160051

DOE REVIEW DRAFT

EVALUATION REPORT ON REMEDIATION OF THE NFSS RESIDUES

NIAGARA FALLS, NEW YORK

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ACRONYMS AND ABBREVIATIONS

ANL	Argonne National Laboratory
BNI	Bechtel National, Inc.
BTU	British thermal unit
CEP	catalytic extraction processing
Ci	curie(s)
EIS	Environmental Impact Statement
EM	Environmental Management
EPA	Environmental Protection Agency
FEMP	Fernald Environmental Management Project
FS	Feasibility Study
g	gram(s)
K	potassium
lb	pound
LSA	low specific activity
MED	Manhattan Engineer District
MMT	Molten Metals Technology
NAS/NRC	National Academy of Sciences/National Research Council
NFSS	Niagara Falls Storage Site
NTS	Nevada Test Site
ORNL	Oak Ridge National Laboratory
pCi	picocuries
PEG	polyethylene glycol
Ra	radium
ROD	Record of Decision
SAIC	Science Applications International Corporation
SEG	Scientific Ecology Group
Th	thorium
tpd	tons per day
UMTRAP	Uranium Mill Tailing Remedial Action Program
WCS	Waste Containment Structure
WIPP	Waste Isolation Pilot Plant

EXECUTIVE SUMMARY

In August 1996, a technical working group from the Formerly Utilized Sites Remedial Action Program (FUSRAP) was assigned to perform a preliminary evaluation of possible alternatives for removal of high radium concentration residues from the Niagara Falls Storage Site (NFSS). These residues resulted from the processing of ores (such as Belgian Congo ores) which contained very high concentrations of uranium. The objectives of this effort were to develop one or more alternative(s) which were considered technically feasible, and which could provide the basis for a cost estimate for the FUSRAP 10-year plan for NFSS. The working constraints for the group included the following:

- The alternatives must comply with the National Academy of Sciences (NAS) recommendations to develop a program to remove the high level residues from the NFSS site.

- The program for ultimate disposition of the residues should meet the funding and schedule constraints of the current United States (U. S) Department of Energy (DOE) Environmental Management (EM) 10-Year Plan for the NFSS (projected budget of approximately $100 million 1998$, with a completion date of 2006).

Initial activities of the group included a review of the process proposed by Fernald for treatment of a very similar waste stream (a large portion of the wastes from both Fernald and NFSS came from the same process). In addition, early in this process the technical working group held a brainstorming session using additional experts to generate ideas and concepts. These concepts included several schemes for removing, treating, and disposing of the residue materials. The ideas were screened and combined to form a few promising alternatives for more detailed analysis. The most promising approaches for removal, treatment, transportation, and disposal were first analyzed. These were then combined to form the following three alternatives for detailed evaluation:

- Alternative 1 - Excavation, ex-situ vitrification, and transport to the Nevada Test Site (NTS) for disposal

- Alternative 2 - Excavation, solidification, and transport to NTS for disposal

- Alternative 3 - Excavation, chemical separation of the radium, and storage of the radium at ORNL (or other suitable facility), with disposal of the chemical extraction wastes either onsite or at NTS

More detailed evaluation of these alternatives indicated that currently, the alternative which best fits the constraints of the NAS recommendations, and the 10-year plan is Alternative 2 (excavation, solidification, and transport to NTS for disposal). However, because both vitrification and chemical extraction offer advantages not available through solidification, these alternatives should be more thoroughly evaluated before the NFSS remediation strategy is finalized.

The current best estimate of cost to implement Alternative 2 is $157 million, with a range of approximately $114 million to $292 million. Alternative 1, involving vitrification of all residues (within the 10-year plan schedule), would cost from approximately $101 million to $235 million based on vendor estimates, and up to $400 million based on Fernald data. Alternative 3, chemical extraction of the radium is the alternative with the most uncertainty, both for technical feasibility and cost. The range of costs associated with Alternative 3 are $106 million to $225 million. The costs discussed in this report are in 1998 dollars, and include the cost of assessment, remedial design, and remedial action, in accordance with the 1996 DOE guidance on 10-year plan cost estimating.

As part of the review of alternatives, the technical team also looked at how costs would be impacted if only the K-65 residues were removed. While this approach does not fully meet the NAS recommendations to remove all of the high level residues, it does account for those residues which present the most risk at the site. The team felt that if significant cost savings could be realized by limiting the removal to the K-65 residues, with minimal public health impacts, then this option should be evaluated for each alternative. Under the vitrification alternative, addressing only the K-65 residues results in an estimated cost of $74 million versus $172 million for all residues. For solidification, the cost to solidify and dispose of only the K-65 residues (leaving the rest of the residues onsite) ranges from $66 million to $93 million, with a best estimate of $78 million.

These costs provide evidence that it may be worth revisiting the complete removal recommendation with the NAS. This is particularly true since the concentration of radium-226 (Ra-226) in the remaining residues are significantly lower than the K-65 residues. In fact, many closed Uranium Mill Tailing Remedial Action Program (UMTRAP) sites contain radium concentrations and total curie levels that are similar to those found in the non-K-65 residues.

The following specific recommendations related to remediation of the NFSS residues were developed by the technical working group:

1) Because of the complex nature of any remedial action conducted on the NFSS residues, the environmental analyses, treatment studies, and preliminary remedial action design work necessary to support remedial actions should be initiated as soon as possible.

    This effort should include continued additional analyses necessary to support selection of the final preferred alternative for the NFSS residues. Until such further analyses are conducted, none of the alternatives or technologies discussed in this report should be considered completely eliminated from consideration.

    As part of this effort, it is recommended that FUSRAP representatives [DOE, Bechtel National, Inc. (BNI), Science Applications International Corporation (SAIC)] visit Fernald and take the necessary time to collect as much information as possible concerning experience with vitrification of the K-65 residues at that site. Numerous telephone conversations have been held with Fernald personnel during this study, but schedule constraints prevented visiting the Fernald site during this effort. Such an extended site visit would offer the opportunity to collect valuable information on available characterization and treatment studies data, current plans for Fernald activities, lessons learned, and cost data.

2) Additional characterization data on the residues are necessary prior to final selection of any of the three alternatives evaluated in this study. A potential opportunity exists for FUSRAP to participate in a proposed additional characterization sampling event at Fernald. Silo 1 contains residues that are almost identical to the NFSS K-65 residues. FUSRAP should investigate the possibility of participating with Fernald in any additional characterization efforts, and in particular, expanding the effort to include collection of samples from Silo 1 for FUSRAP treatability studies. It may only be necessary to provide additional funds to FEMP to gain the necessary information.

3) Continue investigation of the ongoing research activities regarding beneficial use of Ra-226, and chemical extraction of radium from the residues. Preliminary contacts have indicated that research is ongoing at the National Institutes of Health (NIH), which if successful, could cause some increased demand for radium for use in cancer treatment. Presuming that the radium content of the K-65 wastes may become a valuable national resource in the near future, an individual within FUSRAP should be

designated to maintain current knowledge of all potentially applicable radium recovery techniques. Contacts should be maintained with the individual in DOE who is in charge of maintaining a database of processes for the treatment of such wastes (Jerry McClure of DOE in Germantown, Maryland). In addition, contact should be maintained with individuals at Hanford who are maintaining the National Inventory of Sources of Radium. (This effort was started in June 1996, and is being coordinated by Robert Schenter).

4)   Presuming that the K-65 wastes may become a valuable national resource in the future, proceed with the additional work recommended in this report, with the primary focus on stabilization. This continued work should proceed with the understanding that the residue wastes may become an "ore" of radium, and may require recovery in the future. Inappropriate modes of stabilization (such as vitrification) and disposal (such as very deep burial in a remote location) may make the extraction of the radium content of these residues difficult to impossible. It is also highly recommended that the FUSRAP maintain cognizance on the Rio Algom proposed efforts with the Fernald K-65 residues regarding recovery of precious metals and radium. Unlike the Fernald K-65 residues, a portion of the NFSS K-65 residues have already been through one round of extraction of the precious metals. Although the current proposal for retrieving the material is conceptual and the feasibility has yet to be demonstrated, should the concept be demonstrated to be successful and feasible at Fernald, then the concept should be considered more strongly for the NFSS K-65 residues. One consideration could even include shipping the material to the Fernald Site for treatment using the demonstrated recovery process.

5)   Consider development of a strategy to revisit the NAS recommendation to remove all residues offsite. From the results of this study, it appears that a good case can be made that removal of only the K-65 residues will provide for protection of public health, will result in substantial cost savings, will allow completion of the work within the DOE 10-year plan, and is supported by ample precedent in UMTRAP.

It should be emphasized that this report does not represent a comprehensive "Feasibility Study-like" analysis of the potential alternatives for remediation of the NFSS residues. It represents the results of a focused, 3-week effort to evaluate likely alternatives for remediation of the NFSS residues for use in DOE's 10-year plan. As such, none of the potential technologies, or alternatives should be considered as "rejected" based on this report. Much more characterization data and treatability testing are required before final selection of the preferred alternative is made for this project.

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1. INTRODUCTION

1.1 DESCRIPTION AND HISTORY OF NFSS AND RESIDUES

The Niagara Falls Storage Site (NFSS) is located in the Town of Lewiston, Niagara County, New York. The site is part of a former Manhattan Engineer District (MED) site, which in turn was part of the former Lake Ontario Ordnance Works. Beginning in 1944, the NFSS was used for the storage of radioactive material that resulted from the processing of uranium ores during the development of the atomic bomb. For the purposes of this report, the term "residues" applies to radioactive materials which resulted from the processing of uranium ores, and which contain high radium concentrations. The term "wastes" is used for all other contaminated material at the site.

Additional residues were brought to the site several years after World War II. As part of an interim action conducted from 1983 to 1985, residues and wastes were consolidated in a diked containment area in the southwest corner of the NFSS. The residues which are the focus of this study are contained in reinforced concrete cellars of the previously existing buildings (buildings 410, 411, 413, and 414) within this diked area. In 1986, the entire area containing the residues and wastes [the Waste Containment Structure (WCS)] was covered with an interim facility cap. This cap was designed to retard radon emissions and to reduce rainwater intrusion into the residues and wastes. Figure 1-1 shows the approximate location of these residues in the WCS.

The residues addressed in this report include the K-65, L-30, F-32, and L-50 residue streams. These residues account for less than 6 percent of the volume of the material in the WCS, but almost 99 percent of the radium-226 (Ra-226) inventory. Approximately 95 percent of the total Ra-226 inventory at the NFSS is contained in the K-65 residues alone. The average Ra-226 concentrations in the four residue groups are 300 picocuries per gram (pCi/g) for the F-32s, 3,300 pCi/g for the L-50s, 12,000 pCi/g for the L-30s, and 520,000 pCi/g for the K-65 residues. While highly concentrated in the NFSS, radium is a naturally occurring radionuclide that exists throughout the world. Natural background soils in the Niagara Falls area contain about 2 pCi/g of Ra-226. Table 1-1 provides a summary of the average concentrations, total curie content, and volumes associated with the residues and wastes at the NFSS. A more detailed summary of available non-radiological characterization data for the residues is provided in Appendix A.

During World War II, the African Metals Corporation (Afrimet) supplied the federal government with the uranium ore (pitchblende ore) from the former Belgian Congo, but retained ownership of the residues because of the radium and other potentially recoverable metals that remained in the residues after the uranium was extracted. In 1983, as a result of negotiations with Afrimet, and in consideration of common defense and security arrangements between the United States (U. S.) and Belgium, Afrimet and the Department of Energy (DOE) signed an agreement whereby Afrimet paid DOE $8 million and DOE took title to the residues and released Afrimet from its obligations with respect to the residues (DOE 1986).

In September 1986, DOE issued a Record of Decision (ROD) for remedial actions at the NFSS that provided for long-term in-place management of the residues and wastes consistent with the guidance provided in the U. S. Environmental Protection Agency (EPA) regulations for uranium mill tailings (40 CFR 192). This would have included construction of a long-term cap over the WCS. EPA and the New York State Departments of Health and Environmental Conservation expressed concerns over the DOE plan for long-term management of the residues. At the request of DOE, the National Academy of Sciences/National Research Council (NAS/NRC) agreed to review and evaluate the effectiveness of the present and proposed WCSs at NFSS, and to determine if any additional actions should be taken at the site to protect public health.
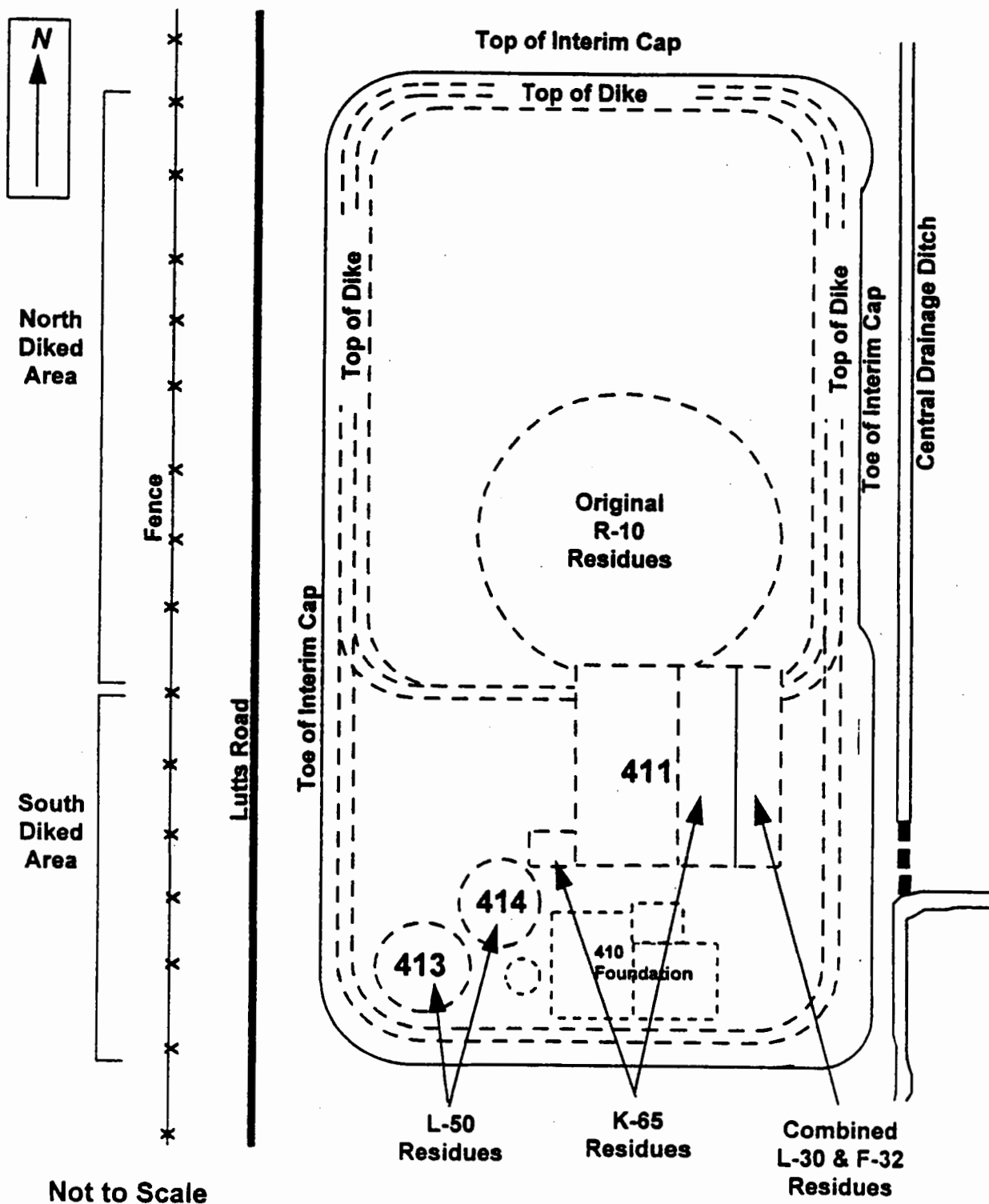
Figure 1-1. Plan View of the WCS - Location of Cellars of Building 410, 411, 413, and 414 Containing Residue Wastes

Table 1-1. Average Concentration and Inventory of Ra-226 and Th-230 in Each Waste Type Stored in the WCS

Description	Volume[a] m³ (yd³)	Av. Conc. of Ra-226 Dry wt[a] (pCi/g)	Av. Conc. of Ra-226 Damp wt (pCi/g)	Ra-226 Inventory (Ci)[a,b]	Av. Conc. of Th-230 Dry wt (pCi/g)	Av. Conc. of Th-230 Damp wt (pCi/g)	Th-230 Inventory (Ci)
K-65 Residues	3,000 (3,925)	520,000	348,400	1,881	54,000.0[a]	36,180	195.0[a,b]
L-30 Residues	6,000 (7,850)	12,000	8,040	87	12,000	8,040	87
F-32 Residues	500 (655)	300	201	0.2	300	201	0.2
L-50 Residues	1,500 (1,960)	3,300	2,211	6	3,300	2,211	6
R-10 Residues and Soil	45,000 (58,860)	95	63.7	5	95	63.7	5
Remaining Contaminated Soils	134,500 (175,925)	16	10.7	3	16	10.7	3

[a]*BNI 1994.*
[b]Curie content is calculated on the basis of average damp concentrations of Ra-226 and Th-230.

1.2 SUMMARY OF NAS REPORT RECOMMENDATIONS

A four-person subcommittee of the NAS Committee on Remediation of Buried and Tank Wastes reviewed documentation on the NFSS and received presentations from DOE and its contractors during three meetings in 1994. The subcommittee also visited the Fernald Environmental Management Project (FEMP) to review how similar residues were going to be remediated at that site. The committee's final report, *Safety of the High-Level Uranium Ore Residues at the Niagara Falls Storage Site, Lewiston, New York* was published in late 1995.

The committee made three recommendations for future actions by DOE to manage the NFSS high-level residues in a way that provides protection of the health and safety of the public and the environment, both in the short- and long-term.

1) Following completion of related or similar treatment technology studies such as the FEMP vitrification demonstration and related cost-risk-benefit studies, a program should be developed by DOE for removal, treatment, and disposal off-site of the NFSS high-level residues. Because there is no immediate hazard to the off-site public from the residues in their present configuration, such studies will help to ensure proper handling of the residues when they are removed for disposal, as well as to provide an example for future remediation of other sites containing radioactive residues.

2) After removal of the high-level residues, remaining wastes should be buried under a suitable protective cap.

3) The adequacy of site monitoring and maintenance activities necessary to ensure the safety of the public and the integrity of the NFSS should be assured. An alternative NFSS monitoring strategy should be developed to measure and track transport of radiological and chemical contaminants from the NFSS WCS, as well as those reaching NFSS from contiguous waste disposal areas off site, both prior to and following removal of the residues.

