transferred from the gas to the liquid, so as the streams leave the column, the liquid stream is enriched in tritium and the gas stream depleted in it. Outside the column, the liquid is electrolyzed to provide not only the hydrogen stream for the exchange reaction, but also a product hydrogen stream which is enriched in tritium. At the opposite end of the column, the depleted hydrogen stream is recombined with oxygen from the electrolysis to form a detritiated water stream which provides liquid reflux to the column and the detritiated water product [40,51,70,79].

This process was developed by AECL at CRNL in 1971 to separate T_2O from D_2O . This process is attractive for treatment of very dilute tritium streams in light water because of favorable separation factors and its ability to concentrate tritium. This process is more complex than the LPCE process and requires handling of tritiated water at a concentration much higher than the feed concentration. The process also operates at mild operating conditions. Prior to this research, from 1943-1956 the heavy water Trail plant in British Columbia was operating in the gas phase due to poisoning of the catalyst. This process was too costly due to the size and complexity of the exchange columns. Research at AECL continued due to the discovery of a wet proofed catalyst that could be used in the liquid phase. This research at CRNL led to a laboratory scale demonstration at Mound Laboratory in Miamisburg, Ohio. From this demonstration, a small pilot-scale plant was built in 1975 for production of heavy water. Equilibrium in the electrolysis

cell unit was reached only after prolonged operation. Due to this fact, the plant was decommissioned in 1983 [79]. AECL's process is being used at two heavy water plants. One of the plants built in 1988 is Darlington, in Ontario, Canada, and the other is at Grenoble, France. A patent belonging to AECL has detailed flowsheets for treatment of both light and heavy water by CECE. It is claimed the process can achieve decontamination factors of 10^7 and volume reduction factors of 100.

A process called ELEX (Electrolysis Chemical Exchange) has been developed in Belgium. Research began with a bench scale demonstration in 1978. Results of this demonstration were the decontamination factor was always greater than 100, and the volume reduction factor increased with time as concentration of tritium in the electrolyzer increased [70]. After the bench scale operation, a pilot plant was constructed in 1984.

In 1988, the Japanese built a pilot plant facility in order to recover tritium from light water. The pilot plant had a capacity of 3.6 L/day. This research was based on the Canadian catalyst developed by AECL. Tritiated water was concentrated to an order of magnitude of 10^4 [36].

A pilot operation was conducted in Karlsruhe in 1980. This process was to recover tritium from aqueous waste of nuclear fuel reprocessing plants contaminated with tritium in the form of HTO. Substantial energy reduction was achieved by substituting conventional water electrolysis with high temperature steam electrolysis. The radioactive inventory was minimized and no secondary waste was produced [77].

Advantages of this process are a higher separation factor and higher recovery than the Girdler-Sulfide process. Due to the higher separation factor, this implies smaller exchange columns and lower water and gas flows. Also, the operating conditions are close to ambient. The process chemistry is simple and it uses only one exchange reaction. This system is non-corrosive, non-toxic and has a low environmental impact [1]. The process involves three products, H_2 , D_2O , and O_2 , that can possibly be commercially sold. Disadvantages of this process are large amounts of energy are required for electrolysis, the stability of the Pt catalyst is a concern, and the high cost of the catalyst. This process is commercially used for removal of high level tritium from D_2O at low flow rates, but has not been developed for low level tritium. Another disadvantage is the entire volume of the clean stream must be removed in the form of hydrogen gas [1].

This technology was selected for full evaluation.

VI.B.3 Membrane Processes

A membrane is a solid separation barrier that separates two phases that differ in concentration. Without the membrane barrier that restricts bulk flow between the phases in contact with it, no separation would occur. In separation applications, the goal is to allow one component of a mixture to permeate, pass through, the membrane freely, while hindering passage of other components. The membrane can be homogeneous or heterogeneous, symmetric or asymmetric in structure; it may be solid or liquid; and it may be neutral, carry either positive or negative charges, or have functional groups with specific binding or complexing abilities. Mass transport through a membrane can occur via diffusion of individual molecules or convection induced by a concentration, pressure, temperature, electrical potential gradient or a combination of these potentials. Energy requirements per stage is linear resulting in high energy costs. The size of the stage changes to account for diminished flows. In using membranes for separation, energy is the separating agent. Membranes belong to a group of separation processes in which the separating agent must be added to each stage and cannot be reused. This requirement is a negative feature because it increases operating costs considerably. This process finds application when it provides a high enough separation factor for only a single stage [1,20,39,76,83].

Work is currently being done at Pacific Northwest National Laboratories (PNNL) to develop a polyphosphazene membrane for separation of tritium. This membrane separation is pressure driven and

maintains a liquid phase throughout permeation, much like reverse osmosis [55,56]. In previous laboratory experiments, membranes demonstrated the ability to retain levels of tritium. The membranes are subjected to an annealing process at 75-100°C. Reduction of tritium obtained with this membrane is 40%. The best separation is occurring at 5°C. The researchers believe this is an indication that separation takes place at the membrane surface by some mechanism involving water aggregates or clusters that tend to hold HTO somewhat more strongly than they do water [1]. Poly[bis(phenoxy)phosphazene] provided separation of tritiated water up to 31% within the range of 4 to 23°C. At 4°C, the 5-10% carboxylated-polyphosphazene membrane showed a tritiated water separation of 43%. However, separation approaches zero above 10°C. A carboxyl content of 20-30% proved to be less efficient for separation [55,56].

A cost analysis was conducted at PNNL for the membrane research. To reduce tritium by 90% the total capital and operational costs ranged from \$7,000,000 to \$80,000,000 [80]. To assist in comparing these costs to those for other technologies, we have converted them to \$ / 1000 gallons. Based on the treatment scenario [80], the normalized costs range from about \$8000 to \$90000 per 1000 gallons. The authors used a simple cascade design for the cost evaluation. This design processes a stream sequentially through a series of membrane cells. In each cell the tritium concentration in the process stream was increased by a factor of 2.2. The final stream is higher in tritium concentration and lower in volume allowing for proper disposal. A design problem occurred when it was assumed the depleted stream was to be piped back to the original source. Tritium concentration is increasing in the feed to each sequential cell, but only the depleted stream from the first cell is actually lower in tritium concentration than the water in the original source. A feedback design may be more appropriate instead of this case [1]. It is clear that the membrane process is early in development (current systems are still operating on a cm size scale). Substantial process developments are needed and may improve the marginal cost performance.

Osborne and McElroy at CRNL have studied permeation through membranes to separate and monitor HT and HTO species. Dimethyl silicone and Nafion are polymeric materials utilized for this study. Nafion is chemically stable and a cation exchange material. Results showed for Nafion membranes the permeability of HTO is much higher than for HT. The basic setup included a Nafion membrane in the form of tubing that separates two countercurrent flows. Sample flow is assumed to contain a mixture of HT and HTO. Detector flow is clean air. HTO can permeate the membrane easily, so it will be transferred to the detector flow while HT will largely remain in the sample flow. Maximum discrimination achieved by this method is equal to the ratio of the permeation rates of the two species. For Nafion, the ratio of 10³ is what is achievable with a single diffusion stage and practical flow rates. This process is bench scale only [79].

This technology was not selected for full evaluation. The limited cost evaluation provided in Allen [1] is incorporated into the discussion of results.

VI.B.4 Direct Onsite Immobilization or Storage

An important class of tritium reduction scenarios involves modifying the fundamental hydrogeology of the groundwater system. Such modification can involve aggressive and/or invasive technologies such as ground freezing, traditional surface capping, or physical/biological barriers to lateral flow. Intermediate methods involve pumping water and storage on site (e.g., using tanks or immobilization in solid wasteforms). Less aggressive alternative methods of altering the hydrogeology in desirable ways are also possible. A notable alternative involves reducing recharge using a combination of increased evapotranspiration and maximized runoff. Such a proposal, known as "the Accelerated Approach," was documented for the F & H Area Seepage Basins [85]. Specific "technologies" proposed in the Accelerated Approach to achieve tritium reduction goals included adding appropriate plant species, fertilization, pumping and/or drip irrigation, surface recontouring, debris/litter removal, and strategic smoothing. This combination of actions was termed "surface enhancements". Also included in this section is the use of tanks to containerize and minimize the source of the tritiated groundwater for a long period of time.

Under natural gradient, flow will be generally toward the downgradient wetland/stream. Figure VI-1 represents the water balance for the site using representative values. The water balance shown is consistent with field measurements and studies, for the F&H Area, and with the previous transit time measurements and numerical groundwater modeling performed at the site. It is clear from the figure that downgradient barriers (vertical cut off walls, etc.) would only temporarily reduce tritium releases from the site. Following installation, the head would increase behind the barrier, increasing the water flow velocity until the water release to the stream once again balanced infiltration. Thus, to a first approximation, the groundwater system is similar to a plug flow reactor, in which the hydraulic residence time is fully determined by the inflow rate and the system volume (not by baffles or other structures). Similar problems occur for systems that involve pumping water near the outcrop and reinjecting upgradient. A pump-treat-reinjection system would be effective in the early years in intercepting water prior to its entering the wetland. As the water is reinjected, however, the system would re-equilibrate until the net groundwater flow to the wetlands would again approach infiltration (shifted around the recovery system).

Based upon the water balance figures, reduction in infiltration is the only directly controllable means to improve the effectiveness of such a remediation (each gpm of infiltration reduction directly translates to flux reduction to surface water). A comprehensive set of surface enhancements represent the most environmentally protective implementation of infiltration reduction. The important components of the surface enhancements include: i) grading, smoothing and construction of lined-engineered drainages to maximize the run-off term, and ii) modifying plant communities and fertilizing to maximize evapotranspiration.

VI.B.4.a Ground Freezing

Ground freezing and frozen barrier technology was developed for the construction industry. Traditional uses include water control and site stability control during construction activities. Examples of modern commercial applications include construction of large subway, highway or water supply tunnels. As a result of the experience base, reputable firms are available to provide ground freezing services and rough costs are available. Additionally, ground freezing for groundwater contamination containment has recently been examined and the performance and costs have been reported in detail by the Scientific Ecology Group (SEG) [69] (complete performance information is currently posted on the Internet at <http://eagle.haz.ornl.gov:80/plumesfa/intech/fsbt>).

Ground freezing requires drilling and installation of refrigerant piping into the target zone. The piping is typically installed on a close spacing (approximately 8 ft on center). Following installation, an environmentally safe refrigerant solution (brine) is circulated to freeze the water in the soil pores. Freeze plants are used to maintain the containment.

Freezing results in a broader area of immobilization than most physical barrier emplacements and an approach based on immobilizing and holding large areas of the plume to allow for decay was selected for examination. This would provide performance far superior to simple downgradient walls or baffles and is suited to the diffuse nature of the freezing process. Conceptually, ground freezing based tritium reduction would consist of creating a network of frozen cells that encapsulate the plume. Based on the referenced field test, the resulting "honeycomb" could encapsulate about 30% more volume than the initial frozen target volume.

Ground freezing has the advantage of clearly defined and documentable immobilization of the tritium plume. Unfortunately, the process results in relatively extensive collateral environmental damage. The negative environmental impacts include: extremely high energy use (resulting in increased CO₂ production and related large scale power generation problems), large scale construction activities near healthy terrestrial/wetland/stream ecosystems (raw materials use, site clearing and sedimentation), large amounts of equipment transport (fuel use and CO₂ emissions), and related issues. Qualitatively, these

collateral impacts offset some of the tritium reduction benefits. Further, the size and complexity of the project would result in a substantial time period for implementation.

This technology was selected for full evaluation.

VI.B.4.b Storage Tanks

One option for detritiation of groundwater is to separate it from the environment by withdrawing it as a relatively high concentration liquid before it becomes more dilute. The groundwater can be stored in either stainless steel or carbon steel tanks. This option permits an initial recovery of the tritiated water and reduces the offsite dose. It requires only a partial initial investment in tankage, with additional tankage constructed as needed. If an alternate detritiation technology becomes favorable at a later date, the investment in sequestering the relatively high concentration tritiated water may result in a significant reduction in costs.

Interestingly, there is a long period of record for storage of water in carbon steel tanks. The Steel Plate Fabricators Association (SPFA) in Des Plaines, IL recognizes tanks that have continuously served for water storage for at least 100 years through its "Century Club" program. Six tanks were added to the list in 1995. These tanks, along with the 13 tanks named earlier (all of which are still in service) brings the total number of identified tanks to 19. The senior member of the club has been in continuous service since 1881 in Dedham, MA. Appropriate maintenance activities similar to those applied to the Century Club tanks was assumed for the carbon steel tank detailed economic analysis.

This technology was selected for full evaluation.

VI.B.4.c Infiltration Reduction

The purpose of this strategy is to reduce infiltration and the resulting tritium release. The proposed surface enhancements would result in a primary benefit of reducing and leveling the annual tritium releases in proportion to the infiltration reduction. The ultimate population dose (i.e., the basis of the FEI) is not proportional to infiltration reduction, but rather to increased decay during the longer travel time. The proposed actions to reduce infiltration consist of two basic elements, 1) surface smoothing to minimize surface retention (increase runoff), and 2) vegetative enhancements to maximize evapotranspiration. This approach to infiltration reduction is designed to minimally affect the ecology and natural environment downgradient of the basins and in the streams and wetlands.

Certain vegetation types have inherently higher evapotranspiration (Et) values than other types. By changing the type and amount of vegetation, a drastic reduction in recharge can be achieved. Recharge reduction through vegetative changes is a long term proposition, but can be effectively achieved through longterm vegetative management.

A series of preliminary studies would be needed to identify and quantify the existing topographic, soil, and vegetative conditions. These studies include soil surveys of the affected area, infiltration tests, and baseline vegetative studies. Results of the studies would be used in designing the infiltration reduction.

Construction actions are straightforward and can be implemented on a fast track approach, consisting primarily of smoothing and leveling the existing grade, planting and fertilizing. Specific problem areas would be dealt with in the design as needed. Problem areas include areas requiring erosion control and wetland protecting structures. While construction could be implemented rapidly, the vegetation management plan would implement planting of different species during their optimal planting season. Interim grasses would be seeded during the summer months, with seeding of more hardy species during the optimal planting periods.

The proposed surface enhancements have the advantages of reducing and leveling tritium releases, and increasing tritium decay using natural and sustainable processes. Further, the action is simple and can be implemented rapidly without delay for complex planning. Little energy is used and local ecosystems are considered and protected more explicitly than is possible with large construction projects. Finally the costs are relatively low, both in terms of volume treated and curies averted. Unfortunately, the process results in relatively small reductions in tritium release. A reduction of only a few hundred Curies per year may not meet the performance needs for the site. Finally, the performance is more difficult to measure than pump and treat processes and explicit immobilization methods such as ground freezing. Documenting performance is further complicated by the relatively small magnitude of the expected tritium reduction since historical annual variations in observed releases are on the order of a few hundred curies.

This technology was selected for full evaluation.

VI.B.5 Frequency Based Separation - Lasers

This method is based on laser-induced dissociation of a tritiated molecule that yields easily separated products. It is necessary to find a suitable tritium substituted molecule that has selective absorption bands in the range of IR wavelengths suitable for large scale applications. The process is based on using a laser tuned to the right frequency to specifically excite isotopically enriched molecular species over all others present. In the excited state the species can be preferentially reacted or adsorbed. Wavelengths of spectral absorption lines of atoms and molecules have slightly different values, depending on their isotopic constitution. This is known as the isotope shift. In most cases isotope shifts are small. The narrow spectral linewidth available from tunable lasers allows energy to be deposited by absorption in a molecule with one isotopic composition, but not in the same molecule with a different isotopic composition. The process requires coupling the highly efficient laser enrichment technology with several others that have significantly less efficiency. At present, the conceptualized processes use gaseous halogenated hydrocarbons as the molecular species in the laser. Unfortunately, this requires a preprocess to convert tritiated water to the halogenated hydrocarbon and post processes that recover the tritium rich species and purify it in cryogenic distillation [21,79].

Work at Ontario Hydro and Lawrence Livermore National Laboratory involved projects for laser isotope separation of tritium. The laser isotope process consists of two sections. The first section is where steam from evaporated tritiated water passes upward through a stripper column where tritium is transferred to a working fluid. Enriched working fluid is then transferred to a reaction column where tritium is exchanged for hydrogen in CF_3H . The mixture of CF_3H and CF_3T in vapor form is exposed to a laser beam that selectively decomposes CF_3T forming C_2F_4 and TF . Chemical and physical methods are used to separate TF from CF_3H and C_2F_4 . The depleted stream is condensate from the stripper column [1]. It was predicted in 1989 by Ontario Hydro researchers, that a plant based on laser isotope separation would cost about half of the cost of a CECE plant. Results of testing indicated that the complexities of the process reduced the efficiency of the exchange and decomposition steps to where the process was no longer economically feasible. All work on this research was then stopped at Ontario Hydro [1]. Use of CFC's in the vapor phase in this process possessed an environmental problem. This research was conducted on bench scale only.

Starting in 1979 work on the use of halogenated methanes for IR laser-induced multiphoton dissociation was investigated by the Institute of Physical and Chemical Research (RIKEN) in Wako, Saitama, Japan, Lawrence Livermore National Laboratory (LLNL), Livermore, CA, and at Ontario Hydro Research Division (OHRD), Toronto, Ontario, Canada. Studies continued at RIKEN using halogenated ethanes and propanes. There is an extensive description of this research in *Tritium Isotope Separation* [79].

This technology was not selected for full evaluation.

VI.B.6 Electrolysis Plus

Electrolysis is a method by which chemical reactions are carried out by passage of electric current through a solution containing an electrolyte. An electrolyte, such as KOH, H₂SO₄, K₂CO₃, etc., is necessary in solution to make the water more electrically conducting. Electrolysis usually involves the decomposition of water. If a current is passed through an aqueous solution the water decomposes according to:

with hydrogen evolved at the cathode and oxygen at the anode. This reaction separates hydrogen isotopes from the aqueous phase into the gas and so it is one of the most commonly used techniques in isotopic separation and can be used for enrichment of both D and T. Electrolysis can be used simply to convert feed water into gas for subsequent isotopic separation processes based on elemental hydrogen. Rates of evolution of the three isotopes at the cathode are not identical, and so electrolysis can be used for separating isotopes [3,29,31,48,49,53,63]. The rate determining step is proton and deuteron transfer between water molecules adjacent to the cathode and those adsorbed on the cathode surface. Metal electrode surfaces may be classified according to whether they give high or low overvoltages. High overvoltage metals such as Hg, Pb, Zn, Sn, and Cd give low separation factors. The metal-hydrogen bond is weak and permits exchange between the adsorbed gas and the adjacent water molecules. Platinum electrodes also have low separation factors, but the catalytic exchange efficiency is high. For metals such as Pt, Pd, Ni, Ag and Fe, high separation factors result due to strong hydrogen bonding which reduces the exchange [36]. Electrolysis can be used as a sole separation technique; however, it uses a large quantity of energy per mole of hydrogen evolved. To reduce energy requirements for isotopic enrichment it is often coupled with other separation methods that use less energy per stage to further purify hydrogen isotopes. In the case of environmental remediation, since the energy to produce hydrogen at the feed using electrolysis will dominate costs for this process, only electrolysis of the feed is considered in the analysis. Additional enrichment by any other means will only increase its operating costs. The enrichment effect of electrolysis is based on the higher precipitation velocity of the lighter hydrogen isotopes as compared to tritium which is reinforced by irreversible kinetic effects with higher current densities. If current densities are smaller the separation factor is determined solely by the equilibrium constant of the exchange equilibrium [62].

At DOE facilities, tritiated water is sent to an electrolytic cell where it is decomposed into oxygen, deuterium/tritium, and deuterium. Deuterium gas is oxidized to heavy water and is sent back to the reactor. Deuterium/tritium may be compressed and stored, oxidized to water, or stored in pressurized containers [49].

Washburn and Urey proposed concentrating deuterium by the electrolysis of water. The Norsk Hydro Company, in Rjukan, Norway, was the first heavy water production plant based on this process. This plant made use of cheap hydroelectric power to produce electrolytic hydrogen for ammonia synthesis and by-product heavy water. German scientists Harteck, Hoyer, and Suess had the idea of recovering deuterium from hydrogen gas by adsorption in water. A nickel catalyst for carrying out this reaction in the gas phase was developed. The plant was destroyed in 1943. A second electrolysis and exchange plant was built in Glomfjord, Norway. A steady flow electrolytic process without recycle was used at a plant in Ems, Switzerland to produce hydrogen enriched sixfold in deuterium over natural abundance. This process is also being used at the Indian government's fertilizer plant in Nangal, India [3]. A similar exchange process was developed by Urey and Taylor in the United States. Standard Oil Development Company designed the exchange equipment and installed it in the electrolytic hydrogen plant of the

Consolidated Mining and Smelting Company at Trail, British Columbia, where it operated until 1955. The final concentration was by electrolysis [3].

The Manhattan Project, at Morgantown, West Virginia, and at Trail, British Columbia, used the electrolytic process to refine crude heavy water from a primary plant. These plants were operated batchwise. There were no diaphragms in the cells, so the product was a mixture of hydrogen and oxygen. The gases were recombined in a burner, and the water was recycled to the primary plant when its deuterium content was leaner than primary plant product or to the next batch of the electrolytic plant when its deuterium content was richer than primary plant product [3]. Batch electrolysis was also used to concentrate deuterium from 90 to 99.87% at the heavy water production plant at the Savannah River Plant.

Electrolysis has a high separation factor. It is the oldest large scale industrially used process for hydrogen isotopic exchange. This process is relatively simple and requires little sample handling and supervision. The hydrogen produced is depleted in the heavy isotopes (D and T). Electrolysis, however, has a relatively high activity content in the electrolyzer in the form of HTO, which is more toxic than HT. High maintenance expenses and high power consumption are disadvantages that must be reduced for this process [62]. Several stages of electrolysis are required to achieve the tritium separation and enrichment. There is also an absence of commercial cell designs that are sufficiently leak free to enable processing tritium enriched water. High energy costs may be overcome by recombining the gases in a fuel cell. This will allow recovery of most of the electrical energy [54].

This technology was selected for full evaluation.

Table VI-1 Guide to Identification of the Technology Classes and Specific Processes Evaluated

Technology Class (bold text) and Specific Processes (standard text)	Synonyms and Abbreviations	Key Developers	Recent or Proposed Additions to Class
Evaporation/Distillation			
Evaporation by Heating and Evaporation by Humidification		- traditional chemical engineering technologies	
Distillation	- vacuum distillation	- Sulzer Brothers Ltd. - Heavy Water Group, Ontario Hydro Research Division, Canada - others	
Mass Transfer Based Equilibrium Processes			
Stripping		- traditional chemical engineering process	
Sparging	- bubble-mediated isotope exchange	- Slattery and Ingraham	
Extraction	- liquid nitrogen extraction - liquid neon extraction - organic solvent extraction	- Augood - various	
Adsorption	- carbon - proprietary - related technologies (for gas separation) palladium and Rainey nickel	- various	Adsorption and Catalytic Exchange (ACE) by Atomic Energy of Canada (AECL)
Homogeneous Exchange Reactions - Girdler-Sulfide	GS	- Geib and Spevack	
Heterogeneous Ion Exchange - Liquid Phase Catalytic Exchange	- LPCE - Dual Temperature Liquid Phase Catalytic Exchange (DTLPCE) - related technology: Vapor Phase Catalytic Exchange (VPCE), Sulzer	- Chalk River Nuclear Laboratory (CRNL) - University of South Carolina	MIT Studies using biological catalysts in place of precious metals
Heterogeneous Ion Exchange - Combined Electrolysis Catalytic Exchange	CECE	AECL at CRNL	Electrolysis Chemical Exchange (ELEX) developed in Belgium
Membrane Processes			
		- Pacific Northwest National Laboratory (PNNL) - Osborne and McElroy at CRNL	

Table VI-1   Guide to Identification of the Technology Classes and Specific Processes Evaluated
(continued)

Technology Class (bold text) and Specific Processes (standard text)	Synonyms and Abbreviations	Key Developers	Recent or Proposed Additions to Class
Direct Onsite Immobilization or Storage			
Ground Freezing	frozen barrier technology	- Scientific Ecology Group (SEG) - FreezeWall	
Storage Tanks		- traditional chemical engineering process	
Infiltration Reduction	Surface Enhancements Accelerated Approach	Savannah River Site	
Frequency Based Separation			
Lasers		- Ontario Hydro Lawrence Livermore National Laboratory - Institute of Physical and Chemical Research (RIKEN), Japan	
Electrolysis Plus	- bulk electrolysis - related technologies: cryogenic distillation metal hydride separation thermal diffusion mass spectrometry gas chromatography	- Washburn and Urey - Norsk Hydro Company, Rjukan, Norway - Harteck, Hoyer, and Suess	

Figure VI-1. Simplified Subsurface Water Balance Diagram Used to Scope Potential Performance of In-Place Immobilization Options

VII.0 RESULTS

VII.A Summary

All of the detailed analysis tables, flow diagrams for each process, assumptions, and results are provided in Appendix A. The various graphs and tables in the following sections detail the evaluation results in various ways to facilitate the needs of potential users. In general cost terms, the technologies clustered in three distinct groups. As expected, the costs for all three groups (in traditional units of \$/1000 gallons) were greater than classical water treatment technologies.

Classical treatment technology costs are typically below \$10/1000 gallons. The higher cost for tritium treatment derives from the similarity in properties between the contaminant, HTO, and water, H₂O. Various organizations and researchers have used widely different concepts to overcome the challenges. These concepts, in turn, lead to different capital and operational costs in practice. The "low" cost group (ranging from about \$50 per 1000 gallons up to \$500 per 1000 gallons) consists of the GS process, two types of evaporation, and infiltration reduction using surface enhancements. The "intermediate" cost group (about \$500 per 1000 gallons up to \$5000 per 1000 gallons) includes stripping and sparging, DTLPCE, two types of storage tanks, and ground freezing. The "high" cost group (\$5000 per 1000 gallons to greater than \$10000 per 1000 gallons) includes CECE and electrolysis. To help understand the reason for the groupings, we developed a summary table that qualitatively identifies the "overwhelming costs" (table VII-1). In the "lowest" group both equipment and energy costs were low. In the "intermediate" group, the costs for each technology were affected by either high equipment costs (e.g., tanks and DTLPCE) or by high energy costs (e.g., ground freezing and sparging). In the "highest" cost group, both equipment and energy costs were considered high. Importantly, costs provide only part of the answer. Most of the technologies in the "low" cost groups have significant negative performance issues that deserve consideration. Similarly, some of the technologies in the high cost group might provide extremely high performance or provide features and options beyond the needs of environmental cleanup. For all of the technologies, the graphs and tables below identify the various normalized costs, assess key aspects of effectiveness and safety, and provide information about the expected costs over the projected operational life.

