GENERATING LOW LEVEL MIXED WASTE MANAGEMENT ALTERNATIVES

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ABSTRACT

A series of low level mixed waste (LLMW) treatment technologies developed from engineering experience alone may not represent the optimum treatment system, especially when good design alternatives may be overlooked. The use of modeling enables planners and decision makers to consider alternatives that fall within a specified range of costs, as well as being different with respect to other selected treatment and disposal options. However, no existent models are developed specifically for the generation of different treatment and disposal alternatives. The overall objective of this project was to develop a waste stream life-cycle model for generating preliminary LLMW treatment systems based on performance and other criteria.

A variety of handling, treatment, and disposal technologies were examined and selected for input to form waste-specific treatment trains. These treatment trains form the basis of the cost evaluation procedure that is necessary in life-cycle costs evaluations. Waste-specific multioption flow charts were then added to enable the model to select treatment systems appropriate for six types of LLMW. The developed mathematical model was used to generate a given number of treatment alternatives in a treatment system. Also, cost, performance measures, and regulatory and technical requirements can be used as evaluation criteria in this analysis.

The model was used to illustrate the generation of treatment and disposal alternatives for 32,000 drums of mixed-waste sludge stored at the Oak Ridge K-25 site. Two primary treatment techniques emerged as the most cost efficient; Thermal Desorption and Acid Digestion. Although Thermal Desorption is the most cost efficient, Acid Digestion is the most efficient at reducing the waste volume. If slightly higher total life-cycle costs are acceptable, relaxing the costs constraints placed on the model can produce many other alternatives with other, previously unexplored technologies. A decision maker will probably have more technologies to choose from than those available at this particular time. It is very difficult for a decision maker to examine all of the possibilities and the way

that they relate to technical and economic issues. The model can examine a large number of alternatives and provide results based on user-provided cost constraints. The model is user-friendly which allows it to be easily configured for examining other types of waste.

INTRODUCTION

The term "mixed waste" used in this research is waste that satisfies the definition of low-level radioactive legacy waste in the Low-Level Radioactive Waste Policy Amendments Act of 1985 (LLRWPAA) and contains hazardous waste that either: 1) is listed as a hazardous waste in Subpart D of 40 CFR Part 261; or 2) causes the waste to exhibit any of the hazardous waste characteristics identified in Subpart C of 40 CFR Part 261 (1). The need to provide LLMW treatment capacity has been driven by changes in Resources Conservation and Recovery Act (RCRA), Land Disposal Restriction (LDR) requirements and the need to reduce current stockpiles . Hazardous waste must meet 40 CFR 268.40 LDR treatment standards prior to disposal in a land based unit. LDR treatment standards include technology standards and concentration based standards (2). The Federal Facility Compliance Act of 1992 waived sovereign immunity for the Department of Energy (DOE) and required DOE to develop plans and facilities for achieving RCRA compliance (3) under a constrained schedule. The high cost of treating and disposing of LLMW provides incentives to DOE and others to develop optimized mixed waste treatment technologies based on life-cycle costs. The variety of sources and types of mixed waste demands the evaluation of numerous efficient and innovative alternatives or combinations of alternatives to satisfy all disposal problems. Other factors such as volume reduction, health risk, simplicity, resource recovery, and energy efficiency should also be considered when considering process options.

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BACKGROUND

The decision process involved in cleaning sites contaminated with mixed waste, treating mixed waste, or disposing of mixed waste is frequently supported by computer modeling. The models previously used were designed to assist decision makers in evaluating and planning mixed waste management options with the primary intent of reducing the amount of untreatable mixed waste and treating the large volumes of stockpiled mixed waste. For example, the life cycle cost (LCC) model developed by Buitrago et al. (4) uses Monte Carlo simulation to accurately model cost uncertainties and varied project life often encountered with DOE projects. More specifically, the model develops cost estimates for remediating a site using three waste remediation alternatives: 1) in-situ vitrification; 2) in-situ cementation, and 3) dry removal. The program for the LCC model is written in Microsoft Excel version 5.0 macro language. The model utilizes a variety of user friendly features which allow the decision-maker to conduct what-if scenarios and analyses, as well as budgeting for projected costs. Variables and cost elements are the fundamental building blocks of the LCC model. Variables are the scalar values that are used in the model such as volume of waste, energy consumed, and disposal costs per unit volume. Cost elements may be represented by vectors or as a series of payments that are discounted over time at a given interest rate. The cost elements are expressed as functions of variables, distributions, or constant dollar amounts. Cost curves are generated to predict LCC at various waste volumes and to identify break-even points between alternatives.