1.3 NFSS RESIDUES TECHNICAL GROUP CHARTER AND PROCESS

In the summer of 1996, DOE established a goal of accelerating the cleanup of DOE sites and completing all actions necessary to achieve a safe and secure end state within 10 years. As part of the draft 10-year plan developed by the Oak Ridge Operations, the remedy for NFSS was proposed as completion of the final disposal cap with the residues left in place. DOE Headquarters comments requested that the proposed remedy be reevaluated and that an alternative remedy be developed which was consistent with the recommendations of the NAS and which could still be completed within the constraints of the 10-year plan.

To meet the objectives outlined above, DOE formed a technical working group to specifically evaluate options for the remediation of the NFSS residues. The assignment to the technical working group was to develop alternatives for removal of the residues which could be completed within the schedule and funding constraints for NFSS outlined in the FUSRAP 10 year plan [completion by 2006, within a budget of approximately 100 million dollars (1998 dollars)]. Each alternative developed was to include an evaluation of technical feasibility, as well as an estimate of cost. The overriding considerations were that the selected alternative must comply with the recommendations of the NAS, and must fit within the constraints of DOE's 10-year plan.

The first action the technical working group took was to convene a brainstorming session to look at all of the possibilities available for meeting the objectives outlined above. This brainstorming effort was aimed at

identifying all possible technologies and alternatives for removal and treatment of the NFSS residues, and to identify pros and cons for each alternative. The brainstorming session included experts from DOE, Oak Ridge National Laboratory (ORNL), Bechtel National, Inc. (BNI), Science Applications International Corporation (SAIC), and Argonne National Laboratory (ANL). Results of the brainstorming are shown in Appendix B. During the process several technologies and issues were identified for future consideration and analyses. The technologies were grouped as shown below:

Technologies

Removal
        Freeze removal
        Re-suspension process (slurry method)
        Sequential excavation (cell by cell)

Treatment
        In-situ Treatment Methods
                In situ vitrification (ISV)
                Chemical separation
        Ex-situ Treatment Methods
                Density/air flotation
                Electrical separation
                Chemical separation
                Liquid extraction
                Asphalt/polymer solidification/stabilization
                PEG (polyethylene glycol)
                Ex-situ vitrification
                Catalytic extraction (M4)
                Deep well injection

Each of these technologies are described and evaluated as part of the screening analyses discussed in Section 2.

The brainstorming effort was useful for generating a wide range of options for further consideration by the technical working group. A very useful additional output from the brainstorming session was a list of broad programmatic/policy issues and critical assumptions which must be addressed under any remedial action covering the NFSS residues. A summary of the most important issues and assumptions used for analyses of alternatives is provided below.

Broad (Programmatic/Policy) Issues

- To know how much material must be removed from (or can remain in) the disposal cell is critical in order to design any treatment option. As an initial starting point for this effort, it was assumed that because the NAS recommended that the R-10 residues and other wastes remain on site, the Ra-226 concentration in these materials would be an acceptable level for disposal onsite of any waste stream from residue treatment. (This concentration is approximately 100 pCi/g.) In addition, the group assumed that because the R-10 residues and other waste only represent approximately 20 curies (Ci) (total radium and thorium), the treatment and removal process would have to be efficient enough so that the residual total activity was in the tens of curies (similar to what exists in the R-10 residues and wastes).

Because these values (approximately 100 pCi/g and 20 Ci) imply a total treatment and removal efficiency greater than 99 percent (which is not practical), a second approach was evaluated for determining a target removal level, and residual concentration level. This approach would require removal of at least 90 percent of the residue curies, leaving 10 percent of the original residue radioactivity in the treatment waste stream for onsite disposal (approximately 200 Ci of Ra-226 remaining onsite).

The working group also assumed that a residual concentration in the range of 100 to 1,000 pCi/g would be acceptable for disposal of the treatment waste stream onsite. This implies a very high removal efficiency for the K-65 material, although the removal efficiencies for the other residues can be much lower. This concentration range is consistent with the range of average Ra-226 concentrations in inactive uranium mill tailings piles (see Table 4-1).

- Additional characterization data are needed to evaluate any of the treatment options. The data available are not sufficient for adequate treatment process evaluation or design purposes.

- The environmental analyses and documentation, treatability studies, and engineering design work for remediation of the residues will be significant and should start as soon as possible. Work should begin in FY97 in order to have a reasonable chance to complete the project by 2006.

Key Assumptions

- The project must be complete by the end of 2006, with the startup of remediation activities to begin no later than 2003. Ideally, the treatment facility will be designed for about an 8 month operation (i.e., a few tons per hour operation), but a several year schedule for operations is acceptable.

- At least 90 percent of the Ra-226 curies will be removed (leaving approximately 200 Ci). Curie may be left from residual material not removed by the excavation or from residues of the treatment process which are replaced in the NFSS disposal cell.

- Residues replaced in the cell will be of radioactive concentrations similar to the other materials in the cell, e.g., 100 to 1,000 pCi/g of Ra-226. Using the L-50 residues as a baseline (approximately 3,300 pCi/g) it may be possible to increase this concentration. However, it is unlikely that the average concentration could be increased much beyond 1,000 pCi/g for Ra-226.

- The total cost goal for the project is 50 to 100 million dollars (1998 dollars).

- Radon off-gas treatment will be provided.

- The treatment operations (and portions of the excavation operation) will be conducted in an enclosed facility or structure to provide radiation and radon control.

- Exposure of the material to the environment will be minimized, e.g., short time periods from excavation to processing and no blending or storage piles.

- The preference is to use commercially available equipment.

- Additional land will probably be needed for a radiation buffer area for radon.

- Environmental documentation will be performed under CERCLA guidance (likely through a Feasibility Study/Proposed Plan and revised ROD).

- Onsite staffing requirements for the remediation operation will not be similar to normal FUSRAP sites. Additional senior regulatory, health and safety, community relations, transportation, security, and management personnel will be required due to the high hazard, high visibility nature of this work.

- Equipment leaving the site will be decontaminated, but due to expected contamination levels, much of the equipment will likely be placed in the disposal cell at NFSS.

Using the information generated during the brainstorming session, the technical working group performed an initial screening of alternatives as described in Section 2. The three most feasible alternatives were further evaluated as discussed in Section 3. Section 4 provides conclusions and recommendations from the technical working group analyses.

It should be emphasized that this report does not represent a comprehensive "Feasibility Study-like" analysis of the potential alternatives for remediation of the NFSS residues. It represents the results of a focused, three week effort to evaluate likely alternatives for remediation of the NFSS residues for use in DOE's 10-year plan. As such, none of the potential technologies, or alternatives should be considered as "rejected" based on this report. Much more characterization data and treatability testing are required before final selection of the preferred alternative is made for this project.

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2. SCREENING OF POTENTIAL REMOVAL, TREATMENT, TRANSPORTATION, AND DISPOSAL OPTIONS

2.1 INTRODUCTION

As noted previously, a group of senior technical experts generated an initial listing of potential treatment technologies for the NFSS residues during a "brain storming" session (see Appendix B). A rapid assessment of respective technology utility in achieving the NAS recommendations was performed and several candidates were identified as more promising. These identified alternatives can serve as background material for FUSRAP Group's decisions on including treatment in out-year plans at NFSS and as the basis for first order cost estimates. However, no technology or approach should be considered as excluded from further consideration based solely on this rapid assessment process. This was not a full feasibility study but a planning tool to support preparation of the 10-year plan. More detailed screening analyses and evaluations will be conducted as part of a subsequent full feasibility study (i.e., evaluating potential remedies to reduce risk, achieving cost-effective threat mitigation, and reaching regulatory compliance).

Solving the NFSS residue issue will involve the removal, treatment, transportation, and disposal of some or all the materials within the diked WCS. Processes to remove, treat, and transport the residue material must be capable of dealing with material that is difficult to handle both from a materials handling perspective (much of the residue material is the consistency of peanut butter), as well as from a personnel safety perspective. Dose rates to workers in the vicinity of the residues are likely to be in the tens to hundreds of millirems per hour (mrem/hr). In addition, random emission rates from the uncovered residues will be high enough to require containment methods (cover and filtration) during removal and treatment operations. The initial list of potential technologies, processes, or techniques for the phases of this remediation plus brief respective of pros and cons are summarized below.

2.2 REMOVAL TECHNOLOGIES

The first obstacle to solving the NFSS residue problem is to remove the material from areas where it was placed as part of an earlier interim action. The actual physical status of this material and the configuration within which it is stored is uncertain with respect to structural stability of the walls and obstacles that may have been placed in the unit during waste placement activities (e.g., drums, miscellaneous equipment, etc.). These uncertainties were noted but not factored into the removal alternative evaluations at this time. Three excavation alternatives were proposed: freezing the residues then removal, slurrying the residues out, and sequential mechanical excavation. Each alternative was evaluated from the stand point of implementation, dose to the worker, and the form of the material for input into the treatment processes. The goal was to be able to remove greater than 90 percent of the curies contained in the residues from the underground storage areas. This withdrawal efficiency can be achieved by focusing on the removal of the K-65 residues, which contain approximately 95 percent of the radium in the residues. These residues are segregated from the other material by sand layers and/or geomembranes, which make the removal efficiency high. After excavation, the only material expected to be left will be a small amount that adheres to the concrete walls of the confining structure.

2.2.1 Freeze Removal

Soil freezing has been employed on large-scale engineering projects for a number of years. While this technology has many construction applications, its primary use for the NFSS residues would be to stabilize the material during excavation and to potentially provide some reduction in radon off-gassing. After in place

freezing, the residues would be cut into manageable blocks for removal and transport to the selected ex-situ treatment process to limit the exposure to the residues.

The main concern with the freezing of the residues is that they are contained within a concrete structure and upon freezing the water expansion would create problems in their removal (and in containment wall structural stability). This method would also require installation of risers and piping to accomplish freezing. This would be a very complicated construction task at this site. Another issue is that the material would need to be stockpiled while it thaws, since it cannot be processed while frozen. This results in longer holding times or large inputs of thermal energy to thaw. This could cause additional exposure concerns. For this reason it was discarded as a removal technique.

2.2.2 Re-Suspension/Slurry

The second alternative was to slurry the material out of the underground structure. While the materials were originally placed in the cells at the site as a slurry, they were subsequently dewatered in-place to some degree. The main concern with this process is the additional water that may have to be added and thus managed as an additional waste stream. In addition, the current configuration of the residues in the WCS requires removal of several feet of overburden (waste and soil) to get to the residue material.

The impact of additional volumes of water on subsequent treatment processes would vary. For solidification/stabilization and chemical separation, water addition would be required in any case. For ex-situ vitrification, the water would severely affect its operation and costs. While minimizing worker and environmental exposures during removal, the uncertainties of removing most deposited material and the volumes of new waste water that may be generated make this technique less desirable. It offers promise, but its viability is dependent on the method of treatment selected.

2.2.3 Sequential Excavation/Removal

The last alternative is the mechanical excavation of the residues. This is the most straight forward approach using standard soil and waste removal equipment and short distance transfer techniques. A primary concern with this method of removal is worker radiation exposure, both from direct gamma radiation as well as potential inhalation exposures to contaminated dust and radon. It is expected that direct external gamma dose rates over the open excavation could be in tens to hundreds of mrem/hr. Exposure could be controlled by limiting the size of the excavation face opening, and hence the amount of residues exposed at any given time. For the excavation of the K-65 residues, it is likely that further emissions controls such as an enclosure with a radon removal system will be utilized.

The use of shielded earth moving and transfer equipment, coupled with worker exposure time restrictions, can support safe removal operations. The sequential, mechanical excavation of the residues is the method of choice for our initial evaluation for the residues as it best meets all requirements and conditions.

2.3 TREATMENT

The residues could be treated after removal to meet one or more of the following purposes:

- Stabilize the material prior to shipment so that radon offgassing, and the potential for contaminant (dust) release in the event of an accident is minimized.

- Meet disposal facility WAC.

•   Extract radium, uranium, and/or precious metals from the residues for recovery.

All of these potential purposes were considered as appropriate in the evaluation of each of the following treatment technologies.

2.3.1 In Situ Vitrification (ISV)

In-place heating and melting of soil and waste is a proven technology. ISV destroys combustible and some hazardous constituents, while immobilizing the inorganic and nonvolatile metallic constituents in a durable glass and/or crystalline product. Electrodes are placed below ground for heating or plasma arc torches may be employed for well defined shallow zones of contamination. The final waste volume and mass may be reduced significantly by evaporation of moisture, combustion and/or decomposition of organic components, and consolidation of the waste into a dense glass matrix.

This technology would not meet the NAS recommendation for offsite disposal of the residues. While effective in a silica matrix, the expected high water content of the K-65 residues, coupled with the uncertainties of forming glass and the unknown off-gas control requirements, are severe constraints on this process. It was thus excluded as a future alternative.

2.3.2 In Situ Chemical Separation

Since the residues were placed in an underground concrete structure with some drainage (dewatering) piping capabilities at the bottom, in-place chemical separation and recovery through the existing drainage pipes was a logical recommendation. This process is in essence a below-ground heap-leaching pile. The chemical extraction system is applied to the top of the buried waste and the pregnant-solution collected through a lower tier collection system resting above some impermeable barrier. The process involves the addition (injection) of reactant solution, its recirculation, and ultimate removal of the radium-bearing solution. The porosity of the sludge/soil and mobility of the washing solutions are essential for success. If porosity is too tight, no flow will occur and thus no contact time. If porosity is too great, the reactant solution takes the path of least resistance and does not provide adequate contact time.

This approach would most likely not achieve the necessary radium removal levels to meet the NAS recommendations as typical removal efficiencies are less than 90 percent under ideal conditions. Additionally, the porosity of the sludge and necessary mobility of the reacting solution through the residues is not present in-situ. This technique was not recommended for additional evaluations.

2.3.3 Ex Situ Air Flotation

This approach is used in the mining industry for removing high value metals from ores. This process uses air attached to fine particles to float selected constituents of the residues to the surface of a flotation tank. Low-density solids are best removed by this technique. Microbubbles of air are attached to the particles by contact, formation at the solid-liquid interface, or entrapped under larger parts of flocs.

The K-65 residues have a large number of metals that would compete for chemicals added to aid in flotation; and getting the residues in a form where the bubbles would work could present obstacles. The effectiveness of radium separation with this technique is also uncertain. In addition, it is likely that extensive off gas treatment would be required to deal with radon. While some potential may exist for this process, its lack of selectiveness and effectiveness ruled out its consideration for additional evaluation as a stand alone treatment process. This technology may warrant some future consideration as a pre-treatment method, or as a unit process in a treatment train.

2.3.4 Ex Situ Electrical Separation

The prospect of using electrical gradients to separate metals holds promise in many remedial situations. The process is known as electrokinetics and is a combination of electro-osmosis and electrical migration together with electrolysis reactions to effect the metals separation.

As was noted above, the NFSS residues contain a large number of metals that may move in response to the applied electrical gradients if the viscous form could be modified with pretreatment. It is also highly questionable if effective separation could be assured for the highly insoluble form of radium present. Finally, the effectiveness of this process is a function of media porosity and this is questionable at best. Thus while some potential exists for this process, lack of specificity and effectiveness does not warrant recommending further additional evaluation.

2.3.5 Ex Situ Chemical Separation

A very appealing suggestion is to chemically react the residue in a manner that results in concentrated radium salts for offsite disposal, and a low-level sludge that could be returned to the existing NFSS burial sites for capping. Such ex situ chemical separations are theoretically straightforward and have been recommended by other organizations reviewing the disposition of the NFSS residues. The process involves a complex set of unit processes involving the addition of acids and salts and removal of precipitates. A detailed discussion of the various recommended processes and reviews of their applicability to the problem at hand are presented in Appendix C.

While this process is theoretically "doable" and offers the prospect of smaller quantities of material shipped offsite, its effectiveness is questionable given the number of complex unit operations and the radioactive operating environment. Without samples upon which to perform treatability studies, the materials handling and process effectiveness issues can only be assumed. Accordingly, it is recommended that this technology be carried to the next evaluation stage. The authors recognize that many questions need to be further explored before a definitive recommendation can be made on chemical separation as the recommended process.

Although not evaluated by the technical working group directly during the three week effort, a preliminary evaluation of limited information regarding a Rio Algom proposal for treating the K-65 residues at the Fernald Site was performed. Based on that evaluation, it is highly recommended that the FUSRAP maintain cognizance on the Rio Algom proposed efforts with the Fernald K-65 residues regarding recovery of precious metals and radium. Unlike the Fernald K-65 residues, a portion of the NFSS K-65 residues have already been through one round of extraction of the precious metals. Although the current proposal for retrieving the material is conceptual and the feasibility has yet to be demonstrated, should the concept be demonstrated to be successful and feasible at Fernald, then the concept should be considered more strongly for the NFSS K-65 residues. One consideration could even include shipping the material to the Fernald Site for treatment using the demonstrated recovery process.

2.3.6 Ex Situ Liquid Extraction

Since the residues consist of a "peanut butter-like sludge," it may be effective to use liquid extraction to remove the radium. Liquid extraction involves the transfer of a solute from one phase to another, without a chemical change. The extracting fluid must be immiscible in the aqueous phase and the density differential must enable separation. When appropriate media, phase, mixing, and temperature conditions are maintained, the process can achieve high removal efficiencies.

In this situation, it is unclear what liquid would serve as the solute and what its selectivity for radium would be. Radium sulfate is highly insoluble and would most likely have to be converted to a more soluble carbonate (bicarbonate) or chloride form for this process to be effective. Also, the problem of adequate liquid surface interfaces might retard the extraction process and it is unclear what mechanical or hydraulic methods would be required to ensure mixing and contact surfaces. Extensive treatability studies would obviously be required. The uncertainties and problems associated with large scale use of this technique removed it from consideration for additional studies.

2.3.7 Ex Situ Solidification/Stabilization

A well proven waste fixation and handling process used for radioactive wastes involves adding chemicals to solidify the waste. Solidification and stabilization reduce contaminant solubility and mobility through chemical changes and physically encapsulate non-reactive species. It improves handling by forming a solidified waste form, and reduces contaminant losses to transport media such as infiltrating water by decreasing the surface area of the waste medium. In solidification, a reagent is added to transform the waste into solid-like material. Wastes that exist as liquids or semisolids are often solidified to improve the handling and physical characteristics. The chemistry of the waste is not necessarily modified by solidification; however, the waste may be microencapsulated by the solidified matrix. In stabilization, a reagent is added to transform the material so that the hazardous constituents are in their least mobile or toxic form. Wastes that leach heavy metals or other contaminants are often stabilized to immobilize the hazardous constituents. Thermoplastic materials are generally more expensive to use than inorganic binding agents, but are more successful with some organic contaminants. Organic polymers generally consist of urea formaldehyde, polyacrylates, or polyacrylamides. They are designed to trap solid particles and allow some liquid to escape.