Each of the summary graphs and charts is discussed in more detail below.

VII.B Cost Results

Feed rate and flow conditions, concentration treated, FEI, normalized costs, and initial cost for all of the technologies evaluated in detail are provided on table VII-2. These costs and the related information are plotted on the summary graphs and are the basis of the discussion provided below.

Figures VII-1 and VII-2 show the relationship between the cost to treat a specified volume and the cost per Curie averted for the low flow scenario and high flow scenario, respectively. A simple comparison of these two graphs indicates the technologies applied to the low flow scenario are much more efficient than the high flow scenario in reducing tritium releases. This is because the volume based costs are relatively similar for the two scenarios, while the cost per Ci averted is much higher for the high flow scenario because the water contains much less tritium.

A principal feature of figures VII-1 and VII-2 is the impact of the FEI on the relative costs. Those technologies/strategies that treat the entire target volume with an FEI approaching 1.0 show a direct relationship between the gallons treated and the Ci averted. This is because the tritium in the influent water is "completely" removed from the treated water. For technologies with an FEI <1.0, the impacts of release of a secondary waste result in higher costs per curie averted for any given treatment volume (i.e., these technologies plot above the line). These technologies are somewhat less efficient because some of the treatment cost is spent shifting tritium from one phase to another. Similarly, if a technology/strategy does not treat the entire target volume (e.g., ground freezing and infiltration reduction) the cost per Ci

averted changes. The distance from the 45° line to the data point is related to these two factors. For example, for the low flow case, the infiltration reduction treatment approach has the lowest FEI (0.10) — this strategy lies farthest from the 45° line. For both low volume and high volume scenarios, the graphs show electrolysis and CECE are the most expensive options in both of the costing approaches. Similarly, evaporation (direct heating), Girdler-Sulfide, evaporation (humidification) and infiltration reduction are the lowest cost options. Both of the evaporation techniques have relatively low FEIs because they release all of the tritium (HTO) to the atmosphere. Girdler-Sulfide treatment has an FEI of 0.99, but has a safety risk of using hydrogen sulfide in the process. Infiltration reduction has a competitive cost in terms of \$/1000 gallons but a relatively higher cost per Ci averted. In the low flow case, the cost per Ci averted is similar to the more expensive DTLPCE, stripping/sparging, and tank technologies. Stripping and sparging and DTLPCE are the next most cost effective techniques. Stripping and sparging shifts contamination from groundwater to air. DTLPCE concentrates the contamination into a much smaller stream which is assumed to be isolated onsite. The next most cost effective techniques are carbon steel storage tanks and stainless steel storage tanks. Each of these requires an enormous amount of land for their respective tank farm, although all the contamination will be contained onsite. Similar to GS, DTLPCE, and tanks, the more expensive technologies, electrolysis and CECE, perform well in terms of effectiveness (FEI). Electrolysis converts all the contamination to HT gas, which is vented to the atmosphere (HT has essentially no population impact). CECE produces a concentrated stream, which is sequestered onsite.

Many of these same basic relationships can be seen when normalized costs are plotted versus total capitalized cost (total capitalized cost is a measure of the entire 20 year cost for each technology deployment). Figures VII-3 and VII-4 show this relationship between total capitalized cost for each treatment technique and cost per Ci averted for low volume and high volume scenarios, respectively. As for the earlier graphs, technologies with FEIs approaching 1.0 show a direct relationship, while those with FEI <1.0 are vertically displaced from the 45° line by an amount corresponding to their deviation from an FEI of 1.0. This displacement is illustrated by large displacements of infiltration reduction (FEI = 0.1) and moderate displacement of evaporation (FEI = 0.6). Evaporation (direct heating) is the most cost effective technique for the low flow case; evaporation transfers tritium (HTO) to the atmosphere resulting in the low FEI. Evaporation (humidification) has somewhat higher costs than the direct heating method and similar FEI. For the low flow scenario, GS is the next lowest total capitalized cost system (GS has the lowest total capitalized cost for the high flow scenario). In all scenarios, GS has a relatively low cost per Ci averted because it has a high FEI. GS has the safety risk of using hydrogen sulfide in the process. Infiltration reduction has a low total capitalized cost, but a higher cost per Ci averted than the next two higher cost technologies — stripping/sparging and DTLPCE. Stripping/sparging has the next higher total capitalized cost, but has a slightly higher cost per Ci averted than DTLPCE because it has an FEI of 0.6, while DTLPCE has an FEI of 0.99. Stripping and sparging is similar to the evaporation techniques in that it merely moves the tritium (HTO) contamination from groundwater to air. DTLPCE, carbon steel storage tanks and stainless steel storage tanks have the next higher total capitalized costs, respectively. All have an FEI of 0.99 and all sequester tritium contamination onsite. The DTLPCE technique reduces the groundwater stream to a concentrated, much lower volume, stream. Storage tanks hold contamination onsite, but take a large amount of land for the tank farm. The highest cost techniques are CECE and electrolysis. Electrolysis converts all contamination to gas (HT), which is vented to the atmosphere. CECE produces a concentrated stream which is sequestered onsite, and is slightly less expensive than electrolysis.

The next two graphs, figures VII-5 and VII-6, show the relationship between total capitalized cost (over a 20 year life) for each treatment technique and cost per 1000 gallons treated. All systems show a direct relationship. As in the other summary graphs, GS, evaporation and infiltration reduction are the most cost effective technologies. Stripping/sparging, DTLPCE, and tanks cluster in a medium cost group. Electrolysis and CECE have the highest projected total project costs (and the highest treatment cost per 1000 gallons).

The final two summary graphs, figures VII-7 and VII-8, provide more detailed information on the projected spending profile for each of the proposed technology deployments. This information provides managers important data for decisionmaking. In particular, technologies that have extremely high capital (up front) costs can be distinguished from technologies that have a more even spending profile. Note, all costs on the graph are in present \$ (the sum of all years add up to the total capitalized costs presented earlier). These graphs show that the highest initial capital outlays are for electrolysis and CECE systems, respectively. Yearly expenditures for electrolysis and CECE are similar and decrease over time. It is apparent, however, that electrolysis and CECE have both higher capital costs and higher operating costs than the rest of the technologies. Ground freezing has a very high initial cost for installation and the initial energy needed for freezing. After the first year, costs for ground freezing are relatively low. The spending profile for stainless steel storage tanks and carbon steel storage tanks are interesting. Because of the need to continuously build new capacity (capital infrastructure), tank costs increase steadily throughout deployment. By using this tritiated water in other applications at SRS, such as water for concrete to fill the vaults or for saltstone as two examples, capacity needs will decrease. Thus, finding a productive use for this water will lower the costs for the tanks, making them more attractive. All the other systems have very similar costs that remain approximately constant over time. Slightly higher costs in year 10 are seen for CECE and DTLPCE to account for catalyst replacement.

VII.C Evaluation Matrix

Table VII-3 summarizes the costs, advantages, disadvantages, fatal flaws and related information in a matrix form. An evaluation of the technologies in use or under development for detritiation of groundwater should include more than just an evaluation of cost -- the evaluation matrix is the approach selected to capture and summarize cost information along with related issues. For those cells in the table where a summary number or letter is used, the key is provided on the table and in the methods discussion in Chapter III. For numerical scores, the convention in the table is that low numbers (e.g., 1) are better or more mature, and higher numbers (e.g., 3) are less desirable. For example, if a technology completely and safely eliminates public exposure to tritium in the treated water, its public acceptability would be assigned as 1. If a technology only minimally reduces tritium releases and/or shifts tritium to a new pathway, its public acceptability would be assigned a 3. Technologies with satisfactory scores in public and regulatory acceptability were (starting with the best scores): storage tanks, DTLPCE, CECE, GS, ground freezing and electrolysis. Public and regulatory scores for evaporation and stripping/sparging were marginal, suggesting these technologies may not be viable. Of the technologies with satisfactory scores in public and regulatory acceptability, several are relatively mature (GS, CECE, tanks, electrolysis, and infiltration reduction), while one (DTLPCE) is at the bench scale.

Table VII-1. Overwhelming Cost Factors

System	Equipment Cost	Energy Cost
Evaporation (direct heating)	low	low
Evaporation (humidification)	low	low
Girdler-Sulfide (GS)	low	low
Infiltration Reduction using Surface Enhancements	low	low
Stripping/Sparging	low	high
Dual Temperature Liquid Phase Catalytic Exchange (DTLPCE)	high	low
Carbon Steel Storage Tanks	high	low
Stainless Steel Storage Tanks	high	low
Ground Freezing	high	low
Combined Electrolysis Catalytic Exchange (CECE)	high	high
Electrolysis	high	high

Table VII-2. Summary of Aqueous Detritiation Technology Cost Evaluation

Technology Class/Process	Feed Conditions		F.E.I. (0-1)	Costs		Total Project Cost over 20 yrs \$**
	flowrate (gpm)	conc. (pCi/ml)		\$/1000 gal. treated	\$/Ci averted	
Evaporation/Distillation and Related Processes						
Evaporation (Direct Heating)	25	25,000	0.60	\$ 66	\$ 1,122	\$ 17,253,884
	250	3,000	0.60	\$ 66	\$ 9,349	\$ 172,538,920
Evaporation (Humidification)	25	25,000	0.60	\$ 155	\$ 2,653	\$ 40,808,311
	250	3,000	0.60	\$ 154	\$ 21,950	\$ 405,110,328
Mass Transfer Based Equilibrium Processes						
Stripping and Sparging	25	25,000	0.60	\$ 1,102	\$ 18,829	\$ 289,657,771
	250	3,000	0.60	\$ 650	\$ 92,592	\$ 1,708,878,083
Exchange Reactions						
Homogeneous Exchange						
Girdler Sulfide (GS)	25	25,000	0.99	\$ 162	\$ 1,673	\$ 42,465,683
	250	3,000	0.99	\$ 61	\$ 5,295	\$ 161,238,451
Heterogeneous Exchange						
Dual Temperature Liquid Phase	25	25,000	0.99	\$ 1,442	\$ 14,925	\$ 378,851,810
Catalytic Exchange (DTLPCE)	250	3,000	0.99	\$ 980	\$ 84,592	\$ 2,576,017,833
Combined Electrolysis/Catalytic Exchange (CECE)	25	25,000	0.99	\$ 12,606	\$ 130,511	\$ 3,312,833,393
	250	3,000	0.99	\$ 15,073	\$ 1,300,778	\$ 39,611,823,266
Direct onsite immobilization or storage						
Storage Tanks -Carbon Steel	25	25,000	0.99	\$ 2,471	\$ 25,580	\$ 649,312,876
	250	3,000	0.99	\$ 1,535	\$ 132,461	\$ 4,033,741,616
Storage Tanks -Stainless Steel	25	25,000	0.99	\$ 5,903	\$ 61,117	\$ 1,551,368,704
	250	3,000	0.99	\$ 4,385	\$ 378,380	\$ 11,522,582,012
Infiltration Reduction	*	*	0.10	\$ 150	\$ 8,000	\$ 22,600,000
Ground Freezing	*	*	0.75	\$ 5,820	\$ 79,000	\$ 564,000,000
	*	*	0.75	\$ 5,820	\$ 671,000	\$ 6,090,000,000
Electrolysis plus						
Electrolysis plus release	25	25,000	1.00	\$ 14,279	\$ 146,351	\$ 3,752,437,383
	250	3,000	1.00	\$ 14,279	\$ 1,219,898	\$ 37,524,076,601

* does not pump water to the surface. Infiltration reduction is assumed to "treat" 150,000,000 gallons over 20 years.

Ground Freezing is assumed to treat 97,000,000 and 1,050,000,000 gallons for the two scenarios, respectively.

** total capitalized cost in present \$

limited evaluation of membrane separation and laser frequency separation indicated relatively high costs, near the upper end of the tabulated values.

Table VII-3.   Evaluation Matrix for Aqueous Detritiation Technologies and Strategies

Matrix is located in map pocket at end of document.

Figure VII-1. Summary of cost evaluation for the low flow scenario: cost per 1000 gallons treated versus the cost per Ci averted.

Figure VII-2. Summary of cost evaluation for the high flow scenario: cost per 1000 gallons treated versus the cost per Ci averted.

Figure VII-3. Summary of cost evaluation for the low flow scenario: cost per Ci averted versus the total capitalized cost.

Figure VII-4. Summary of cost evaluation for the high flow scenario: cost per Ci averted versus the total capitalized cost.

Figure VII-5. Summary of cost evaluation for the low flow scenario: cost per 1000 gallons treated versus the total capitalized cost.

Figure VII-6. Summary of cost evaluation for the high flow scenario: cost per 1000 gallons treated versus the total capitalized cost.

Figure VII-7. Summary of cost evaluation for the low flow scenario: annual projected cost over the 20 year projected action (all costs are in present \$ and sum to the total capitalized cost).

Figure VII-8. Summary of cost evaluation for the high flow scenario: annual projected cost over the 20 year projected action (all costs are in present \$ and sum to the total capitalized cost).

VIII.0 CONCLUSIONS

Results of the detailed evaluation for aqueous detritiation closely follow trends identified by Rae for heavy water purification [62]. In particular, both studies identify the Girdler-Sulfide (GS) process as relatively economical. Both studies identify implementations of liquid phase catalytic exchange as moderately economical. Also, both studies identify processes that involve electrolysis (CECE and bulk electrolysis) as substantially more costly than other systems evaluated. Based upon Rae's prior analysis, several separation technologies were deemed uneconomic because their separation factors are very near 1. We did not evaluate these technologies, namely water distillation and crystallization. Several additional alternative tritium reduction strategies were evaluated, however, including onsite immobilization and volume reduction through optimized pump and treat design. A few new technologies, such as the membrane separation process from PNNL and laser frequency isotope separation (both of these were discussed in the Hanford detritiation evaluation), require additional development prior to detailed engineering analysis.

Highlights of the results of our detailed analysis include:

- For each technology/strategy, the cost per Ci averted ($cost_h$) was much higher for the high flow-low concentration scenario. This indicates that strategic or surgical pump and treat design and related strategies are critical to cost effectiveness in cases where the programmatic objective is tritium reduction rather than complete capture.
- For each technology/strategy, the cost per 1000 gallons ($cost_w$) was calculated for the two flow scenarios. In many cases, the volume normalized costs were almost identical, and in the remaining cases the volume normalized costs were within a factor of 3 (even though flow rates differed by a factor of 10). This suggests that, for tritium contamination at "environmental" levels, volume normalized costs are a reasonable basis for initial scoping of possible costs at other sites, especially for sites with flow rates similar to those in the scenarios evaluated.
- Girdler-Sulfide (GS) is the least expensive process that performs isotope separation. Calculated costs of GS were in the range of 5x to 50x traditional wastewater treatment costs. GS processes do pose relatively high process risk, high worker risk, and potential catastrophic release risk (a large inventory of high pressure hydrogen sulfide is needed, resulting in combined toxicity and flammability hazards). As with other large-complex facilities, many years would be required for design, construction, and testing prior to operation of a GS plant. GS is potentially viable.
- Dual Temperature Liquid Phase Catalytic Exchange (DTLPCE) is a promising isotope separation option. This technology is in the "intermediate" cost group but eliminates the high process hazards associated with GS. DTLPCE is earlier in the development cycle and would require several years of work (scale up, design, construction, and testing) prior to operation. New catalysts currently in development are expected to improve the performance of LPCE and DTLPCE, making these technologies more competitive with GS. DTLPCE is potentially viable.
- Storage tanks provide a high degree of confidence and isolation of tritium from the environment. Tanks are in the "intermediate" cost group. Tanks are most cost effective (and environmentally justified) for the low volume high concentration scenario. In this implementation, they would not cause extreme collateral environmental damage that would result from clearing land and building the large number of tanks needed for the high volume case. Carbon steel tanks have been shown to provide reliable long term service (nineteen tanks in the U.S. have been in service for more than 100 years). Also, carbon steel tanks are significantly cheaper than stainless steel tanks. Stainless steel would provide a very high level of performance. Design, construction and initial operation of tanks would require much less time than construction of isotope separation facilities. Tanks are potentially viable.
- Infiltration reduction (through surface enhancements) and ground freezing bound the possible actions to slow down or immobilize the plume in place. Surface enhancements are relatively inexpensive, rapid to deploy, and are sensitive to the local ecology, but this strategy only modestly reduces tritium

release making it difficult to monitor performance. Ground freezing is in the "intermediate" cost group and shows promise, especially if extremely high concentration zones can be targeted. Ground freezing would require several years to design and implement. Infiltration reduction (in combination with other actions) and ground freezing are potentially viable.

- The two evaporation technologies are in the lowest cost group. These technologies do not perform any isotope separation -- they simply change liquid water into gaseous water that is released to the atmosphere. While this would result in a lower overall population dose, the total curies released is unchanged. Because of this, these processes are considered potentially unacceptable. Stripping and sparging, technologies in the "intermediate" cost range, are based on the same basic strategy (converting liquid HTO into gaseous HTO). Assuming the viability of the basic strategy, it is clear from the analysis that there is no reason to consider stripping or sparging versus simple evaporation. Evaporation, stripping and sparging are not considered viable based on the evaluation matrix.
- The "high" cost group consists of electrolysis and CECE. While both of these technologies provide a high level of performance with regard to reducing environmental tritium release, they are not clearly superior to GS, DTLPCE, or tanks. Both technologies have very high capital/equipment costs (requiring a large initial expenditure) and high energy and operating costs. Both technologies would require many years for design, construction, and testing prior to operation. Technologies that involve electrolysis (CECE and bulk electrolysis) are not considered viable unless significant improvements in economics are realized.

A limited assessment of two lab scale technologies based on the literature reports was also performed. A previous cost evaluation of the membrane separation process, currently operating at a lab scale at PNNL, suggested relatively high costs. Unless significant improvements in economics are realized the process would not be considered viable. Ongoing research is targeted at refining and optimizing the design and operation. Following process refinement a practical cost evaluation will be needed to determine if the process is competitive with some of the viable alternatives identified above (e.g., GS, DTLPCE, tanks, infiltration reduction, and ground freezing). Another lab scale technology, laser frequency isotope separation, has been shown to be theoretically possible. Unfortunately, current economic evaluations and process issues associated with halogenated organics suggest the technology may not be viable.

Many new technologies that are under development or that will be proposed in the future may be able to be evaluated by using the technology class concept. Each technology we evaluated was intended to represent an attractive (or strongly advocated) tritium reduction process/strategy. Thus, the evaluated technologies should be good representatives of the performance for the classes. The first step in estimating the performance of a new technology is determining its appropriate class. Unless the new technology embodies a fundamental theoretical improvement that would alter the performance versus the technology evaluated, its economics would likely be similar.

RELEVANT LITERATURE / REFERENCES

1. Allen, W.L., Tritiated Wastewater Treatment and Disposal Evaluation for 1995, DOE/RL-95-68, Westinghouse Hanford Company, Richland, Washington, August 1995.
2. Baumgarten, P.K., "Trip Report: WSRC-NPR-HWPF Canadian visit to AECL and Ontario Hydro, May 9-11, 1990," Westinghouse Savannah River Company, NPR-TIN-90-900132, July 6, 1990.
3. Benedict, M., T. Pigford and H. Levi, "Separation of Isotopes of Hydrogen and Other Light Elements," Nuclear Chemical Engineering, 2nd ed., McGraw Hill, New York, 1981.
4. Billet, Reinhard, Ullmann's Encyclopedia of Industrial Chemistry, "Evaporation," vol. B3, 5th ed., 1988, pp. 3-1 to 3-2.
5. Branan, Carl R., Rules of Thumb for Chemical Engineers, Gulf Publishing Company, Houston, 1994.
6. Butler, J.P., "Hydrogen Isotope Separation By Catalyzed Exchange Between Hydrogen and Liquid Water," Separation Science and Technology, 15(3), 1980.
7. Butler, J.P., J.H. Rolston and W.H. Stevens, "Novel Catalysts for Isotopic Exchange between Hydrogen and Liquid Water," Separation of Hydrogen Isotopes, ACS Symposium Series 68, Washington, D.C., 1978.
8. Chemical Engineering, McGraw Hill, New York, New York, continuing.
9. Code of Federal Register, 10CFR Ch. I, Pt. 50, Appendix I, pp. 789-792, 1992.
10. Cohen, J. J., "On Determining the Cost of Radiation Exposure to Populations for Purposes of Cost-Benefit Analyses," Health Physics, 25:527-528, 1973.
11. Cohen, J. J., Optimization of Public and Occupational Radiation Protection at Nuclear Power Plants, NUREG/CR-3665, U. S. Nuclear Regulatory Commission, Washington, D.C., 1984.
12. Dixon, K. L., V. A. Rogers, Results of the Fourth Quarter Tritium Survey of the F- and H- Area Seepines: March 1993 (U), WSRC-TR-93-526, Rev 0, Westinghouse Savannah River Company, Aiken, South Carolina, July 1993.
13. DOE, Tritiated Wastewater Treatment and Disposal Evaluation for 1994, DOE/RL-94-77, U. S. Department of Energy, Richland, Washington, August 1994.
14. DOE Order 1360.8a, Analyses of Benefits and Costs for Information Technology Resource Initiatives, U. S. Department of Energy, Washington, D. C., May 18, 1992.
15. Felder, Richard M. and Ronald W. Rousseau, Elementary Principles of Chemical Processes, John Wiley & Sons, New York, 1978.
16. Westinghouse Savannah River Company, Savannah River Technology Center Environmental Monthly Report: August/September 1995, SRT-ESS-95-009, Westinghouse Savannah River Company, Aiken, SC 29808.
17. Geankoplis, Christie J., Transport Processes and Unit Operations, 3rd ed., Prentice Hall, New Jersey (1993).
18. Grant, Mary Howe and Jacqueline I. Kroschwitz, Kirk Othmer Encyclopedia of Chemical Technology, "Hydrogen," vol. 13, 4th edition, 1995, pp. 838-894.
19. Grant, Mary Howe and Jacqueline I. Kroschwitz, Kirk Othmer Encyclopedia of Chemical Technology, "Evaporation," vol. 9, 4th edition, 1994, pp. 959-960.
20. Grant, Mary Howe and Jacqueline I. Kroschwitz, Kirk Othmer Encyclopedia of Chemical Technology, "Membrane Technology," vol. 16, 4th edition, 1995, pp. 135-137.
21. Grant, Mary Howe and Jacqueline I. Kroschwitz, Kirk Othmer Encyclopedia of Chemical Technology, "Lasers," vol. 15, 4th edition, 1995, pp. 44-46.
22. Grant, Mary Howe and Jacqueline I. Kroschwitz, Kirk Othmer Encyclopedia of Chemical Technology, "Extraction," vol. 10, 4th edition, 1993, pp. 125-126.
23. Grant, Mary Howe and Jacqueline I. Kroschwitz, Kirk Othmer Encyclopedia of Chemical Technology, "Adsorption," vol. 1, 4th edition, 1991, pp. 493-494.
24. Grant, Mary Howe and Jacqueline I. Kroschwitz, Kirk Othmer Encyclopedia of Chemical Technology, "Distillation," vol. 8, 4th edition, 1993, pp. 311-312.
25. Grayson, Mark and David Eckroth, Kirk Othmer Encyclopedia of Chemical Technology, "Isotopes," vol. 13, 3rd edition, 1981, pp. 838-864.
26. Hall, Richard S., Jay Matley, and Kenneth J. McNaughton, "Current Costs of Process Equipment," Chemical Engineering, April 5, 1982, pp. 80-116.
27. Hammerli, M., W.H. Stevens and J.P. Butler, "Combined Electrolysis and Catalytic Exchange (CECE) Process for Hydrogen Isotope Separation," Proceedings of the Symposium on 'Separation of Hydrogen Isotopes', ACS Symposium Series 68, Washington, D.C. (1978).

28. Haussinger, Peter, Reiner Lohmuller, and Allan M. Watson, Ullmann's Encyclopedia of Industrial Chemistry, "Hydrogen," vol. A13, 5th ed., 1989, pp. 297-442.
29. Heaberlin, S. W., J. B. Burnham, R. H. V. Gallucci, M. F. Mullen, R. J. Nesse, L. A. Nieves, J. J. Tawil, M. B. Triplett, S. A. Weakly and A. R. Wusterbarth, A Handbook for Value-Impact Assessment, NUREG/CR-3568, U. S. Nuclear Regulatory Commission, Washington, D.C., 1983.
30. Henley, Ernest and J.D. Seader, Equilibrium-Stage Separation Operations in Chemical Engineering, John Wiley & Sons, New York, 1981.
31. Horton, Henry J., John C. Corey and Richard M. Wallace, Tritium Loss from Water Exposed to the Atmosphere," Environmental Science & Technology, 5(4), April 1971, pp. 338-343.
32. Ingraham, Neil L. and Robert E. Criss, "The Effects of Surface Area and Volume on the Rate of Isotopic Exchange Between Water and Water Vapor," Water Resources Center, Desert Research Institute, Las Vegas, Nevada, January 1993.
33. Ingraham, Neil S., "Final Report On the Exchange of Tritium Between Water and Vapor," Water Resources Center, Desert Research Institute, Las Vegas, Nevada, February 1993.
34. International Commission on Radiological Protection (ICRP), Recommendation of the International Commission on Radiological Protection, ICRP Publication 26, Pergamon Press, New York, New York, 1977.
35. International Commission on Radiological Protection (ICRP), Cost-Benefit Analysis in the Optimization of Radiation Protection, ICRP Publication 37, Pergamon Press, New York, New York, 1983.
36. Isomura, S., K. Suzuki, and M. Shibuya, "Separation and Recovery of Tritium by Hydrogen Water Isotopic Exchange Reaction," Fusion Technology, 14 (1988).
37. Kalyanam, K.M. and S.K. Sood, "A Comparison of Process Characteristics for the Recovery of Tritium from Heavy Water and Light Water Systems," Fusion Technology, 14, September 1988.
38. Keating, K.B. and V.D. Sutlic, Fax Transmittal, "Economics of Electroorganic Synthesis," DuPont, Wilmington, DE, November 7, 1995.
39. King, C. Judson, Separation Processes, 2nd ed., McGraw-Hill, New York, 1980.
40. King, Charles, M., V. Van Brunt, R.B. King, and A.R. Garber, "Concepts for Detritiation of Waste Liquids (U)," WSRC-MS-91-027, Westinghouse Savannah River Company, Savannah River Site, Aiken, S.C., February, 1991.
41. Kitamoto, Asashi, Y. Takashima, and M. Shimizu, "Effective Method For Recovering and Enriching Tritium From Tritiated Water by Dual-Temperature H₂O-H₂ Exchange Process," Fusion Technology, 8, 1985.
42. Kotaka, Masahiro, Makoto Okamoto and Jacob Bigeleisen, "Anomalous Mass Effects in Isotopic Exchange Equilibria," J. Am. Chem. Soc., 114, 1992.
43. Lightfoot, E.N. and M.C.M. Cockrem, "What are Dilute Solutions?," Separation Science and Technology, 22(2&3), 1987.
44. London, H., "Dual-Temperature Exchange," Separation of Isotopes, George Newnes Limited, London, 1961.
45. Looney, B. B., J. S. Haselow, C. M. Lewis, M. K. Harris, D. E. Wyatt, C. S. Hetrick, "Projected Tritium Releases from F&H Area Seepage Basins and the Solid Waste Disposal Facilities to Fourmile Branch (U)," WSRC-RP-93-459, Westinghouse Savannah River Company, Aiken, South Carolina, March 1993.
46. Looney, Brian B., Fax Transmittal, Report Outline and FEI Calculation, October 24, 1995. All information in this fax has been incorporated verbatim into this document (WSRC-RP-96-0075).
47. McCabe, Warren and Julian C. Smith, Unit Operations of Chemical Engineering, 3rd edition, McGraw-Hill, New York, 1976.
48. Mersmann, Alfons, Ullmann's Encyclopedia of Industrial Chemistry, "Adsorption," vol. B3, 5th ed., 1988, pp. 9-1 to 9-4.
49. Merwin, S. E., J. B. Martin, J. M. Selby, and E. J. Vallario, Two Example Applications of Optimization Techniques to Radiation Protection Programs of United States Department of Energy Contractors, IAEA-SM-285/21, International Atomic Energy Agency, Vienna, Austria, 1986.
50. Miller, Mark A. and Andrew Carey, Ullmann's Encyclopedia of Industrial Chemistry, "Natural Isotopes," vol. A15, 5th ed., 1990, pp. 1-61.
51. Mills, T.K., R.E. Ellis, and M.L. Rogers. "Recovery of Tritium from Aqueous Waste Using Combined Electrolysis Catalytic Exchange," Proceedings of the American Nuclear Society Topical Meeting on Tritium Technology in Fission, Fusion, and Isotopic Applications, pp. 422-424 (1980).
52. Morishita, Taizo, Shohei Isomura, Hirozumi Izawa, and Ryohei Nakane, "Tritium Removal by Hydrogen Isotopic Exchange Between Hydrogen Gas and Water on Hydrophobic Catalyst," Tritium Technology in Fission and Fusion of Isotopes and Applications, A.N.S. National Topical Meeting, 1980.