A second waste treatment system model was developed by Los Alomos National Laboratory to provide waste treatment system capacities for risk and cost calculations (5). The treatment system model consists of linked unit operations. The function of each unit operation depends on the input waste streams, waste matrix, and contaminants. The output of a unit operation consists of waste streams whose matrix, contaminants, and volume/mass are altered by treatment. The resultant output is treated a second time, if necessary, to meet disposal requirements. The cost of a treatment system is determined by the volume/mass of the waste, as well as the treatment options chosen which provide for minimal resultant waste. The Los Alamos modeling program utilizes three treatment systems and flowsheets for various configurations of waste streams: 1) Debris & Residue Grouted, 2) Debris & Residue Melted, and 3) Non-Thermal Processing.

The Oak Ridge National Laboratory developed the Mixed Waste Integrated Program (MWIP) for the DOE for the purpose of selecting technical alternatives for mixed waste treatment (6,7). The goal of the analysis is to supply a multicriteria decision methodology tool which is used to evaluate distinct alternatives. The goal of this methodology is to clarify 1) the factors used to evaluate these alternatives; 2) the evaluator's view of the importance of the factors; and 3) the relative value of each alternative (7). The selected methodology must consider the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) decision making criteria for application to the analysis of subsystems developed by the DOE Office of Technology Development. The model was applied to the treatment of 32,000 drums of mixed-waste sludge at the Oak Ridge K-25 Site for validation and reliability testing of the model. The methodology of the model includes a hierarchy of activities necessary to remediate a mixed-waste problem. The hierarchy includes the following steps: 1) identifying the problem; 2) assessing the problem; 3) establishing system requirements; 4) selecting an alternative; 5) remediating the site; and 6) storing, or treating and disposing of the waste.

Based on US Environmental Protection Agency's guidance, problem identification and assessment deals primarily with current or potential threats to human health or the environment and characterization of the physical, chemical, and regulatory nature of the problem. The system requirements are established based on an analysis of program requirements, physical characterization, and regulatory environment. The CERCLA balancing criteria are used as a technical basis for quantifying system requirements (8,9). Idaho National Engineering Laboratory (10) proposed a performance-based technology filter for the alternatives analysis in selecting a process technology option based on a quantified score (10). The implementation of the option selected in the alternatives analysis remediates the problem site. The treated waste is either stored until further treatment options are applied, or disposed of according to a prescribed treatment plan.

The above models can be used successfully for mixed waste treatment and disposal to meet various regulatory requirements. However, a series of mixed waste treatment and disposal technologies developed from engineering experience alone may not represent the optimum treatment system, especially when good design alternatives are overlooked. The use of models should enable planners and decision makers to consider alternatives that fall within the specified range of costs, as well as being different with respect to other selected decision variables.

APPROACH

Model and Assumptions

The model used in this analysis was originally developed to generate alternatives for solid waste management (11,12). Waste-specific multioption flow charts were added to enable the user to select from among six types of low-level mixed wastes. Instead of total annual capital cost, the low-level mixed waste model utilizes total life-cycle cost. This is an improvement when considering wastes which are subject to long-term cost fluctuations. The model is used to generate the least cost alternative and a given number of treatment alternatives in a treatment system. Only those solutions that meet the minimum requirements (e.g., criteria on total treatment cost, treatment efficiency, or other specific objectives) while maintaining significant differences between design variables should be considered (13).

The Bounded Implicit Enumeration (BIE) algorithm (11) is used to identify all designs within the specified range of the least cost solution. In this analysis, the range is arbitrarily set at 5%. The BIE algorithm is an optimization technique that is improved over traditional enumeration algorithms which examine large numbers of alternatives. BIE calculates the lower bound at each stage which is added to the up-to-date objective-function value. This approach makes the objective function of potential solutions at each stage a "lower bound" higher than that in the conventional enumeration approach, thus reducing the number of combinations considered before reaching the final stage.