This is a very proven, non-controversial means for safely minimizing solid or liquid releases from sludges and soils during their transport to permanent disposal sites. For most waste forms, costs and schedules can be predicted and regulator and stakeholder buy-in is relatively easy to secure. There are, however, some concerns that would have to be overcome for this technology to be effectively utilized for the NFSS residues. Radon emissions would still be a problem with this technique, and there are uncertainties associated with solidification of materials (such as the NFSS residues) which contain high nitrate and sulfate content. In addition, the volume for transport and ultimate disposal include all the original wastes plus increases as a result of additives and swelling. Given the favorable rankings of these processes on other projects, they are recommended to be carried forward for additional studies and evaluations.

2.3.8 Ex Situ Polyethylene Glycol (PEG)

This extraction process involves a selective partitioning of fine particulates between two immiscible aqueous phases. The selective portioning of particulates is based on physicochemical interactions between the particle surface and the liquid phases, rather than on bulk phase properties such as density. Consequently, particle size should be small enough that particle settling due to gravity is slow compared to the rate of liquid/liquid phase separation.

This is an unproven technology for this type of waste and its effectiveness is questionable. While it might separate barium and radium sulfates from the other materials, it is unlikely to be able to separate barium from radium mix. To have any probability of success, extensive treatability studies would be required. Accordingly, it was not carried forward for future consideration.

2.3.9 Ex Situ Vitrification

Ex situ vitrification of radioactive wastes into glass logs, pebbles, or shards is increasingly being used on DOE mixed wastes. Vitrification processes destroy, immobilize, or remove wastes during the addition of high thermal energy. Gases generated by the process must be collected and treated before discharge. The final waste volume and mass may be reduced significantly by evaporation of moisture, combustion and/or decomposition of organic components, and consolidation of the waste into a dense glass matrix. While effective at solidifying and stabilizing certain forms of radioactive and hazardous waste, it does not reduce radioactivity. Vitrification will change the form of residues from a leachable sludge into an immobile solid - trapping radionuclides and preventing waste from contaminating soil, ground water, and surface water. The waste is not encapsulated or surrounded by the glass; it becomes part of the glass. Each waste atom is separately bound in the glass structure by a chemical bond.

Vitrification is the method being evaluated by Fernald as the treatment of choice for K-65 residues at that facility. As with any glass-making operation, the nature of the NFSS residues plays a critical role in cost-effective glass formation. While effective in vitrification within a silica matrix, the high water content of the K-65 residues coupled with the uncertainties of forming glass present unanswered questions. Fernald has had difficulties with its vitrification process but other systems across the DOE complex have worked successfully on other soil, sludge, and waste combinations. As this is a baseline technology for the comparable residues at Fernald, this technology will be carried forward as an alternative to be further tracked and evaluated.

2.3.10 Ex Situ Catalytic Extraction [Molten Metals Technology (MMT)]

Catalytic Extraction Processing (CEP), Molten Metals Technology's (MMT's) proprietary waste recycling technology, uses a molten metal bath to transform wastes into elemental products. Waste materials are introduced into the metal bath, where its catalytic and solvent properties dissolve molecular bonds, reducing compounds to elements. By adding select chemicals, these elements are reconfigured into raw materials for reuse or sale. The process occurs in a sealed system, avoiding the harmful emissions of conventional treatment methods. Molten Metals Technology claims its technology will safely and effectively reduce the volume of radioactive and mixed wastes. It is claimed that the molten metal bath separates radioactive components from non-radioactive elements, significantly reducing the volume of radioactive material. The manufacturer claims that radioactive elements are then sealed into a stable form for final disposal and non-radioactive elements are reconfigured into safe gases, ceramics, and metals.

MMT's CEP holds great promise, but it is unproven on material such as the K-65 residues. Radium will most likely go to the slag layer on the top of the molten metal and be as a soluble oxide that may require stabilization dependent on the slag form. A dedicated CEP unit would most likely be required and these are more expensive and complex than a vitrification unit. It is also unclear as to the timing of when this technology would be available and its schedule reliability for performing the separation. Accordingly, this process was not recommended to be carried forward for additional studies.

2.3.11 Deep Well, Underground Injection

The underground injection of hazardous and radioactive wastes is an old and controversial disposal method. Generally, this disposal technology places materials in well-confined geological formations that are deep below the surface and well removed from groundwater resources. Wells must be constructed in geologic formations beneath and isolated from groundwater drinking water supplies and the formation must have sufficient volume and porosity for permanent containment.

While this approach can be very cost-effective, it is highly controversial and would most likely not be accepted by regulators or stakeholders. Past incidences of well leakages to soil and water-bearing strata and the generation of abnormal seismic pressures make the use of this technique to manage the residue waste undesirable. Also, wastes that are viscous, like the K-65 residues, will foul the injection process and are usually not candidates for deep well injection without the addition of large quantities of liquids. It is not recommended that this approach be evaluated during future studies.

2.4 TRANSPORTATION

A variety of packaging combinations are available to the NFSS project. They fall into three major types: 1) Type A, 2) Industrial, and 3) Type B. There have been significant changes in the regulations since the original transportation evaluations were performed and reported in the 1986 Environmental Impact Statement for the NFSS K-65 residues, and since similar evaluations were performed for the Fernald K-65 residues. These changes (which took effect in April of 1996) increased the amount of radioactivity that can now be shipped per package, and added a new class function of packaging called "Industrial Packages" (IP's). The change in regulations also affected the classification of the waste. The residues can now be classified as Low Specific Activity (LSA) II material. This classification significantly increases the shipping options for the residues at NFSS.

2.4.1 Type A Package

For shipment of materials using Type A packages, the shipper must keep the total radioactivity in the package below the quantities specified in 49 CFR 173 for "special form" and "normal form" conditions. Package activity limits for special form and normal form shipments are specified using A1 (special form) and A2 (normal form) values. The Type A package is designed to contain less than the A1/A2 values of the material being shipped under normal conditions and maintain its integrity. The issue with the shipment of the residues in Type A Packages is the low A2 value for thorium-230. The low value drives the shipping packages to a smaller than optimal size. This drives up the cost of handling and transport of the waste.

2.4.2 Industrial Package

The industrial package is the new class function for shipping criteria-based wastes. It is not guided by A1 and A2 values, but by a concentration based number that is used to determine the level of container needed in shipment. This type of package has specific design criteria associated with it which means that the waste package can be optimized to fit those design criteria. The Industrial Package is the method of choice for the NFSS residues since it provides optimal flexibility and lower costs.

2.4.3 Type B Package

A Type B Package is one that will maintain its integrity under normal transport conditions and hypothetical accident conditions. This lets you ship higher level material, but it limits the amount of waste per shipment because the internal volume of this type of package is limited.

2.5 DISPOSAL SITES

2.5.1 Nevada Test Site (NTS), NV

The DOE Nevada Test Site's (NTS's) only limit on receipt of radioactive waste is that the material must contain less than 100 nanoCuries per gram (nCi/g) of transuranics. The K-65 residues do exceed 100 nCi/g of

Ra-226, but this material is not a transuranic waste and could be accepted by the facility for disposal. The material must meet NTS packaging requirements. As Industrial Packaging meets these requirements, NTS was identified as the disposal site best meeting all task requirements and conditions.

2.5.2 Chem-Nuclear, Barnwell, SC

The Chem-Nuclear Facility in Barnwell, SC can no longer accept non-compact waste and their License Limit is only 10 nCi/g for Ra-226. It is possible to petition the state to exceed the license limits, but Chem-Nuclear felt that they would not approve anything above 100 nCi/g.

2.5.3 US Ecology, WA

The US Ecology facility in Richland, WA can accept Ra-226 in concentrations up to 100 nCi/g with prior approval from the state. According to US Ecology there is no way the state would approve any higher concentrations, but there does exist a methodology for petitioning the state for a higher limit.

2.5.4 DOE Hanford, WA

The DOE Hanford Facility can accept the residues. However, due to restrictions on shallow land disposal at Hanford, the residues may have to be packaged to meet the waste acceptance criteria for the Waste Isolation Pilot Plant (WIPP). Reclassifying the material in this manner would require several steps being taken, including characterization and compliance plans for WIPP.

2.5.5 Envirocare, UT

The Envirocare facility in Clive, Utah has a license limit of 2 nCi/g for Ra-226. Due to the nature of Envirocare's charter (debris and bulky volumetric material of extremely low activity) it is unlikely that this limit could be exceeded.

2.5.6 Rio Algom, Ambrosia Lake, NM

Rio Algom Mining Corporation has submitted an unsolicited proposal to DOE to accept K-65 and other residue material from the FEMP. This proposal includes determining the feasibility of extracting valuable metals from the residues, and long-term retrievable storage of the residues in a tailings pile located at Ambrosia Lake, New Mexico, owned by a subsidiary of Rio Algom and licensed by the NRC.

Disposal of residues at this site would be subject to the approval of NRC, EPA, DOE, and the State of New Mexico and would need to be in accordance with the NRC license requirements regarding receipt of byproduct materials (11e.(2)) and limitations. The license amendment granted by NRC in May 1997 stated that Quivira Mining Company (a subsidiary of Rio Algom) can receive up to 10,000 yd^3 of 11e.(2) byproduct material per generator anually, not to exceed 100,000 yd^3 annually from all generators. The 100,000 yd^3 limit is to include in-situ facilities.

2.6   RANKING/SELECTION OF TECHNOLOGIES AND ALTERNATIVES FOR DETAILED EVALUATION

2.6.1 Evaluation Measures and Weightings

To perform the initial screening of possible technologies, processes, or techniques that might be effective in resolving the NFSS residues problem, a ranking of each technology against five criteria (or evaluation

measures) was performed. The criteria were established to parallel the nine CERCLA statutory remedy selection steps for feasibility studies. These criteria were combined and streamlined to present a more coherent set of rapid evaluation tools to gauge the effectiveness of each alternative. The evaluation measures included:

- Effectiveness in achieving the remediation recommendations of the NAS to permanently remove the high level residues from the NFSS site
- Technical feasibility
- Implementability
- Community/regulatory acceptance
- Cost-effectiveness
- Schedule confidence

For each of these five criteria or evaluation measures, a simple 3-tier ranking system was used to allow for quick comparison among the alternatives. These three levels ranked the alternative by its ability to 1) exceed, 2) simply meet, or 3) not meet the norms for that criteria measure. For example, each alternative's effectiveness in achieving the NAS remediation objectives was ranked whether it could 1) meet or exceed, 2) marginally meet, or 3) fail to meet the NAS recommendations. Likewise for the technical feasibility & implementability of a technology, it was ranked as to demonstrated capabilities to perform an NFSS remediation (i.e., ranging from proven commercially available technologies to unproven bench scale studies).

These rankings were done individually and then composited together with an overall ranking and recommendation as to each alternative's viability to be carried forward for more detailed evaluation.

2.6.2 Summary

Table 2-1 (NFSS Residue Remediation Comparisons) presents the results of this screening comparison. Colors have been added to aid the reader in quickly seeing the relative standing of each technology (e.g., green being high and favorable, red being low and unfavorable). The comparisons indicate that one approach appears best for removal, transportation, and ultimate disposal site, respectively: sequential excavation/removal, shipment in an industrial package, and disposal at NTS. Re-suspension and slurry transfer of the residues was also considered a potentially feasible removal technology, particularly since this technology was effectively used when the residues were transferred to the WCS. However, because the residues are in a different configuration (under several feet of waste and soil overburden), this technology would likely not be as effective as under the previous configuration (all residues together in a storage silo). However, this removal technology has not been dropped from future consideration.

For treatment, three alternatives were carried forward. Two were considered more technically feasible and cost-effective [1) ex situ solidification/stabilization and 2) vitrification]. The third, ex situ chemical extraction, may result in less material being shipped offsite for disposal if several technical barriers can be overcome.

To repeat our earlier caveat, this is not an exclusive list but a working tool of general observations after a 3-week effort. This listing may help in assessing the feasibility and relative costs of competing methods but should not be taken to represent a firm, final recommendation of one approach over another. That determination must await the more detailed screening analyses and evaluations will be conducted as part of a subsequent full feasibility study and remedial recommendation.

Table 2-1. NFSS Residue Remediation Comparisons

PHASE	TECHNOLOGY	EVALUATION						ALTERNATIVES FOR DETAILED EVALUATION
		Effectiveness	Feasibility	Acceptance	Costs	Timing	Overall	
Removal	Freeze Removal							
	Re-Suspension/Slurry							
	Sequential Excavation/Removal							
Treatment	In Situ Vitrification (ISV)							
	In Situ Chemical Separation							
	Ex Situ Air Flotation							
	Ex Situ Electrical Separation							
	Ex Situ Chemical Separation							
	Ex Situ Liquid Extraction							
	Ex Situ Solidification / Stabilization							
	Ex Situ PEG							
	Ex Situ Vitrification							
	Ex Situ Catalytic Extraction (M4)							
	Deep Well, Underground Injection							
Transportation	Type A Package							
	Industrial Package							
	Type B Package							
Disposal Sites	Nevada Test Site (NTS), NV							
	Chem-Nuclear, Barnwell, SC							
	US Ecology, WA							
	DOE Hanford, WA							
	Envirocare, UT							
	Rio Algom, NM							

LEGEND

EVALUATION MEASURE	TERMINOLOGY	RELATIVE SCALE
Effectiveness in achieving NAS remediation recommendations	Meets or exceeds	
	Marginal	medium
	Fails	
Technical feasibility & implementability	Proven, commercially available	
	Pilot scale, developing	medium
	Bench scale, unproven	
Community/regulatory acceptance	Ultimate acceptance	
	Lingering reluctance	medium
	Open hostility	
Cost-effectiveness	Much better than baseline	
	About equal to baseline	medium
	Much worse than baseline	
Schedule confidence	Better than planned	
	Normal construction uncertainty	medium
	Unsure or unknown	

3. EVALUATION OF SELECTED ALTERNATIVES

3.1 INTRODUCTION

After brainstorming and screening analyses, the alternatives selected for further evaluation included the following:

- Alternative 1 - Excavation, ex situ vitrification, and disposal at NTS
- Alternative 2 - Excavation, solidification with polymers, and disposal at NTS
- Alternative 3 - Excavation, chemical extraction of radium and barium, and storage of concentrated residues at ORNL (or other similar facility)

As discussed in Section 2, the alternatives screening resulted in a single most favorable method for excavation. Thus for the evaluations described below, the excavation and residue removal process is similar across all of the alternatives. Transportation and disposal are common for Alternatives 1 and 2, with transport as an LSA shipment in an industrial package (shielded for K-65 residues) container and disposal at NTS as the preferred options. For Alternative 3, the concentrated radium/barium material would be taken to a facility (such as ORNL) with the capability to handle highly radioactive material. The waste stream from Alternative 3 would either go to NTS, or preferably stay onsite. The main difference between the alternatives is how the residues are treated after excavation and prior to disposal. As described in Section 2, the three most favorable treatment methods were vitrification, solidification/stabilization, and chemical extraction. Evaluations of each alternative (including a description of the alternative, feasibility of the alternative, and overall cost associated with the alternative) are provided in the following sections.

3.2 ALTERNATIVES EVALUATION

3.2.1 Alternative 1 - Excavation, Ex-situ Vitrification, and Disposal at NTS

Alternative Description

This alternative is based on the vitrification alternative being proposed by Fernald for the K-65 waste stream. Modifications have been made to include site-specific excavation and removal, vitrification information from several vendors, and recent changes in transportation regulations.

Under Alternative 1, the NFSS disposal cell will be opened by removing the interim cell cover from the area where the residues are placed. Top soil will be discarded. The site (central ditch and roads) may be reconfigured to provide operating and storage areas. Clay will be stockpiled for reuse. The excavation will be sequential, with both top and side excavation mechanical methods being considered. The costing is based on excavation from the top. The area of excavation will be limited to reduce radon emissions and to reduce the radiation dose rates to workers. Initial removal of the topsoil and cap will be conducted using standard construction methods with health physics monitoring. It is expected that about one-third of the WCS cover will be removed in order to extract the residues. As the cover excavation operation nears the level where the residues are contained, the level of protection for workers will increase. During excavation of the K-65 residues, workers will use fresh air supplied breathing systems (Level A or Level B protection). A building or containment structure with an off-gas control system will be used to minimize the potential for airborne releases of radon and contaminated dust.

The residue streams will be kept separate to the extent possible. Because of the sand buffers and geomembranes that were installed, it is estimated that up to approximately 99 percent of the K-65 material can

be excavated. Some materials such as contamination on silo rubble and material in drums that were reused will remain in the WCS. The K-65 material contains a large slime fraction (<400 mesh) and a sand fraction. The material is expected to contain a large water content and have the consistency of peanut butter. The L-30/F32 mixed stream will be excavated in a similar manner. Greater than 90 percent removal is expected for these residues. The L-50 residues are contained within the former Building 413 and 414 treatment plant basins. These residues will also be excavated with an expected removal efficiency of greater than 90 percent.

Ex situ vitrification would be conducted in a unit constructed and operated onsite. The design would build on experience from the unit at Fernald and other vitrification facilities. The following general vitrification plant characteristics represent a range of assumptions based on conversations with vitrification vendors, and Fernald personnel:

- Size of melter should be 20 to 30 tons per day.

- Length of the vitrification campaign would range from approximately 3 to 8 years for all the residues (depending on the size of the melter and efficiency of operation).

- Waste loading would be approximately 50 to 80 percent.

- Labor cost would be approximately $130,000 to $152,000 per month.

- Chemical costs would be on the order of $40 to $500/ton of glass.

- Capital costs to design, build, and startup are estimated to be in the range of $22 to $80 million (per melter unit).

It is assumed that limited glass forming additives would be required and that the glass product would be in the form of pellets, gems, or a monolith. Offgas control equipment would be required, and the melter unit and support equipment would not be re-used but rather buried at NTS.

Transportation will be in IP-2 industrial packaging for LSA Type 2 material. Each package will contain about 10,000 pounds of waste material. Shielding will be provided for the K-65 residue shipments. It is expected that approximately 2,670 containers will be needed to transport all of the vitrified residues to NTS. Use of the IP-2 packages will allow transport of all residues in 850 shipments. For this evaluation, the transportation mode is assumed to be by truck. It is possible that a mixed mode of truck and rail could be performed at a reduced rate. Disposal is assumed to be at NTS in shallow land burial.