53. Muller, Eckart, Rosemarie Berger, Walter Kisters, and Michael Cox, Ullmann's Encyclopedia of Industrial Chemistry, "Liquid-Liquid Extraction," vol. B3, 5th ed., 1988, pp. 6-1 to 6-3.
54. Munson, L. H., W. N. Herrington, D. P. Higby, R. L. Kathren, S. E. Merwin, G. A. Stoetzel, E. J. Vallario, Health Physics Manual of Good Practices for Reducing Radiation Exposure to Levels that are As Low As Reasonably Achievable (ALARA), PNL-67577, UC-610, Prepared for the U.S. Department of Energy, Pacific Northwest Laboratory, Richland, Washington, June 1988.
55. Nelson, David A., James B. Duncan, George A. Jensen and Sarah D. Burton, "Isotopomeric water separations with supported polyphosphazene membranes," Journal of Membrane Science, 1995 (in press).
56. Nelson, David A., James B. Duncan, George A. Jensen, Sarah D. Burton, "Separation of HTO from Water using Membrane Technology," Proceedings of the 34th Conference of the Canadian Nuclear Society, 73-83 (1994).
57. Nixon, Philip, Lynn St. Clair, and Beth Wheat, "Ground Water Extraction, Treatment, and Upgradient Injection Systems Provide a Mechanism to Control Tritium Plumes at DOE Facilities," Environmental Remediation '91, "Cleaning up the Environment for the 21st Century", U.S. Department of Energy, Oak Ridge, TN, September 1991.
58. Office of Management and Budget, "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs," Circular No. A-94, Revised. Transmittal Memorandum No. 64, Washington, DC, October 1992.
59. Office of Management and Budget, "1995 Discount Rates for OMB Circular No. A-94," Memorandum for the Heads of Department and Agencies, Washington, DC, February 7, 1995.
60. Peters, Max S. and Klaus D. Timmerhaus, Plant Design and Economics for Chemical Engineers, 4th edition, Mc-Graw Hill, New York, 1991.
61. Pikulik, Arkadie and Hector E. Diaz, "Cost Estimating for Major Process Equipment," Chemical Engineering, October 10, 1977, pp. 106-122.
62. Rae, H.K., "Selecting Heavy Water Processes," Separation of Hydrogen Isotopes, ACS Symposium Series 68, Washington, D.C. (1978).
63. Rogers, Michael L., "Water Detritiation for Present and Future Fusion Plants," Fusion Technology, 10 (1986).
64. Rogers, M.L., P.H. Lamberger, R.E. Ellis and T.K. Mills, "Catalytic Detritiation of Water," Proceedings of the Symposium on 'Separation of Hydrogen Isotopes', American Chemical Society Symposium Series 68, Washington, D.C. (1978).
65. Rolston, J.H., and J.W. Goodale, "Isotopic Exchange Between Hydrogen and Water Vapor over Supported Metal Catalysts. Part I. Kinetics of the Exchange," Canadian Journal of Chemistry, 50, 1972.
66. Rolston, J.H., J. den Hartog, and J.P. Butler, "The Deuterium Isotope Separation Factor between Hydrogen and Liquid Water," The Journal of Physical Chemistry, 80(10), 1976.
67. Schafer, John, W. III, and V. Van Brunt, "Aqueous Detritiation Chemical-Exchange Flowsheet: Analysis Code Description and Benchmarking," Chemical Engineering Department, University of South Carolina, for SCUREF Task Order #15, B-19864, for Westinghouse Savannah River Company, Savannah River Site, Aiken, SC, October 1991.
68. Schwirian-Spann, Amy L., correspondence to B. Looney and K. Jerome, Phone conversation with James Duncan from Westinghouse Hanford Company, University of South Carolina, February 8, 1996.
69. SEG, "Scientific Ecology Group Final Report: Demonstration of Ground Freezing Technology at SEG Facilities in Oak Ridge, TN," Scientific Ecology Group, prepared for Martin Marietta Energy Systems, Inc., Hazardous Waste Remedial Actions Program, February 1995.
70. Segal, M.G., "Methods of Removal of Tritium from Aqueous Effluent: A Review of International Research and Development," Central Electricity Generating Board, Technology Planning and Research Division, Berkeley Nuclear Laboratories, Berkley, TPRD/B/1042/R88, January 1988.
71. Showalter, W. Eric, Steven R. Booth, R. Wayne Hardie, "Methods for Evaluating Investment Strategies for Environmental Technologies," Remediation, Autumn 1995.
72. Slattery, Michael W. and Neil L. Ingraham, "Reducing Tritium Levels In Water By Low-Temperature By Isotopic Exchange of Oxygen and Hydrogen Isotopes Between Water and Water Vapor," Nevada Operations Office, Department of Energy, Las Vegas, Nevada, DOE/NV/10845-26, UC-703, September 1993.
73. Slattery, Michael and Neil L. Ingraham, "Detritiation of Water by Isotopic Exchange: Experimental Results," Environmental Science and Technology, 28(8), pp. 1417-1421, 1994.
74. Spagnolo, D.A., A.E. Everatt, P.W.K. Seto and K.T. Chuang, "Enrichment and Volume Reduction of Tritiated Water Using Combined Electrolysis Catalytic Exchange," Fusion Technology, 14 (1988).
75. Stichlmair, Johann, Ullmann's Encyclopedia of Industrial Chemistry, "Distillation and Rectification," vol. B3, 5th ed., 1988, pp. 4-1 to 4-4.

76. Strathmann, Heinrich, Ullmann's Encyclopedia of Industrial Chemistry, "Membranes and Membrane Separation Processes," vol. A16, 5th ed., 1990, pp. 187-190.
77. Suppiah, S., K.T. Chuang and J.H. Rolston, "Diffusional Effects in Wetproofed Catalysts for Isotopic Exchange Between Hydrogen Gas and Water Vapour," The Canadian Journal of Chemical Engineering, 65, April 1987.
78. Treybal, Robert E., Mass Transfer Operations, 3rd edition, McGraw-Hill, New York, 1980.
79. Vasaru, Gheorghe, Tritium Isotope Separation, CRC Press, Boca Raton, 1993.
80. Villegas, Antonio, Lavelle Clark, and Andrew Schmidt, A Systems Engineering Analysis to Examine the Economic Impact for Treatment of Tritiated Water in the Hanford KE-Basin, PNL-SA-24970, Presented at the Waste Management 1995 Conference, Pacific Northwest Laboratory, Richland, Washington, February 1995.
81. Vivian, G. A., and K. J. Donnelly, A Canadian Nuclear Power Producer's Approach to the Optimization of Radiation Protection Design, IAEA-SM-285-52, International Atomic Energy Agency, Vienna, Austria, 1986.
82. Voilleque, P. G., and R. A. Pavlick, "Societal Cost of Radiation Exposure," Health Physics, 43(3):405-409., 1982.
83. Walas, Stanley M., Chemical Process Equipment Selection and Design, Butterworths Series, Boston, 1988.
84. Wankat, Phillip C., Equilibrium Staged Separations, Elsevier, New York, 1988.
85. Weast, Robert C., CRC Handbook of Chemistry and Physics, 60th edition, CRC Press, Inc., Boca Raton, 1979.
86. WSRC, "F&H Area Hazardous Waste Management Facilities Accelerated Approach Proposal (U)," WER-ERD-93-0093, Westinghouse Savannah River Company, Aiken, South Carolina, March 1993.

APPENDIX A: COST EVALUATION DETAILED INFORMATION

APPENDIX A COST EVALUATION DETAILED INFORMATION

Detailed information is provided in Appendix A on the following processes:

- Evaporation (Direct heating and humidification)
- Stripping and Sparging
- Girdler-Sulfide
- Dual Temperature Liquid Phase Catalytic Exchange
- Combined Electrolysis/Catalytic Exchange
- Storage Tanks (Carbon Steel and Stainless Steel)
- Surface Enhancements
- Electrolysis

This section includes the following information on each of the specific processes which underwent a full evaluation:

- process flow diagram
- assumptions for process design
- assumptions for capital investment costs
- assumptions for production costs
- capital investment cost sheets [presented separately for both low volume - high concentration and high volume - low concentration scenarios]
- estimation of total product cost sheets [presented separately for both low volume - high concentration and high volume - low concentration scenarios]
- total costs (present worth basis) sheets [presented separately for both low volume - high concentration and high volume - low concentration scenarios]
- system cost breakdown by year (from year 0 through 20) [presented separately for both low volume - high concentration and high volume - low concentration scenarios]
- graph of total cost versus year (from year 0 through 20) [presented separately for both low volume - high concentration and high volume - low concentration scenarios]

The following references were used in development of the material presented in Appendix A: 5,8,15,26,39,43,47,60,62,63,67,78,83,84,85.

TAB A1:   Evaporation by Direct Heating

Evaporation (Direct Heating)

Evaporation (Direct Heating)

1. The low flow case pumping rate is 25 gpm.
2. The high flow case pumping rate is 250 gpm.
3. All groundwater pumped is evaporated.
4. Assume that groundwater is available at 45°F.
5. Assume saturated steam is available at 100 psi (339°F) and is condensed and cooled to 212°F.
6. Assume the overall heat transfer coefficient, U , for the evaporator is 500 BTU/hr·ft²·°F (from Rules of Thumb for Chemical Engineers, Carl R. Branan, ed., Gulf Publishing, Houston, 1994, p.33, Table 3, U for steam-water evaporators ranges from 350-750 BTU/hr·ft²·°F).
7. From this information, the necessary heat transfer area is approximated as 209 ft² and 2096 ft² for the low and high flow cases, respectively.
8. Perry's, p. 11-37, lists the largest stainless steel evaporator as a 200 ft² single effect agitated film evaporator.
9. Each of these evaporators cost \$70,000 (1968 dollars) and this was scaled to the 1995 value of \$234,562 (using the CE Cost Index values of 114 for 1968 and 382 for June 1995).
10. One single effect, 316 stainless steel, 200 ft² agitated film evaporators is used for the low flow case.
11. Ten such evaporators are required for the high flow case.
12. Steam cost is \$3.43/1000lb (from Peters and Timmerhaus, adjusted to 1995 values).
13. 16,945.5 lb steam/hr is required for the low flow case, and 169,455.1 LB steam/hr is required for the high flow case.

Evaporation (Direct Heating) - Assumptions for Capital Investment Costs

1. The total installed equipment cost is calculated as 43% of the fixed capital investment cost. This is slightly below the Peters and Timmerhaus estimate.
2. The purchased equipment cost is calculated as 19% of the fixed capital investment.
3. The installation costs are estimated at 40% since the equipment is not particularly complicated.
4. The instrumentation costs are estimated at 18%.
5. The piping costs are estimated at 45% since the equipment will not require extensive piping.
6. The electrical costs are estimated at 25% since the evaporators will not require extensive wiring.
7. The building costs are estimated at 10% since no extensive buildings are required.
8. The service facilities and yard improvements are estimated at 40% since only connection to existing service facilities is required.
9. The land costs are estimated at 4% since this scenario requires minimal land.
10. The engineering costs are estimated at 30% since this technology has not been used for remediation.
11. The construction costs are estimated at 30% since this technology has not been used for remediation.
12. The contingency costs are estimated at 15% since this technology has not been used for remediation.
13. The working capital costs are estimated at 15%.

Evaporation (Direct Heating) - Assumptions for Production Costs

1. The direct production costs are 68% of the total product cost. This is slightly above the Peters and Timmerhaus estimate.
2. The raw materials are estimated as 0% since the only raw material is groundwater and the cost of pumping this groundwater is included in the utilities.
3. The operating labor is estimated as 10% of the total product cost.
4. The direct supervisory and clerical labor cost is estimated as 10% of the total product cost.
5. The utilities cost is calculated as 41% of the total product cost. This is above the Peters and Timmerhaus estimate, but evaporating water requires a significant energy input.
6. The maintenance and repairs cost is estimated as 7% since the equipment is complicated.
7. The operating and supplies cost is estimated as 0.5% of the fixed capital investment.
8. The laboratory charges are estimated as 1% since this technology requires minimal laboratory work.
9. The patents and royalties cost is estimated as 0% of the total product cost since this technology is not patented.
10. The fixed charges are calculated as 7%. This is slightly below the Peters and Timmerhaus estimate.
11. The depreciation is estimated as 10% of the fixed capital investment for machinery and equipment.
12. The local taxes are estimated as 1%. Although the government will not be required to pay taxes, this will be used for donations to support the local community.
13. The insurance is estimated as 0.4% of the fixed capital investment.
14. The rent is estimated as 0% since the government will not be required to rent land or buildings for this project.
15. The plant overhead costs are estimated as 70% of the cost for operating labor, supervision, and maintenance.
16. The administrative costs are estimated as 15% of the costs for operating labor, supervision and maintenance.
17. The distribution and selling costs are estimated as 0% since this is a remediation project.
18. The research and development costs are estimated as 2% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
19. The financing cost is estimated as 0% since the government will borrow no money for this project.

Capital Investment Cost**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 534,801
1. Purchased equipment (15-40% of fixed capital investment)	19%	\$ 234,562	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 93,825	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 42,221	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 105,553	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 58,641	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 23,456
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 93,825
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 9,382
Total Direct Cost			\$ 661,465
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 198,439
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 198,439
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 186,767
Total Indirect Costs			\$ 583,645
III. Fixed-capital Investment			\$ 1,245,110
IV. Working capital (10-20% of total capital investment)	15%		\$ 219,725
V. Total capital investment			\$ 1,464,836

Estimation of Total Product Cost**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	68%		\$ 855,044
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 125,623	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 125,623	
4. Utilities (10-20% of total product cost)	41%	\$ 509,158	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	7%	\$ 87,158	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 6,226	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 1,256	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	7%		\$ 88,421
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 70,989	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 12,451	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 4,980	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i>, or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 236,883
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 75,885
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 50,761	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 25,125	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 1,256,234
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	1,464,836
Capitalized Total Product Cost	\$	15,789,048
Present Value Cost for 20 year life	\$	17,253,884
Gallons/minute treated (basis)		25
Total Gallons Treated in 20 years		263,000,000
Product Cost/1000 gallons treated	\$	66
Ci/year removed		1282
Total Tritium Concentration (Ci)		25,640
FEI		0.60
Product Cost/Ci averted	\$	1,122

System Cost Breakdown

Evaporation, Low Volume-High Concentration

WSRC-RP-96-0075

Rev 0

February 26, 1996

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 1,464,836	\$ 0	\$ 1,464,836
Year 1		\$ 1,197,554	\$ 1,197,554
Year 2		\$ 1,141,615	\$ 1,141,615
Year 3		\$ 1,088,288	\$ 1,088,288
Year 4		\$ 1,037,453	\$ 1,037,453
Year 5		\$ 988,993	\$ 988,993
Year 6		\$ 942,796	\$ 942,796
Year 7		\$ 898,757	\$ 898,757
Year 8		\$ 856,775	\$ 856,775
Year 9		\$ 816,754	\$ 816,754
Year 10		\$ 778,602	\$ 778,602
Year 11		\$ 742,233	\$ 742,233
Year 12		\$ 707,562	\$ 707,562
Year 13		\$ 674,511	\$ 674,511
Year 14		\$ 643,004	\$ 643,004
Year 15		\$ 612,968	\$ 612,968
Year 16		\$ 584,336	\$ 584,336
Year 17		\$ 557,041	\$ 557,041
Year 18		\$ 531,021	\$ 531,021
Year 19		\$ 506,216	\$ 506,216
Year 20		\$ 482,570	\$ 482,570

Capital Investment Cost**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 5,348,014
1. Purchased equipment (15-40% of fixed capital investment)	19%	\$ 2,345,620	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 938,248	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 422,212	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 1,055,529	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 586,405	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 234,562
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 938,248
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 93,825
Total Direct Cost			\$ 6,614,648
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 1,984,395
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 1,984,395
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 1,867,665
Total Indirect Costs			\$ 5,836,454
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 12,451,103
IV. Working capital (10-20% of total capital investment)	15%		\$ 2,197,253
V. Total capital investment			\$ 14,648,356

Estimation of Total Product Cost (per year)**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	68%		\$ 8,550,448
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 1,256,234	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 1,256,234	
4. Utilities (10-20% of total product cost)	41%	\$ 5,091,584	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	7%	\$ 871,577	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 62,256	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 12,562	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	7%		\$ 884,210
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 709,895	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 124,511	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 49,804	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 2,368,832
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 758,854
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 507,607	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 251,247	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 12,562,344
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	14,648,356
Capitalized Total Product Cost	\$	157,890,564
Present Value Cost for 20 year life	\$	172,538,920
Gallons/minute treated (basis)		250
Total Gallons Treated in 20 years		2,630,000,000
Product Cost/1000 gallons treated	\$	66
Ci/year removed		1538
Total Tritium Concentration (Ci)		30,760
FEI		0.60
Product Cost/Ci averted	\$	9,349

System Cost Breakdown

Evaporation, High Volume-Low Concentration

WSRC-RP-96-0075

Rev 0

February 26, 1996

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 14,648,356	\$ 0	\$ 14,648,356
Year 1		\$ 11,975,543	\$ 11,975,543
Year 2		\$ 11,416,151	\$ 11,416,151
Year 3		\$ 10,882,890	\$ 10,882,890
Year 4		\$ 10,374,537	\$ 10,374,537
Year 5		\$ 9,889,931	\$ 9,889,931
Year 6		\$ 9,427,961	\$ 9,427,961
Year 7		\$ 8,987,570	\$ 8,987,570
Year 8		\$ 8,567,750	\$ 8,567,750
Year 9		\$ 8,167,541	\$ 8,167,541
Year 10		\$ 7,786,025	\$ 7,786,025
Year 11		\$ 7,422,331	\$ 7,422,331
Year 12		\$ 7,075,626	\$ 7,075,626
Year 13		\$ 6,745,115	\$ 6,745,115
Year 14		\$ 6,430,043	\$ 6,430,043
Year 15		\$ 6,129,688	\$ 6,129,688
Year 16		\$ 5,843,363	\$ 5,843,363
Year 17		\$ 5,570,413	\$ 5,570,413
Year 18		\$ 5,310,213	\$ 5,310,213
Year 19		\$ 5,062,166	\$ 5,062,166
Year 20		\$ 4,825,707	\$ 4,825,707

TAB A2:   *Evaporation by Humidification*

Evaporation (Humidification)

Evaporation (Humidification)

1. The low flow case pumping rate is 25 gpm.
2. The high flow case pumping rate is 250 gpm.
3. All groundwater pumped is evaporated by pumping through a standard cooling tower.
4. Assume that groundwater is supplied to the system at 45° F.
5. Assume a 15° F approach.
6. The 30 year average January temperature for Aiken, SC (based on SE Regional Climate Center Climatological Normals, 1961-90) is ~ 45° F. Assuming 80% humidity, this is a wet bulb of 42° F.
7. Assume a 15° F cooling range.
8. Determine heat load requirement and recirculation rate to evaporate either 25 gpm or 250 gpm.
9. From the heat load, approach, and cooling range, determine the temperature to which the cooling tower feed must be heated to get the appropriate heat load.
10. Make a similar calculation for a summer case of 80° F, 100% humidity.
11. Size the fan and pump on the winter case and size the preheater on the summer case.
12. Assume 1ft² tower area/gpm recirculated.
13. Determine the pump and fan power requirements using correlations in the Marley Cooling Tower Selection Guide.

1. The total installed equipment cost is calculated as 43% of the fixed capital investment cost. This is slightly below the Peters and Timmerhaus estimate.
2. The purchased equipment cost is calculated as 19% of the fixed capital investment.
3. The installation costs are estimated at 40% since the equipment is not particularly complicated.
4. The instrumentation costs are estimated at 18%.
5. The piping costs are estimated at 45% since the equipment will not require extensive piping.
6. The electrical costs are estimated at 25% since the evaporators will not require extensive wiring.
7. The building costs are estimated at 10% since no extensive buildings are required.
8. The service facilities and yard improvements are estimated at 40% since only connection to existing service facilities is required.
9. The land costs are estimated at 4% since this scenario requires minimal land.
10. The engineering costs are estimated at 30% since this technology has not been used for remediation.
11. The construction costs are estimated at 30% since this technology has not been used for remediation.
12. The contingency costs are estimated at 15% since this technology has not been used for remediation.
13. The working capital costs are estimated at 15%.

Evaporation (Humidification) - Assumptions for Production Costs

1. The direct production costs are 50% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
2. The raw materials are estimated as 0% since the only raw material is groundwater and the cost of pumping this groundwater is included in the utilities.
3. The operating labor is estimated as 10% of the total product cost.
4. The direct supervisory and clerical labor cost is estimated as 10% of the total product cost.
5. The utilities cost is calculated as 13% of the total product cost.
6. The maintenance and repairs cost is estimated as 7% since the equipment is not complicated.
7. The operating and supplies cost is estimated as 0.5% of the fixed capital investment.
8. The laboratory charges are estimated as 1% since this technology requires minimal laboratory work.
9. The patents and royalties cost is estimated as 0% of the total product cost since this technology is not patented.
10. The fixed charges are calculated as 17%.
11. The depreciation is estimated as 10% of the fixed capital investment for machinery and equipment.
12. The local taxes are estimated as 1%. Although the government will not be required to pay taxes, this will be used for donations to support the local community.
13. The insurance is estimated as 0.4% of the fixed capital investment.
14. The rent is estimated as 0% since the government will not be required to rent land or buildings for this project.
15. The plant overhead costs are estimated as 70% of the cost for operating labor, supervision, and maintenance.
16. The administrative costs are estimated as 15% of the costs for operating labor, supervision and maintenance.
17. The distribution and selling costs are estimated as 0% since this is a remediation project.
18. The research and development costs are estimated as 2% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
19. The financing cost is estimated as 0% since the government will borrow no money for this project.