The computer program was originally written in Fortran 77. For this analysis, the program was run on a mainframe computer. Waste-specific multioption flow charts were added to enable the user to select from among six types of low-level mixed wastes. The program consists of a main program, subprograms that allow the user to create a new file, read or modify an existing file, and technology subprograms that determine the life-cycle cost of each process option. The main program allows the user to choose to create a new file, read an existing file, modify an existing file, run the BIE algorithm, or exit the program. If creating a new file, the user is prompted to enter the title of the analysis, the number of stages in the treatment train, and the number of process options in each stage. The program was altered for this analysis to allow the user to choose from among six types of LLMW, enter the mass of the LLMW in kg or volume in cubic meters, and the density of the waste in kg/m^3. The program then calls the appropriate subprograms based on the options chosen, and creates a file containing the alternatives generated by the model based on cost optimization. The alternatives selected during the cost optimization process are further assessed with other evaluation criteria to further enhance the selection of a final set of alternatives.

The costs presented in this analysis form part of the Waste Management Facility Cost Information (WMFCI) for low-level mixed waste developed by the DOE for treating complex waste streams that will be addressed in the PEIS. This report contains cost information for four different applications: 1) large waste generator modules; 2) small waste generator modules using new buildings and equipment; 3) small waste generator modules placing new equipment in existing buildings; and 4) portable treatment equipment (Feizollahi and Shropshire, 1994). Only the cost information (cost curves) developed for the large waste generator modules are used in this analysis. The costs developed by DOE for planning level life-cycle cost estimates have an accuracy of plus or minus 30%. The estimates used in the WMFCI report are good for comparative alternative evaluations and are not site specific.

The cost estimating procedure recommended by Feizollahi and Shropshire (14) is adopted in this analysis. The procedure consists of five steps: 1) define the treatment process selection based on the waste stream requirements and waste type; 2) define the capacity requirements for each module; 3) prepare cost estimates for each module required to provide treatment and disposal (TD) for the waste stream utilizing the module cost curves; 4) add the individual module costs to obtain a total waste stream cost; 5) add transportation costs for off-site shipments to obtain the total option cost (step 5 is not utilized in this analysis). The unit life-cycle cost estimates and throughput capacities used in this analysis are based on an approach referred to as anchoring. Anchoring provides a comparison of estimates based on either the actual costs incurred by an operating facility or estimates of facilities that are actually being designed and built. The process rates and life-cycle costs used in this analysis were selected from the cost curves developed by

Feizollahi and Shropshire (14) which represent the range of facility costs over the estimated capacity. All costs are based on 1994 dollars, and an operating and maintenance period of 10 years for a facility

Additional assumptions must be made to facilitate cost development and model operation. These include:

- The operational life for a facility is 10 years.
- A new facility may operate a maximum of 4,032 hr/year.
- The cost of transportation, other than between the Certification and Shipping stage and the Disposal stage are not included.
- The costs of waste handling (e.g., site inspection, excavation, etc.) prior to the Receiving and Inspections stage are not included.
- This analysis considers only solid LLMW, not aqueous LLMW.
- The waste is not stored after the Certification and Shipping stage, it is sent to one of the applicable disposal technologies.
- All costs are considered to include the Life-Cycle of the facility and are based on 1994 U.S. dollars. An 8% discount rate is assumed to calculate present and future worth of alternatives.
- The disposal process options Life-Cycle costs are listed as dollars/m^3, and a default density of 140 kg/m^3 is assumed for the average solid LLMW unless the user enters a different value.
- The numerical and figures-of-merit evaluation criteria assume that all criteria have the same weight.
- Disposal option #4, Bore Hole Disposal, assumes low sensitivity handling practices and a cost of $2,125,000 per Bore Hole. Each Bore Hole holds 5 drums, each containing 0.2m^3 of waste for a total of 1 m^3 of waste per bore hole.

The system creates treatment alternatives (treatment trains) that are feasible, cost efficient, and different. The development of alternatives must be waste-specific. Although there are certain aspects that are shared between different wastes and their corresponding treatment scenarios, each waste type must be handled in a specific manner. Constraints are placed in the model selection process to reject options which are not feasible. These constraints consists of waste-specific treatment trains and cost restrictions.

Description of Treatment Process Options

The treatment options were selected from those presented in the WMFCI guide (14). The report describes life-cycle cost information for treatment alternatives involved in managing LLMW. Alternatives were selected based on the criteria that they offer treatment for a wide range of LLMW. The following two generalized categories are available: 1) Media Handling and Treatment, 2) Disposal Options. From these two categories, 35 treatment/disposal technologies were modeled. These are categorized into eight different stages: 1) Receiving; 2) Waste Sorting; 3) Pre-Treatment;, and 4) Primary Treatment 5) Secondary Treatment; 6) Pre-

Disposal, 7) Disposal Front-End Support, and 8) Disposal/Storage. In some instances, more than one pre-treatment is necessary, thereby increasing the total number of stages. The minimum number of stages modeled are eight, and the maximum are ten.