Feasibility and Cost

Vitrification is technically feasible for the residues. There are two scoping costs for Alternative 1 which are referred to as Alternative 1A (all residues) and 1B (K-65 residues) [see Figure 3-1]. Based on the ongoing work at Fernald and recent conversations with several vitrification contractors, vitrification of all of the NFSS residues could take from approximately 3 to 8 years.

Discussions with vitrification vendors and Fernald personnel indicated that a wide range of costs and operating parameters can be assumed for vitrification of the NFSS residues. A range of estimated costs was developed based on vender estimates and Fernald experience (see Figure 3-1). Based on vendor estimates, the cost to vitrify all of the NFSS residues could range from approximately $101 million to $235 million. Based on Fernald data (scaled to the FUSRAP NFSS site conditions), the estimated cost to vitrify the residues would be approximately $400 million. This wide range of costs provides a good indication of the uncertainty associated with the vitrification option. Additional characterization and treatment studies will be essential to reduce the

Figure 3-1. Alternative Analysis - Cost Estimate Results
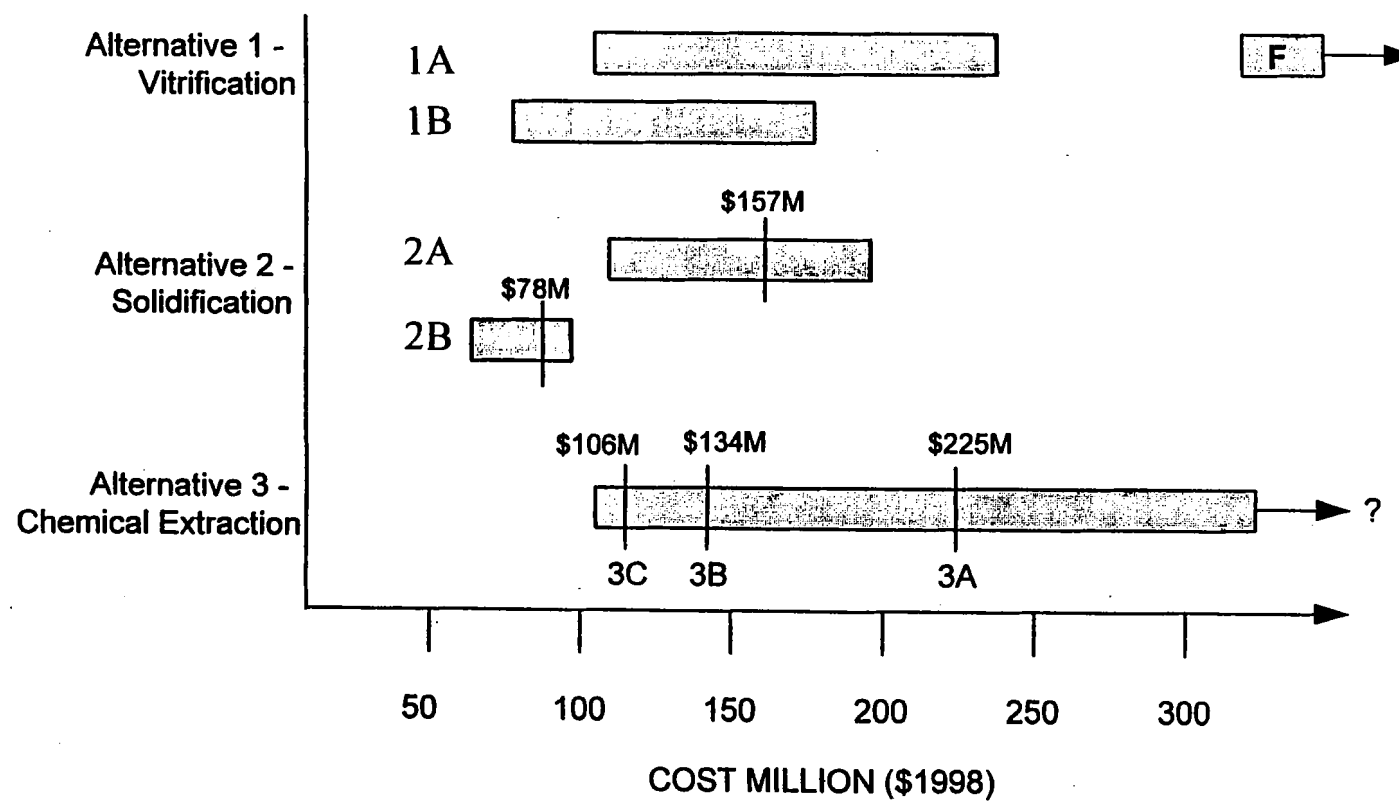
uncertainty associated with the cost of vitrification of the NFSS residues. Detailed cost estimates for all these alternatives are provided in Appendix D.

An option to vitrify only the very high radium concentration K-65 wastes (Alternative 1-B) was considered as a subset of Alternative 1. This option would include removal and vitrification of the K-65 residues, but would leave the other residues onsite with ultimate disposal in the final WCS. While this option does not comply with the NAS recommendation to remove all residues, it does provide for some interesting comparisons. The range of costs for this option is $74 million to $172 million. Under this option, the most hazardous materials (K-65 residues) would be removed at a cost that is significantly less than the cost to vitrify all of the residues. The residues that remain are similar in total curie content and average Ra-226 concentration to closed uranium mill tailings sites. Disposal of these residues in the NFSS WCS under a long-term cap can be demonstrated to be similar to UMTRAP sites in terms of public health protection. This option is discussed in more detail in Section 4.

3.2.2   Alternative 2 - Excavation, Solidification with Polymers, and Disposal at NTS

Alternative Description

For Alternative 2, excavation and transportation is similar to alternative 1 and will not be discussed further.

After excavation, solidification would be performed ex-situ at a plant on site. A range of solidification agents is possible, e.g., bitumen, cement with stabilizers, resin, and inorganic polymers. Expansion of the waste (both volume and mass) can range from a few percent to approximately four times the original size. For evaluation purposes a range of volume increases from 100 percent to 300 percent has been assumed. Mixing of the residues would be done in a blade-type mixer and the product would be cast directly into the IP-2 shipping containers. It is expected that approximately 10,500 containers will be needed to transport all of the solidified residues to NTS. Use of the IP-2 packages will allow transport of all residues in approximately 3,400 truck shipments.

Transportation and disposal would be similar to the first alternative, though larger in scale.

Feasibility and Cost

For purposes of eliminating contamination by dust losses the process of stabilization by solidification has been used with success. In this process the residues are mixed with a solidifying agent which causes the residues to "set" into a compact mass. The process has several undesirable properties, i.e., (1) the actinides are not removed from the residues and (2) the total mass and volume of the treated material increases. However the process does render the residues into a form suitable for shipment. Depending on the solidification process chosen, the emission of radon gas may or may not be attenuated (but not eliminated). A laboratory study would be required to determine the best stabilization process for this alternative.

The costs to solidify and dispose of all the residues under Alternative 2 range from $114 million to $191 million, with a best estimate of $157 million. There are two scoping cost estimates for Alternative 2 which are referred to as Alternative 2A (all residues) and 2B (K-65 residues) [see Figure 3-1]. The cost is highly dependent on the volume increase and the type of solidification agent. The low end of the range shown is based on 100 percent expansion using a concrete-like matrix, while the high end of the range is based on use of more expensive polymer agents, with an estimated expansion of approximately 200 percent. The best estimate value of $157 million is based on use of a polymer agent, with an expansion of 100 percent. Because of the sulfates, nitrates,

and other salts present in the residues, it is expected that the more expensive polymer solidification agents will be necessary to meet regulatory requirements.

As with Alternative 1, an option to solidify only the K-65 residues was also evaluated. Under this option (Alternative 2B) the other residues are assumed to stay onsite. The cost to implement this modified alternative ranges from approximately $66 million to $93 million with a best estimate of $78 million (based on the same assumptions used for the discussion above for solidification of all residues). This represents a savings of approximately $79 million compared with the Alternative 2A best estimate, and brings the estimated cost within the DOE 10-year plan target range of 50 to 100 million dollars. Detailed cost estimates for Alternatives 2A and 2B are shown in Appendix D.

3.2.3 Alternative 3 - Excavation, Chemical Extraction of Radium and Barium, and Storage of Concentrated Residues at ORNL

Alternative Description

Under Alternative 3, excavation and removal from the WCS is similar to Alternative 1.

After excavation and removal, the residues would be moved to a facility onsite for chemical extraction of the radium from the K-65 residues. The other residues would be solidified as in Alternative 2. The chemical extraction would be based on a process similar to those investigated and dropped by previous companies (as discussed in detail in Appendix C). This alternative would separate the radium and barium from the slime fraction (approximately 70 percent of the K-65 residues) and process the waste from the extraction through evaporation and solidification. It is assumed that a large portion of the treatment waste stream would have to be disposed of offsite (50 to 100 percent for cost estimating). Figure 3-2 shows a block diagram of Alternative 3.

The process is likely to include the following steps: sodium carbonate addition to metathesize the radium and barium sulfates to carbonates; acid chloride leach to remove lead; solubilization of the carbonates in acid; evaporation to remove the large volumes of water, and solidification of the waste sludge from evaporation. If radium is the desired product then an additional step such as fractional distillation is needed to separate the barium from the radium. If possible, the waste from the residue treatment would be returned to the disposal cell. This assumes that the concentration of Ra-226 in the waste stream is low enough to be acceptable to state regulators (and possibly the NAS). The Hazen research conducted in 1974 indicated that recovery of radium would likely be less than 80 percent. If removal of radium from the K-65 residues is 80 percent or less, then the residual waste from treatment would contain 200 Ci or more Ra-226, with an average concentration which is likely greater than the concentrations in the other residue streams that the NAS recommended removing.

As indicated above, disposal of the waste stream would be in the NFSS disposal cell (WCS) to the greatest extent possible. The radium/barium concentrate would be transported to Oak Ridge in a heavily shielded container for storage in the isotope storage facility.

Feasibility and Cost

There are three ballpark cost estimates for Alternative 3 which are referred to as Alternative 3A (all residues), 3B (all K-65 residues), and 3C (disposal of 50 percent of the K-65 residues) [see Figure 3-1].

Appendix C contains a detailed discussion of chemical treatment of the NFSS residues. The most successful treatment employed thus far was conducted by Hazen Research Inc., under contract to Cotter Corporation. The process is discussed by Battelle in their report of May 15, 1981 to DOE. Flow sheets describing the processes reviewed by Hazen are included in Appendix C.

**Figure 3-2. Modified System to Achieve Some Resource Recovery
(Blocked Diagram of Alternative 3)**
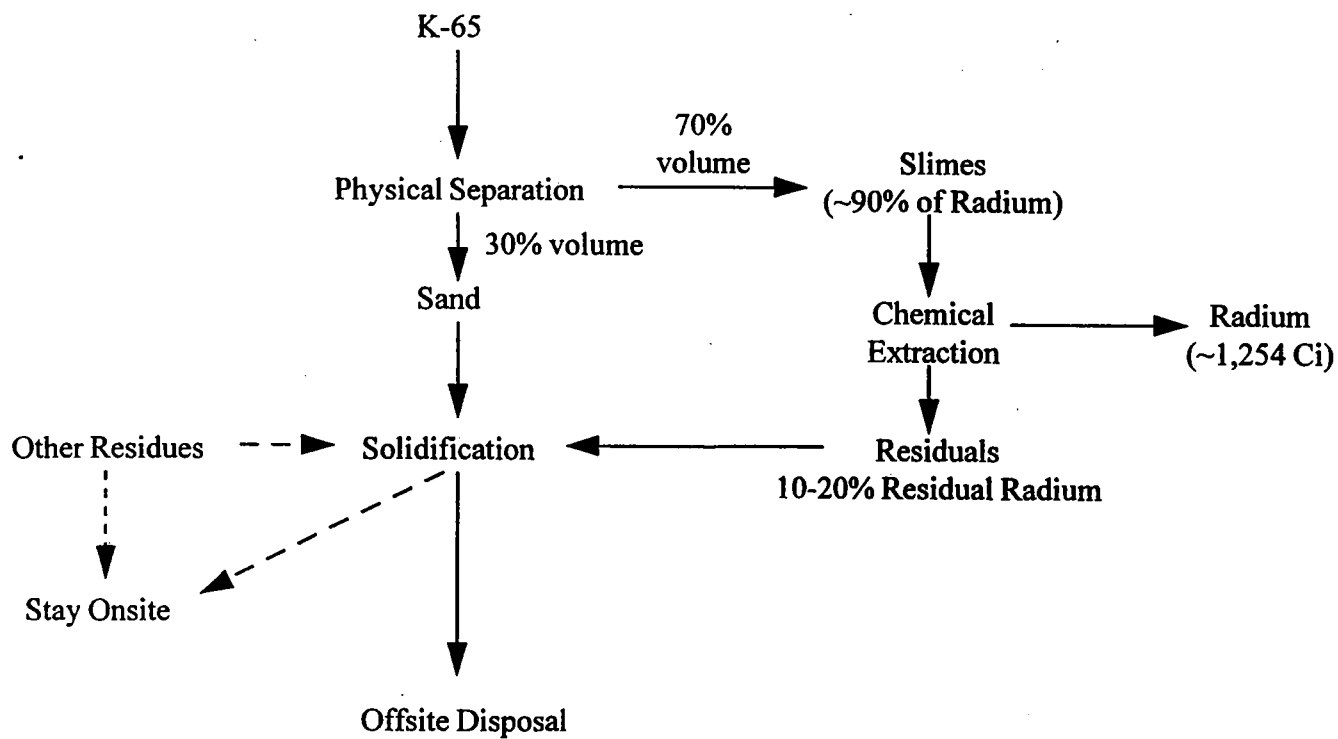
Hazen's work had as its purpose the removal of a discrete lead product (for concentration of polonium), a precious metals concentrate, and radium in solution. These products would be sold to defray the costs of the process. At the time of the test work the ultimate goal of the research was the recovery of the nickel and cobalt values. Separation of the actinides was necessary from a marketing point of view as well as for the potential value of these materials. Battelle discussed the flow sheet and pointed out several serious flaws that would make the circuit inoperable (including the generation of large volumes of liquid waste).

Any chemical treatment to extract radium must also extract barium, as these two elements were co-precipitated during the production of the residues and they have very similar chemical characteristics. The market for polonium is inadequate to dedicate a process flow step for lead recovery, as any equipment employed would subsequently be useless. Similarly, precious metals are present in low concentrations and processing to recover them would be uneconomical.

The principal investigator for Hazen believes that no more than 80 percent of the radium could be removed from the residues. Battelle believes that even less than this could be recovered due to the failure of this process to remove radium from the "sand" or coarse fraction of the residues. There is no doubt that chemical extraction by chloride, carbonate or perhaps chelating agent leaching could produce a solution or precipitate of a technical grade radium salt, given that anything can be done if enough resources are devoted to the project. A costly research and development effort would likely be required to develop a process that will assure success. No such process exists at the moment, however, the unit cost of treating a relatively small amount of material such as the 11,000 m³ at the NFSS would be extremely high due to circuit complexity.

For cost estimating, it has been assumed that under Alternative 3A (extraction of all residues), and 3B (extraction of just the K-65 residues) 100 percent of the waste stream must be solidified and shipped offsite to NTS. Alternative 3C is the same as Alternative 3-B, with the assumption that only 50 percent of the waste stream must be shipped offsite for disposal.

Because no process has been developed and demonstrated that could be used to extract the barium and radium from the residues on an industrial scale, estimating costs is very uncertain. A very preliminary estimate of cost has been prepared using data from a scoping study for radium separation from the NFSS K-65 residues prepared by the National Lead Company of Ohio in 1978 as a starting point. The chemical extraction process described in this reference was scaled up based on the size of the facilities required for Alternative 2, and estimated equipment costs from this reference were escalated to $1998 and doubled.

For Alternative 3A (extraction of all residues), the estimated cost is $225 million. This assumes that 100 percent of the waste stream from chemical extraction must be evaporated, solidified, and disposed offsite. Alternatives 3-B and 3-C are the same except for the amount of waste disposed offsite. Estimated cost for Alternative 3-B (extraction from only the K-65 residues, and disposal of all waste offsite is approximately $134 million. If only 50 percent of the waste from K-65 extraction is disposed offsite, the estimated cost drops to approximately $106 million. It should be noted that the cost estimates associated with Alternative 3 are the most uncertain cost estimates in this analysis. They are based on very broad assumptions (including that a process can be developed which will work on an industrial scale), and should be treated as "ballpark" estimates only. The uncertainty in the Alternative 3 estimates could easily be ± 100 percent. In addition, at this time no costs have been included for transport, storage and maintenance of the highly concentrated radium/barium material.

3.3 EVALUATION SUMMARY FOR COMBINED ALTERNATIVES

The purpose of the overall comparative evaluation of alternatives is to provide an assessment of each complete alternative (including excavation, treatment, and disposal options) against the other alternatives. From

this evaluation, the decision makers can determine if sufficient information is available to select the preferred alternative, or if one or more alternatives should be carried forward into a more detailed Feasibility Study-type analysis.

To assist in the overall combined alternatives evaluation, a more detailed (but qualitative) technical review was performed of the general treatment technologies (vitrification, solidification, and chemical extraction) used in the three alternatives. The results from this technical review are summarized in Table 3-1. These results, and the results from the cost analyses were factored into the overall combined alternatives analysis discussed below.

The alternatives discussed in Section 3.2 are compared in this section using the general evaluation criteria of effectiveness, implementability, and cost. The effectiveness criteria is primarily a measure of if and how well the alternative meets the conditions of compliance with NAS recommendations and DOE's 10-year plan. The implementability criteria provides a measure of how difficult the alternative is to implement, and how likely it is to work for the NFSS conditions (i.e., has the alternative been demonstrated to work in other, similar remedial actions). Costs for each alternative are compared on the basis of the 10-year plan cost in $1998.

Table 3-2 provides a summary of the comparison of effectiveness, implementability, and cost for each of the options. For completeness, the vitrification and solidification alternatives have been shown with an option to address only the K-65 residues (option B in each case). While these options score low in terms of effectiveness due to not meeting the complete current NAS recommendation, the cost differential associated with this partial removal option is significant, and may warrant further discussions with the NAS.

Alternatives 1A, 2A, and 3A include removal of all residues and are thus effective in terms of compliance with the major NAS recommendation. Alternatives 1B, 2B, and 3B are not effective in meeting the complete (current) NAS recommendation to remove all residues. However, they are effective in terms of removal of the most hazardous (K-65) residue stream.

Both of the vitrification alternatives (1A and 1B) are considered implementable, but very uncertain from both a technical and cost perspective. This qualification to implementability is based primarily on discussions with Fernald personnel involved in constructing and starting up the FEMP OU-4 vitrification facility. Solidification (Alternatives 2A and 2B) is considered implementable with lower technical uncertainty. The implementability of chemical extraction is considered extremely uncertain (almost unknown) at this point. No processes have been found that show demonstrated success on an industrial scale, and thus this option is considered the least likely in terms of implementability.