Capital Investment Cost**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 1,879,176
1. Purchased equipment (15-40% of fixed capital investment)	19%	\$ 824,200	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 329,680	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 148,356	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 370,890	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 206,050	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 82,420
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 329,680
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 32,968
Total Direct Cost			\$ 2,324,244
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 697,273
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 697,273
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 656,257
Total Indirect Costs			\$ 2,050,804
III. Fixed-capital Investment			\$ 4,375,048
IV. Working capital (10-20% of total capital investment)	15%		\$ 772,067
V. Total capital investment			\$ 5,147,115

Estimation of Total Product Cost**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	61%		\$ 1,727,233
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 283,733	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 283,733	
4. Utilities (10-20% of total product cost)	29%	\$ 828,800	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	7%	\$ 306,253	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 21,875	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 2,837	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	11%		\$ 310,692
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 249,442	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 43,750	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 17,500	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 611,604
II. General expenses			
= administrative costs+distribution and selling costs+ research and development costs			\$ 187,805
A. Administrative costs (about 15% of costs for operating labor, <i>supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 131,058	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 56,747	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 2,837,334
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	5,147,115
Capitalized Total Product Cost	\$	35,661,196
Present Value Cost for 20 year life	\$	40,808,311
Gallons/minute treated (basis)		25
Total Gallons Treated in 20 years		262,800,000
Product Cost/1000 gallons treated	\$	155
Ci/year removed		1282
Total Tritium Concentration (Ci)		25,640
FEI		0.60
Product Cost/Ci averted	\$	2,653

System Cost Breakdown

Humidification, Low Volume-High Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 5,147,115	\$ 0	\$ 5,147,115
Year 1		\$ 2,704,799	\$ 2,704,799
Year 2		\$ 2,578,454	\$ 2,578,454
Year 3		\$ 2,458,012	\$ 2,458,012
Year 4		\$ 2,343,195	\$ 2,343,195
Year 5		\$ 2,233,742	\$ 2,233,742
Year 6		\$ 2,129,401	\$ 2,129,401
Year 7		\$ 2,029,934	\$ 2,029,934
Year 8		\$ 1,935,114	\$ 1,935,114
Year 9		\$ 1,844,722	\$ 1,844,722
Year 10		\$ 1,758,553	\$ 1,758,553
Year 11		\$ 1,676,409	\$ 1,676,409
Year 12		\$ 1,598,102	\$ 1,598,102
Year 13		\$ 1,523,453	\$ 1,523,453
Year 14		\$ 1,452,291	\$ 1,452,291
Year 15		\$ 1,384,453	\$ 1,384,453
Year 16		\$ 1,319,783	\$ 1,319,783
Year 17		\$ 1,258,135	\$ 1,258,135
Year 18		\$ 1,199,366	\$ 1,199,366
Year 19		\$ 1,143,342	\$ 1,143,342
Year 20		1,089,935	1,089,935

Evaporation (Humidification-Low Flow) Yearly Expenditures

Capital Investment Cost**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 18,748,440
1. Purchased equipment (15-40% of fixed capital investment)	19%	\$ 8,223,000	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 3,289,200	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 1,480,140	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 3,700,350	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 2,055,750	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 822,300
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 3,289,200
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 328,920
Total Direct Cost			\$ 23,188,860
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 6,956,658
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 6,956,658
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 6,547,443
Total Indirect Costs			\$ 20,460,759
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 43,649,619
IV. Working capital (10-20% of total capital investment)	15%		\$ 7,702,874
V. Total capital investment			\$ 51,352,493

Estimation of Total Product Cost (per year)**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	61%		\$ 17,101,551
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 2,814,625	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 2,814,625	
4. Utilities (10-20% of total product cost)	29%	\$ 8,170,433	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	7%	\$ 3,055,473	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 218,248	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 28,146	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	11%		\$ 3,099,761
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 2,488,667	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 436,496	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 174,598	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 6,079,307
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 1,865,634
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 1,302,709	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 562,925	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 28,146,253
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	51,352,493
Capitalized Total Product Cost	\$	353,757,835
Present Value Cost for 20 year life	\$	405,110,328
Gallons/minute treated (basis)		250
Total Gallons Treated in 20 years		2,628,000,000
Product Cost/1000 gallons tr	\$	154
Ci/year removed		1538
Total Tritium Concentration (Ci)		30,760
FEI		0.60
Product Cost/Ci averted		

System Cost Breakdown

Humidification, High Volume-Low Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 51,352,493	\$ 0	\$ 51,352,493
Year 1		\$ 26,831,509	\$ 26,831,509
Year 2		\$ 25,578,178	\$ 25,578,178
Year 3		\$ 24,383,392	\$ 24,383,392
Year 4		\$ 23,244,416	\$ 23,244,416
Year 5		\$ 22,158,642	\$ 22,158,642
Year 6		\$ 21,123,587	\$ 21,123,587
Year 7		\$ 20,136,880	\$ 20,136,880
Year 8		\$ 19,196,263	\$ 19,196,263
Year 9		\$ 18,299,583	\$ 18,299,583
Year 10		\$ 17,444,788	\$ 17,444,788
Year 11		\$ 16,629,922	\$ 16,629,922
Year 12		\$ 15,853,119	\$ 15,853,119
Year 13		\$ 15,112,602	\$ 15,112,602
Year 14		\$ 14,406,675	\$ 14,406,675
Year 15		\$ 13,733,722	\$ 13,733,722
Year 16		\$ 13,092,204	\$ 13,092,204
Year 17		\$ 12,480,652	\$ 12,480,652
Year 18		\$ 11,897,667	\$ 11,897,667
Year 19		\$ 11,341,913	\$ 11,341,913
Year 20		\$ 10,812,119	\$ 10,812,119

TAB A3:   Stripping and Sparging

Stripping

Sparging

Stripping and Sparging

1. The low flow case pumping rate is 25 gpm.
2. The high flow case pumping rate is 250 gpm.
3. Sparge air is saturated with water by bubbling through a water filled tank.
4. Volume of water remains unchanged during sparging operation.
5. 50% of tritium is transferred to humidified air stream every 45 days.
6. Pumped groundwater is stored in 500,000 gallon stainless steel tanks with sparge air entering along the bottom of the tanks.
7. Each 500,000 gallon storage tank requires 66,840 cfm humidified sparge air flow and a 116,667 gallon water tank to humidify the sparge air.
8. The high flow, low concentration storage tanks will have the initial 0.15×10^{-12} mg/L tritium concentration reduced to less than the drinking water standard (1 ppQd) in 360 days, and may then be discharged so the tank may be reused.
9. The low flow, high concentration storage tanks will have the initial 0.125×10^{-11} mg/L tritium concentration reduced to less than the drinking water standard (1 ppQd) in 495 days, and may then be discharged so the tank may be reused.
10. In year 0, build 22 tanks for the high flow case, and 3 tanks for the low flow case.
11. A total of 263 tanks are required for the high flow case, 22 built initially, and the remainder built during the first year. Since the concentration in these tanks will be lower, the tanks may be emptied approximately one year after filling.
12. A total of 37 tanks are required for the low flow case, 3 built initially, and the remainder built during the first and second year. Since the concentration in these tanks will be higher, the tanks will be emptied approximately 1 1/2 years after filling.
13. The present value of the tanks built after year 0 are included in the total cost.
14. Add 15% to the total tank cost to account for pumps, fans, and breather vents.
15. A total of 19 KW /tank is required for the sparge air fan, and 8 KW/tank are required for the tank pumps.

Stripping and Sparging - Assumptions for Capital Investment Costs

1. The total installed equipment cost is calculated as 43% of the fixed capital investment cost. This is slightly below the Peters and Timmerhaus estimate.
2. The purchased equipment cost is calculated as 4% of the fixed capital investment. This is below the Peters and Timmerhaus estimate.
3. The installation costs are estimated at 40% since the equipment is not particularly complicated.
4. The instrumentation costs are estimated at 18%.
5. The piping costs are estimated at 45% since the equipment will not require extensive piping.
6. The electrical costs are estimated at 25% since the equipment will not require extensive wiring.
7. The building costs are estimated at 10% since no extensive buildings are required.
8. The service facilities and yard improvements are estimated at 40% since only connection to existing service facilities is required.
9. The land costs are estimated at 4% since this scenario requires minimal land.
10. The engineering costs are estimated at 30% since this technology has not been used for remediation.
11. The construction costs are estimated at 30% since this technology has not been used for remediation.
12. The contingency costs are estimated at 15% since this technology has not been used for remediation.
13. The working capital costs are estimated at 15%.

Stripping and Sparging - Assumptions for Production Costs

1. The direct production costs are 47% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
2. The raw materials are estimated as 0% since the only raw material is groundwater and the cost of pumping this groundwater is included in the utilities.
3. The operating labor is estimated as 10% of the total product cost.
4. The direct supervisory and clerical labor cost is estimated as 10% of the total product cost.
5. The utilities cost is calculated as 8% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
6. The maintenance and repairs cost is estimated as 7% since the equipment includes fans.
7. The operating and supplies cost is estimated as 0.5% of the fixed capital investment.
8. The laboratory charges are estimated as 1% since this technology requires minimal laboratory work.
9. The patents and royalties cost is estimated as 0% of the total product cost since this technology is not patented.
10. The fixed charges are calculated as 18%.
11. The depreciation is estimated as 10% of the fixed capital investment for machinery and equipment.
12. The local taxes are estimated as 1%. Although the government will not be required to pay taxes, this will be used for donations to support the local community.
13. The insurance is estimated as 0.4% of the fixed capital investment.
14. The rent is estimated as 0% since the government will not be required to rent land or buildings for this project.
15. The plant overhead costs are estimated as 70% of the cost for operating labor, supervision, and maintenance.
16. The administrative costs are estimated as 15% of the costs for operating labor, supervision and maintenance.
17. The distribution and selling costs are estimated as 0% since this is a remediation project.
18. The research and development costs are estimated as 2% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
19. The financing cost is estimated as 0% since the government will borrow no money for this project.

Capital Investment Cost (Year 0 Investment)**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 6,686,100
1. Purchased equipment (15-40% of fixed capital investment)	4%	\$ 2,932,500	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 1,173,000	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 527,850	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 1,319,625	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 733,125	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 293,250
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 1,173,000
D. Land (1-2% of fixed-capital investment or 4-8% of <i>purchased-equipment cost</i>)	4%		\$ 117,300
Total Direct Cost			\$ 8,269,650
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 2,480,895
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 2,480,895
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 2,334,960
Total Indirect Costs			\$ 7,296,750
III. Fixed-capital Investment			\$ 15,566,400
IV. Working capital (10-20% of total capital investment)	15%		\$ 2,747,012
V. Total capital investment			\$ 18,313,412

Capital Investment Cost (Present Value of Year 1 Investment)**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 50,990,276
1. Purchased equipment (15-40% of fixed capital investment)	4%	\$ 22,364,156	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 8,945,663	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 4,025,548	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 10,063,870	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 5,591,039	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 2,236,416
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 8,945,663
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 894,566
Total Direct Cost			\$ 63,066,921
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 18,920,076
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 18,920,076
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 17,807,131
Total Indirect Costs			\$ 55,647,283
III. Fixed-capital Investment			\$ 118,714,204
IV. Working capital (10-20% of total capital investment)	15%		\$ 20,949,565
V. Total capital investment			\$ 139,663,769

Capital Investment Cost (Present Value of Year 2 Investment)**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 20,253,526
1. Purchased equipment (15-40% of fixed capital investment)	4%	\$ 8,883,125	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 3,553,250	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 1,598,963	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 3,997,406	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 2,220,781	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 888,313
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 3,553,250
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 355,325
Total Direct Cost			\$ 25,050,413
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 7,515,124
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 7,515,124
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 7,073,058
Total Indirect Costs			\$ 22,103,306
III. Fixed-capital Investment			\$ 47,153,719
IV. Working capital (10-20% of total capital investment)	15%		\$ 8,321,245
V. Total capital investment			\$ 55,474,964

Estimation of Total Product Cost**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	47%		\$ 2,879,545
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 606,320	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 606,320	
4. Utilities (10-20% of total product cost)	8%	\$ 493,363	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	7%	\$ 1,089,648	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 77,832	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 6,063	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	18%		\$ 1,105,442
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 887,513	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 155,664	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 62,266	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i>, or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 1,611,601
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 466,607
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 345,343	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 121,264	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 6,063,195
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Evaporation, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	213,452,145
Capitalized Total Product Cost	\$	76,205,625
Present Value Cost for 20 year life	\$	289,657,771
Gallons/minute treated (basis)		25
Total Gallons Treated in 20 years		263,000,000
Product Cost/1000 gallons treated	\$	1,102
Ci/year removed		1282
Total Tritium Concentration (Ci)		25,640
FEI		0.60
Product Cost/Ci averted	\$	18,829

System Cost Breakdown

Stripping/Sparging, Low Volume-High Concentration

WSRC-RP-96-0075

Rev 0

February 26, 1996

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 18,313,412	\$ 0	\$ 18,313,412
Year 1	\$ 133,139,914	\$ 4,219,383	\$ 137,359,296
Year 2	\$ 50,413,407	\$ 5,509,987	\$ 55,923,395
Year 3		\$ 5,252,609	\$ 5,252,609
Year 4		\$ 5,007,254	\$ 5,007,254
Year 5		\$ 4,773,359	\$ 4,773,359
Year 6		\$ 4,550,390	\$ 4,550,390
Year 7		\$ 4,337,836	\$ 4,337,836
Year 8		\$ 4,135,211	\$ 4,135,211
Year 9		\$ 3,942,050	\$ 3,942,050
Year 10		\$ 3,757,913	\$ 3,757,913
Year 11		\$ 3,582,376	\$ 3,582,376
Year 12		\$ 3,415,039	\$ 3,415,039
Year 13		\$ 3,255,519	\$ 3,255,519
Year 14		\$ 3,103,450	\$ 3,103,450
Year 15		\$ 2,958,484	\$ 2,958,484
Year 16		\$ 2,820,290	\$ 2,820,290
Year 17		\$ 2,688,551	\$ 2,688,551
Year 18		\$ 2,562,966	\$ 2,562,966
Year 19		\$ 2,443,246	\$ 2,443,246
Year 20		\$ 2,329,120	\$ 2,329,120

Capital Investment Cost (Year 0 Investment)**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 49,031,400
1. Purchased equipment (15-40% of fixed capital investment)	4%	\$ 21,505,000	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 8,602,000	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 3,870,900	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 9,677,250	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 5,376,250	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 2,150,500
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 8,602,000
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 860,200
Total Direct Cost			\$ 60,644,100
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 18,193,230
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 18,193,230
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 17,123,040
Total Indirect Costs			\$ 53,509,500
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 114,153,600
IV. Working capital (10-20% of total capital investment)	15%		\$ 20,144,753
V. Total capital investment			\$ 134,298,353

Capital Investment Cost (Present Value of Year 1 Investment)**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 371,671,624
1. Purchased equipment (15-40% of fixed capital investment)	4%	\$ 163,013,870	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 65,205,548	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 29,342,497	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 73,356,242	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 40,753,468	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 16,301,387
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 65,205,548
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 6,520,555
Total Direct Cost			\$ 459,699,114
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 137,909,734
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 137,909,734
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 129,797,397
Total Indirect Costs			\$ 405,616,866
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 865,315,980
IV. Working capital (10-20% of total capital investment)	15%		\$ 152,702,820
V. Total capital investment			\$ 1,018,018,800

Estimation of Total Product Cost (per year)**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	47%		\$ 20,969,706
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 4,428,200	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 4,428,200	
4. Utilities (10-20% of total product cost)	8%	\$ 3,507,504	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	7%	\$ 7,990,752	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 570,768	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 44,282	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	18%		\$ 8,106,575
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 6,508,425	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 1,141,536	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 456,614	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 11,793,007
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 3,412,713
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 2,527,073	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 885,640	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 44,282,001
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Evaporation, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	1,152,317,153
Capitalized Total Product Cost	\$	556,560,930
Present Value Cost for 20 year life	\$	1,708,878,083
Gallons/minute treated (basis)		250
Total Gallons Treated in 20 years		2,630,000,000
Product Cost/1000 gallons treated	\$	650
Ci/year removed		1538
Total Tritium Concentration (Ci)		30,760
FEI		0.60
Product Cost/Ci averted	\$	92,592

System Cost Breakdown

Stripping/Sparging, High Volume-Low Concentration

WSRC-RP-96-0075

Rev 0

February 26, 1996

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 134,298,353	\$ 0	\$ 134,298,353
Year 1	\$ 970,465,968	\$ 42,213,538	\$ 1,012,679,505
Year 2		\$ 40,241,695	\$ 40,241,695
Year 3		\$ 38,361,959	\$ 38,361,959
Year 4		\$ 36,570,027	\$ 36,570,027
Year 5		\$ 34,861,799	\$ 34,861,799
Year 6		\$ 33,233,364	\$ 33,233,364
Year 7		\$ 31,680,996	\$ 31,680,996
Year 8		\$ 30,201,140	\$ 30,201,140
Year 9		\$ 28,790,410	\$ 28,790,410
Year 10		\$ 27,445,576	\$ 27,445,576
Year 11		\$ 26,163,562	\$ 26,163,562
Year 12		\$ 24,941,432	\$ 24,941,432
Year 13		\$ 23,776,389	\$ 23,776,389
Year 14		\$ 22,665,766	\$ 22,665,766
Year 15		\$ 21,607,022	\$ 21,607,022
Year 16		\$ 20,597,733	\$ 20,597,733
Year 17		\$ 19,635,589	\$ 19,635,589
Year 18		\$ 18,718,388	\$ 18,718,388
Year 19		\$ 17,844,031	\$ 17,844,031
Year 20		\$ 17,010,515	\$ 17,010,515

TAB A4:   Girdler-Sulfide

Girdler-Sulfide

WSRC-RP-96-0075
Rev 0
February 26, 1996

Girdler-Sulfide

1. The low flow case pumping rate is 25 gpm.
2. The high flow case pumping rate is 250 gpm.
3. The low flow, high concentration, inlet concentration is 0.125×10^{-11} atom fraction T.
4. The high flow, low concentration, inlet concentration is 0.15×10^{-12} atom fraction T.
5. The exiting enriched stream is 0.81×10^{-9} atom fraction T at 0.3475×10^{-1} kmol/hr for the high volume case, and 0.2913×10^{-1} kmol/hr for the low volume case (this is based on health and safety guidelines).
6. The exiting depleted stream is 0.1×10^{-14} atom fraction T at 188.877 kmol/hr for the high volume case, and 18.86 kmol/hr for the low volume case (this is based on the drinking water standard of 1 ppQd).
7. The enriched water stream will be sequestered on site in stainless steel tanks at a storage cost of \$1/gallon.
8. For the high flow case, there are 155.16 hot stages, and 74.07 and 59.10 cold stages.
9. For the low flow case, there are 158.24 hot stages, and 97.01 and 44.33 cold stages.
10. For the high flow case, the hot liquid flow is 1739.49 kmol/hr and the cold liquid flows are 1550.61 and 1739.52 kmol/hr in the columns.
11. For the low flow case, the hot liquid flow is 189.69 kmol/hr and the cold liquid flows are 170.83 and 189.72 kmol/hr in the columns.
12. The gas flow is 3418.18 kmol/hr for the high flow case and 371.69 kmol/hr for the low flow case.
13. The column diameters were calculated based on the liquid and gas flow rates using the Sherwood-Lobo correlation (Walas, p. 441). The correlation was used to calculate the flooding diameter, then a diameter giving 80% of flooding was selected for system design.
14. A 5' diameter column was chosen for the high flow case and a 0.5' diameter column was chosen for the low flow case.
15. The actual staged tower volume will be 0.7 times that calculated (Rae).
16. From Branan, the height of an equivalent theoretical plate, HETP, is 1.3'-1.8' for 1" pall rings. Therefore, we chose 1.5' per stage for the HETP in these cases.
17. Each tower was limited to 175' height and 3 diameters were allowed in each tower for vapor disengagement and liquid hold-up space (Branan).
18. The packed tower costs (no internals) and the costs for tower internals were obtained from "Current Costs of Process Equipment," Chemical Engineering, April 5, 1982, and were brought to 1995 dollars using the CE Cost Index of 382 for June 1995.
19. For the low flow case, \$45,000 was added for pumps, \$60,000 for tanks, and \$150,000 for heat exchangers.
20. For the high flow case, \$56,178 was added for pumps, \$60,000 for tanks, and \$150,000 for heat exchangers.
21. The utility costs were assumed to be approximately those of the catalytic exchange case.

1. The total installed equipment cost is calculated as 43% of the fixed capital investment cost. This is slightly below the Peters and Timmerhaus estimate.
2. The purchased equipment cost is calculated as 19% of the fixed capital investment.
3. The installation costs are estimated at 40% since the equipment is not particularly complicated.
4. The instrumentation costs are estimated at 18%.
5. The piping costs are estimated at 45% since the equipment will not require extensive piping.
6. The electrical costs are estimated at 25% since the columns will not require extensive wiring.
7. The building costs are estimated at 10% since no extensive buildings are required.
8. The service facilities and yard improvements are estimated at 40% since only connection to existing service facilities is required.
9. The land costs are estimated at 4% since this scenario requires minimal land.
10. The engineering costs are estimated at 30% since this technology has not been used for remediation.
11. The construction costs are estimated at 30% since this technology has not been used for remediation.
12. The contingency costs are estimated at 15% since this technology has not been used for remediation.
13. The working capital costs are estimated at 15%.

Girdler-Sulfide - Assumptions for Production Costs

1. The direct production costs are 52% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
2. The raw materials are estimated as 0.5% since the only raw materials are groundwater (the cost of pumping this groundwater is included in the utilities) and hydrogen sulfide.
3. The operating labor is estimated as 10% of the total product cost.
4. The direct supervisory and clerical labor cost is estimated as 10% of the total product cost.
5. The utilities cost is calculated as 4% of the total product cost. This is below the Peters and Timmerhaus estimate.
6. The maintenance and repairs cost is estimated as 10% since the equipment is complicated.
7. The operating and supplies cost is estimated as 1% of the fixed capital investment.
8. The laboratory charges are estimated as 5% since this technology requires some laboratory work.
9. The patents and royalties cost is estimated as 6% of the total product cost since this technology is patented.
10. The fixed charges are calculated as 13%.
11. The depreciation is estimated as 10% of the fixed capital investment for machinery and equipment.
12. The local taxes are estimated as 1%. Although the government will not be required to pay taxes, this will be used for donations to support the local community.
13. The insurance is estimated as 0.4% of the fixed capital investment.
14. The rent is estimated as 0% since the government will not be required to rent land or buildings for this project.
15. The plant overhead costs are estimated as 70% of the cost for operating labor, supervision, and maintenance.
16. The administrative costs are estimated as 15% of the costs for operating labor, supervision and maintenance.
17. The distribution and selling costs are estimated as 0% since this is a remediation project.
18. The research and development costs are estimated as 2% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
19. The financing cost is estimated as 0% since the government will borrow no money for this project.

Capital Investment Cost**Girdler-Sulfide, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 2,224,532
1. Purchased equipment (15-40% of fixed capital investment)	19%	\$ 975,672	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 390,269	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 175,621	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 439,052	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 243,918	
3. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 97,567
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 390,269
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 39,027
Total Direct Cost			\$ 2,751,395
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 825,419
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 825,419
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 776,864
Total Indirect Costs			\$ 2,427,702
III. Fixed-capital Investment			\$ 5,179,097
IV. Working capital (10-20% of total capital investment)	15%		\$ 913,958
V. Total capital investment			\$ 6,093,055

Estimation of Total Product Cost**Girdler-Sulfide, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	53%		\$ 1,536,075
1. Raw materials (10-50% of total product cost)	0.5%	\$ 14,470	
2. Operating labor (10-20% of total product cost)	10%	\$ 289,394	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 289,394	
4. Utilities (10-20% of total product cost)	6%	\$ 185,011	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	10%	\$ 517,910	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	1.0%	\$ 51,791	
7. Laboratory charges (10-20% of operating labor)	5%	\$ 14,470	
8. Patents and royalties (0-6% of total product cost)	6%	\$ 173,636	
B. Fixed Charges (10-20% of total product cost)	13%		\$ 367,792
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 295,284	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 51,791	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 20,716	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 767,688
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 222,383
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 164,505	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 57,879	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 2,893,938
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Girdler-Sulfide, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	6,093,055
Capitalized Total Product Cost	\$	36,372,628
Present Value Cost for 20 year life	\$	42,465,683
Gallons/minute treated (basis)		25
Total Gallons Treated in 20 years		262,800,000
Product Cost/1000 gallons treated	\$	162
Ci/year removed		1282
Total Tritium Concentration (Ci)		25,640
FEI		0.99
Product Cost/Ci averted	\$	1,673

System Cost Breakdown

Girdler-Sulfide, Low Volume-High Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 6,093,055	\$ 0	\$ 6,093,055
Year 1		\$ 2,758,759	\$ 2,758,759
Year 2		\$ 2,629,894	\$ 2,629,894
Year 3		\$ 2,507,048	\$ 2,507,048
Year 4		\$ 2,389,941	\$ 2,389,941
Year 5		\$ 2,278,304	\$ 2,278,304
Year 6		\$ 2,171,882	\$ 2,171,882
Year 7		\$ 2,070,431	\$ 2,070,431
Year 8		\$ 1,973,719	\$ 1,973,719
Year 9		\$ 1,881,524	\$ 1,881,524
Year 10		\$ 1,793,636	\$ 1,793,636
Year 11		\$ 1,709,853	\$ 1,709,853
Year 12		\$ 1,629,984	\$ 1,629,984
Year 13		\$ 1,553,846	\$ 1,553,846
Year 14		\$ 1,481,264	\$ 1,481,264
Year 15		\$ 1,412,072	\$ 1,412,072
Year 16		\$ 1,346,113	\$ 1,346,113
Year 17		\$ 1,283,234	\$ 1,283,234
Year 18		\$ 1,223,293	\$ 1,223,293
Year 19		\$ 1,166,151	\$ 1,166,151
Year 20		\$ 1,111,679	\$ 1,111,679

Girdler-Sulfide (Low Flow) Yearly Expenditures

Capital Investment Cost**Girdler-Sulfide, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	43%		\$ 8,803,650
1. Purchased equipment (15-40% of fixed capital investment)	19%	\$ 3,861,250	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 1,544,500	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 695,025	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 1,737,563	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 965,313	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 386,125
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 1,544,500
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 154,450
Total Direct Cost			\$ 10,888,725
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 3,266,618
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 3,266,618
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 3,074,464
Total Indirect Costs			\$ 9,607,699
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 20,496,424
IV. Working capital (10-20% of total capital investment)	15%		\$ 3,617,016
V. Total capital investment			\$ 24,113,439

Estimation of Total Product Cost (per year)

Girdler-Sulfide, High Volume-Low Concentration

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	52%		\$ 5,639,489
1. Raw materials (10-50% of total product cost)	0.5%	\$ 54,551	
2. Operating labor (10-20% of total product cost)	10%	\$ 1,091,016	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 1,091,016	
4. Utilities (10-20% of total product cost)	4%	\$ 439,139	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	10%	\$ 2,049,642	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	1.0%	\$ 204,964	
7. Laboratory charges (10-20% of operating labor)	5%	\$ 54,551	
8. Patents and royalties (0-6% of total product cost)	6%	\$ 654,610	
B. Fixed Charges (10-20% of total product cost)	13%		\$ 1,455,546
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 1,168,596	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 204,964	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 81,986	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 2,962,172
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 852,954
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 634,751	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 218,203	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 10,910,162
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Girdler-Sulfide, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	24,113,439
Capitalized Total Product Cost	\$	137,125,012
Present Value Cost for 20 year life	\$	161,238,451
Gallons/minute treated (basis)		250
Total Gallons Treated in 20 years		2,628,000,000
Product Cost/1000 gallons treated	\$	61
Ci/year removed		1538
Total Tritium Concentration (Ci)		30,760
FEI		0.99
Product Cost/Ci averted	\$	5,295

System Cost Breakdown

Girdler-Sulfide, High Volume-Low Concentration

WSRC-RP-96-0075

Rev 0

February 26, 1996

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 24,113,439	\$ 0	\$ 24,113,439
Year 1		\$ 10,400,536	\$ 10,400,536
Year 2		\$ 9,914,715	\$ 9,914,715
Year 3		\$ 9,451,587	\$ 9,451,587
Year 4		\$ 9,010,092	\$ 9,010,092
Year 5		\$ 8,589,221	\$ 8,589,221
Year 6		\$ 8,188,008	\$ 8,188,008
Year 7		\$ 7,805,537	\$ 7,805,537
Year 8		\$ 7,440,931	\$ 7,440,931
Year 9		\$ 7,093,357	\$ 7,093,357
Year 10		\$ 6,762,018	\$ 6,762,018
Year 11		\$ 6,446,156	\$ 6,446,156
Year 12		\$ 6,145,049	\$ 6,145,049
Year 13		\$ 5,858,007	\$ 5,858,007
Year 14		\$ 5,584,372	\$ 5,584,372
Year 15		\$ 5,323,520	\$ 5,323,520
Year 16		\$ 5,074,852	\$ 5,074,852
Year 17		\$ 4,837,800	\$ 4,837,800
Year 18		\$ 4,611,821	\$ 4,611,821
Year 19		\$ 4,396,397	\$ 4,396,397
Year 20		\$ 4,191,036	\$ 4,191,036

TAB A5: Dual Temperature Liquid Phase Catalytic Exchange

Dual Temperature Liquid Phase Catalytic Exchange

WSRC-RP-96-0075

Rev 0

February 26, 1996

Contaminated
Groundwater Feed

Liquid

Gas

Cold

Electrolysis

Tritiated Water
Product

Hot

Depleted
Groundwater

Dual Temperature Liquid Phase Catalytic Exchange

1. The low flow case pumping rate is 25 gpm.
2. The high flow case pumping rate is 250 gpm.
3. The low flow, high concentration, inlet concentration is 0.125×10^{-11} atom fraction T.
4. The high flow, low concentration, inlet concentration is 0.15×10^{-12} atom fraction T.
5. The exiting enriched stream is 0.81×10^{-9} atom fraction T at 0.3475×10^{-1} kmol/hr for the high volume case, and 0.2913×10^{-1} kmol/hr for the low volume case (this is based on health and safety guidelines).
6. The exiting depleted stream is 0.1×10^{-14} atom fraction T at 188.877 kmol/hr for the high volume case, and 18.862 kmol/hr for the low volume case (this is based on the drinking water standard of 1 ppQd).
7. The enriched water stream will be sequestered on site in stainless steel tanks at a storage cost of \$1/gallon.
8. For the high flow case, there are 149.62 hot stages, and 71.27 and 56.94 cold stages.
9. For the low flow case, there are 152.6 hot stages, and 93.37 and 42.72 cold stages.
10. For the high flow case, the hot liquid flow is 1679.48 kmol/hr and the cold liquid flows are 1490.61 and 1679.52 kmol/hr in the columns.
11. For the low flow case, the hot liquid flow is 183.12 kmol/hr and the cold liquid flows are 164.26 and 183.15 kmol/hr in the columns.
12. The gas flow is 5383.57 kmol/hr for the high flow case and 585.26 kmol/hr for the low flow case.
13. The column diameters were calculated based on the liquid and gas flow rates using the Sherwood-Lobo correlation (Walas, p. 441). The correlation was used to calculate the flooding diameter, then a diameter giving 80% of flooding was selected for system design.
14. A 6.5' diameter column was chosen for the high flow case and a [0.65]' diameter column was chosen for the low flow case.
15. The actual staged tower volume will be 0.7 times that calculated (Rae).
16. From Branan, the height of an equivalent theoretical plate, HETP, is 1.3'-1.8' for 1" pall rings. Therefore, we chose 1.5' per stage for the HETP in these cases.
17. Each tower was limited to 175' height and 3 diameters were allowed in each tower for vapor disengagement and liquid hold-up space (Branan).
18. The packed tower costs (no internals) and the costs for tower internals were obtained from "Current Costs of Process Equipment," Chemical Engineering, April 5, 1982, and were brought to 1995 dollars using the CE Cost Index of 382 for June 1995.
19. The catalyst cost is \$300/L (provided by AECL) and must be replaced after 10 years.
20. For the low flow case, \$45,000 was added for pumps, \$60,000 for tanks, and \$150,000 for heat exchangers.
21. For the high flow case, \$56,178 was added for pumps, \$60,000 for tanks, and \$150,000 for heat exchangers.
22. To calculate the utility costs, it was assumed that chilled water was available at 40° F at a cost of \$0.32/1000 gallons, steam was available at 100 psi at a cost of \$2.52/1000 lb., and the total electricity used was \$20/hour for the low flow case and \$40/hour for the high flow case.
23. The direct costs are calculated based on the cost of the purchased equipment, and additional costs are calculated based on the equipment cost including the cost of an equivalent amount of ceramic saddle packing instead of catalyst.
24. Catalyst replacement costs were included at the present value of the future replacement cost.
25. The equivalent packing was estimated at $\$100/\text{ft}^3$, which allows for additional expenses associated with activation of catalyst packing.