The solidification alternatives (2A and 2B) appear to be the most cost effective. Alternative 2A is estimated to cost $157 million (best estimate), which is outside the upper bound of the target cost range ($50 to 100 million) assumed for this study. However, if agreement could be reached with the NAS on removal of K-65 residues only, Alternative 2B would fall in the middle of the target range at $78 million. The vitrification alternatives for all residues were estimated to cost greater than $100 million, ranging from $101 million to $235 million based on vendor estimates, and up to approximately $400 million based on Fernald data. For vitrification of K-65 residues only, the range of cost is estimated as $74 million to $172 million. Sufficient data is not available at this time to develop a cost estimate for chemical extraction that is on the same level of confidence as those for vitrification and solidification. However, using the available data from historical documents, a cost range of $106 million to $225 million was estimated (not including transport, storage, and maintenance of the radium concentrate in Oak Ridge).

Table 3-1. Initial Technical Assessment of General Treatment Technologies

Assessment Criteria	Alternative 1 Vitrification	Alternative 2 Solidification	Alternative 3 Chemical Extraction
Volume to Offsite Disposal	~40%	100-300%	50-100%
Volume Left Onsite	0	0	50-100%
Proven on this Type of Waste?	yes	yes	no
Pass TCLP (probability)	high	moderate	low
Radon Emission (during process)	high	moderate	high
Long-Term Radon	low	moderate	moderate/high
Long-Term Stability	high	moderate to low	low
Long-Term Maintenance	low	moderate	high
EPA Acceptance	high	moderate	low?
Resource Recovery	low	moderate	high

Table 3-2. Summary of Combined Alternatives Evaluation

Criteria	Alternative 1-A Vitrification of all Residues	Alternative 1-B Vitrification of K-65 only	Alternative 2-A Solidification of all Residues	Alternative 2-B Solidification of K-65 only	Alternative 3 Chemical Extraction of Radium/Barium (includes A, B, and C)
Effectiveness	Effective in complying with NAS recommendations Does not fit within DOE 10-year plan	Not completely compliant with NAS recommendations (in present form) Fits within DOE 10-year plan	Effective in complying with NAS recommendations Fits within DOE 10-year plan	Not completely compliant with NAS recommendation (in present form) Fits within DOE 10-year plan	Effective in complying with NAS recommendations (3A, 3B, and 3-C do not meet NAS requirements) Uncertain if will meet DOE 10-year plan
Implementability	Implementable, but high level of technical and cost uncertainty based on Fernald experience Not yet successfully demonstrated on residue material	Implementable, but high level of technical and cost uncertainty based on Fernald experience Not yet successfully demonstrated on residue material	Implementable, lower technical uncertainty	Implementable - lower technical uncertainty	Unknown if implementable process can be developed on an industrial scale Very high technical uncertainty - not demonstrated previously
Cost	$101 M - 235 M	$74 M - 172 M	$114 M - 191 M best estimate: $157 M	$66 M - 93 M best estimate: $78 M	Cost range approximately $106 M to $225 M, but very uncertain and does not include cost of transportation and storage in Oak Ridge

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Based on the information obtained during this study (as summarized in Section 3.3) solidification of the residues appears to offer the most cost-effective method for meeting the NAS recommendation to remove the residues, and to fit into the DOE 10-year plan schedule. Alternative 2A (excavation, solidification, and disposal at NTS) probably should be used as the best estimate for NFSS residues remediation for the current DOE 10-year plan. However, because both vitrification and chemical extraction offer advantages not available through solidification, these alternatives should be more thoroughly evaluated before the NFSS remediation strategy is finalized. In particular, chemical extraction may offer future benefits which cannot be adequately quantified using data available today. As part of this study, the following facts have been obtained relating to the future value of chemical extraction of radium:

- There is little if any market for radium and its daughters at present.

- Currently a number of studies are underway at such organizations as the National Institutes of Health (NIH) and others in which the treatment of certain tumors will require radium or its daughters. Results of these studies are sufficiently positive to cause the NIH investigators to inquire as to where they may get larger amounts of radium or its daughters.

- A recent inventory of radium resources in the U. S. has concluded that there are only two significant resources in this country: these are the K-65 wastes at Fernald, OH (FEMP) and Lewiston, NY (NFSS).

- The investigation of processes to recover radium from the K-65 wastes essentially ended in the early 1970s. However, since the early 1990s, renewed interest in developing these processes has been noted.

This study has been able to evaluate only the early radium recovery schemes developed up until the early 1970s, none of which were successful on an industrial scale (and not very successful on a bench scale). Even if these processes were effective in recovering radium compounds the economic justification for doing so does not exist at present. However, several processes for the recovery of radium have been developed in the post-1991 period. It is not known how successful these processes are, or if they are the only such processes available. Because of these recent events, recommendations are included below to continue investigation of ongoing research in radium extraction in parallel with the stabilization and disposal actions suggested in this report.

4.2 RECOMMENDATIONS

Followup actions presented below are recommended by the technical working group:

1) Because of the complex nature of any remedial action conducted on the NFSS residues, the environmental analyses, treatment studies, and preliminary remedial action design work necessary to support remedial actions should be initiated as soon as possible.

This effort should include continued additional analyses necessary to support selection of the final preferred alternative for the NFSS residues. Until such further analyses are conducted, none of the alternatives or technologies discussed in this report should be considered completely eliminated from consideration.

As part of this effort, it is recommended that FUSRAP representatives (DOE, BNI and SAIC) visit Fernald and take the necessary time to collect as much information as possible concerning experience with vitrification of the K-65 residues at that site. Numerous telephone conversations have been held with Fernald personnel during this study, but schedule constraints prevented visiting the Fernald site during this effort. Such an extended site visit would offer the opportunity to collect valuable information on available characterization and treatment studies data, current plans for Fernald activities, lessons learned, and cost data.

2) Additional characterization data on the residues is necessary prior to final selection of any of the three alternatives evaluated in this study. A unique opportunity exists for FUSRAP to participate in a planned characterization sampling event at Fernald during FY97. FEMP personnel plan to take additional samples from Silo 2 in order to gain additional characterization data to support vitrification work. At this time they do not plan to enter Silo 1. Silo 1 contains residues that are almost identical to the NFSS K-65 residues. FUSRAP should quickly investigate the possibility of participating (sharing funds) in this characterization effort, and in particular, expanding the effort to include collection of samples from Silo 1 for FUSRAP treatability studies.

The following data should be included in any characterization study:

- Sieve analysis and radium, uranium, and thorium activity by sieve size for +4, -4+20, -20+100, -100+200, -200+400, and -400 mesh waste particle sizes.

- Moisture content

- pH

- Oxidation/reduction potential

- Qualitative and quantitative determination of all cations and anions, metals, and oxides.

- Mineralogical examination and determination of all minerals present.

- Chemical form of radium, uranium, and thorium compounds present.

- Cation exchange capacity.

- Atterberg limits-liquid and plastic limits, optimum moisture content, etc.

- In-place density.

- Determination of total organic compounds.

- Determination of volume of radon present per volume of waste.

- Determination of total RCRA metals and TCLP from 40 CFR 268, Appendix 1 for 8 metals and 31 organic analyses.

- Gamma, Beta, and X-ray activity levels on the surface of waste containers from which samples were taken.

3)   Continue investigation of the ongoing research activities regarding beneficial use of Ra-226, and chemical extraction of radium from the residues. Preliminary contacts have indicated that research is ongoing at the NIH, which if successful, could cause some increased demand for radium for use in cancer treatment. Presuming that the radium content of the K-65 wastes may become a valuable national resource in the near future, an individual within FUSRAP should be designated to maintain current knowledge of all potentially applicable radium recovery techniques. Contacts should be maintained with the individual in DOE who is in charge of maintaining a database of processes for the treatment of such wastes (Jerry McClure of DOE in Germantown, Maryland). In addition, contact should be maintained with individuals at Hanford who are maintaining the National Inventory of Sources of Radium. (This effort was started in June of 1996, and is being coordinated by Robert Schenter).

4)   Presuming that the K-65 wastes may become a valuable national resource in the future, proceed with the stabilization processes recommended in this report, keeping in mind that these wastes may become an "ore" of radium, and may require recovery in the future. Inappropriate modes of stabilization (such as vitrification) and disposal (such as very deep burial in a remote location) may make the extraction of the radium content of these residues difficult to impossible.

5)   Consider development of a strategy to revisit the NAS recommendation to remove all residues offsite. From the results of this study, it appears that a good case can be made that removal of only the K-65 residues will provide for protection of public health, will result in substantial cost savings, will allow completion of the work within the DOE 10-year plan, and is supported by ample precedent in UMTRAP. With regard to the precedent issue, Table 4-1 provides a summary of the radiological characteristics of inactive uranium mill tailings piles. This table shows that for these inactive tailings piles, the maximum Ra-226 concentration ranges from 120 to 5,400 pCi/g, and the total remaining Ra-226 activity ranges from 20 to 2,130 Ci. For the non-K-65 residues at NFSS, Ra-226 average concentrations are 300 pCi/g for the F-32s, 3,300 pCi/g for the L-50s, and 12,000 pCi/g for the L-30s, representing a total Ra-226 activity of 93 Ci.

Table 4-1. Radioactivity in Inactive Uranium Mill Tailing Piles

Location	Amount of Tailings (Millions of Tons)	Area of Tailings (Acres)	Average Ore Grade[a] ($\%$ U_3O_8)	Radium-226[b] Average Concentration (pCi/g)	Radium-226[c] Maximum Measured Concentration (pCi/g)	Radium-226 (Ci)	Radon-222[d] Assumed Release Rate (Ci/y)	Radon-222 Estimated Release Rate (pCi/m²s)	Radon-222[e] Measured Release Rate (pCi/m²s)
Monument Valley, Arizona	1.2	30	0.04	50	1,300	50	200	50	14-29
Tuba City, Arizona	0.8	22	0.33	920	1,880	670	2,600	920	11-400
Durango, Colorado	1.6	21	0.25	700	1,800	1,200	1,900	700	35-310
Grand Junction, Colorado	1.9	59	0.28	780	1,800	1,350	5,900	780	25-660
Gunnison, Colorado	0.5	39	0.15	420	1,100	200	2,100	420	480
Maybell, Colorado	2.6	80	0.098	270	600	640	2,800	270	75-100
Naturita, Colorado	0.0	(23)	Tailings pile has been moved, only residual contamination remains					1-124	
New Rifle, Colorado	2.7	32	0.31	870	1,900	2,130	3,600	870	70-1,400
Old Rifle, Colorado	0.4	13	0.36	1,000	5,400	320	1,700	1,000	210-1,300
Slick Rock (NC), Colorado	0.04	19	0.28	780	350	30	1,900	780	4-250
Slick Rock (UC), Colorado	0.35	6	0.25	690	120	70	500	690	6-24
Lowman, Idaho	0.09	5	0.19	530	240	10	300	530	50-150
Ambrosia Lake, New Mexico	2.6	105	0.23	640	900	1,520	8,600	640	40-300
Shiprock, New Mexico	1.5	72	0.25	700	4,000	950	6,400	700	53-160 (g)(440-1200-2200)
Belfield, North Dakota	(h)0	(i)7.5	-	-	-	-	-	-	1.3-63
Bowman, North Dakota	(h)0	(i)12	-	-	-	-	-	-	48-94

See footnotes at end of table.

Table 4-1 (continued)

Location	Amount of Tailings (Millions of Tons)	Area of Tailings (Acres)	Average Ore Grade (a) (% U_3O_8)	Radium-226 (b) Average Concentration (pCi/g)	Radium-226 (c) Maximum Measured Concentration (pCi/g)	Radium-226 (Ci)	Radon-222 (d) Assumed Release Rate (Ci/y)	Radon-222 Estimated Release Rate (pCi/m²s)	Radon-222 (e) Measured Release Rate (pCi/m²s)
Lakeview, Oregon	0.13	30	0.15	420	420	50	1,600	420	187-710 (j)(3-31)
Canonsburg, Pennsylvania	0.4	18	-	-	4,200	-	-		185-296
Falls City, Texas	2.5	146	0.16	450	160	1,020	8,400	450	3-78
Green River, Utah	0.12	9	0.29	810	220	20	900	810	32-128
Mexican Hat, Utah	2.2	68	0.28	784	1,900	1,560	6,800	784	16-1,600
Salt Lake City, Utah	1.7	100	0.32	900	2,000	1,380	11,500	900	(k)1-20 (l)(130-300-650)
Converse County, Wyoming	0.19	5	0.12	340	650	60	200	340	190-2,860
Riverton, Wyoming	0.9	72	0.20	560	1,100	(m)544	5,100	560	50-80
Total	24.42	970.5				13,774	73,000		

NC North Continent pile.   UC Union Carbide pile.

(a) Phase II Reports (FB76-78).

(b) Calculated from average ore grade, assuming 700 pCi/g per 0.25%.

(c) Phase II Reports (FB76-78). Value shown is for highest reported soil, sediment, or tailings sample. Tailings were not sampled in all cases.

(d) Calculated from average radium-226, assuming 1 pCi/m²s of radon-222 is released (annual average) for each pCi of radium-226 per gram of tailings.

(e) Phase II Reports (FB76-78), unless indicated otherwise.

(f) Pile has been removed from site; only residual amounts remain.

(g) Bernhardt, et al. (Be75), reported values ranging from 590 to 1,320 pCi/m²s for uncovered and 440 to 2,200 pCi/m²s for stabilized tailings.

(h) Residual contamination only.

(i) Area within site boundaries.

(j) Bernhardt, et al. (Be75), reported values for stabilized tailings ranging from 3 to 31 pCi/m²s.

(k) Measurements by FBDU are based on a sample of tailings in a barrel, with varying moisture contents.

(l) Bernhardt, et al. (Be75), reported values for 11 sites ranging from 130 to 650 pCi/m²s, with a median of about 300 pCi/m²s. Measurements by Bernhardt indicated overlapping ranges of radon release rates for uncovered and covered (up to several feet) tailings.

(m) Sw76.

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5.0 REFERENCES

Battelle 1981. *Preliminary Assessment of Alternatives for processing and disposal of the AFRIMET Residues* (Final), May.

BNI 1994. *Failure Analysis Report for the Niagara Falls Storage Site, Lewiston, New York* (Draft), November.

DOE 1986. *Final Environmental Impact Statement: Long-Term Management of the Existing Radioactive Wastes and Residues at the Niagara Falls Storage Site*, (Final) DOE/EIS-0109F, Washington, D. C., April.

National Research Council 1995. *Safety of the High-Level Uranium Ore Residues at the Niagara Falls Storage Site, Lewiston, New York*, Washington, D. C.

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APPENDIX A: SUMMARY OF AVAILABLE NON-RADIOLOGICAL CHARACTERIZATION DATA FOR THE RESIDUES

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Concentrations of Nonradiological Elements in the NFSS Residues[1],[2]

Element	K-65 Average	K-65 Range	L-30[3] Average	L-30[3] Range	L-50 Average	L-50 Range	Weighted Average[4]
Arsenic	5	--	27	15-50	31	20-50	2
Barium	30,000	--	6,100	1,900-20,000	20,000	--	15,000
Boron	300	--	140	100-200	100	--	172
Cadmium	<5	--	<1	--	<1	--	2.1
Cerium	2,000	--	1,200	1,000-1,500	240	200-300	1,200
Cesium	1	--	1.4	1-2	0.71	0.5-1	1.2
Chromium	100	--	244	200-300	140	100-200	180
Cobalt	2,000	--	5,100	2,600-10,000	7,700	5,900-10,000	4,700
Copper	500	--	2,300	1,100-5,000	2,400	2,000-3,000	1,800
Fluorine	30	--	39	30-50	50	--	37
Gold	0.2	--	0.37	<0.2-0.7	<0.2	--	0.28
Iodine	1	--	0.35	0.3-1	0.55	0.3-1	0.68
Iron	5,000	--	26,000	10,000-66,000	20,000	--	19,000
Lanthanum	2,000	--	1,000	--	220	100-500	1,100
Lead	56,000	33,000-95,000	13,000	7,500-23,500	4,900	3,200-7,600	23,000
Lithium	100	--	200	--	200	--	170
Manganese	100	--	31,000	20,000-50,000	71,000	50,000-100,000	30,000
Molybdenum	10,000	--	860	500-1,500	300	--	3,300
Mercury	0.5	--	0.3	--	0.5	--	0.5
Neodymium	1,000	--	160	50-500	100	--	390
Nickel	3,000	--	17,000	6,200-50,000	24,000	20,000-30,000	14,000
Niobium	50	--	24	20-30	14	10-20	30
Palladium	20	--	3.5	2-6.2	2.4	2-3	8
Platinum	<0.5	--	0.32	0.2-<0.5	<0.5	--	0.41
Praesodymium	2,000	--	55	20-150	24	20-30	590
Selenium	100	--	50	--	39	30-50	62
Silver	<3	--	1	<0.5-<2	<0.5	--	1.4
Strontium	500	--	240	200-300	240	200-300	310
Tellurium	20	--	24	20-30	39	30-50	26
Thorium	5	--	2.4	2-3	1.4	1-2	4.8
Uranium	3,800	500-30,000	5,000	830-30,000	790	300-2,100	3,900
Vanadium	2,000	--	2,400	2,000-3,000	2,400	2,000-3,000	1,500
Yttrium	30	--	39	30-50	30	--	35
Zinc	100	--	77	30-200	200	--	100
Zirconium	300	--	100	--	71	50-100	140

[1] Adapted from Anderson et al. (1981--Appendix F and Tables 3-2, 3-3, and 3-4) and Litz (1974).

[2] For many elements, two or more analyses were performed. The lack of range for an entry indicates agreement among the analyses or that only one analysis was completed. Averages are geometric means of the high and low values in the range or are the single number reported.

[3] The small amount of F-32 residues have been combined with the L-30 residues during the ongoing interim remedial actions, but the resulting concentrations of elements in the combined residues will be almost the same as in the L-30 residues.

[4] Weighted averages based on: K-65, 28%; L-30, 55%; L-50, 18%.

Table 3.8. Concentrations of Nonradiological Elements in the NFSS Wastes

| | Concentration (ppm) | | | | | | | |
| Element | R-10 Pile in 1980[1] | | New Naval Waste Area[1] | | Onsite Central Ditch Sediments[1] | | Weighted Average[2] | Natural Soil[3] (Worldwide) |
	Average	Range	Average	Range	Average	Range		
Arsenic	1.6	0.5-5	1.2	0.5-3	1.2	0.5-3	1.4	0.1-40
Barium	230	100-500	100	20-500	500	50-5000	280	100-3000
Cadmium	0.3	--	0.2	--	0.2	--	0.26	--
Cerium	22	5-100	5.5	1-30	14.1	2-100	17.7	3-170
Chromium	24	20-30	16	5-50	45	10-200	28	5-1500
Cobalt	100	5-2000	7.7	2-30	55	10-300	75	0.05-65
Copper	141	20-1000	24	3-200	45	10-200	99	2-250
Fluorine	17	3-100	20	10-50	141	10-2000	48	20-700
Iron	14,000	10,000-20,000	31,000	10,000-100,000	22,000	10,000-50,000	19,000	2000-550,000
Lanthanum	14	2-100	4.5	1-20	7.1	1-50	11	2-180
Lead	51	4-650	17	<0.4-740	4.5	<0.4-51	34	2-300
Lithium	244	200-300	63	20-200	95	30-300	180	3-350
Manganese	450	200-1000	450	200-1000	450	100-2000	450	20-10,000
Mercury	0.3	--	0.4	--	0.3	--	0.3	0.1-40
Nickel	240	20-3000	16	5-50	100	10-1000	170	2-750
Selenium	0.77	<0.3-<2	0.55	<0.3-<1	0.55	<0.3-<1	0.68	--
Silver	0.23	--	0.14	--	0.14	--	0.19	--
Strontium	100	50-200	77	30-200	122	30-500	100	4-2000
Uranium	14	1-200	5.5	0.1-300	14	1-200	13	0.7-9
Vanadium	95	30-300	22	10-50	141	30-100	96	3-500
Zinc	4.4	2-10	10	1-100	4.4	1-20	5.2	1-900
Zirconium	100	10-1000	17	3-100	12	5-30	66	60-2000

[1] Adapted from Anderson et al. (1981--Section 6, Appendix A, and Appendix I). Ranges as reported in Anderson et al. (1981). Averages are geometric means of the high and low values in the range or are the single number reported.

[2] Because these are the only wastes for which comparable elemental data are available, a weighted average for the total 180,000 m^3 of wastes was obtained by weighting the concentrations as follows: R-10 Pile, 60%; New Naval Waste Area, 15%; and Onsite Ditch Sediments, 25%.

[3] Adapted from Bowen (1979). Data from heavily polluted soils, soils near ore bodies, and serpentine soils have been excluded.

APPENDIX B - RESULTS OF THE BRAINSTORMING PROCESS

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NIAGARA FALLS STORAGE SITE
TREATMENT METHODS FOR K-65 RESIDUES
Brainstorming Session
August 27, 1996

The following individuals participated in the brainstorming session to identify treatment alternatives for the Niagara Falls Storage Site (NFSS) K-65 residues on August 27: Ken Atwood (BNI), Bob Beels (BNI), Debbie Browning (SAIC), Mark Kaye (BNI), Ron Kirk (DOE), Beji Malek (SAIC), Grady Maraman (ANL), Ed McNamee (BNI), Dick Philippone (BNI), Mike Ryan (BNI), Ken Skinner (BNI), George Stephens (SAIC), John Waddell (SAIC), Ed Walker (BNI), Jack Watson (ORNL), and Ralph Wright (SAIC).

WORKSHOP GOALS

- Develop a list of technically feasible treatment alternatives for the NFSS K-65 residues.
- Identify the pros and cons (key issues associated with each treatment alternative.

TREATMENT CONSTRAINTS

- Must comply with NAS recommendations
  - Removal, treatment, and offsite disposal of all residues
  - Remaining waste can stay on-site under protective cap
- Must fit within funding projections for the FUSRAP Ten-Year Plan
  - Cost less than approximately $100 million; project completion by 2006.

BROAD ISSUES TO BE ADDRESSED

1) Need buffer space at the site for radon control
2) Health & Safety
3) Environmental regulations/documentation (EE/CA, FS-EIS?)
4) Community relations
5) Need data and characterization (bench scale and pilot scale information required)
6) Decontamination and disposition of equipment
7) How far to go with treatment? What is the economic cost/benefit analysis?)
8) How feasible is the schedule?
9) How much radium 226 has to be removed?
10) Does the waste meet the disposal criteria?

11)   Moisture content - volume reduction issue, as well as need to dry to ship/dispose
12)   Disposal options (NTS, SRS, OR, residues back in hole)
13)   Transportation risks
14)   Cost of removal, treatment, and disposal

ASSUMPTIONS
1)   The baseline is vitrified waste removed and disposed of at NTS.
2)   All alternatives will require some excavation.
3)   Characterization data is needed (AFRIMET, Fernald, National Lead
      Industries, etc.).
4)   Final acceptability criteria for secondary waste needs to be established.
5)   If an EIS is required, this will impact the schedule, cost, development
      work   (regulatory and community relations strategy must be
      developed and efforts began   soon).

BRAINSTORMING SESSION SUMMARY

Section 1.0 summarizes the various removal methods and pros and cons of each
method. Section 2.0 summarizes the treatment alternatives by in situ and ex situ
methods and the issues (pro and con) related to each alternative for management of
the residues.

1.0   REMOVAL

1.1   Freeze Removal

PROS
- Allows for vertical segregation
- Improves ease in handling
- Proven technology
- Does not alter the state of the waste
- Can decrease radon with use of hypalon® bag

CONS
- Must maintain the technology
- Requires significant preparation for the frozen state
- Results in possible addition of moisture

1.2   Re-Suspension Process (Slurry Mining)

PROS
- Method has been used previously
- Method is amenable to remote handling
- Compatible with treatment or injection

x
CONS
- Heavy slurry equipment would be required

> - Possible volume increase and/or excavation addition
> - Water addition

1.3 Sequencing Removal Cell-by-Cell

PROS

> - Radon would be limited
> - External gamma releases would be limited
> - Only one area would be exposed at any time
> - Would match the pace of treatment more effectively
> - Residues could be segregated
> - Would allow for "practice" on lower level residues

CONS

> - Could spread the contamination
> - Modification of equipment would be needed

2.0 TREATMENT

2.1 In Situ Treatment Methods

The in situ treatment methods discussed included: in situ vitrification, activation, and chemical separation.

2.1a. In Situ Vitrification

PROS

> - Minimizes worker exposure
> - Greatly reduced handling and costs

CONS

> - Requires retrofitting the cell
> - Don't have the necessary data (e.g., silica content)
> - May have high moisture content, thus affecting the amount of energy required
> - Don't know the final size of the melt

This would not be the final treatment

2.1b. In-situ Chemical Separation

PROS

- Minimizes worker exposure
- Potential cost savings

CONS

- Requires retrofitting the storage cell
- Engineering issues must be addressed related to use of equipment inside of cell
- Don't know the permeability of waste
- Need additional unavailable data (further characterization required)
- Percent removal of residues is uncertain
- Amount of waste would be increased due to re-slurry process
- Re-slurrying could cause other unknown reactions
- Possible compromise in control of the process

2.2   Ex Situ Treatment Methods

The following ex situ treatment methods were identified and discussed: density/air floatation, electrical separation, chemical

- Low treatment cost
- May decrease the radon control problem
- Polymer is effective for radon emission reduction

CONS
- Volume would increase
- Transportation and disposal would increase
- There are questions of long-term stability
- Major radon control issue

2.2f. PEG (polyethylene glycol) Method

PROS
- One of the most efficient methods

CONS
- Requires changing the suspension fluid
- Unproven for this waste (sulfates)
- Requires high salt concentration and temperature and salt variation
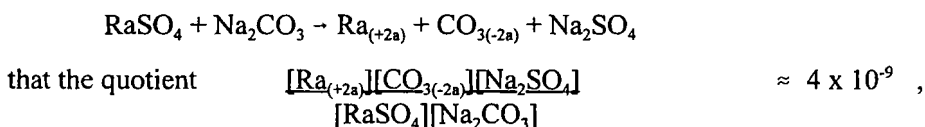- Results in the generation of an additional waste stream (salt, PEG)

2.2g. Slurry Injection Underground Method

PROS
- Relatively inexpensive
- Permanent solution
- No transportation, disposal or exposure
- Engineering is feasible

indeed exist as Ba^{+2} and Ra^{+2}. However, these diagrams are not quantitative— they do not indicate how much of a material will exist as a particular phase or ion under a given set of conditions. It is known that while the solubility products for the carbonate salts of Ra and Ba (solubility product equals, for example, $[Ba^{+2}]\cdot[SO4^{-2}]$) are larger than the corresponding sulfate salts, they are still very small. Thus, due to the insolubility of both sulfates and carbonates of Ra and Ba, all of the proposed flow schemes required the use of large volumes of water. This water would of course be contaminated and would require a substantial investment in evaporation equipment.

In 1978, the National Lead of Ohio, Inc., Feed Materials Production Center, published a document titled *Scoping Investigation of Alternative Methods for Disposal of Radioactive Residues Stored at the DOE-Niagara Falls Site*. The study proposed a sodium carbonate leach process. The proposed facility would be operated batch-wise with batches of 36,287 kilograms (80,000 pounds) per batch. The overall processing rate would be 18.1 tons per day (20 short tons per day). This process again relies upon the assumption that Ba and Ra sulfates, in the presence of a large excess of sodium carbonate, would be converted to carbonate. Filtration of the solids fraction of the process stream would yield a combined residue plus Ra & Ba carbonates. Treatment of this residue with nitric acid would then yield separable Ra and Ba nitrates and a filterable residue. This scheme obviously relied entirely upon the metathesis of the Ba and Ra sulfates with sodium carbonate -- reactions that do not occur to any appreciable extent.

The reasons for the failure of the preceding processes can be seen by examination of Tables C-1 through C-4. The thermodynamics of the leaching of barium sulfate with sodium chloride brine and with sodium carbonate brine, similarly the thermodynamics of the leaching of radium sulfate with the same reagents have been calculated and tabulated. Note that in all cases the ΔG for the reaction is positive in sign, indicating that under ordinary conditions the reaction will not proceed (in fact the opposite reaction will prevail). This does not mean that the reaction cannot occur at all— the Ks given for the reaction at each temperature indicate, for instance, for the reaction

$$RaSO_4 + Na_2CO_3 \rightarrow Ra_{(+2a)} + CO_{3(-2a)} + Na_2SO_4$$

that the quotient $\dfrac{[Ra_{(+2a)}][CO_{3(-2a)}][Na_2SO_4]}{[RaSO_4][Na_2CO_3]} \approx 4 \times 10^{-9}$,

indicating that for reasonable values of $[Na_2CO_3]$ and $[Na_2SO_4]$ that the value of $[RaSO4$ must be many orders of magnitude larger than that of $[Ra_{(+2a)}]$.

In 1981, the National Lead of Ohio, Inc., commissioned Battelle Columbus Laboratories to prepare a document titled, *Final Report on Preliminary Assessment of Alternatives for Processing and Disposal of the Afrimet Residues*. This document was prepared for DOE. This document critically reviews the previous work performed on the uranium leach residues and concludes that "three specific technologies are recommended due to their demonstrated applicability and minimal health and environmental risks." They are:

1. calcination followed by immobilization,
2. fluidized-bed incineration followed by immobilization, and
3. vitrification

A personal conversation (30 August 1969) with Dr. John Litz, formerly of Hazen Research, Inc. and the principal investigator during Hazen's 1974 work, revealed that he does not consider chemical extraction to be a viable option for the removal of radium from the residues and considers stabilization (or immobilization as referenced above) to be the only workable remedy.

Solidification and Stabilization

Solidification and Stabilization (S&S) appears to be the treatment of choice for the NFSS residues. The life of various types of stabilized materials is not known at present. S&S also characteristically increases both the mass and volume of the stabilized waste. However, S&S will permit the residues to be transported and disposed without contamination due to dust loss. Other aspects of the S&S process appear to require further evaluation.

Most conventional S&S treatments consist of thoroughly mixing a material with a cementitous material, with or without an additional reactive material such as very fine silica. Portland cement - Type S&S processes, can be tailored to yield products varying in physical strength from somewhat friable aggregates to material resembling concrete. While it can be very strong, portland cement products have the disadvantage of porosity, indicating that radon gas given off by decomposing radium can work its way to the aggregate surface and mix with the ambient air, creating potentially hazardous situations. In recent years new technologies have been developed that may permit the use of S&S in ways that may minimize off-gassing. These technologies are:

Organic polymeric cements
Inorganic polymeric cements
Molten sulfur (which hardens to a solid)

Organic polymeric cements are characterized by organic resins such as vinyl esters. Wastes are mixed in appropriate equipment with two or three organic components. Polymerization of the resin takes place and the mix hardens into a solid mass. While relatively expensive, a certain amount of moisture in the residue feed can be tolerated.

Inorganic polymer cements are somewhat similar to portland cement in that they are silicate based. However, they often consist of soluble silicates which can be homogeneously mixed with the residue. Slight acidification with either a solid or liquid acid will cause the precipitation of silicic acid, which forms a continuous silicate skeleton which in turn contains the residue within a silicate matrix. These materials are often proprietary and their exact ingredient mix and method of operations is frequently not well known. These materials tend to be intermediate in price between portland and organic cement.

Sulfur cement is simply made by mixing the residue with molten sulfur. Certain stabilizing reagents are mixed with the mass while it is still plastic and stop the recrystallization process. Consequently the mass retains many of the characteristics of amorphous sulfur such as elasticity. Costs for this material are not known, however, the main component (elemental sulfur) is a low-cost industrial commodity. The residue must be completely dry before this material can be used.

All three of these S&S options have the feature that the polymer that does the stabilization completely surrounds the particles of waste. Consequently there is a continuous phase of polymer surrounding the waste particles and off-gassing is stopped, along with dusting. Most of these systems also exhibit a considerable degree of chemical resistance.

Figure C-1. Radium Extraction Process Flow Diagram

FIGURE A-2. RADIUM PROCESS RESIDUE TREATMENT
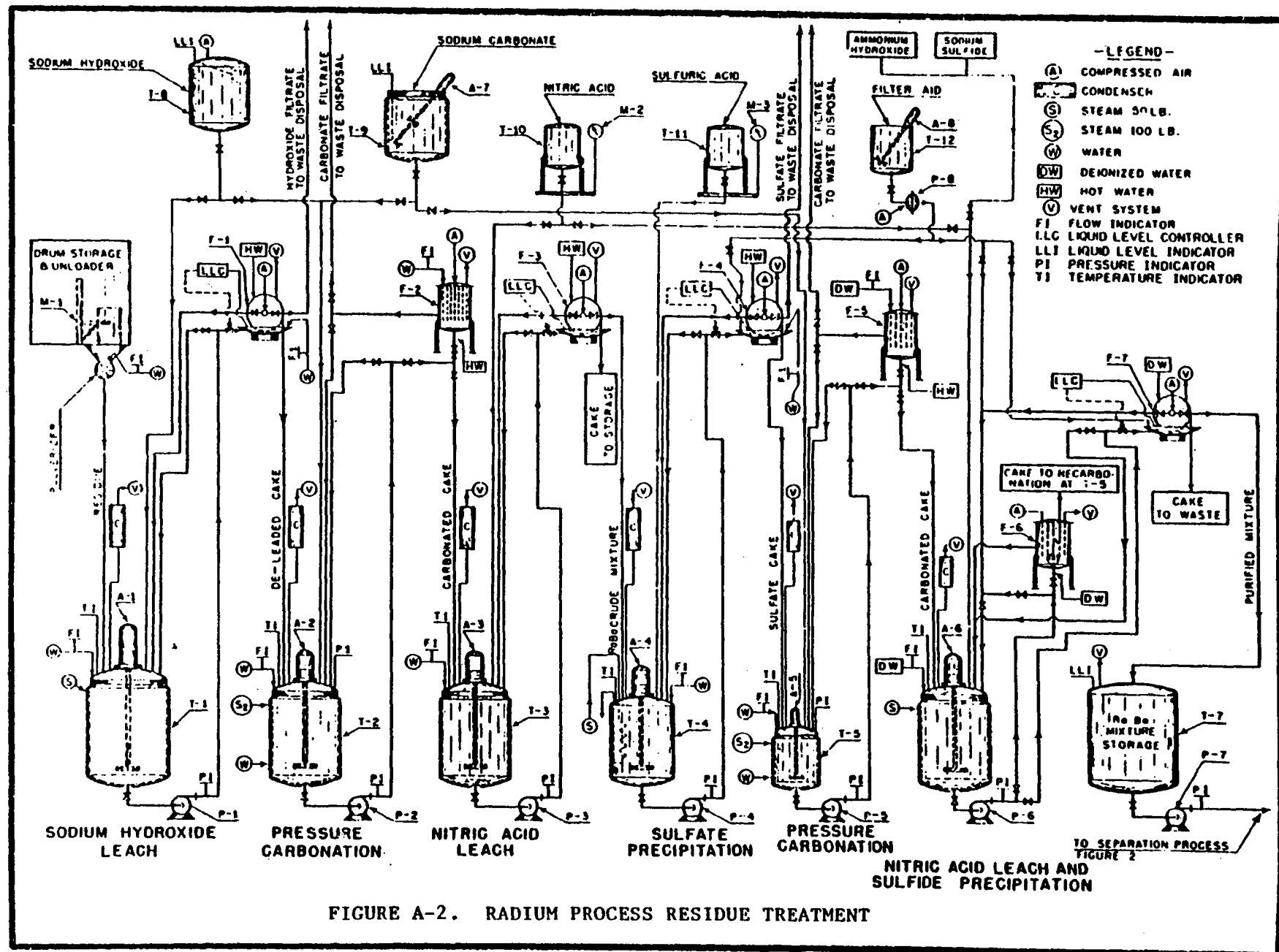
[Source: Rawlings, 1951 (Plate #5303)]

Figure C-1 (continued)