Dual Temperature Liquid Phase Catalytic Exchange - Assumptions for Capital Investment Costs

1. The total installed equipment cost is calculated as 52% of the fixed capital investment.
2. The purchased equipment cost is calculated as 31% of the fixed capital investment.
3. The installation costs are estimated at 50% since the equipment is relatively complicated.
4. The instrumentation costs are estimated at 25% since the equipment will require close monitoring.
5. The piping costs are estimated at 75% since the equipment will require extensive piping.
6. The electrical costs are estimated at 25%.
7. The building costs are estimated at 10% since no extensive buildings are required.
8. The service facilities and yard improvements are estimated at 40% since only connection to existing service facilities is required.
9. The land costs are estimated at 4% since this scenario requires minimal land.
10. The engineering costs are estimated at 30% since this technology has not been used for remediation.
11. The construction costs are estimated at 30% since this technology has not been used for remediation.
12. The contingency costs are estimated at 15% since this technology has not been used for remediation.
13. The working capital costs are estimated at 15%.

Dual Temperature Liquid Phase Catalytic Exchange - Assumptions for Production Costs

1. The direct production costs are 52% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
2. The raw materials are estimated as 0.5% since the only raw materials are groundwater (the cost of pumping this groundwater is included in the utilities) and hydrogen.
3. The operating labor is estimated as 20% of the total product cost.
4. The direct supervisory and clerical labor cost is estimated as 15% of the total product cost.
5. The utilities cost is calculated as 0.2% of the total product cost. This is below the Peters and Timmerhaus estimate.
6. The maintenance and repairs cost is estimated as 10% since the equipment is complicated.
7. The operating and supplies cost is estimated as 0.5% of the fixed capital investment.
8. The laboratory charges are estimated as 1% since this technology requires minimal laboratory work.
9. The patents and royalties cost is estimated as 6% of the total product cost since this technology is patented.
10. The fixed charges are calculated as 8%. This is slightly below the Peters and Timmerhaus estimate.
11. The depreciation is estimated as 10% of the fixed capital investment for machinery and equipment.
12. The local taxes are estimated as 1%. Although the government will not be required to pay taxes, this will be used for donations to support the local community.
13. The insurance is estimated as 0.4% of the fixed capital investment.
14. The rent is estimated as 0% since the government will not be required to rent land or buildings for this project.
15. The plant overhead costs are estimated as 70% of the cost for operating labor, supervision, and maintenance.
16. The administrative costs are estimated as 15% of the costs for operating labor, supervision and maintenance.
17. The distribution and selling costs are estimated as 0% since this is a remediation project.
18. The research and development costs are estimated as 2% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
19. The financing cost is estimated as 0% since the government will borrow no money for this project.

Capital Investment Cost**Dual Temperature Liquid Phase Catalytic Exchange, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	50%		\$ 13,102,083
1. Purchased equipment (15-40% of fixed capital investment)	50%	\$ 10,394,999	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	50%	\$ 773,453	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	25%	\$ 386,726	
4. Piping, installed (10-80% of purchased-equipment cost)	75%	\$ 1,160,179	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 386,726	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 154,691
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 618,762
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 61,876
Total Direct Cost			\$ 13,937,411
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 4,181,223
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 4,181,223
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 3,935,269
Total Indirect Costs			\$ 12,297,716
III. Fixed-capital Investment			\$ 26,235,127
IV. Working capital (10-20% of total capital investment)	15%		\$ 4,629,728
V. Total capital investment			\$ 30,864,856
VI. Capitalized equipment cost (including 15% installation)			\$ 6,381,730

Estimation of Total Product Cost**Dual Temperature Liquid Phase Catalytic Exchange, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	53%		\$ 14,273,487
1. Raw materials (10-50% of total product cost)	0.5%	\$ 135,897	
2. Operating labor (10-20% of total product cost)	20%	\$ 5,435,869	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	15%	\$ 4,076,902	
4. Utilities (10-20% of total product cost)	0.7%	\$ 185,011	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	10%	\$ 2,623,513	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 131,176	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 54,359	
8. Patents and royalties (0-6% of total product cost)	6%	\$ 1,630,761	
B. Fixed Charges (10-20% of total product cost)	8%		\$ 2,046,432
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 1,679,140	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 262,351	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 104,941	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 8,495,399
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 2,364,030
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 1,820,443	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 543,587	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 27,179,347
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)

Dual Temperature Liquid Phase Catalytic Exchange, Low Volume-High Concentration
(calculation basis in bold, assumptions in italics/bold, \$300/L catalyst basis)

Total Capital Investment Cost	\$	37,246,586
Capitalized Total Product Cost	\$	341,605,225
Present Value Cost for 20 year life	\$	378,851,810
Gallons/minute treated (basis)		25
Total Gallons Treated in 20 years		262,800,000
Product Cost/1000 gallons treated	\$	1,442
Ci/year removed		1282
Total Tritium Concentration (Ci)		25,640
FEI		0.99
Product Cost/Ci averted	\$	14,925

System Cost Breakdown

Dual Temperature Liquid Phase Catalytic Exchange, Low Volume-High Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 30,864,856	\$ 0	\$ 30,864,856
Year 1		\$ 25,909,769	\$ 25,909,769
Year 2		\$ 24,699,494	\$ 24,699,494
Year 3		\$ 23,545,752	\$ 23,545,752
Year 4		\$ 22,445,903	\$ 22,445,903
Year 5		\$ 21,397,429	\$ 21,397,429
Year 6		\$ 20,397,930	\$ 20,397,930
Year 7		\$ 19,445,119	\$ 19,445,119
Year 8		\$ 18,536,815	\$ 18,536,815
Year 9		\$ 17,670,939	\$ 17,670,939
Year 10	\$ 6,381,730	\$ 16,845,509	\$ 23,227,239
Year 11		\$ 16,058,636	\$ 16,058,636
Year 12		\$ 15,308,519	\$ 15,308,519
Year 13		\$ 14,593,440	\$ 14,593,440
Year 14		\$ 13,911,764	\$ 13,911,764
Year 15		\$ 13,261,929	\$ 13,261,929
Year 16		\$ 12,642,449	\$ 12,642,449
Year 17		\$ 12,051,906	\$ 12,051,906
Year 18		\$ 11,488,947	\$ 11,488,947
Year 19		\$ 10,952,285	\$ 10,952,285
Year 20		\$ 10,440,691	\$ 10,440,691

Capital Investment Cost**Dual Temperature Liquid Phase Catalytic Exchange, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	52%		\$ 92,852,573
1. Purchased equipment (15-40% of fixed capital investment)	31%	\$ 85,851,675	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	50%	\$ 2,000,257	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	25%	\$ 1,000,128	
4. Piping, installed (10-80% of purchased-equipment cost)	75%	\$ 3,000,385	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 1,000,128	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 400,051
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 1,600,205
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 160,021
Total Direct Cost			\$ 95,012,850
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 28,503,855
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 28,503,855
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 26,827,158
Total Indirect Costs			\$ 83,834,867
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 178,847,717
IV. Working capital (10-20% of total capital investment)	15%		\$ 31,561,362
V. Total capital investment			\$ 210,409,079
VI. Capitalized equipment cost (including 15% installation)			\$ 59,035,540

Estimation of Total Product Cost (per year)

Dual Temperature Liquid Phase Catalytic Exchange, High Volume-Low Concentration
(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	52%		\$ 95,745,701
1. Raw materials (10-50% of total product cost)	0.5%	\$ 917,597	
2. Operating labor (10-20% of total product cost)	20%	\$ 36,703,862	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	15%	\$ 27,527,896	
4. Utilities (10-20% of total product cost)	0.2%	\$ 439,139	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	10%	\$ 17,884,772	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 894,239	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 367,039	
8. Patents and royalties (0-6% of total product cost)	6%	\$ 11,011,159	
B. Fixed Charges (10-20% of total product cost)	8%		\$ 14,304,171
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery</i> and equipment and 2-3% of building value for buildings.	10%	\$ 11,800,303	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 1,788,477	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 715,391	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 57,481,571
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 15,987,866
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 12,317,479	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 3,670,386	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 183,519,309
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)

Dual Temperature Liquid Phase Catalytic Exchange, High Volume-Low Concentration

(calculation basis in bold, assumptions in italics/bold, \$300/L catalyst basis)

Total Capital Investment Cost	\$	269,444,619
Capitalized Total Product Cost	\$	2,306,573,214
Present Value Cost for 20 year life	\$	2,576,017,833
Gallons/minute treated (basis)		250
Total Gallons Treated in 20 years		2,628,000,000
Product Cost/1000 gallons treated	\$	980
Ci/year removed		1538
Total Tritium Concentration (Ci)		30,760
FEI		0.99
Product Cost/Ci averted	\$	84,592

System Cost Breakdown

Dual Temperature Liquid Phase Catalytic Exchange, High Volume-Low Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 210,409,079	\$ 0	\$ 210,409,079
Year 1		\$ 174,946,911	\$ 174,946,911
Year 2		\$ 166,774,939	\$ 166,774,939
Year 3		\$ 158,984,689	\$ 158,984,689
Year 4		\$ 151,558,331	\$ 151,558,331
Year 5		\$ 144,478,866	\$ 144,478,866
Year 6		\$ 137,730,092	\$ 137,730,092
Year 7		\$ 131,296,560	\$ 131,296,560
Year 8		\$ 125,163,547	\$ 125,163,547
Year 9		\$ 119,317,013	\$ 119,317,013
Year 10	\$ 59,035,540	\$ 113,743,578	\$ 172,779,117
Year 11		\$ 108,430,484	\$ 108,430,484
Year 12		\$ 103,365,571	\$ 103,365,571
Year 13		\$ 98,537,246	\$ 98,537,246
Year 14		\$ 93,934,457	\$ 93,934,457
Year 15		\$ 89,546,671	\$ 89,546,671
Year 16		\$ 85,363,842	\$ 85,363,842
Year 17		\$ 81,376,399	\$ 81,376,399
Year 18		\$ 77,575,213	\$ 77,575,213
Year 19		\$ 73,951,586	\$ 73,951,586
Year 20		\$ 70,497,222	\$ 70,497,222

TAB A6: Combined Electrolysis/Catalytic Exchange

Combined
Electrolysis/Catalytic
Exchange

WSRC-RP-96-0075
Rev 0
February 26, 1996

Combined Electrolysis Catalytic Exchange

1. The low flow case pumping rate is 25 gpm.
2. The high flow case pumping rate is 250 gpm.
3. The low flow, high concentration, inlet concentration is 0.125×10^{-11} atom fraction T.
4. The high flow, low concentration, inlet concentration is 0.15×10^{-12} atom fraction T.
5. The exiting enriched stream is 0.81×10^{-9} atom fraction T at 0.3475×10^{-1} kmol/hr for the high volume case, and 0.2913×10^{-1} kmol/hr for the low volume case (this is based on health and safety guidelines).
6. The exiting depleted stream is 0.1×10^{-14} atom fraction T at 188.877 kmol/hr for the high volume case, and 18.862 kmol/hr for the low volume case (this is based on the drinking water standard of 1 ppQd).
7. The enriched water stream will be sequestered on site in stainless steel tanks at a storage cost of \$1/gallon.
8. For CECE, the liquid/gas ratio is 1.0 on a molar basis, and the overall catalyst reduction factor is 24 (Hammerli, et al.).
9. The L/G was determined based on the inlet liquid flows.
10. The column diameters were calculated based on the liquid and gas flow rates using the Sherwood-Lobo correlation (Walas, p. 441). The correlation was used to calculate the flooding diameter, then a diameter giving 80% of flooding was selected for system design.
11. A 5' diameter column was chosen for the high flow case and a 1.6' diameter column was chosen for the low flow case.
12. The actual staged tower volume will be 0.7 times that calculated (Rae).
13. From Branan, the height of an equivalent theoretical plate, HETP, is 1.3'-1.8' for 1" pall rings. Therefore, we chose 1.5' per stage for the HETP in these cases.
14. Each tower was limited to 175' height and 3 diameters were allowed in each tower for vapor disengagement and liquid hold-up space (Branan).
15. The packed tower costs (no internals) and the costs for tower internals were obtained from "Current Costs of Process Equipment," Chemical Engineering, April 5, 1982, and were brought to 1995 dollars using the CE Cost Index of 382 for June 1995.
16. The catalyst cost is \$300/L (provided by AECL) and must be replaced after 10 years.
17. The catalyst volume was scaled by a factor of 24 (Hammerli et al.).
18. The tower height was determined from the required catalyst volume and the calculated tower diameter.
19. Internals and pumps, etc. were estimated at \$100,000 for the low flow case, and \$70,000 for the high flow case.
20. The electrolyzer was sized and its utility costs were based on information provided by V. Van Brunt and from the DuPont work.
21. The direct costs are calculated based on the cost of the purchased equipment, and additional costs are calculated based on the equipment cost including the cost of an equivalent amount of ceramic saddle packing instead of catalyst.
22. Catalyst replacement costs were included at the present value of the future replacement cost.
23. The equivalent packing was estimated at \$100/ft³, which allows for additional expenses associated with activation of catalyst packing.

Combined Electrolysis Catalytic Exchange - Assumptions for Capital Investment Costs

1. The total installed equipment cost is calculated as 45% of the fixed capital investment. This is slightly below the Peters and Timmerhaus estimate.
2. The purchased equipment cost is calculated as 16% of the fixed capital investment.
3. The installation costs are estimated at 50% since the equipment is relatively complicated.
4. The instrumentation costs are estimated at 25% since the equipment will require close monitoring.
5. The piping costs are estimated at 75% since the equipment will require extensive piping.
6. The electrical costs are estimated at 40% since the electrolyzer and controls require wiring.
7. The building costs are estimated at 10% since no extensive buildings are required.
8. The service facilities and yard improvements are estimated at 40% since only connection to existing service facilities is required.
9. The land costs are estimated at 4% since this scenario requires minimal land.
10. The engineering costs are estimated at 30% since this technology has not been used for remediation.
11. The construction costs are estimated at 30% since this technology has not been used for remediation.
12. The contingency costs are estimated at 15% since this technology has not been used for remediation.
13. The working capital costs are estimated at 15%.

1. The direct production costs are 52% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
2. The raw materials are estimated as 0% since the only raw material is groundwater and the cost of pumping this groundwater is included in the utilities.
3. The operating labor is estimated as 20% of the total product cost.
4. The direct supervisory and clerical labor cost is estimated as 15% of the total product cost.
5. The utilities cost is calculated as 0.3% of the total product cost. This is below the Peters and Timmerhaus estimate.
6. The maintenance and repairs cost is estimated as 10% since the equipment is complicated.
7. The operating and supplies cost is estimated as 1% of the fixed capital investment.
8. The laboratory charges are estimated as 1% since this technology requires minimal laboratory work.
9. The patents and royalties cost is estimated as 6% of the total product cost since this technology is patented.
10. The fixed charges are calculated as 7%. This is slightly below the Peters and Timmerhaus estimate.
11. The depreciation is estimated as 10% of the fixed capital investment for machinery and equipment.
12. The local taxes are estimated as 1%. Although the government will not be required to pay taxes, this will be used for donations to support the local community.
13. The insurance is estimated as 0.4% of the fixed capital investment.
14. The rent is estimated as 0% since the government will not be required to rent land or buildings for this project.
15. The plant overhead costs are estimated as 70% of the cost for operating labor, supervision, and maintenance.
16. The administrative costs are estimated as 15% of the costs for operating labor, supervision and maintenance.
17. The distribution and selling costs are estimated as 0% since this is a remediation project.
18. The research and development costs are estimated as 2% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
19. The financing cost is estimated as 0% since the government will borrow no money for this project.

Capital Investment Cost**Catalytic Exchange Coupled with Electrolysis, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	45%		\$ 129,251,815
1. Purchased equipment (15-40% of fixed capital investment)	16%	\$ 44,810,905	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	50%	\$ 22,221,292	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	25%	\$ 11,110,646	
4. Piping, installed (10-80% of purchased-equipment cost)	75%	\$ 33,331,938	
5. Electrical, installed (10-40% of purchased-equipment cost)	40%	\$ 17,777,034	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 4,444,258
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 17,777,034
D. Land (1-2% of fixed-capital investment or 4-8% of <i>purchased-equipment cost</i>)	4%		\$ 1,777,703
Total Direct Cost			\$ 153,250,810
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%	\$ 45,975,243	
B. Construction expense and contractor's fee (6-30% of direct cost)	30%	\$ 45,975,243	
C. Contingency (5-15% of fixed-capital investment)	15%	\$ 43,270,817	
Total Indirect Costs			\$ 135,221,303
III. Fixed-capital Investment			\$ 288,472,113
IV. Working capital (10-20% of total capital investment)	15%		\$ 50,906,843
V. Total capital investment			\$ 339,378,956
VI. Capitalized equipment cost (including 15% installation)			\$ 265,653

Estimation of Total Product Cost**Catalytic Exchange Coupled with Electrolysis, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	49%		\$ 115,910,040
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	20%	\$ 47,311,531	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	15%	\$ 35,483,648	
4. Utilities (10-20% of total product cost)	0.4%	\$ 909,813	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	10%	\$ 28,847,211	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	1.0%	\$ 2,884,721	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 473,115	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	9%		\$ 21,020,430
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 16,981,821	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 2,884,721	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 1,153,888	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 78,149,673
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 21,477,512
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 16,746,359	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 4,731,153	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 236,557,655
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Catalytic Exchange Coupled with Electrolysis, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	339,644,610
Capitalized Total Product Cost	\$	2,973,188,783
Present Value Cost for 20 year life	\$	3,312,833,393
Gallons/minute treated (basis)		25
Total Gallons Treated in 20 years		262,800,000
Product Cost/1000 gallons treated	\$	12,606
Ci/year removed		1282
Total Tritium Concentration (Ci)		25,640
FEI		0.99
Product Cost/Ci averted	\$	130,511

System Cost Breakdown

Catalytic Exchange Coupled with Electrolysis, Low Volume-High Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 339,378,956	\$ 0	\$ 339,378,956
Year 1		\$ 225,507,775	\$ 225,507,775
Year 2		\$ 214,974,046	\$ 214,974,046
Year 3		\$ 204,932,361	\$ 204,932,361
Year 4		\$ 195,359,734	\$ 195,359,734
Year 5		\$ 186,234,255	\$ 186,234,255
Year 6		\$ 177,535,038	\$ 177,535,038
Year 7		\$ 169,242,172	\$ 169,242,172
Year 8		\$ 161,336,675	\$ 161,336,675
Year 9		\$ 153,800,453	\$ 153,800,453
Year 10	\$ 265,653	\$ 168,608,694	\$ 168,874,348
Year 11		\$ 139,767,642	\$ 139,767,642
Year 12		\$ 133,238,934	\$ 133,238,934
Year 13		\$ 127,015,190	\$ 127,015,190
Year 14		\$ 121,082,164	\$ 121,082,164
Year 15		\$ 115,426,276	\$ 115,426,276
Year 16		\$ 110,034,582	\$ 110,034,582
Year 17		\$ 104,894,739	\$ 104,894,739
Year 18		\$ 99,994,985	\$ 99,994,985
Year 19		\$ 95,324,104	\$ 95,324,104
Year 20		\$ 90,871,405	\$ 90,871,405

Capital Investment Cost**Catalytic Exchange Coupled with Electrolysis, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	45%		\$ 1,288,826,267
1. Purchased equipment (15-40% of fixed capital investment)	16%	\$ 446,657,339	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	50%	\$ 221,623,402	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	25%	\$ 110,811,701	
4. Piping, installed (10-80% of purchased-equipment cost)	75%	\$ 332,435,103	
5. Electrical, installed (10-40% of purchased-equipment cost)	40%	\$ 177,298,722	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 44,324,680
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 177,298,722
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 17,729,872
Total Direct Cost			\$ 1,528,179,541
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 458,453,862
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 458,453,862
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 431,485,988
Total Indirect Costs			\$ 1,348,393,712
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 2,876,573,253
IV. Working capital (10-20% of total capital investment)	15%		\$ 507,630,574
V. Total capital investment			\$ 3,384,203,827
VI. Capitalized equipment cost (including 15% installation)			\$ 2,459,865

Estimation of Total Product Cost (per year)**Catalytic Exchange Coupled with Electrolysis, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	52%		\$ 1,512,989,549
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	20%	\$ 576,440,949	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	15%	\$ 432,330,712	
4. Utilities (10-20% of total product cost)	0.3%	\$ 9,098,136	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	10%	\$ 287,657,325	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	1.0%	\$ 28,765,733	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 5,764,409	
8. Patents and royalties (0-6% of total product cost)	6%	\$ 172,932,285	
B. Fixed Charges (10-20% of total product cost)	7%		\$ 209,606,464
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 169,334,438	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 28,765,733	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 11,506,293	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 907,500,290
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 252,108,443
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 194,464,348	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 57,644,095	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 2,882,204,745
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Catalytic Exchange Coupled with Electrolysis, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	3,386,663,692
Capitalized Total Product Cost	\$	36,225,159,574
Present Value Cost for 20 year life	\$	39,611,823,266
Gallons/minute treated (basis)		250
Total Gallons Treated in 20 years		2,628,000,000
Product Cost/1000 gallons treated	\$	15,073
Ci/year removed		1538
Total Tritium Concentration (Ci)		30,760
FEI		0.99
Product Cost/Ci averted	\$	1,300,778

System Cost Breakdown

Catalytic Exchange Coupled with Electrolysis, High Volume-Low Concentration

Year	Capital Costs	Maintenance Costs	Yearly Cost
Year 0	\$ 3,384,203,827	\$ 0	\$ 3,384,203,827
Year 1		\$ 2,747,573,637	\$ 2,747,573,637
Year 2		\$ 2,619,231,303	\$ 2,619,231,303
Year 3		\$ 2,496,883,987	\$ 2,496,883,987
Year 4		\$ 2,380,251,656	\$ 2,380,251,656
Year 5		\$ 2,269,067,356	\$ 2,269,067,356
Year 6		\$ 2,163,076,602	\$ 2,163,076,602
Year 7		\$ 2,062,036,799	\$ 2,062,036,799
Year 8		\$ 1,965,716,682	\$ 1,965,716,682
Year 9		\$ 1,873,895,788	\$ 1,873,895,788
Year 10	\$ 2,459,865	\$ 1,786,363,954	\$ 1,788,823,819
Year 11		\$ 1,702,920,833	\$ 1,702,920,833
Year 12		\$ 1,623,375,437	\$ 1,623,375,437
Year 13		\$ 1,547,545,698	\$ 1,547,545,698
Year 14		\$ 1,475,258,053	\$ 1,475,258,053
Year 15		\$ 1,406,347,048	\$ 1,406,347,048
Year 16		\$ 1,340,654,955	\$ 1,340,654,955
Year 17		\$ 1,278,031,416	\$ 1,278,031,416
Year 18		\$ 1,218,333,094	\$ 1,218,333,094
Year 19		\$ 1,161,423,350	\$ 1,161,423,350
Year 20		\$ 1,107,171,926	\$ 1,107,171,926

CECE (High Flow) Yearly Expenditures

TAB A7:   Ground Freezing

GROUND FREEZING

sealed assemblies to circulate brine and freeze the plume

Ground Freezing

An important class of tritium reduction scenarios involves modifying the fundamental hydrogeology of the groundwater system. Such modification can involve aggressive and/or invasive technologies such as ground freezing to totally immobilize the plume.