FIGURE A-3.   RADIUM PROCESS SEPARATION BY FRACTIONAL PRECIPITATION—RADIUM RICH SIDE
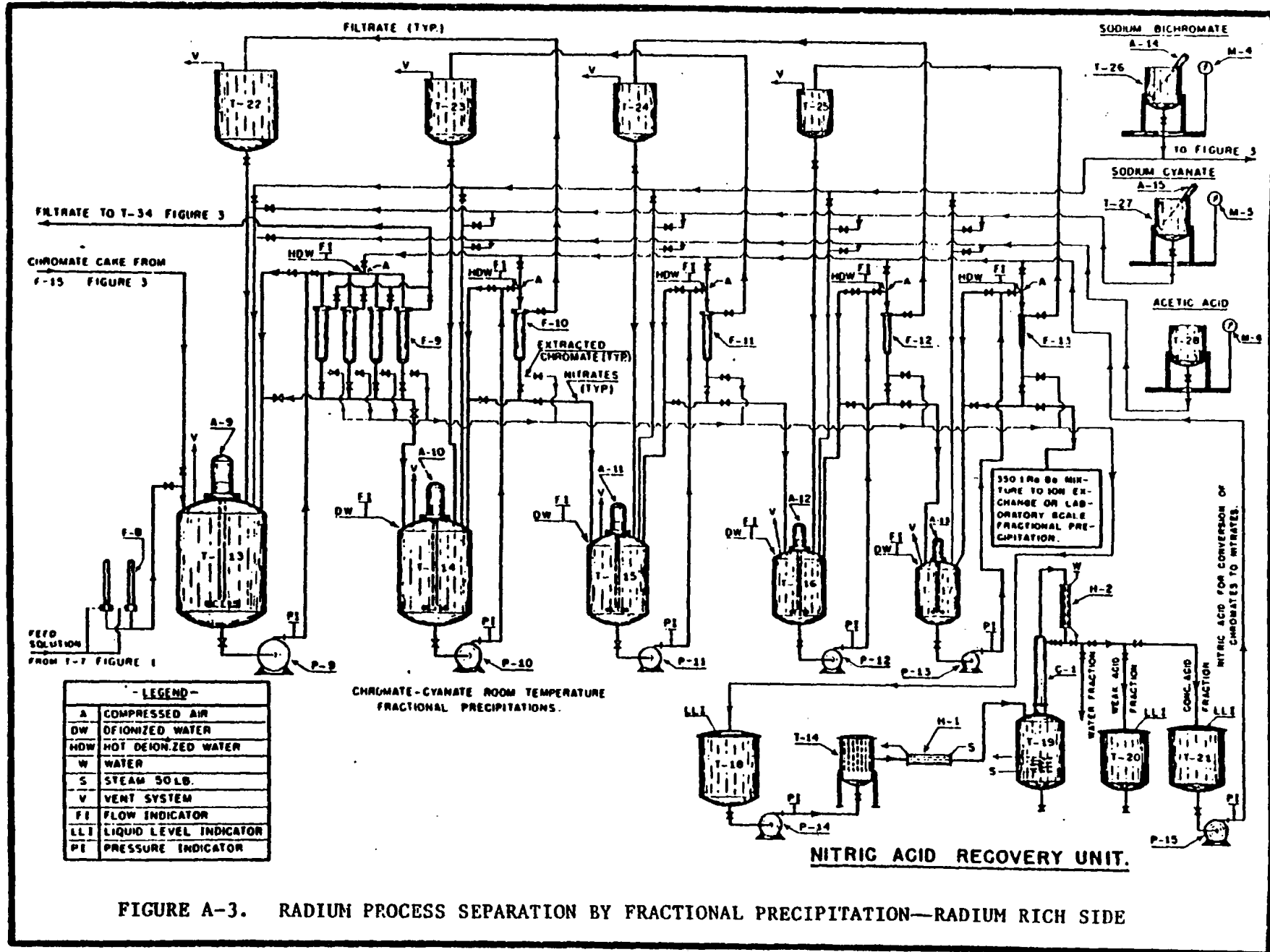
[Source: Rawlings, 1951 (Plate #5241)]

Figure C-1 (continued)

FIGURE A-4. RADIUM PROCESS SEPARATION BY FRACTIONAL PRECIPITATION—BARIUM RICH SIDE
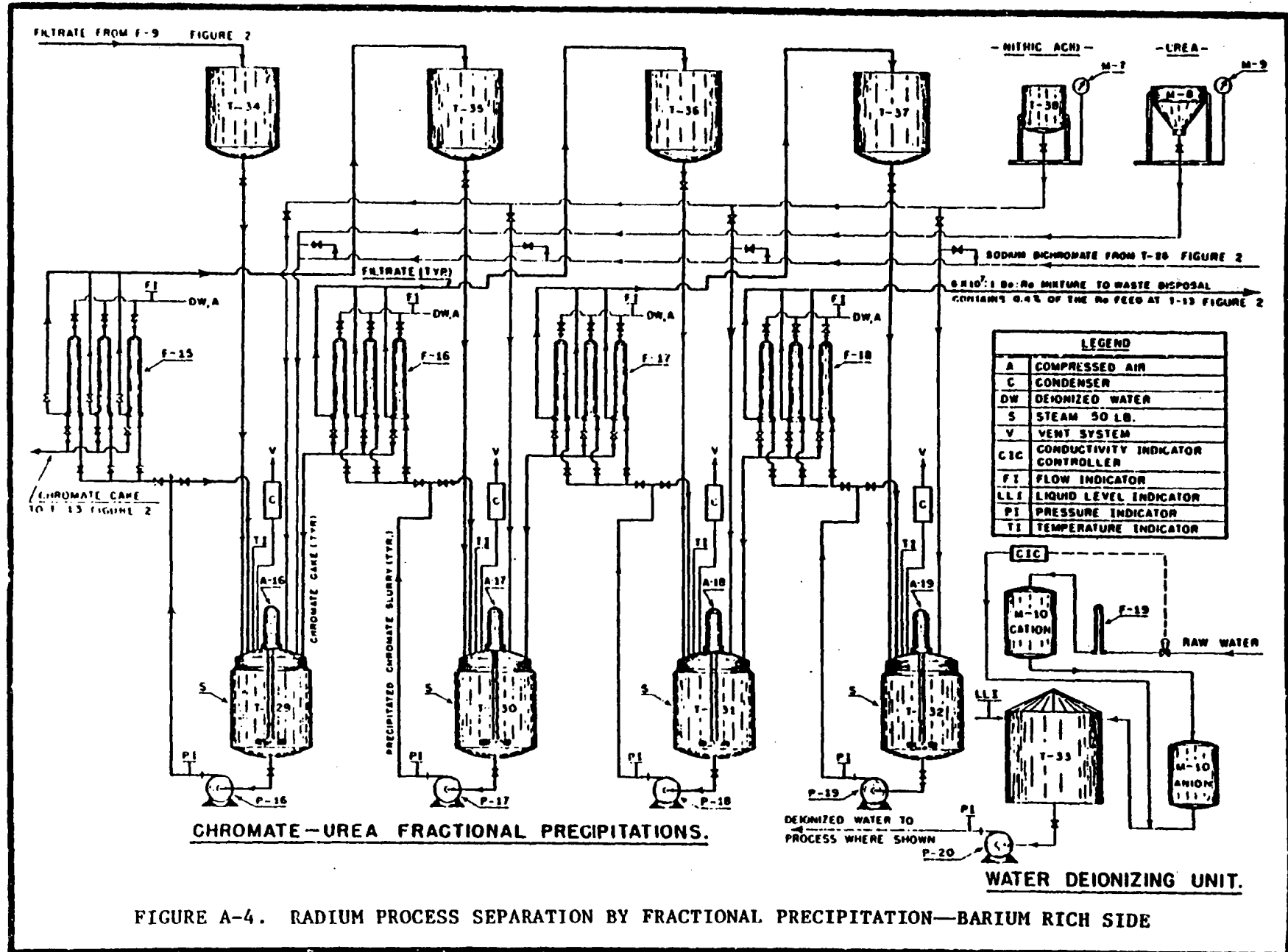
[Source: Rawlings, 1951 (Plate #5242)]

Figure C-1 (continued)
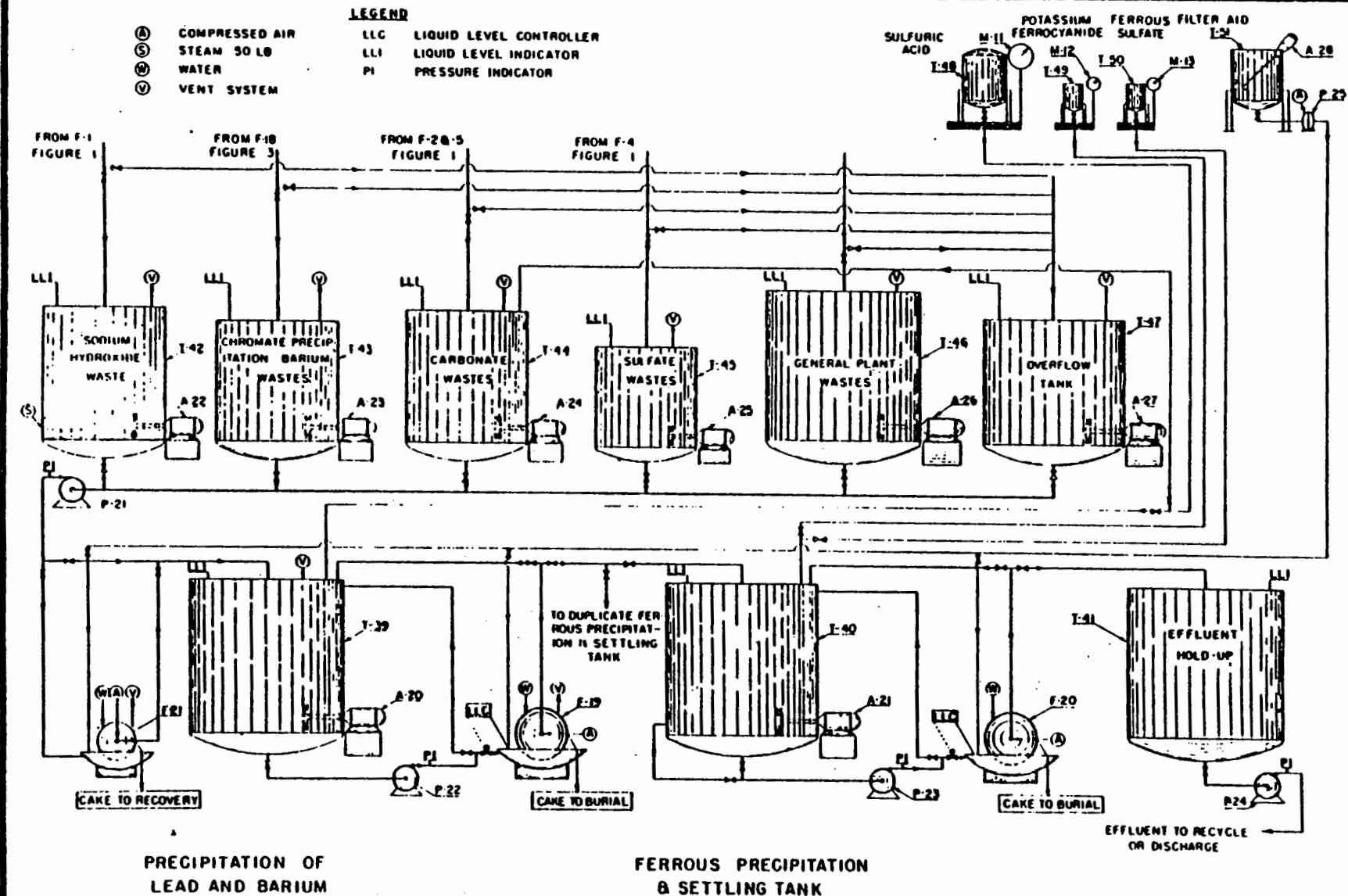
FIGURE A-5.   RADIUM PROCESS WASTE DISPOSAL

[Source: Rawlings, 1951 (Plate #5378)]

Figure C-2

Ba - C - S - H2O - System at 25.00 C

Eh (Volts) vs pH diagram with labeled regions: BaO2, Ba(HCO3)2(a), BaCO3, Ba(+2a), BaH2

File: C:\HSC\BACS25.IEP
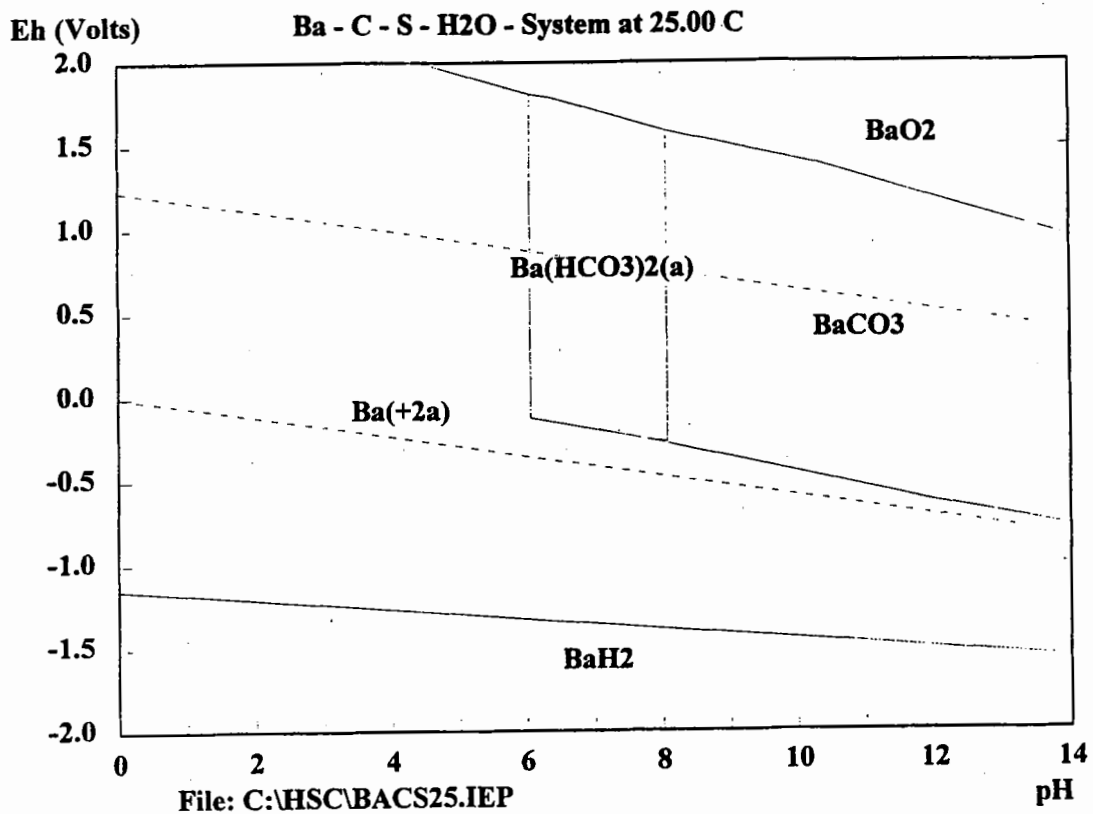
	Molality m mol / kg		Pressure p bar
C	2.000E+00	C	1.000E+00
S	1.000E-06	S	1.000E+00
Ba	1.000E-06	Ba	1.000E+00

C-8

Figure C-3

Eh (Volts)   **Ra - C - S - H2O - System at 25.00 C**

2.0

1.5

1.0

0.5

0.0   Ra(+2a)

-0.5

-1.0

-1.5

-2.0

0   2   4   6   8   10   12   14

File: C:\HSC\RACS25.IEP   **pH**

	Molality m		**Pressure p**
	mol / kg		**bar**
C	2.000E+00	C	1.000E+00
S	1.000E-06	S	1.000E+00
Ra	1.000E-06	Ra	1.000E+00
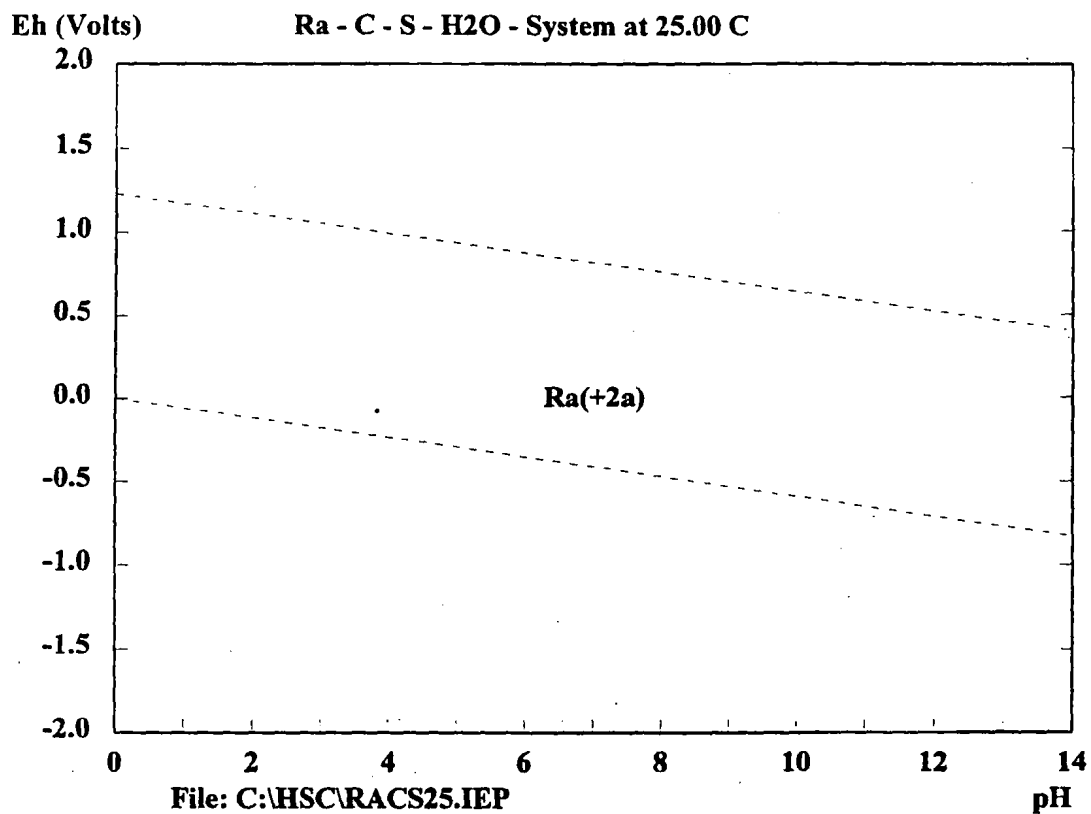
Table C-1. Thermodynamics of Leaching Barium Sulfate with Sodium Chloride Brine

```
================================================================================
BaSO4 + 2NaCl(a) = Ba(+2a) + 2Cl(-a) + Na2SO4
```
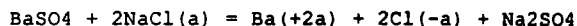
T C	deltaH kcal	deltaS cal	deltaG kcal	K
0.00	8..360	-15.862	12.693	6.977E-011
10.00	7.708	-18.206	12.863	1.177E-010
20.00	7.028	-20.567	13.057	1.841E-010
30.00	6.319	-22.942	13.274	2.687E-010
40.00	5.584	-25.329	13.516	3.685E-010
50.00	4.821	-27.726	13.781	4.775E-010
60.00	4.032	-30.131	14.070	5.875E-010
70.00	3.217	-32.542	14.384	6.893E-010
80.00	2.375	-34.959	14.721	7.744E-010
90.00	1.508	-37.381	15.083	8.359E-010
100.00	0.615	-39.806	15.469	8.696E-010

Formula	FW g/mol	Conc. wt-%	Amount mol	Amount g	Volume l-or-ml
BaSO4	233.388	66.630	1.000	233.388	51.864 ml
NaCl(a)	58.443	33.370	2.000	116.886	0.000 ml
	g/mol	wt-%	mol	g	l-or-ml
Ba(+2a)	137.330	39.207	1.000	137.330	0.000 ml
Cl(-a)	35.453	20.243	2.000	70.906	0.000 ml
Na2SO4	142.037	40.550	1.000	142.037	52.999 ml

Table C-2. Thermodynamics of Leaching Barium Sulfate with Sodium Carbonate Brine

```
================================================================================
BaSO4 + Na2CO3(a) = Ba(+2a) + CO3(-2a) + Na2SO4
```
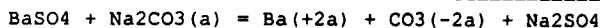
T C	deltaH kcal	deltaS cal	deltaG kcal	K
0.00	8.389	-15.794	12.703	6.839E-011
10.00	7.730	-18.165	12.873	1.156E-010
20.00	7.042	-20.553	13.067	1.809E-010
30.00	6.325	-22.956	13.284	2.643E-010
40.00	5.582	-25.370	13.526	3.625E-010
50.00	4.810	-27.794	13.792	4.695E-010
60.00	4.012	-30.226	14.082	5.772E-010
70.00	3.188	-32.665	14.396	6.765E-010
80.00	2.336	-35.109	14.735	7.589E-010
90.00	1.459	-37.558	15.099	8.177E-010
100.00	0.556	-40.011	15.486	8.492E-010

Formula	FW g/mol	Conc. wt-%	Amount mol	Amount g	Volume l-or-ml
BaSO4	233.388	68.770	1.000	233.388	51.864 ml
Na2CO3(a)	105.989	31.230	1.000	105.989	0.000 ml
	g/mol	wt-%	mol	g	l-or-ml
Ba(+2a)	137.330	40.465	1.000	137.330	0.000 ml
CO3(-2a)	60.009	17.682	1.000	60.009	0.000 ml
Na2SO4	142.037	41.852	1.000	142.037	52.999 ml

Table C-3. Thermodynamics of Leaching Radium Sulfate with Sodium Chloride Brine
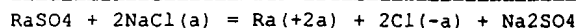
```
=========================================================================
RaSO4 + 2NaCl(a) = Ra(+2a) + 2Cl(-a) + Na2SO4

        T         deltaH        deltaS        deltaG         K
        C          kcal           cal          kcal
      0.00         9.920         -7.823        12.057      2.249E-010
     10.00         9.399         -9.698        12.145      4.218E-010
     20.00         8.855        -11.587        12.251      7.339E-010
     30.00         8.288        -13.489        12.377      1.193E-009
     40.00         7.698        -15.403        12.521      1.823E-009
     50.00         7.084        -17.331        12.685      2.633E-009
     60.00         6.447        -19.271        12.868      3.613E-009
     70.00         5.787        -21.224        13.070      4.731E-009
     80.00         5.103        -23.188        13.292      5.933E-009
     90.00         4.396        -25.164        13.534      7.150E-009
    100.00         3.665        -27.150        13.796      8.305E-009
```

Formula	FW g/mol	Conc. wt-%	Amount mol	Amount g	Volume l-or-ml
RaSO4	322.083	73.373	1.000	322.083	0.000 ml
NaCl(a)	58.443	26.627	2.000	116.886	0.000 ml
Ra(+2a)	226.025	51.490	1.000	226.025	0.000 ml
Cl(-a)	35.453	16.153	2.000	70.906	0.000 ml
Na2SO4	142.037	32.357	1.000	142.037	52.999 ml

Table C-4. Thermodynamics of Leaching Radium Sulfate with Sodium Carbonate Brine
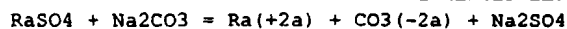
```
=========================================================================
RaSO4 + Na2CO3 = Ra(+2a) + CO3(-2a) + Na2SO4

        T         deltaH        deltaS        deltaG         K
        C          kcal           cal          kcal
      0.00         4.215        -24.032        10.779      2.371E-009
     10.00         3.426        -26.868        11.033      3.042E-009
     20.00         2.611        -29.695        11.316      3.654E-009
     30.00         1.770        -32.515        11.627      4.139E-009
     40.00         0.904        -35.327        11.967      4.444E-009
     50.00         0.011        -38.135        12.334      4.548E-009
     60.00        -0.909        -40.938        12.729      4.455E-009
     70.00        -1.856        -43.738        13.153      4.193E-009
     80.00        -2.830        -46.536        13.604      3.805E-009
     90.00        -3.832        -49.332        14.083      3.340E-009
    100.00        -4.860        -52.126        14.591      2.843E-009
```

Formula	FW g/mol	Conc. wt-%	Amount mol	Amount g	Volume l-or-ml
RaSO4	322.083	75.240	1.000	322.083	0.000 ml
Na2CO3	105.989	24.760	1.000	105.989	41.860 ml
Ra(+2a)	226.025	52.801	1.000	226.025	0.000 ml
CO3(-2a)	60.009	14.018	1.000	60.009	0.000 ml
Na2SO4	142.037	33.181	1.000	142.037	52.999 ml

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APPENDIX D - COST ESTIMATES SUMMARY DATA

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COST ESTIMATING MAJOR ASSUMPTIONS

- All costs are displayed in $1998. Estimates are produced in $1996.
- Estimates include Screening and Assessment, Remedial Design and Remedial Action only. 30 year O&M not included.
- Source for equipment cost and output is Means unless otherwise cited.
- All costs taken from Means include subcontractor overhead, profit and location adjustment factor.
- Productivity adjustments are used in many elements for weather and other delays.
- Monitoring, sampling, analysis occurs year-round.
- Remedial Design cost is calculated as 10% of Remedial Action Costs less Treatment, Transportation and Disposal. Remedial Design for Vitrification is assumed equal to that of Solidification, since the design scope is similar and treatment duration is a major reason for cost differences.
- Soil density is 1.5 tons per cy (insitu).
- Soil expansion factor is 1.3.

Niagara Falls Project
FUSRAP Remediation Alternatives
WBS Cost Summary
$1998 Mil

WBS NUMBER	WBS NAME	1A	1B	2A	2B	3A	3B	3C
1.0	FUSRAP Program	$ 130	$ 101	$ 157	$ 78	$ 225	$ 134	$ 106
1.1	FUSRAP Projects	98.2	76.6	118.9	58.9	170.5	101.5	80.3
1.1.1	Niagara Falls FUSRAP Project	98.2	76.6	118.9	58.9	170.5	101.5	80.3
1.1.1.1	Project Screening and Assessment	10.7	10.7	10.7	10.7	10.7	10.7	10.7
1.1.1.2	Remedial Design	1.0	1.0	1.0	0.8	1.0	0.8	0.8
1.1.1.3	Remedial Action	81.2	62.3	104.7	45.6	156.3	88.2	67.0
1.1.1.3.1	Remedial Action Sitework	81.2	62.3	104.7	45.6	156.3	88.2	67.0
1.1.1.3.1.1	Monitoring, Sampling and Analysis	3.1	1.6	1.6	1.2	1.6	1.2	1.2
1.1.1.3.1.2	Site Development	2.6	2.6	2.6	2.6	2.6	2.6	2.6
1.1.1.3.1.3	Building and Services	0.6	0.5	0.5	0.5	0.5	0.5	0.5
1.1.1.3.1.4	Excavation and Backfill	3.9	2.9	2.9	2.2	2.9	2.2	2.2
1.1.1.3.1.5	Other Collection and Control	-	-	-	-	-	-	-
1.1.1.3.1.6	Disposal	4.9	1.3	19.1	5.2	23.4	9.5	4.8
1.1.1.3.1.7	Transportation	8.2	4.6	32.3	18.0	47.2	32.9	16.4
1.1.1.3.1.8	Treatment	50.2	45.7	42.7	14.0	75.2	37.5	37.5
1.1.1.3.1.9	Demolition, Decontamination and Decommissioning	-	-	-	-	-	-	-
1.1.1.3.1.10	Site Management	-	-	-	-	-	-	-
1.1.1.3.1.11	Site Engineering and Technical Support	-	-	-	-	-	-	-
1.1.1.3.1.12	Site Environmental Compliance	-	-	-	-	-	-	-
1.1.1.3.1.13	Site Institutional Controls, Surveillance and Maintenance	0.4	0.1	0.1	0.1	0.1	0.1	0.1
1.1.1.3.1.14	Reserved (site)	7.3	3.0	2.8	1.7	2.8	1.7	1.7
1.1.1.3.2	Remedial Action Management	-	-	-	-	-	-	-
1.1.1.3.3	Remedial Action Engineering and Technical Support	-	-	-	-	-	-	-
1.1.1.3.4	Remedial Action Environmental Compliance	-	-	-	-	-	-	-
1.1.1.3.5	Remedial Action Institutional Controls, Surveillance and Maintenanc	-	-	-	-	-	-	-
1.1.1.3.6	Reserved (RA)	-	-	-	-	-	-	-
1.1.1.4	Post Remedial Action Activities	-	-	-	-	-	-	-
1.1.1.5	Disposal Siting	-	-	-	-	-	-	-
1.1.1.6	Project Management	-	-	-	-	-	-	-
1.1.1.7	Project Engineering and Technical Support	-	-	-	-	-	-	-
1.1.1.8	Project Environmental Compliance	-	-	-	-	-	-	-
1.1.1.9	Project Institutional Controls, Surveillance and Maintenance	-	-	-	-	-	-	-
1.1.1.10	Reserved (project)	5.2	2.5	2.4	1.7	2.4	1.7	1.7
1.2	Discovery and Designation	-	-	-	-	-	-	
1.3	Program Management & Integration	11.8	9.2	14.3	7.1	20.5	12.2	9.6
1.4	Reserved	-	-	-	-	-	-	-
	CONTINGENCY 20%)	19.6	15.3	23.8	11.8	34.1	20.3	16.1

NIAGARA FALLS SITE KEY PARAMETERS

PARAMETER			
Excavation Volume, Total (insitu / exsitu cy)		14,387	18,704
Excavation Volume, K-65 (insitu / exsitu cy)		3,924	5,101
Excavation Volume, L-30 (insitu / exsitu cy)		7,848	10,202
Excavation Volume, F-32 (insitu / exsitu cy)		654	850
Excavation Volume, L-50 (insitu / exsitu cy)		1,962	2,550
Cap Removal Volume, Total (insitu / exsitu cy)		83,333	108,333
Expansion Factor, Soil		1.30	
Residue Density (tons per cy, insitu)		1.52	
Solidification Expansion		100%	
Disposal Fee ($/cy)	$	476.82	
Volume per LSA box (cy)		3.6	
Containers per trip (K-65)		2	
Containers per trip (other residue)		4	
Cost per trip	$	4,050	
Loading Rate ($/cy)	$	25.00	
Available construction weeks per year		44	

VOLUME / MASS FLOW DIAGRAM

	K-65	L-30	F-32	L-50
VOLUME (INSITU CY)	3,924	7,848	654	1,962
DENSITY (TONS / INSITU CY)	1.5	1.5	1.5	1.5
MASS (TONS)	5,951	11,902	992	2,975

	K-65 EXCAVATION	L-30 EXCAVATION	F-32 EXCAVATION	L-50 EXCAVATION
EXPANSION FACTOR	1.3	1.3	1.3	1.3
VOLUME (EXSITU CY)	5,101	10,202	850	2,550

	K-65 SOLIDIFICATION	L-30 SOLIDIFICATION	F-32 SOLIDIFICATION	L-50 SOLIDIFICATION
MASS MULTIPLIER	N/A	N/A	N/A	N/A
EXIT MASS	N/A	N/A	N/A	N/A
VOLUME MULTIPLIER	200%	200%	200%	200%
EXIT VOLUME	10,202	20,404	1,700	5,101
LOST SPACE IN CONTAINERS	0%	0%	0%	0%
EFFECTIVE VOLUME	10,202	20,404	1,700	5,101
% WASTE	100%	100%	100%	100%
% OTHER	0%	0%	0%	0%
WASTE MASS (TONS)	N/A	N/A	N/A	N/A
OTHER MASS (TONS)	N/A	N/A	N/A	N/A
WASTE VOLUME (CY)	10,202	20,404	1,700	5,101
OTHER VOLUME (CY)	0	0	0	0

K-65 TRANSPORT & DISPOSAL	L-30 TRANSPORT & DISPOSAL	F-32 TRANSPORT & DISPOSAL	L-50 TRANSPORT & DISPOSAL

VOLUME / MASS FLOW DIAGRAM

	K-65	L-30	F-32	L-50
VOLUME (INSITU CY)	3,924	7,848	654	1,962
DENSITY (TONS / INSITU CY)	1.5	1.5	1.5	1.5
MASS (TONS)	5,951	11,902	992	2,975

K-65 EXCAVATION	**L-30** EXCAVATION	**F-32** EXCAVATION	**L-50** EXCAVATION

	K-65	L-30	F-32	L-50
EXPANSION FACTOR	1.3	1.3	1.3	1.3
VOLUME (EXSITU CY)	5,101	10,202	850	2,550

K-65 VITRIFICATION	**L-30** VITRIFICATION	**F-32** VITRIFICATION	**L-50** VITRIFICATION

	K-65	L-30	F-32	L-50
MASS MULTIPLIER	N/A	N/A	N/A	N/A
EXIT MASS	N/A	N/A	N/A	N/A
VOLUME MULTIPLIER (Insitu)	43%	43%	43%	43%
EXIT VOLUME	2,193	4,387	366	1,097
LOST SPACE IN CONTAINERS	18%	18%	18%	18%
EFFECTIVE VOLUME	2,588	5,176	431	1,294
% WASTE	100%	100%	100%	100%
% OTHER	0%	0%	0%	0%
WASTE MASS (TONS)	N/A	N/A	N/A	N/A
OTHER MASS (TONS)	N/A	N/A	N/A	N/A
WASTE VOLUME (CY)	2,193	4,387	366	1,097
OTHER VOLUME (CY)	0	0	0	0

K-65 TRANSPORT & DISPOSAL	**L-30** TRANSPORT & DISPOSAL	**F-32** TRANSPORT & DISPOSAL	**L-50** TRANSPORT & DISPOSAL

ALT 1A   COMPLETE VITRIFICATION

	EnVitCo	Arrakis	Duratek HI
Capital Costs ($Mil)	$ 22	$ 41	$ 80
Chemicals cost per ton of glass	$ 40	$ 200	$ 500
Size of melter (tons per day)	30	30	20
Efficiency	80%	80%	80%
Waste loading	85%	82%	50%
Volume reduction	57%	57%	57%
Electricity per ton of glass (kWh/ton)	200	200	200
Capacity (tons per day)	24	24	16
Effective capacity (tons per day)	20	20	8
Glass required (tons)	3,851	4,790	21,820
Operations duration (months)	35	37	90
Disposal volume (cy)	9,490	9,490	9,490
Containers	2,670	2,670	2,670
Shipments	850	850	850
Total Cost ($1998 Mil)	$ 101	$ 130	$ 235

ALT 1B   PARTIAL VITRIFICATION

	EnVitCo	Arrakis	Duratek HI
Capital Costs ($Mil)	$ 22	$ 41	$ 80
Chemicals cost per ton of glass	$ 40	$ 200	$ 500
Size of melter (tons per day)	30	30	20
Efficiency	80%	80%	80%
Waste loading	85%	82%	50%
Volume reduction	57%	57%	57%
Electricity per ton of glass (kWh/ton)	200	200	200
Capacity (tons per day)	24	24	16
Effective capacity (tons per day)	20	20	8
Glass required (tons)	1,050	1,306	5,951
Operations duration (months)	10	10	25
Disposal volume (cy)	2,588	2,588	2,588
Containers	728	728	728
Shipments	364	364	364
Total Cost ($1998 Mil)	$ 74	$ 101	$ 172

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ALT 2A COMPLETE SOLIDIFICATION

	REAGENT COST N/A			REAGENT COST INCLUDED		
Expansion Factor	100%	200%	300%	50%	100%	200%
Operations duration (months)	9.0	9.0	9.0	9.0	9.0	9.0
Reagent unit cost	$ -	$ -	$ -	$ 20.00	$ 20.00	$ 20.00
Loading	0%	0%	0%	40%	40%	40%
Reagent cost ($Mil)	$ -	$ -	$ -	$ 30.22	$ 30.22	$ 30.22
Total treatment cost ($Mil)	$ 10	$ 10	$ 10	$ 40	$ 40	$ 40
Disposal volume (cy)	37,407	56,111	74,814	28,055	37,407	56,111
Containers	10,523	15,782	21,044	7,891	10,523	15,782
Shipments	3,349	5,022	6,698	2,511	3,349	5,022
Total Cost ($1998 Mil)	$ 114	$ 148	$ 182	$ 140	$ 157	$ 191

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ALT 2B PARTIAL SOLIDIFICATION

	REAGENT COST N/A			REAGENT COST INCLUDED		
Expansion Factor	100%	200%	300%	50%	100%	200%
Operations duration (months)	2.5	2.5	2.5	2.5	2.5	2.5
Reagent unit cost	$ -	$ -	$ -	$ 20.00	$ 20.00	$ 20.00
Loading	0%	0%	0%	40%	40%	40%
Reagent cost ($Mil)	$ -	$ -	$ -	$ 8.24	$ 8.24	$ 8.24
Total treatment cost ($Mil)	$ 5	$ 5	$ 5	$ 13	$ 13	$ 13
Disposal volume (cy)	10,202	15,303	20,404	7,651	10,202	15,303
Containers	2,870	4,304	5,739	2,152	2,870	4,304
Shipments	1,435	2,152	2,870	1,076	1,435	2,152
Total Cost ($1998 Mil)	$ 66	$ 81	$ 97	$ 70	$ 78	$ 93

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ALT. 3 CHEMICAL SEPARATION

	3A		3B		3B	
Disposal %		100%		100%		50%
Expansion Factor	$	1.00	$	1.00	$	1.00
Operations duration (months)		9.0		2.5		2.5
Reagent unit cost	$	20.00	$	20.00	$	20.00
Loading		40%		40%		40%
Reagent cost ($Mil)	$	38.63	$	12.98	$	12.98
Total treatment cost ($Mil)	$	70	$	35	$	35
Disposal volume (cy)		45,798		18,593		9,297
Containers		12,883		5,230		2,615
Shipments		4,529		2,615		1,308
Total Cost ($1998 Mil)	$	225	$	134	$	106

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