Ground freezing and frozen barrier technology was developed for the construction industry. Traditional uses include water control and site stability control during construction activities. Examples of modern commercial applications include construction of large subway, highway or water supply tunnels. As a result of the experience base, reputable firms are available to provide ground freezing services and rough costs are available. Additionally, ground freezing for groundwater contamination containment has recently been examined and the performance and costs have been reported in detail in: Scientific Ecology Group, Final Report: Demonstration of Ground Freezing Technology at SEG Facilities in Oak Ridge, TN., prepared for Martin Marietta Energy Systems, Inc., Hazardous Waste Remedial Actions Program, February 1995 (complete performance information is currently posted on internet at <http://eagle.haz.ornl.gov:80/plumesfa/intech/fsbt>).

Ground freezing requires drilling and installation of refrigerant piping into the target zone. The piping is typically installed on a close spacing (approximately 8 ft on center). Following installation, an environmentally safe refrigerant solution (brine) is circulated to freeze the water in the soil pores. Freeze plants are used to maintain the containment.

For purposes of a scoping calculation, costs are attributed to (or determined by) units of frozen volume (ft^3). Documented costs are approximately $\$10/\text{ft}^3$ for freezing and the first year of operation, and approximately $\$1/\text{ft}^3$ (present \$) per year to maintain the system. Freezing results in a broader area of immobilization than most physical barrier emplacements and an approach based on immobilizing and holding large areas of the plume to allow for decay was selected for examination. This would provide performance far superior to simple downgradient walls or baffles and is suited to the diffuse nature of the freezing process. Conceptually, ground freezing based tritium reduction would consist of creating a network of frozen cells that encapsulate the plume. Based on the referenced field test, the resulting "honeycomb" could encapsulate about 30% more volume than the initial frozen target volume. Thus, for the high concentration scenario, the target frozen volume would be approximately 25 million ft^3 (or 32.4×10^6 total $\text{ft}^3/1.3$). Similarly, for the low concentration scenario, the target frozen volume would be 270 million ft^3 . With the additional assumption that 20 years of maintenance would provide an average delay of two half lives, all of the required scoping numbers may be estimated. Key assumptions were provided in the background / scenario development section and the overall results for ground freezing are summarized below:

plume volume (ft ³ total volume)	initial target frozen volume (ft ³)	0 year cost (\$)	annual operational cost (present \$)	total cost* (present \$)	Tritium in target plume (Ci)	Tritium reduction (%)	indexed costs: cost _w (\$/1000gal) cost _h (\$ / Ci averted)
high conc. scenario 32.4x10 ⁶	25x10 ⁶	250x10 ⁶	25x10 ⁶	564x10 ⁶	9500	75	\$5820 per 1000 gal \$79,000 per Ci
low conc. scenario 350x10 ⁶	270x10 ⁶	2,700x10 ⁶	270x10 ⁶	6,090x10 ⁶	12100	75	\$5820 per 1000 gal \$671,000 per Ci

* assumes 4.9% discount rate over 20 year operating period to account for time value of money

Ground freezing has the advantage of clearly defined and documentable immobilization of the tritium plume. Unfortunately, the process results in relatively extensive collateral environmental damage. The negative environmental impacts include: extremely high energy use (resulting in increased CO₂ production and related large scale power generation problems), large scale construction activities near healthy terrestrial/wetland/stream ecosystems (raw materials use, site clearing and sedimentation), large amounts of equipment transport (fuel use and CO₂ emissions), and related issues. Qualitatively, these collateral impacts offset some of the the tritium reduction benefits. Further, the size and complexity of the project would result in a substantial time period for implementation.

tritium costs freeze

WSRC-RP-96-0075

Rev 0

February 26, 1996

Time value of money		Annual Costs for plume immobilization (ground freezing)		
interest rate =	4.90	low volume	high volume	
		annual o&m =	2.50E+07	2.70E+08 in (current \$)
year	equiv. current \$			
0	1.00	2.50E+08	2.70E+09	= capital/startup
1	0.95	2.38E+07	2.57E+08	
2	0.91	2.27E+07	2.45E+08	
3	0.87	2.17E+07	2.34E+08	
4	0.83	2.06E+07	2.23E+08	
5	0.79	1.97E+07	2.13E+08	
6	0.75	1.88E+07	2.03E+08	
7	0.72	1.79E+07	1.93E+08	
8	0.68	1.71E+07	1.84E+08	
9	0.65	1.63E+07	1.76E+08	
10	0.62	1.55E+07	1.67E+08	
11	0.59	1.48E+07	1.60E+08	
12	0.56	1.41E+07	1.52E+08	
13	0.54	1.34E+07	1.45E+08	
14	0.51	1.28E+07	1.38E+08	
15	0.49	1.22E+07	1.32E+08	
16	0.47	1.16E+07	1.26E+08	
17	0.44	1.11E+07	1.20E+08	
18	0.42	1.06E+07	1.14E+08	
19	0.40	1.01E+07	1.09E+08	
20	0.38	9.60E+06	1.04E+08	
		o&m total	3.14E+08	3.39E+09
		grand total	5.64E+08	6.09E+09
		gallons	9.69E+07	1.05E+09
		\$/1000 gal	5820	5820
		Ci	9500	12100
		FEI	0.75	0.75
		\$/Ci averted	79000	671000

Ground Freezing (Low Flow) Yearly Expenditures

Ground Freezing (High Flow) Yearly Expenditures

TAB A8:   Storage Tanks (Carbon Steel)

Storage Tanks

Storage Tanks, Carbon Steel

1. The low flow case pumping rate is 25 gpm.
2. The high flow case pumping rate is 250 gpm.
3. The tanks used are carbon steel, 11,000,000 gallon tanks, painted, and cathodically protected.
4. Tanks must be fabricated on-site, which will take approximately 1 year per tank.
5. The tanks are API 650, cone roofed, 48' high, 200' diameter and cost \$1,311,000 each. 10% was added to each tank for breather vents and pumps.
6. The cost was determined from Cost Estimating for Major Process Equipment, Chemical Engineering, October 10, 1977, figure 10, and scaled to 1995 costs using the current CE Cost Index value (382 for June 1995).
7. The low flow case will require 24 tanks (1.2 tanks per year) and the high flow case will require 240 tanks (12 tanks per year).
8. For the low flow case, three tanks are built initially (including one maintenance tank) with one additional tank begun every 10 months. The present value of the tanks installed after year 0 are included in the spreadsheet..
9. For the high flow case, fifteen tanks are built initially (including three maintenance tanks) with one additional tank begun every month. The present value of the tanks installed after year 0 are included in the spreadsheet..
10. Energy requirements for pumping 25 and 250 gpm are 0.8 KW and 8 KW respectively. At \$0.08 per KWh, the costs are \$561 and \$5,607 per year respectively.
11. Additional utility requirements are assumed to be minimal and estimated at \$10/day (for both cases), making the total utility requirements \$4,211 per year for the low flow case, and \$9,257 per year for the high flow case.
12. Maintenance costs for the carbon steel tanks will be greater than those for the stainless steel, due to the routine maintenance required on the tanks. Therefore, the maintenance for the carbon steel tanks is calculated as 5% of the fixed capital investment, rather than the 2% used for the stainless steel tanks.
13. Three (high flow) and one (low flow) additional tanks were included in this case for maintenance purposes.
14. The low flow case will require 49.6 acres for 100' tank to tank spacing and 50' tank to tank farm wall spacing.
15. The high flow case will require 496 acres for 100' tank to tank spacing and 50' tank to tank farm wall spacing.

Storage Tanks, Carbon Steel - Assumptions for Capital Investment Costs

1. The total installed equipment cost is calculated as 53% of the fixed capital investment cost.
2. The purchased equipment cost is calculated as 22% of the fixed capital investment.
3. The installation costs are estimated at 40% since the equipment is not particularly complicated.
4. The instrumentation costs are estimated at 18%.
5. The piping costs are estimated at 60% since the equipment will require extensive piping.
6. The electrical costs are estimated at 25% since the tanks will not require extensive wiring.
7. The building costs are estimated at 10% since no extensive buildings are required.
8. The service facilities and yard improvements are estimated at 40% since only connection to existing service facilities is required.
9. The land costs are estimated at 8% since this scenario requires extensive land.
10. The engineering costs are estimated at 10% since this technology is well developed.
11. The construction costs are estimated at 20% since this technology is well developed.
12. The contingency costs are estimated at 15% since this technology is well developed.
13. The working capital costs are estimated at 15%.

Storage Tanks, Carbon Steel - Assumptions for Production Costs

1. The direct production costs are 30% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
2. The raw materials are estimated as 0% since the only raw material is groundwater and the cost of pumping this groundwater is included in the utilities.
3. The operating labor is estimated as 10% of the total product cost.
4. The direct supervisory and clerical labor cost is estimated as 10% of the total product cost.
5. The utilities cost is calculated as 0.037% of the total product cost. This is below the Peters and Timmerhaus estimate because tanks require little energy input.
6. The maintenance and repairs cost is estimated as 2% since the equipment is not complicated.
7. The operating and supplies cost is estimated as 0.5% of the fixed capital investment.
8. The laboratory charges are estimated as 1% since this technology requires minimal laboratory work.
9. The patents and royalties cost is estimated as 0% of the total product cost since this technology is not patented.
10. The fixed charges are calculated as 46%. This is slightly below the Peters and Timmerhaus estimate.
11. The depreciation is estimated as 10% of the fixed capital investment for machinery and equipment.
12. The local taxes are estimated as 1%. Although the government will not be required to pay taxes, this will be used for donations to support the local community.
13. The insurance is estimated as 0.4% of the fixed capital investment.
14. The rent is estimated as 0% since the government will not be required to rent land or buildings for this project.
15. The plant overhead costs are estimated as 70% of the cost for operating labor, supervision, and maintenance.
16. The administrative costs are estimated as 15% of the costs for operating labor, supervision and maintenance.
17. The distribution and selling costs are estimated as 0% since this is a remediation project.
18. The research and development costs are estimated as 0% of the total product cost since tank storage is a mature technology. This is slightly below the Peters and Timmerhaus estimate.
19. The financing cost is estimated as 0% since the government will borrow no money for this project.

Capital Investment Cost (Year 0)**Tanks, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	53%		\$ 10,512,909
1. Purchased equipment (15-40% of fixed capital investment)	58%	\$ 4,326,300	
3. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 1,730,520	
4. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 778,734	
5. Piping, installed (10-80% of purchased-equipment cost)	60%	\$ 2,595,780	
6. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 1,081,575	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 432,630
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 1,730,520
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 173,052
Total Direct Cost			\$ 12,849,111
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	10%		\$ 1,284,911
B. Construction expense and contractor's fee (6-30% of direct cost)	20%		\$ 2,569,822
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 2,947,737
Total Indirect Costs			\$ 6,802,471
III. Fixed-capital Investment			\$ 19,651,582
IV. Working capital (10-20% of total capital investment)	15%		\$ 3,467,926
V. Total capital investment			\$ 23,119,508

Capital Investment Cost (Year n)**Tanks, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	53%		\$ 2,919,084
1. Purchased equipment (15-40% of fixed capital investment)	58%	\$ 1,201,269	
3. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 480,508	
4. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 216,228	
5. Piping, installed (10-80% of purchased-equipment cost)	60%	\$ 720,762	
6. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 300,317	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 120,127
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 480,508
D. Land (1-2% of fixed-capital investment or 4-8% of <i>purchased-equipment cost</i>)	4%		\$ 48,051
Total Direct Cost			\$ 3,567,770
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	10%		\$ 356,777
B. Construction expense and contractor's fee (6-30% of direct cost)	20%		\$ 713,554
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 818,488
Total Indirect Costs			\$ 1,888,819
III. Fixed-capital Investment			\$ 5,456,589
IV. Working capital (10-20% of total capital investment)	15%		\$ 962,927
V. Total capital investment			\$ 6,419,517

Estimation of Total Product Cost**Tanks, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	37%		\$ 2,414,562
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 661,450	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 661,450	
4. Utilities (10-20% of total product cost)	0.064%	\$ 4,211	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	5%	\$ 982,579	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 98,258	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 6,614	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	34%		\$ 2,240,280
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 1,965,158	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 196,516	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 78,606	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 1,613,835
II. General expenses			
= administrative costs+distribution and selling costs+ research and development costs			\$ 345,822
A. Administrative costs (about 15% of costs for operating labor, <i>supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 345,822	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	0%	\$ 0	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 6,614,500
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Tanks, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	101,337,582
Capitalized Total Product Cost	\$	547,975,294
Present Value Cost for 20 year life	\$	649,312,876
Gallons/minute treated (basis)		25
Total Gallons Treated in 20 years		263,000,000
Product Cost/1000 gallons treated	\$	2,471
Ci/year removed		1282
Total Tritium Concentration (Ci)		25,640
FEI		0.99
Product Cost/Ci averted	\$	25,580

System Cost Breakdown

Storage Tanks (carbon steel), Low Volume-High Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 23,119,508	\$ 0	\$ 23,119,508
Year 1	\$ 6,119,654	\$ 6,305,529	\$ 12,425,183
Year 2	\$ 5,833,798	\$ 12,021,981	\$ 17,855,779
Year 3	\$ 5,561,294	\$ 17,190,631	\$ 22,751,925
Year 4	\$ 5,301,520	\$ 21,850,182	\$ 27,151,702
Year 5	\$ 5,053,880	\$ 26,036,918	\$ 31,090,798
Year 6	\$ 4,817,807	\$ 29,784,845	\$ 34,602,652
Year 7	\$ 4,592,762	\$ 33,125,820	\$ 37,718,582
Year 8	\$ 4,378,228	\$ 36,089,686	\$ 40,467,914
Year 9	\$ 4,173,716	\$ 38,704,382	\$ 42,878,098
Year 10	\$ 3,978,757	\$ 40,996,062	\$ 44,974,819
Year 11	\$ 3,792,905	\$ 42,989,197	\$ 46,782,102
Year 12	\$ 3,615,734	\$ 44,706,679	\$ 48,322,413
Year 13	\$ 3,446,839	\$ 46,169,910	\$ 49,616,749
Year 14	\$ 3,285,833	\$ 47,398,895	\$ 50,684,728
Year 15	\$ 3,132,348	\$ 48,412,327	\$ 51,544,675
Year 16	\$ 2,986,032	\$ 49,227,660	\$ 52,213,692
Year 17	\$ 2,846,551	\$ 49,861,190	\$ 52,707,742
Year 18	\$ 2,713,586	\$ 50,328,123	\$ 53,041,709
Year 19	\$ 2,586,831	\$ 50,642,641	\$ 53,229,472
Year 20		\$ 50,817,963	\$ 50,817,963

Capital Investment Cost (Year 0)**Tanks, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	53%		\$ 52,564,545
1. Purchased equipment (15-40% of fixed capital investment)	22%	\$ 21,631,500	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 8,652,600	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 3,893,670	
4. Piping, installed (10-80% of purchased-equipment cost)	60%	\$ 12,978,900	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 5,407,875	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 2,163,150
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 8,652,600
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	8%		\$ 1,730,520
Total Direct Cost			\$ 65,110,815
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	10%		\$ 6,511,082
B. Construction expense and contractor's fee (6-30% of direct cost)	20%		\$ 13,022,163
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 14,937,187
Total Indirect Costs			\$ 34,470,431
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 99,581,246
IV. Working capital (10-20% of total capital investment)	15%		\$ 17,573,161
V. Total capital investment			\$ 117,154,408

Capital Investment Cost (Year n)**Tanks, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	53%		\$ 42,051,636
1. Purchased equipment (15-40% of fixed capital investment)	22%	\$ 17,305,200	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 6,922,080	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 3,114,936	
4. Piping, installed (10-80% of purchased-equipment cost)	60%	\$ 10,383,120	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 4,326,300	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 1,730,520
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 6,922,080
D. Land (1-2% of fixed-capital investment or 4-8% of <i>purchased-equipment cost</i>)	8%		\$ 1,384,416
Total Direct Cost			\$ 52,088,652
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	10%		\$ 5,208,865
B. Construction expense and contractor's fee (6-30% of direct cost)	20%		\$ 10,417,730
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 11,949,750
Total Indirect Costs			\$ 27,576,345
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 79,664,997
IV. Working capital (10-20% of total capital investment)	15%		\$ 14,058,529
V. Total capital investment			\$ 93,723,526

Estimation of Total Product Cost (per year)**Tanks, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	36%		\$ 12,219,467
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 3,349,871	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 3,349,871	
4. Utilities (10-20% of total product cost)	0.028%	\$ 9,257	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	5%	\$ 4,979,062	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 497,906	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 33,499	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	34%		\$ 11,352,262
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 9,958,125	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 995,812	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 398,325	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 8,175,163
II. General expenses			
= administrative costs+distribution and selling costs+ research and development costs			\$ 1,751,821
A. Administrative costs (about 15% of costs for operating labor, <i>supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 1,751,821	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	0%	\$ 0	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 33,498,713
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Tanks, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$ 1,259,121,035
Capitalized Total Product Cost	\$ 2,774,620,581
Present Value Cost for 20 year life	\$ 4,033,741,616
Gallons/minute treated (basis)	250
Total Gallons Treated in 20 years	2,630,000,000
Product Cost/1000 gallons treated	\$ 1,535
Ci/year removed	1538
Total Tritium Concentration (Ci)	30,760
FEI	0.99
Product Cost/Ci averted	\$ 132,461

System Cost Breakdown

Storage Tanks (carbon steel), High Volume-Low Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 117,154,408	\$ 0	\$ 117,154,408
Year 1	\$ 89,345,592	\$ 31,933,949	\$ 121,279,542
Year 2	\$ 85,172,156	\$ 60,884,556	\$ 146,056,712
Year 3	\$ 81,193,667	\$ 87,060,852	\$ 168,254,519
Year 4	\$ 77,401,017	\$ 110,658,852	\$ 188,059,869
Year 5	\$ 73,785,526	\$ 131,862,312	\$ 205,647,838
Year 6	\$ 70,338,919	\$ 150,843,445	\$ 221,182,364
Year 7	\$ 67,053,307	\$ 167,763,603	\$ 234,816,910
Year 8	\$ 63,921,170	\$ 182,773,910	\$ 246,695,080
Year 9	\$ 60,935,338	\$ 196,015,871	\$ 256,951,210
Year 10	\$ 58,088,978	\$ 207,621,938	\$ 265,710,916
Year 11	\$ 55,375,575	\$ 217,716,045	\$ 273,091,620
Year 12	\$ 52,788,918	\$ 226,414,121	\$ 279,203,039
Year 13	\$ 50,323,087	\$ 233,824,561	\$ 284,147,648
Year 14	\$ 47,972,437	\$ 240,048,680	\$ 288,021,118
Year 15	\$ 45,731,589	\$ 245,181,139	\$ 290,912,728
Year 16	\$ 43,595,414	\$ 249,310,341	\$ 292,905,756
Year 17	\$ 41,559,022	\$ 252,518,816	\$ 294,077,838
Year 18	\$ 39,617,752	\$ 254,883,569	\$ 294,501,321
Year 19	\$ 37,767,161	\$ 256,476,423	\$ 294,243,584
Year 20		\$ 257,364,329	\$ 257,364,329

TAB A9:   Storage Tanks (Stainless Steel)

Storage Tanks

WSRC-RP-96-0075

Rev 0

February 26, 1996

Storage Tanks, Stainless Steel

1. The low flow case pumping rate is 25 gpm.
2. The high flow case pumping rate is 250 gpm.
3. The tanks used are stainless steel, 11,000,000 gallon tanks.
4. Tanks must be fabricated on-site, which will take approximately 1 year per tank.
5. The tanks are API 650, cone roofed, 48' high, 200' diameter and cost \$11,000,000 each. The cost of breather vents and pumps is included in this price.
6. The cost was scaled from information on available 500,000 gallon tanks (approximately \$1/gallon, with all vents, access panels, flanges, and pumps) obtained from Jim Mohan, Director of Sales and Marketing, Stainless Fabrication, Inc., P.O. Box 11305, Springfield, MO 65808, (417) 865-5696.
7. The low flow case will require 24 tanks (1.2 tanks per year) and the high flow case will require 240 tanks (12 tanks per year).
8. For the low flow case, two tanks are built initially with one additional tank begun every 10 months. The present value of the tanks installed after year 0 are included in the spreadsheet.
9. For the high flow case, twelve tanks are built initially with one additional tank begun every month. The present value of the tanks installed after year 0 are included in the spreadsheet.
10. Energy requirements for pumping 25 and 250 gpm are 0.8 KW and 8 KW respectively. At \$0.08 per KWh, the costs are \$561 and \$5,607 per year respectively.
11. Additional utility requirements are assumed to be minimal and estimated at \$10/day, making the total utility requirements \$4,211 per year for the low flow case, and \$9,257 per year for the high flow case.
12. The low flow case will require 49.6 acres for 100' tank to tank spacing and 50' tank to tank farm wall spacing.
13. The high flow case will require 496 acres for 100' tank to tank spacing and 50' tank to tank farm wall spacing.

Storage Tanks, Stainless Steel - Assumptions for Capital Investment Costs

1. The total installed equipment cost is calculated as 61% of the fixed capital investment cost. This is slightly above the Peters and Timmerhaus estimate.
2. The purchased equipment cost is calculated as 50% of the fixed capital investment. This is slightly above the Peters and Timmerhaus estimate because the stainless tanks are more expensive due to the specialty material.
3. The installation costs are estimated at 40% since the equipment is not particularly complicated.
4. The instrumentation costs are estimated at 18%.
5. The piping costs are estimated at 60% since the equipment will require extensive piping.
6. The electrical costs are estimated at 25% since the tanks will not require extensive wiring.
7. The building costs are estimated at 10% since no extensive buildings are required.
8. The service facilities and yard improvements are estimated at 40% since only connection to existing service facilities is required.
9. The land costs are estimated at 8% since this scenario requires extensive land.
10. The engineering costs are estimated at 10% since this technology is well developed.
11. The construction costs are estimated at 20% since this technology is well developed.
12. The contingency costs are estimated at 15%.
13. The working capital costs are estimated at 15%.
14. Because the same number of tanks are constructed each year for the high volume case, the quantity of purchased equipment will be the same for all years. Thus, capitalized investment costs for years 0 through 19 can be calculated using one spreadsheet, identified as Capitalized Investment Cost (Year n).

Storage Tanks, Stainless Steel - Assumptions for Production Costs

1. The direct production costs are 30% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
2. The raw materials are estimated as 0% since the only raw material is groundwater and the cost of pumping this groundwater is included in the utilities.
3. The operating labor is estimated as 10% of the total product cost.
4. The direct supervisory and clerical labor cost is estimated as 10% of the total product cost.
5. The utilities cost is calculated as 0.014% of the total product cost. This is below the Peters and Timmerhaus estimate because tanks require little energy input.
6. The maintenance and repairs cost is estimated as 2% since the equipment is not complicated.
7. The operating and supplies cost is estimated as 0.5% of the fixed capital investment.
8. The laboratory charges are estimated as 1% since this technology requires minimal laboratory work.
9. The patents and royalties cost is estimated as 0% of the total product cost since this technology is not patented.
10. The fixed charges are calculated as 46%. This is slightly above the Peters and Timmerhaus estimate.
11. The depreciation is estimated as 10% of the fixed capital investment for machinery and equipment.
12. The local taxes are estimated as 1%. Although the government will not be required to pay taxes, this will be used for donations to support the local community.
13. The insurance is estimated as 0.4% of the fixed capital investment.
14. The rent is estimated as 0% since the government will not be required to rent land or buildings for this project.
15. The plant overhead costs are estimated as 70% of the cost for operating labor, supervision, and maintenance.
16. The administrative costs are estimated as 15% of the costs for operating labor, supervision and maintenance.
17. The distribution and selling costs are estimated as 0% since this is a remediation project.
18. The research and development costs are estimated as 0% of the total product cost. This is below the Peters and Timmerhaus estimate because tank storage is a mature technology.
19. The financing cost is estimated as 0% since the government will borrow no money for this project.

Capital Investment Cost (Year 0)**Tanks, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	61%		\$ 26,949,287
1. Purchased equipment (15-40% of fixed capital investment)	58%	\$ 22,000,000	
3. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 1,384,416	
4. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 622,987	
5. Piping, installed (10-80% of purchased-equipment cost)	60%	\$ 2,076,624	
6. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 865,260	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 346,104
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 1,384,416
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 138,442
Total Direct Cost			\$ 28,818,249
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	10%		\$ 2,881,825
B. Construction expense and contractor's fee (6-30% of direct cost)	20%		\$ 5,763,650
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 6,611,245
Total Indirect Costs			\$ 15,256,720
III. Fixed-capital Investment			\$ 44,074,969
IV. Working capital (10-20% of total capital investment)	15%		\$ 7,777,936
V. Total capital investment			\$ 51,852,904

Capital Investment Cost (Year n)**Tanks, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	61%		\$ 11,224,378
1. Purchased equipment (15-40% of fixed capital investment)	58%	\$ 9,163,000	
3. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 576,609	
4. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 259,474	
5. Piping, installed (10-80% of purchased-equipment cost)	60%	\$ 864,914	
6. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 360,381	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 144,152
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 576,609
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 57,661
Total Direct Cost			\$ 12,002,801
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	10%		\$ 1,200,280
B. Construction expense and contractor's fee (6-30% of direct cost)	20%		\$ 2,400,560
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 2,753,584
Total Indirect Costs			\$ 6,354,424
III. Fixed-capital Investment			\$ 18,357,224
IV. Working capital (10-20% of total capital investment)	15%		\$ 3,239,510
V. Total capital investment			\$ 21,596,735

Estimation of Total Product Cost**Tanks, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	30%		\$ 3,304,593
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 1,093,785	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 1,093,785	
4. Utilities (10-20% of total product cost)	0.038%	\$ 4,211	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	2%	\$ 881,499	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 220,375	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 10,938	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	46%		\$ 5,024,546
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings)	10%	\$ 4,407,497	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 440,750	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 176,300	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 2,148,348
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 460,360
A. Administrative costs (about 15% of costs for operating labor, <i>supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 460,360	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	0%	\$ 0	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 10,937,847
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Tanks, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	323,292,732
Capitalized Total Product Cost	\$	1,228,075,971
Present Value Cost for 20 year life	\$	1,551,368,704
Gallons/minute treated (basis)		25
Total Gallons Treated in 20 years		263,000,000
Product Cost/1000 gallons treated	\$	5,903
Ci/year removed		1282
Total Tritium Concentration (Ci)		25,640
FEI		0.99
Product Cost/Ci averted	\$	61,117

System Cost Breakdown

Storage Tanks (stainless steel), Low Volume-High Concentration

WSRC-RP-96-0075

Rev 0

February 26, 1996

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 51,852,904	\$ 0	\$ 51,852,904
Year 1	\$ 20,587,926	\$ 10,426,928	\$ 31,014,854
Year 2	\$ 19,626,241	\$ 19,879,748	\$ 39,505,989
Year 3	\$ 18,709,476	\$ 28,426,713	\$ 47,136,189
Year 4	\$ 17,835,535	\$ 36,131,825	\$ 53,967,360
Year 5	\$ 17,002,417	\$ 43,055,082	\$ 60,057,499
Year 6	\$ 16,208,214	\$ 49,252,715	\$ 65,460,929
Year 7	\$ 15,451,110	\$ 54,777,408	\$ 70,228,518
Year 8	\$ 14,729,371	\$ 59,678,506	\$ 74,407,876
Year 9	\$ 14,041,345	\$ 64,002,210	\$ 78,043,555
Year 10	\$ 13,385,457	\$ 67,791,770	\$ 81,177,228
Year 11	\$ 12,760,207	\$ 71,087,652	\$ 83,847,860
Year 12	\$ 12,164,163	\$ 73,927,709	\$ 86,091,872
Year 13	\$ 11,595,961	\$ 76,347,332	\$ 87,943,293
Year 14	\$ 11,054,300	\$ 78,379,603	\$ 89,433,903
Year 15	\$ 10,537,941	\$ 80,055,430	\$ 90,593,371
Year 16	\$ 10,045,702	\$ 81,403,678	\$ 91,449,380
Year 17	\$ 9,576,455	\$ 82,451,295	\$ 92,027,750
Year 18	\$ 9,129,128	\$ 83,223,423	\$ 92,352,551
Year 19	\$ 8,702,696	\$ 83,743,514	\$ 92,446,210
Year 20	\$ 8,296,183	\$ 84,033,430	\$ 92,329,613

Stainless Steel Storage Tanks (Low Flow) Yearly Expenditure

Capital Investment Cost (Year n)**Tanks, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	61%		\$ 161,695,723
1. Purchased equipment (15-40% of fixed capital investment)	50%	\$ 132,000,000	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	40%	\$ 8,306,496	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	18%	\$ 3,737,923	
4. Piping, installed (10-80% of purchased-equipment cost)	60%	\$ 12,459,744	
5. Electrical, installed (10-40% of purchased-equipment cost)	25%	\$ 5,191,560	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 2,076,624
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 8,306,496
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	8%		\$ 1,661,299
Total Direct Cost			\$ 173,740,142
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	10%		\$ 17,374,014
B. Construction expense and contractor's fee (6-30% of direct cost)	20%		\$ 34,748,028
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 39,858,033
Total Indirect Costs	35%		\$ 91,980,075
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 265,720,218
IV. Working capital (10-20% of total capital investment)	15%		\$ 46,891,803
V. Total capital investment			\$ 312,612,021

Estimation of Total Product Cost (per year)

Tanks, High Volume-Low Concentration

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	30%		\$ 19,901,521
1. Raw materials (10-50% of total product cost)	0%	\$ 0	
2. Operating labor (10-20% of total product cost)	10%	\$ 6,591,671	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 6,591,671	
4. Utilities (10-20% of total product cost)	0.014%	\$ 9,257	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	2%	\$ 5,314,404	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	0.5%	\$ 1,328,601	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 65,917	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	46%		\$ 30,292,105
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 26,572,022	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 2,657,202	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 1,062,881	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 12,948,423
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 2,774,662
A. Administrative costs (about 15% of costs for operating labor, <i>supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 2,774,662	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	0%	\$ 0	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 65,916,711
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Tanks, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$ 4,121,607,586
Capitalized Total Product Cost	\$ 7,400,974,427
Present Value Cost for 20 year life	\$ 11,522,582,012
Gallons/minute treated (basis)	250
Total Gallons Treated in 20 years	2,630,000,000
Product Cost/1000 gallons treated	\$ 4,385
Ci/year removed	1538
Total Tritium Concentration (Ci)	30,760
FEI	0.99
Product Cost/Ci averted	\$ 378,380

System Cost Breakdown

Storage Tanks (stainless steel), High Volume-Low Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 312,612,021	\$ 0	\$ 312,612,021
Year 1	\$ 298,009,553	\$ 62,837,665	\$ 360,847,218
Year 2	\$ 284,089,183	\$ 119,804,890	\$ 403,894,073
Year 3	\$ 270,819,049	\$ 171,312,999	\$ 442,132,048
Year 4	\$ 258,168,779	\$ 217,747,695	\$ 475,916,474
Year 5	\$ 246,109,418	\$ 259,470,561	\$ 505,579,979
Year 6	\$ 234,613,363	\$ 296,820,470	\$ 531,433,833
Year 7	\$ 223,654,302	\$ 330,114,917	\$ 553,769,219
Year 8	\$ 213,207,152	\$ 359,651,278	\$ 572,858,430
Year 9	\$ 203,248,000	\$ 385,707,996	\$ 588,955,996
Year 10	\$ 193,754,051	\$ 408,545,701	\$ 602,299,752
Year 11	\$ 184,703,576	\$ 428,408,266	\$ 613,111,842
Year 12	\$ 176,075,859	\$ 445,523,806	\$ 621,599,665
Year 13	\$ 167,851,152	\$ 460,105,614	\$ 627,956,767
Year 14	\$ 160,010,632	\$ 472,353,054	\$ 632,363,686
Year 15	\$ 152,536,350	\$ 482,452,391	\$ 634,988,741
Year 16	\$ 145,411,201	\$ 490,577,582	\$ 635,988,784
Year 17	\$ 138,618,877	\$ 496,891,021	\$ 635,509,898
Year 18	\$ 132,143,829	\$ 501,544,237	\$ 633,688,066
Year 19	\$ 125,971,238	\$ 504,678,557	\$ 630,649,795
Year 20		\$ 506,425,725	\$ 506,425,725

TAB A10:   Infiltration Reduction

Infiltration Reduction

Infiltration Reduction (using Surface Enhancements)

Description and Assumptions

An important class of tritium reduction scenarios involves modifying the fundamental hydrogeology of the groundwater system. A notable alternative involves reducing recharge using a combination of increased evapotranspiration and maximized runoff. Specific "technologies" proposed in the action to achieve tritium reduction goals include: adding appropriate plant species, fertilization, pumping and/or drip irrigation, surface recontouring, debris/litter removal, and strategic smoothing. This combination of actions was termed "surface enhancements." Because of the collateral environmental damage associated with implementation, traditional infiltration reduction (i.e., capping) is not considered appropriate on the scale needed.

Only one scenario was evaluated, roughly equivalent to the low flow - high concentration scenario for infiltration reduction. The size of the large dilute plume is not amenable to infiltration reduction.

The amount of water entering and exiting the ground is determined by several factors - bounding the magnitude of these various "flows" is the appropriate first step in evaluating in ground containment or stabilization options. The water balance calculations can be further refined to address specific needs. The various input and loss terms of the water balance are shown in the process description figure. SRS rainfall averages approximately 45"/yr. (Hubbard, 1986). Studies of both typical forested areas and grass/shrub areas in the region and on SRS in the vicinity of the F and H Basins indicate that approximately 1/3 (33%) of the rainfall infiltrates and the remainder is lost by runoff, evaporation and transpiration. These studies apportion the losses approximately as follows: runoff (5% of rainfall), evaporation (31%), and transpiration (31%). If the assumption is made, based on the location of the groundwater divide, that the rough size of the available area overlying the plume is approximately 1500 feet by 1000 feet, then the water mass balance is as follows:

input -
    rainfall = 43 million gallons/yr.
outputs -
    runoff = 3 million gallons/yr.
    transpiration = 13 million gallons/yr.
    evaporation = 13 million gallons/yr.
    net of above input and outputs is the
        infiltration/groundwater flow to wetlands = 14 million gallons/yr.

Under natural gradient, flow will be generally toward the downgradient wetland/stream. This water balance is consistent with field measurements, with the previous transit time measurements, and with numerical groundwater modeling performed at the site. It is clear from the figures that downgradient barriers (vertical cut off walls, etc.) would only temporarily reduce tritium releases from the site. Following installation, the head would increase behind the barrier, increasing the water flow velocity until the water release to the stream once again balanced infiltration.

Based upon the water balance figures, reduction in infiltration is the only directly controllable means to improve the effectiveness of such a remediation (each gpm of infiltration reduction directly translates to flux reduction to surface water). A comprehensive set of surface enhancements represent the most environmentally protective implementation of infiltration reduction. As discussed below, such an approach includes a

forest management plan, surface smoothing to maximize runoff, and fertilizing and planting to maximize evapotranspiration. For example, overseeding appropriate areas with cold season grasses through the winter would continue transpiration during the off season. This option represents a "green remediation methods" (a sustainable evapotranspiration based system).

The purpose of performing surface enhancements is to reduce infiltration and the resulting tritium release. Surface enhancements would result in a primary benefit of reducing and leveling the annual tritium releases in proportion of the infiltration reduction. The ultimate population dose (i.e., the basis of the FEI) is not proportional to the infiltration reduction, but rather to the increased decay during the longer travel time. Surface enhancements to reduce infiltration consist of two basic elements, 1) surface smoothing to minimize surface retention (increase runoff), and 2) vegetative enhancements to maximize evapotranspiration. Tests and studies designed to support these activities and quantify their effects would be needed. Surface enhancements would be designed to minimally affect the ecology and natural environment downgradient of the basins and in the streams and wetlands.

Increased Runoff

Normal forest conditions include topographic undulations, forest litter, and uncontrolled vegetative growth. By retaining moisture and reducing runoff, these natural systems promote natural infiltration and recharge to the aquifer system. Reduction in infiltration recharge should be achievable, therefore, by smoothing and leveling the ground surface, removing forest litter, and replacing existing brush with vegetation more conducive to runoff.

Soil and vegetation conditions vary within the area of the proposed extraction-injection system. Surface enhancements will be designed to account for the various combinations of slope, soils, and existing vegetation. For example, existing soil conditions will be used to determine replanting strategies. Areas with a less permeable silt-sand composite soil will support grasses, while more sandy areas can support stands of pine. The SCS-Rational Method (Soil Conservation Service, 1986) to compute runoff was used to compare expected runoff values for existing conditions versus enhanced conditions. Table *1 provides the potential increases in runoff that these simple, environmentally gentle surface enhancements may achieve. Preliminary estimates suggest that surface runoff can be increased to 10-20% of rainfall.

Increased runoff also equates to increased entry velocities and volumes to the Fourmile Branch wetlands. The surface enhancements will include erosion control considerations. Using the existing drainage pathways, natural/sustainable energy dissipation and sediment control structures will be constructed adjacent to the wetlands.

Table 1. Runoff conditions for various vegetative conditions

<u>Existing Conditions</u>		<u>Enhanced Conditions</u>	
<u>Vegetation Conditions</u>	<u>Runoff</u>	<u>Vegetation Conditions</u>	<u>Runoff</u>
Brush	6%	grasses	21%
woods with surface debris	2%	woods with clean forest floor	16%

(Note that numbers listed are percent of rainfall.)

Increased Evapotranspiration

Certain vegetation types have inherently higher evapotranspiration (Et) values than other types. By changing the type and amount of vegetation, a drastic reduction in recharge can be achieved. Recharge reduction through vegetative changes is a long term proposition, but can be effectively achieved through long term vegetative management.

Much documentation has been written, particularly in the timber management and agriculture disciplines, exploring Et values for vegetation. If high Et is desired on a year-round basis, then evergreen vegetation should be applied. The loblolly pine grows abundantly in the SRS area and will provide reasonably high Et values year round. Data derived during a recent test by Savannah River Technology Center (SRTC) clearly illustrate the differences between grasses and loblolly pine. Lysimeters were constructed in the burial grounds, with different vegetative types planted on the surface. Rainfall was measured over time and compared with runoff values and infiltration volumes. Using a mass balance approach, the actual Et values were then determined. The results showed that Et for grasses accounted for 62% of the total rainfall, while loblolly pines accounted for 83%, demonstrating an observed increase of 21% for pine over grasses (Hubbard, 1985). Additional testing by the U.S. Department of Agriculture (Anderson et al., 1976) indicates that for evergreen forests in the southeast, evapotranspiration constitutes between 60 and 80% of the total rainfall.

The introductory figure in this section illustrated the triad between the different mass balance elements. Though some negative, synergistic effects exist, a conservative estimate of the total infiltration following surface enhancements should be approximately 21% of rainfall or less (versus 33% under natural conditions).

Supporting Activities

Supporting activities for surface enhancements were evaluated and described in detail for nearby facilities (DOE, 1993).

A series of preliminary studies would be needed to identify and quantify the existing topographic, soil, and vegetative conditions. This baseline data set would be managed using a Geographic Information System (GIS) and utilized in the design process. The soil survey will identify, on a small finite grid, soil types and stratigraphy. Infiltration testing will be performed on representative soil types to calibrate empirical characteristics.

Baseline vegetative studies will be conducted in both the upland and wetland areas. The upland baseline will be used for design and quantification of improvements while the

wetland study will be used to evaluate any impacts. The baseline vegetation study will identify species types, community extent, density, and basal area. The data acquired would supply the necessary input for numerical Et estimates for each community.

Using the GIS system to support design, areas of existing vegetation would be evaluated. Existing vegetation communities will be optimized to improve Et and a long term vegetation management plan developed to bring vegetation to the optimum level. This management plan would include interim measures to stabilize soil and to enhance Et while the primary vegetation reaches maturity. Existing stands of timber would be managed in such a manner as to maintain an optimal community throughout the task. The duration of this management plan will be approximately 20 years.

Construction actions are straightforward and can be implemented on a fast track approach, consisting primarily of smoothing and leveling the existing grade, planting and fertilizing. Specific problem areas would be dealt with in the design as needed. The problem areas include areas requiring erosion control and wetland protecting structures. While construction could be implemented rapidly, the vegetation management plan would implement planting of different species during their optimal planting season. Interim grasses would be seeded during the summer months, with seeding of more hardy species during the optimal planting periods.

The nearby weather station would be used to monitor atmospheric conditions and rainfall amounts. Additional instrumentation would be installed to allow determination of the different water balance elements. Existing flow stations in Fourmile Branch would be utilized and upgraded as necessary. Monitoring would include both determination of actual runoff values and impacts to the ecosystem and the wetlands.

Specific Assumptions and Scenario Description

Based on the evaluation and project description above, the surface enhancements option can be summarized as follows. The action will result in a reduction of infiltration (to approximately 21% of rainfall versus the baseline of 33%). This increases the transit time of the plume (originally 15 years) by approximately 12% (to 16.8 years) results in increased tritium decay of about 10% (equivalent to an FEI of 0.1). Because of the nature of the action, only the low volume scenario (implementation over an area of 1500 ft by 1000 feet). Based on initial estimates for nearby facilities, rough costs for year 0 would be about \$10 million, with annual costs for monitoring in the range of \$1 million. These values are summarized on the attached pages:

Surface enhancements have the advantages of release reduction/leveling, and tritium decay using natural and sustainable processes. Further, the action is simple and could be implemented rapidly without delay for complex planning. Little energy is used and local ecosystems are considered and protected more explicitly than is possible with large construction projects. Finally the costs are relatively low, both in terms of volume treated and curies averted. Unfortunately, the process results in relatively small reductions in tritium release. A reduction of only a few hundred Curies per year may not meet the performance needs for the site. Finally, the performance is more difficult to measure than pump and treat processes and explicit immobilization methods such as ground freezing. Documenting performance is further complicated by the relatively small magnitude (percentage) of the expected reduction in the context expected variations in annual releases.

gallons treated during 20 year operation (equals infiltration reduction)	0 year cost (\$)	annual operational cost (present \$)	total cost* (present \$)	Tritium in target release (Ci)	Tritium reduction (%) FEI	indexed costs: cost _w (\$/1000gal) cost _h (\$ / Ci averted)
150x10 ⁶	10x10 ⁶	1x10 ⁶	22.6x10 ⁶	approx. 30000	10% 0.1	\$140 per 1000 gal \$7,000 per Ci

* assumes 4.9% discount rate over 20 year operating period to account for time value of money

References for Surface Enhancements Assumptions:

Anderson, H.W., M. D. Hoover, and K. G. Reinhart, 1976. Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Supply, USDA Forest Service Technical Report PSW-18/1976.

DOE 1993. F&H Area Hazardous Waste Management Facility Accelerated Approach Proposal. WER-ERD-93-0093. Westinghouse Savannah River Company, Aiken SC 29808.

Hubbard, J. E., 1986. An Update on the SRP Burial Ground Area Water Balance and Hydrology, DPST-85-958, E. I. duPont de Nemours and Co., Technical Division, Aiken SC 29808.

SCS 1986. Urban Hydrology for Urban Watersheds, Soil Conservation Service, NTIS, Washington DC 1986.

tritium costs surface

WSRC-RP-96-0075

Rev 0

February 26, 1996

Time value of money		Annual Costs for Infiltration Reduction (Surface Enhancements)		
interest rate = 4.90		low volume	high volume	
		annual o&m = 1.00E+06	n/a	in (current \$)
year	equiv. current \$			
0	1.00	1.00E+07	n/a	= capital/startup
1	0.95	9.53E+05	n/a	
2	0.91	9.09E+05	n/a	
3	0.87	8.66E+05	n/a	
4	0.83	8.26E+05	n/a	
5	0.79	7.87E+05	n/a	
6	0.75	7.50E+05	n/a	
7	0.72	7.15E+05	n/a	
8	0.68	6.82E+05	n/a	
9	0.65	6.50E+05	n/a	
10	0.62	6.20E+05	n/a	
11	0.59	5.91E+05	n/a	
12	0.56	5.63E+05	n/a	
13	0.54	5.37E+05	n/a	
14	0.51	5.12E+05	n/a	
15	0.49	4.88E+05	n/a	
16	0.47	4.65E+05	n/a	
17	0.44	4.43E+05	n/a	
18	0.42	4.23E+05	n/a	
19	0.40	4.03E+05	n/a	
20	0.38	3.84E+05	n/a	
		o&m total	1.26E+07	n/a
		grand total	2.26E+07	n/a
		gallons	1.50E+08	n/a
		\$/1000 gal	150	n/a
		Ci	30000	n/a
		FEI	0.10	n/a
		\$/Ci averted	8000	n/a
note: only reduces releases by about 100 or 200 Ci/yr				

Infiltration Reduction (Low Flow) Yearly Expenditures

TAB A11:   Electrolysis

Electrolysis

Electrolysis plus Release

1. The low flow case pumping rate is 25 gpm.
2. The high flow case pumping rate is 250 gpm.
3. All the groundwater pumped is converted into H₂, HT, and O₂.
4. The electrolyzer was sized and its utility costs were based on information provided by V. Van Brunt and from the DuPont work.

Electrolysis - Assumptions for Capital Investment Costs

1. The total installed equipment cost is calculated as 44% of the fixed capital investment cost. This is slightly below the Peters and Timmerhaus estimate.
2. The purchased equipment cost is calculated as 17% of the fixed capital investment.
3. The installation costs are estimated at 50% since the equipment is relatively complicated.
4. The instrumentation costs are estimated at 20%.
5. The piping costs are estimated at 45% since the equipment will not require extensive piping.
6. The electrical costs are estimated at 40% since the electrolyzer will require extensive wiring.
7. The building costs are estimated at 10% since no extensive buildings are required.
8. The service facilities and yard improvements are estimated at 40% since only connection to existing service facilities is required.
9. The land costs are estimated at 4% since this scenario requires minimal land.
10. The engineering costs are estimated at 30% since this technology has not been used for remediation.
11. The construction costs are estimated at 30% since this technology has not been used for remediation.
12. The contingency costs are estimated at 15% since this technology has not been used for remediation.
13. The working capital costs are estimated at 15%.

Electrolysis - Assumptions for Production Costs

1. The direct production costs are 52% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
2. *The raw materials are estimated as 0.5% since the only raw material is groundwater and the cost of pumping this groundwater is included in the utilities.
3. The operating labor is estimated as 15% of the total product cost.
4. The direct supervisory and clerical labor cost is estimated as 10% of the total product cost.
5. The utilities cost is calculated as 9% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
6. The maintenance and repairs cost is estimated as 10% since the equipment is complicated.
7. The operating and supplies cost is estimated as 1% of the fixed capital investment.
8. The laboratory charges are estimated as 1% since this technology requires minimal laboratory work.
9. The patents and royalties cost is estimated as 0% of the total product cost since this technology is not patented.
10. The fixed charges are calculated as 11%.
11. The depreciation is estimated as 10% of the fixed capital investment for machinery and equipment.
12. The local taxes are estimated as 1%. Although the government will not be required to pay taxes, this will be used for donations to support the local community.
13. The insurance is estimated as 0.4% of the fixed capital investment.
14. The rent is estimated as 0% since the government will not be required to rent land or buildings for this project.
15. The plant overhead costs are estimated as 70% of the cost for operating labor, supervision, and maintenance.
16. The administrative costs are estimated as 15% of the costs for operating labor, supervision and maintenance.
17. The distribution and selling costs are estimated as 0% since this is a remediation project.
18. The research and development costs are estimated as 2% of the total product cost. This is slightly below the Peters and Timmerhaus estimate.
19. The financing cost is estimated as 0% since the government will borrow no money for this project.

Capital Investment Cost**Electrolysis, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	44%		\$ 178,742,768
1. Purchased equipment (15-40% of fixed capital investment)	17%	\$ 70,095,203	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	50%	\$ 35,047,602	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	20%	\$ 14,019,041	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 31,542,841	
5. Electrical, installed (10-40% of purchased-equipment cost)	40%	\$ 28,038,081	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 7,009,520
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 28,038,081
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 2,803,808
Total Direct Cost			\$ 216,594,177
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 64,978,253
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 64,978,253
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 61,156,003
Total Indirect Costs			\$ 191,112,509
III. Fixed-capital Investment			\$ 407,706,687
IV. Working capital (10-20% of total capital investment)	15%		\$ 71,948,239
V. Total capital investment			\$ 479,654,925

Estimation of Total Product Cost**Electrolysis, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	52%		\$ 135,882,097
1. Raw materials (10-50% of total product cost)	0.5%	\$ 1,301,972	
2. Operating labor (10-20% of total product cost)	15%	\$ 39,059,162	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 26,039,441	
4. Utilities (10-20% of total product cost)	9%	\$ 24,243,195	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	10%	\$ 40,770,669	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	1.0%	\$ 4,077,067	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 390,592	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	11%		\$ 29,315,546
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings.	10%	\$ 23,607,652	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 4,077,067	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 1,630,827	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 74,108,490
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 21,088,279
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 15,880,391	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 5,207,888	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 260,394,412
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Electrolysis, Low Volume-High Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	479,654,925
Capitalized Total Product Cost	\$	3,272,782,458
Present Value Cost for 20 year life	\$	3,752,437,383
Gallons/minute treated (basis)		25
Total Gallons Treated in 20 years		263,000,000
Product Cost/1000 gallons treated	\$	14,279
Ci/year removed		1282
Total Tritium Concentration (Ci)		25,640
FEI		1.00
Product Cost/Ci averted	\$	146,351

System Cost Breakdown

Electrolysis, Low Volume-High Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 479,654,925		\$ 479,654,925
Year 1		\$ 248,231,089	\$ 248,231,089
Year 2		\$ 236,635,928	\$ 236,635,928
Year 3		\$ 225,582,391	\$ 225,582,391
Year 4		\$ 215,045,177	\$ 215,045,177
Year 5		\$ 205,000,169	\$ 205,000,169
Year 6		\$ 195,424,375	\$ 195,424,375
Year 7		\$ 186,295,877	\$ 186,295,877
Year 8		\$ 177,593,781	\$ 177,593,781
Year 9		\$ 169,298,171	\$ 169,298,171
Year 10		\$ 161,390,058	\$ 161,390,058
Year 11		\$ 153,851,342	\$ 153,851,342
Year 12		\$ 146,664,769	\$ 146,664,769
Year 13		\$ 139,813,888	\$ 139,813,888
Year 14		\$ 133,283,020	\$ 133,283,020
Year 15		\$ 127,057,217	\$ 127,057,217
Year 16		\$ 121,122,227	\$ 121,122,227
Year 17		\$ 115,464,469	\$ 115,464,469
Year 18		\$ 110,070,990	\$ 110,070,990
Year 19		\$ 104,929,447	\$ 104,929,447
Year 20		\$ 100,028,072	\$ 100,028,072

Capital Investment Cost**Electrolysis, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Direct Costs (70-85% of fixed-capital investment)			
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting (50-60% of fixed capital investment)	44%		\$ 1,787,427,684
1. Purchased equipment (15-40% of fixed capital investment)	17%	\$ 700,952,033	
2. Installation, including insulation and painting (25-55% of purchased-equipment cost)	50%	\$ 350,476,017	
3. Instrumentation and controls, installed (6-30% of purchased-equipment cost)	20%	\$ 140,190,407	
4. Piping, installed (10-80% of purchased-equipment cost)	45%	\$ 315,428,415	
5. Electrical, installed (10-40% of purchased-equipment cost)	40%	\$ 280,380,813	
B. Buildings, process and auxiliary (10-70% of purchased-equipment cost)	10%		\$ 70,095,203
C. Service facilities and yard improvements (40-100% of purchased-equipment cost)	40%		\$ 280,380,813
D. Land (1-2% of fixed-capital investment or 4-8% of purchased-equipment cost)	4%		\$ 28,038,081
Total Direct Cost			\$ 2,165,941,782
II. Indirect Costs (15-30% of fixed-capital investment)			
A. Engineering and supervision (5-30% of direct cost)	30%		\$ 649,782,535
B. Construction expense and contractor's fee (6-30% of direct cost)	30%		\$ 649,782,535
C. Contingency (5-15% of fixed-capital investment)	15%		\$ 611,560,033
Total Indirect Costs			\$ 1,911,125,102
III. Fixed-capital Investment (Direct + Indirect Costs)			\$ 4,077,066,884
IV. Working capital (10-20% of total capital investment)	15%		\$ 719,482,391
V. Total capital investment			\$ 4,796,549,275

Estimation of Total Product Cost (per year)**Electrolysis, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

I. Manufacturing Cost			
A. Direct production costs (about 60% of total product cost)	52%		\$ 1,358,802,818
1. Raw materials (10-50% of total product cost)	0.5%	\$ 13,019,602	
2. Operating labor (10-20% of total product cost)	15%	\$ 390,588,070	
3. Direct Supervisory and clerical labor (10-25% of total product cost)	10%	\$ 260,392,047	
4. Utilities (10-20% of total product cost)	9%	\$ 242,419,860	
5. Maintenance and Repairs (2-10% of fixed-capital investment)	10%	\$ 407,706,688	
6. Operating supplies (10-20% of cost for maintenance and repairs, or 0.5-1% of <i>fixed capital investment</i>)	1.0%	\$ 40,770,669	
7. Laboratory charges (10-20% of operating labor)	1%	\$ 3,905,881	
8. Patents and royalties (0-6% of total product cost)	0%	\$ 0	
B. Fixed Charges (10-20% of total product cost)	11%		\$ 293,155,458
1. Depreciation (depends on life period, salvage value, and method of calculation - about 10% of <i>fixed capital investment for machinery and equipment</i> and 2-3% of building value for buildings)	10%	\$ 236,076,521	
2. Local taxes (1-4% of fixed-capital investment)	1%	\$ 40,770,669	
3. Insurance (0.4-1% of fixed-capital investment)	0.4%	\$ 16,308,268	
4. Rent (8-12% of value of rented land and buildings)	0%	\$ 0	
C. Plant-overhead costs (50-70% of cost for <i>operating labor, supervision, and maintenance</i> , or 5-15% of total product cost); includes costs for the following: general plant upkeep and overhead, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities.	70%		\$ 741,080,764
II. General expenses = administrative costs+distribution and selling costs+ research and development costs			\$ 210,881,430
A. Administrative costs (about 15% of costs for <i>operating labor, supervision, and maintenance</i> , or 2-6% of total product cost); includes costs for executive salaries, clerical wages, legal fees, office supplies, and communications.	15%	\$ 158,803,021	
B. Distribution and selling costs (2-20% of total product cost); includes costs for sales offices, salesmen, shipping, and advertising.	0%	\$ 0	
C. Research and development costs (2-5% of every sales dollar or about 5% of <i>total product cost</i>)	2%	\$ 52,078,409	
D. Financing (interest) (0-10% of total capital investment)	0%	\$ 0	
III. Total Product cost = manufacturing cost + general expenses			\$ 2,603,920,470
IV. Gross-earnings cost (gross earnings = total income - total product cost; amount of gross-earnings cost depends on amount of gross earnings for entire company and income-tax regulations; a general range for gross-earnings cost is 30-40% of gross earnings).			N/A

Total Costs (Present Worth Basis)**Electrolysis, High Volume-Low Concentration**

(calculation basis in bold, assumptions in italics/bold)

Total Capital Investment Cost	\$	4,796,549,275
Capitalized Total Product Cost	\$	32,727,527,326
Present Value Cost for 20 year life	\$	37,524,076,601
Gallons/minute treated (basis)		250
Total Gallons Treated in 20 years		2,630,000,000
Product Cost/1000 gallons treated	\$	14,279
Ci/year removed		1538
Total Tritium Concentration (Ci)		30,760
FEI		1.00
Product Cost/Ci averted	\$	1,219,898

System Cost Breakdown

Electrolysis, High Volume-Low Concentration

Year	Capital Costs	Maintenance Costs	Total Cost
Year 0	\$ 4,796,549,275	\$ 0	\$ 4,796,549,275
Year 1		\$ 2,482,288,341	\$ 2,482,288,341
Year 2		\$ 2,366,337,790	\$ 2,366,337,790
Year 3		\$ 2,255,803,422	\$ 2,255,803,422
Year 4		\$ 2,150,432,242	\$ 2,150,432,242
Year 5		\$ 2,049,983,072	\$ 2,049,983,072
Year 6		\$ 1,954,225,998	\$ 1,954,225,998
Year 7		\$ 1,862,941,847	\$ 1,862,941,847
Year 8		\$ 1,775,921,685	\$ 1,775,921,685
Year 9		\$ 1,692,966,334	\$ 1,692,966,334
Year 10		\$ 1,613,885,924	\$ 1,613,885,924
Year 11		\$ 1,538,499,451	\$ 1,538,499,451
Year 12		\$ 1,466,634,367	\$ 1,466,634,367
Year 13		\$ 1,398,126,184	\$ 1,398,126,184
Year 14		\$ 1,332,818,097	\$ 1,332,818,097
Year 15		\$ 1,270,560,626	\$ 1,270,560,626
Year 16		\$ 1,211,211,274	\$ 1,211,211,274
Year 17		\$ 1,154,634,198	\$ 1,154,634,198
Year 18		\$ 1,100,699,903	\$ 1,100,699,903
Year 19		\$ 1,049,284,941	\$ 1,049,284,941
Year 20		\$ 1,000,271,631	\$ 1,000,271,631

APPENDIX B: ECONOMIC DEFINITIONS

APPENDIX B: ECONOMIC DEFINITIONS

<i>direct cost</i>	The cost in good and labor to produce a product which would not be spent if the product were not made [1].
<i>discount factor</i>	The ration of the present worth of one or a series of future payments to the total undiscounted amount of such future payments. Also known as the present-worth factor [1].
<i>discount rate</i>	The rate used to calculate a discount factor.
<i>fixed capital investment</i>	The capital needed to supply the necessary manufacturing and plant facilities [2].
<i>fixed charges</i>	A cost that remains unchanged during short-term changes in production level. Also known as overhead; overhead cost; fixed cost[1].
<i>general expenses</i>	Variable cost associated with production including: administrative expenses, distribution and marketing expenses, research and development expenses, financing expenses, and gross-earnings expenses.
<i>indirect costs</i>	A cost that is not readily identifiable with or chargeable to a specific product or service [1].
<i>life cycle costs</i>	A measurement of the total cost of using equipment over the entire time of service of the equipment; includes initial, operating, and maintenance costs[1].
<i>manufacturing costs</i>	All expenses directly connected with the manufacturing operation or the physical equipment of a process plant itself, including direct production costs, fixed charges and plant overhead costs[2].
<i>product cost</i>	The manufacturing costs and general expenses associated with producing a product.
<i>total capital investment</i>	The sum of the fixed capital investment and the working capital.
<i>working capital</i>	The capital needed for the operation of the plant; raw materials and supplies carried in stock, finished products in stock and semifinished products in the process of being manufactured, accounts receivable, cash kept on hand for monthly payment of operating expenses, accounts payable, and taxes payable [2].

References for Economic Definitions

1. Parker, Sybil P., ed., McGraw-Hill Dictionary of Scientific and Technical Terms, Fifth Edition, McGraw-Hill, Inc., New York, 1994.
2. Peters, Max S. and Klaus D. Timmerhaus, Plant Design and Economics for Chemical Engineers, Fourth Edition, McGraw-Hill, Inc., New York, 1991.

Table VII-3. Evaluation Matrix Results

Technology Class	Current Status of Technology	Advantages of Technology	Disadvantages of Technology	Development Needs	Potential Fatal Flaws in Technology	Regulatory Acceptability	Public Acceptability	Activity Level Treated	Operating/Maintenance Costs	Total Project Costs	Summary Indicators FEL \$/7960 gallons SCI averted
Evaporation/Distillation and Related Processes	Evaporation (Direct Heating)	Simple Process Known Technology Low Cost	Release HTO to environment shifts exposure to downwind population potential local impacts on meteorology		Release of HTO to environment	3	3	A	157,896,564	172,534,910	0.6 650 9,340
									15,789,048	17,253,884	0.6 65 1,122
	Evaporation (Humidification)	Simple Process Known Technology Low Cost	Release HTO to environment shifts exposure to downwind population potential local impacts on meteorology		Release of HTO to environment	3	3	A	353,757,835	405,110,328	0.6 154 21,950
									35,661,196	40,808,311	0.6 155 2,653
	Other Processes Distillation	Simple Process Known Technology Concentrated Stream	Low Separation Factor High Heat of Vaporization Reflex Increases Capital Costs	Enhanced separation by addition of fixed or homogeneous catalyst to increase relative volatility through increased activity	Energy Consumption			A/B	*	*	*
Mass Transfer Based Equilibrium Processes	Stripping and Sparging	Simple Process Known Technology	Release HTO to environment shifts exposure to downwind population potential local impacts on meteorology		Release of HTO to environment	3	3	A	556,260,020	1,709,876,083	0.6 650 92,592
									76,205,625	289,657,771	0.6 1,102 18,829
	Exchange Reactions	Known Technology Homogeneous Catalyst increases efficiency per unit volume of liquid	High Pressure Hydrogen Sulfide High Corrosion increases Maintenance Costs Process Duplication Process Unit Sparing Regeneration of Catalyst Limited Catalyst Suppliers	Improvement in catalyst development	High Pressure Hydrogen Sulfide Inventory Explosion hazard Toxic Hazard	2	2	A	137,125,812	161,238,451	0.99 67 5,205
									36,372,628	42,465,683	0.99 102 1,673
	Dual Temperature Liquid Phase Catalytic Exchange (DTLPEC)	Known Technology Low Temperature Separation Factor Concentrated Stream	Catalyst Suppliers Limited	Improvement in catalyst development		2	1	A	2,366,573,214	2,576,017,833	0.99 989 88,992
									341,685,225	378,851,810	0.99 142 14,925
	Combined Electrolysis and Catalytic Exchange (CECE)	Concentrated Stream Cheaper than LPEC Electrolysis source of hydrogen and high tritium concentration	Catalyst Suppliers Limited	Improvement in catalyst development		2	1	A	36,225,159,947	39,611,823,266	0.99 13,072 1,300,278
									2,973,188,783	3,312,833,393	0.99 12,606 130,511
	Other Processes Extraction and Adsorption	High Separation Factor Known Technology Concentrated Stream	Solvent Cost Solvent Loss	Higher separation factor High loading				A/B	*	*	*
	Membrane Processes	Simple Process Known Technology	High Energy Costs Bench Scale Only Dilute System efficiency improves Membrane durability unknown Tritium reduction low	High separation factor Reduction in costs	Rupture of the membrane Limited evaluation indicates high costs	3	3	A/B	*	*	*
Direct Oxidation Immobilization or Storage	Ground Freezing	In-situ technology plume	High Energy Costs			2	2	A	3,290,000,000	6,690,000,000	0.78 5,280 671,000
									314,000,000	564,000,000	0.75 5,820 79,000
	Storage Tanks-Carbon Steel	Low cost	Limited Space			1	1	A	2,754,620,581	4,023,741,616	0.99 7,535 132,401
									547,975,294	649,212,876	0.99 2,471 25,560
	Storage Tanks-Stainless Steel	Low cost	Limited Space			1	1	A	7,895,974,827	11,422,342,012	0.99 4,385 378,340
									1,228,075,971	1,551,368,704	0.99 6,117 81
	Infiltration Reduction	Reduce tritium release Natural and sustainable process Simple Low energy use Low cost Protects local ecology	Small reductions in tritium Performance difficult to measure			3	3	A/B	12,600,000	22,600,000	0.1 150 8,000
	Frequency Based Separation Laser	Simple Process Known Technology	Proposed processes rely on CFC's Bench Scale showed unfavorable results Site sequential separation processes result in process complexity	Reduce complexity Remove CFC's	Limited evaluation indicates high costs	2	2	A	*	*	*
									*	*	*
	Electrolysis Plus	High Separation Factor Simple Process Known Technology	High cost			2	2	A	32,727,527,225	37,534,076,461	1.0 14,279 1,219,898
									3,272,783,458	3,752,437,383	1.0 14,279 146,351
Other Processes	Electrolysis plus cryogenic distillation Electrolysis plus metal hydride separation Electrolysis plus thermal diffusion Electrolysis plus mass spectrometry Electrolysis plus gas chromatography	Simple Process Known Technology	post electrolysis process unnecessary because electrolysis eliminates population risk same as above same as above same as above same as above					A/B	*	*	*
									*	*	*
									*	*	*
									*	*	*
									*	*	*
									*	*	*

Current Status of Tech.: 1. Commercially Available 2. Pilot-scale tested 3. Bench-scale tested 4. Laboratory, conceptual model

Regulatory Acceptability: 1. Currently Accepted by EPA or State Regulators 2. Likely to be accepted 3. Significant regulatory issues

Public Acceptability: 1. No tritium exposure to public 2. Significantly reduces exposure to public 3. Minimal reduction of tritium exposure or shifting of exposure to new populations

Activity Level Treated: A. High volume/Low concentration B. Low volume/High concentration

Cost Columns: * These technologies were not fully evaluated due to factors such as level of development, availability of design/process information or expectations of similar performance for similar processes

Summary Indicators: See Section III for description of Summary Indicators

Westinghouse Savannah River Company
Document Approval Sheet

Class/EC/DOE/Patent

Org. Code L3630

Document No.
WSRC-RP-96-0075

Title <u>Status and Practicality of Detritiation and Tritium Production Strategies for Environmental Remediation</u>			
Primary Author/Contact (Must be WSRC) <u>Karen M. Jerome</u>		Location <u>773-424</u>	Phone No. <u>5-5223</u>
Position <u>Env. Engineer</u>		Organization Code <u>L3630</u>	
Organization (No Abbreviations) <u>Savannah River Technology Center/Environmental Sciences Section</u>		Keywords <u>Tritiated water, Tritium, cleanup, Environmental Restoration</u>	
Other Authors <u>H.H. Fulbright, B.B. Looney, A.L. Schwirian-Sperry, V. Van Brunt</u>			
Has an invention disclosure been submitted related to this information? ☐ Yes Disclosure No. (If Known) _____ Title _____ Date Submitted _____ ☒ No Do you intend to submit an invention disclosure? If yes, projected date. _____			
Intended Usage ☒ Report ☐ Software ☐ Conference/Meeting/Presentation ☐ External Home Page/Internet ☐ Other _____		Document Type ☐ Abstract ☐ Paper ☒ Technical Deadline _____	
Conference/Meeting Presentation ☐ Journal Article ☐ Published Proceedings ☐ Other _____		Meeting/Journal Title (No Abbreviations) _____	
Reports ☐ Quarterly ☐ Topical ☐ Semiannual ☐ Phase I ☐ Annual ☐ Phase II ☐ Final ☒ Other <u>Technical</u>		Meeting Address (City, State, Country) _____	
Report Dates _____ thru _____		Meeting Date(s) _____ (m/d/y) thru _____ (m/d/y)	
Sponsor _____		_____	
I understand that for the information in this material to be given external distribution, approvals by both WSRC and, as appropriate, DOE-SR are required. Distribution (verbally or published) must be in accordance with policies set forth in WSRC management requirements and procedures (MRP 3.25) and in DOE-SR orders, and the content of the external distribution must be limited to that actually approved. <u>Karen M. Jerome</u> Author's Signature <u>4/1/96</u> Date			
Approvals by Author's Organization			
Derivative Classifier <u>G.E. Moore-Shedrow</u>	Classification <u>U</u>	Topic <u>Environmental</u>	Distribution ☒ Unlimited ☐ Limited (Explain Below)
Explanations <u>NOTE to DOE: For technical review send to Cynthia Anderson's Section. This report was prepared for the Environmental Restoration Department. For public release.</u>			
Manager's Name (Print) <u>D.B. Moore-Shedrow</u>		Manager's Signature <u>D.B. Moore-Shedrow</u>	Date <u>4/1/96</u>
Classification Information (To be Completed by Classification Reviewer)			
Classification (Check One for Each) Overall ☐ S ☐ C ☐ UCNI ☒ U Abstract ☐ S ☐ C ☐ UCNI ☒ U Title ☐ S ☐ C ☐ UCNI ☒ U Cover Letter ☐ S ☐ C ☐ UCNI ☒ U		Classification Guide Topics <u>276 pages</u>	
WSRC Classification Officer's Name (Print) <u>T. R. COUGHENOUR</u> CLASSIFICATION ANALYST		WSRC Classification Officer's Signature <u>T. R. COUGHENOUR</u>	Date <u>1-6-97</u>
Export Control Review (To be Completed by Export Control Reviewing Official)			
Export Control Related ☐ Yes ☒ No			
Export Control Reviewer's Name (Print) <u>T. R. COUGHENOUR</u> CLASSIFICATION ANALYST		Export Control Reviewer's Signature <u>T. R. COUGHENOUR</u>	Date <u>1-6-97</u>
STI Program Use Only			
UC/C Number <u>UC-702</u>		Editor _____	

NOTE OSR 17-8 must be completed in addition to this form when submitting information for review and approval.

Westinghouse
Savannah River Company

P.O. Box 616
Aiken, SC 29802

MSD-STI-96-0669 - P

January 6, 1997

Mr. Norman Nixon,
Patent Office
Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

Dear Mr. Nixon:

REQUEST FOR APPROVAL TO RELEASE SCIENTIFIC/TECHNICAL INFORMATION (U)

Please review the enclosed document for patent considerations. Please be advised that this document will be released within two weeks of the above date. Please complete the WSRC reponse section of this letter and return to the undersigned. Technical questions pertaining to the contents of this document should be addressed to the author or the manager. Questions concerning the processing of this

Jeanne Sellers, Manager
WSRC STI Program

Document No.	WSRC-RP-96-0075
Document Title	Status and Practicality of Detritiation and Tritium Production Strategies for Environmental Remediation (U)
Author	K. M. Jerome
WSRC response due by	February 18, 1997
Patent Related?	☒ No ☐ Yes
WSRC Remarks	
 Norman Nixon, Patent Office WSRC	<u>3-21-97</u> Date <u>J. R. Bozeman</u> Ass't General Counsel

**Westinghouse
Savannah River Company**

P.O. Box 616
Aiken, SC 29802

January 6, 1997

WSRC-RP-96-0075
MSD-STI-96-0669

Ms. W. F. Perrin, Technical Information Officer
U. S. Department of Energy - Savannah River Operations Office

Dear Ms. Perrin:

REQUEST FOR APPROVAL TO RELEASE SCIENTIFIC/TECHNICAL INFORMATION

The attached document is submitted for classification and technical approvals for the purpose of external release. Please complete Part II of this letter and return the letter to the undersigned by 02/18/97. The document has been reviewed for classification by a WSRC classification staff member and has been determined to be Unclassified.

Jeanne Sellers, WSRC STI Program Manager

I. DETAILS OF REQUEST FOR RELEASE

Document Number: WSRC-RP-96-0075

Author's Name: K. M. Jerome

Location: 773-42A

Phone 5-5223

Department: Savannah River Technology Center

Document Title: Status and Practicality of Detritiation and Tritium Production Strategies for Environmental Remediation (U)

Presentation/Publication: Report

Meeting/Journal:

Location:

Meeting Date:

OSTI Reportable

References ☐ Approved for Release/Publicly Available ☒ Routed Concurrently
☐ Included as Attachments ☐ Other

Technical questions pertaining to the contents of this document should be addressed to the author(s) or the manager. Questions concerning the processing of this document should be addressed to the WSRC STI Program Manager, 5-2321 or 5-2099/5-3582.

II. DOE-SR ACTION

Date Received by TIO 1/7/97

☒ Approved for Release ☐ Not Approved
☐ Approved Upon Completion of Changes ☐ Revise and Resubmit to DOE-SR
☐ Approved with Remarks

Remarks _____

W. F. Perrin, Technical Information Officer
DOE-SR

1/30/97
Date

U.S. DEPARTMENT OF ENERGY
ANNOUNCEMENT AND DISTRIBUTION OF DEPARTMENT OF ENERGY (DOE)
SCIENTIFIC AND TECHNICAL INFORMATION (STI)
(When submitting form, input should be typed, not handwritten.)

OMB Control No.
1910-1400

PART I Information Product Identification

A. Identifiers

1. Product/Report Nos.
WSRC-RP-96-0075

2. Award/Contract Nos.
DE-AC09-89SR18035

3. Title

Status and Practicality of Detritiation and Tritium Production Strategies for Environmental Remediation (U)

(Grantees and Awardees skip to Part 1.B.)

4. Funding Office(s)

5. B&R Code(s)

6. Project ID(s)

DOE-SR

7. CRADA Nos.

8. UC/C Category(ies)

9. Information Product Filename

UC-702

B. Information Product Description

1. Report

a. Type   ☐ Quarterly   ☐ Semiannual   ☐ Annual   ☐ Final   ☐ Topical

☐ Other (Specify) _____

b. Dates covered (mm/dd/yyyy)   ____/____/____   thru   ____/____/____

2. Conference

a. Type   ☐ Conference paper   ☐ Published proceedings   ☐ Other (Specify) _____

b. Conference title (No abbreviations) _____

c. Conference location (city/state/country) _____

d. Conference dates (mm/dd/yyyy)   ____ ____ ____   thru   ____ ____ ____

e. Conference sponsor(s) _____

3. Software (Note: Additional forms are required. Follow instructions provided with this form.)

4. Other (Provide complete description.) _____

C. Information Product Format

___ **1. Product not submitted to OSTI** (*i.e., electronic version*) _____

a. Location (FTP, URL, etc.) _____

b. File format ___ SGML ___ HTML ___ Postscript ___ PDF ___ TIFFG4 ___ Other (*Specify*) _____

c. SGML bibliographic record available ___ With product ___ Separately (*Specify*) _____

___ **2. Product submitted to OSTI** (*i.e., electronic, paper, audiovisual, or computer medium*)

a. Number of copies

___ (1) Two for unclassified processing ___ (2) ___ copies for program unclassified distribution

___ (3) One for classified processing ___ (4) ___ copies for standard classified distribution

___ (5) ___ copies for OSTI to reproduce (*Complete part C.3.*)

___ (6) Other (*Complete part C.3.*) _____

b. SGML bibliographic record submitted to OSTI ___ With product ___ Separately (*Specify*) _____

c. Method of transmittal to OSTI

___ (1) **Electronic** (*e.g., FTP, E-mail*) (*Note: Transmit only unclassified unlimited information not subject to access limitations over open systems. Contact OSTI for further information.*)

(a) File format ___ SGML ___ HTML ___ Postscript ___ PDF ___ TIFFG4 ___ Other (*Specify*) _____

___ (2) **Computer medium** (*e.g., magnetic tape or diskette*) (*Complete all. Provide a separate electronic or print abstract.*)

(a) Quantity/type (*Specify*) _____

(b) Machine compatibility (*Specify*) _____

(c) Operating system (*Specify*) _____

(d) File format ___ SGML ___ HTML ___ Postscript ___ PDF ___ TIFFG4 ___ Other (*Specify*) _____

___ (3) **Audiovisual Material** (*Complete all. Provide a separate electronic or print abstract.*)

(a) Quantity/type (*Specify*) _____

(b) Machine compatibility (*Specify*) _____

(c) Sound ___ Yes ___ No (d) Color ___ Yes ___ No (e) Playing time _____

___ (4) **Paper**

___ **3. Additional Instructions/explanations** _____

D. Contact (*Person knowledgeable about the information product and its submission*)

Name Jeanne E. Sellers Position Manager, STI Phone (803) 725-2321

Organization Westinghouse Savannah River Company E-Mail jeanne.sellers@srs.gov

PART II Information Product Announcement and Handling

DOE F 1332.15# (p. 3 of 4)

(DOE/DOE Contractors complete; Grantees and Awardees complete as instructed by contracting officer)

A. Recommendations (Mark at least one)

- ☒ 1. **Unlimited Announcement** (Available to U.S. and non-U.S. public)
- ☐ 2. **Unlimited Announcement/U.S. Dissemination Only**
- ☐ 3. **Classified** (Standard announcement)
- ☐ 4. **OpenNet**
- a. Non-NTIS Availability (Required if not available from NTIS)
- (1) Accession Number _____ (2) Document Location _____
- b. Field Office Acronym SR
- c. Declassification date (mm/dd/yyyy) ____/____/____ Sanitized ____ Never classified ____
- ☐ 5. **Special Handling** (Legal basis must be noted below.)
- ☐ a. Copyrighted material ☐ All ☐ Part (Specify) _____
- ☐ b. Unclassified Controlled Nuclear Information (UCNI)
- ☐ c. Export Control/ITAR/EAR
- ☐ d. Temporary hold pending patent review
- ☐ e. Translation of copyrighted material
- ☐ f. Small Business Innovation Research (SBIR) Release date (mm/dd/yyyy) ____/____/____
- ☐ g. Small Business Technology Transfer (STTR) Release date (mm/dd/yyyy) ____/____/____
- ☐ h. Proprietary
- ☐ i. Protected CRADA information Release date (mm/dd/yyyy) ____/____/____
- ☐ j. Official Use Only (OUO)
- ☐ k. Program-Directed Special Handling (Specify) _____
- ☐ l. Other (Specify) _____

B. Releasing Official**1. Patent Clearance (Mark one)**

- ☐ a. Submitted for DOE patent clearance Date submitted (mm/dd/yyyy) 1/6/97
- ☒ b. DOE patent clearance has been granted
- ☐ c. DOE patent clearance not required

2. Released by

Name

J.R. Bozeman, Asst. General Counsel
Norm Nixon, WSRC Patent Office

Date (mmdd/yyyy)

03 21 97

Phone

(803) 644-6102

E-mail

PART II Bibliographic Information

DOE F 1332.15# (p. 4 of 4)

(Note: Providing the following information is optional. For information products that are to be included in the OpenNet Database, the following information will be used for the OpenNet Database records. For all information products, it will be used in announcing those products, as appropriate, to other parts of the DOE community.)

A. Personal Author/Affiliation K. M. Jerome ; Westinghouse Savannah River Company

B. Performing Organization Westinghouse Savannah River SC US

C. Date of Publication (mm/dd/yyyy) 4/4/96 D. Pages/Size 270

E. Abstract _____

The Savannah River Site (SRS) and other Department of Energy (DOE) facilities are in the process of characterization and clean up of former waste disposal sites. Many of these sites received water or wastewater containing tritium. Treatment of environmental tritium contamination is challenging because properties of the contaminant are similar to those of bulk water. Understanding behavior/treatment options for tritium is an important component of prudent environmental management across the DOE complex.

Current activities of the DOE emphasize environmental protection. DOE has also made an organizational and fiscal commitment to environmental restoration. Specifically, DOE is committed to identification and appropriate use of new (faster and/or better) technologies to improve its environmental clean up efforts and to make them more efficient (reduce costs). Supporting these efforts is a specific objective of our evaluation.

A large percentage of radioactivity released to the environment as a result of SRS operations is in various forms of tritium, a radioactive isotope of hydrogen. Tritium is generated as a product or byproduct of a number of specifically-identified SRS processes. Over the years, tritium has accumulated in various wastes/products, or has entered the environment via the atmosphere or wastewater releases. The releases have been carefully measured and documented. Typically, tritium is the greatest contributor (> 90 %) to the total dose from radionuclides to downstream Savannah River water users. Importantly, the maximum dose commitment to this population is well below

F. Subject Terms tritiated water, tritium, cleanup, Environmental Restoration

G. OpenNet Document Type ☐ Audiovisual Material ☐ Book ☐ Conference ☐ Correspondance ☐ Data ☐ Dissertation/Thesis

H. OpenNet Document Categories _____

I. OpenNet Addressee _____