A particular sequence of treatment technologies is called a treatment train (15). Treatment trains can reduce the volume of materials that need further treatment and/or remediate multiple contaminants within a single medium. A treatment train, for example, might include soil washing, followed by solidification and stabilization measures, and land encapsulation (1). The treatment train developed in this study for the Oak Ridge K-25 case study, Inorganic Sludge, includes the following options: waste receiving, sorting, sludge washing, calcining, filtration, thermal desorption, incineration, fixed-hearth plasma arc, infrared incineration, acid digestion, fast rotary kiln, microwave melter, aqueous treatment, freeze crystalization, grout stabilization, vitrification, polymer stabilization, macro-encapsulation, certification and shipping, disposal front support, engineered disposal, shallow land disposal, dilo disposal, and bore-hole disposal. The treatment trains for Inorganic Particulates, Nonhalogenated Organic Sludge and Particulates, Halogenated Organic Sludge and Particulates, Contaminated Soils, and Inorganic Non-Metal Debris were developed and shown elsewhere (16).

Model Demonstration

To confirm the validity and reliability of the proposed model, it was applied to the treatment of 32,000 drums of low-level mixed waste at the Oak Ridge K-25 site. The Oak Ridge K-25 Site (formerly known as the Oak Ridge Gaseous Diffusion Plant) closed two low-level mixed waste surface impoundment's which were used as settling/holding basins for neutralized waste from the steam plant, metals cleaning facility, plating shop, and sludge generated by the system used for treating the gaseous effluent generated by the uranium enrichment process (Berry, 1992). The waste contained low levels of technetium and uranium radionuclides, as well as products generated from electroplating operations. In an attempt to meet a 1988 RCRA directive closing the ponds, remediation efforts began to remove the sludge and contaminated pond-bottom clay and immobilize it in a concrete grout. The idea behind this action was to use above-ground storage of the drummed waste until the classification of the waste could be changed from hazardous to nonhazardous. The reclassified waste could then be disposed of as Class I radioactive waste. Class I radioactive waste is LLW that is suitable for sanitary/industrial landfill technology and will not expose the public to more than 10 mrem/year at the time of disposal.

Schedule constraints and other process design and control problems made it necessary to store approximately 32,000 barrels of unprocessed sludge. The treatment facility subsequently closed, leaving the 32,000 barrels of sludge along with 16,000 gallons of raw sludge untreated. In August of 1990, the EPA and the Tennessee Department of Environment and Conservation (TDEC) transmitted a letter to the DOE requesting an action plan to correct the RCRA violations stemming from the closure, and to abate, prevent, or eliminate the threat to human health or the environment at the drum storage yards (17). The waste contained enough chloride and flouride to promote corrosion and cause holes to form in the steel drums.

The 32,000 drums at the K-25 site contain approximately 2,600,000 gallons (9,850 m^3) of mixed-waste sludge with a respective density of approximately 1,250 kg/m^3. The treatment and disposal costs for the 32,000 drums using solidification/stabilization technology was originally estimated by Berry at approximately $800 million. Until recently, the waste has been stored at the K-25 Site awaiting treatment. Treatment and disposal contracts for the waste were recently negotiated with Envirocare. The waste is presently being transported from the Oak Ridge Site to another site for treatment and disposal. In order to be transported and treated, the waste had to be transferred to other containers. The Atlas Hazmat Hazardous Waste Storage and Containment System by 21st Century Containers, Ltd. was used for this purpose. Each container will hold 1.35 m^3 and costs approximately $1,000. To accommodate all of the waste, approximately 7,320 containers were needed at a total costs of $7,317,199 (18). The costs associated with managing, manifesting, and handling the material in order to prepare it for shipping is approximately $212/$m^3$ ($2,086,504 for all 9,850 m^3 of waste). The costs associated with repackaging the waste are not available. The stored waste presented no external radiation hazard to inspection or waste handling personnel, and did not present a significant environmental safety and health threat in the controlled storage environment where it was kept. The greatest concern was the stability of the existing storage containers. The situation did, however, pose Occupational Safety and Health Act (OSHA) and RCRA concerns due to the potential release.

Technology options chosen to remediate the waste had to meet certain CERCLA performance and regulatory criteria. The following options were investigated: 1) no action; 2) separation of hazardous and radioactive species; 3) dewatering; 4) drying; and 5) solidification/stabilization. The first two options were eliminated from consideration because they did not meet system requirements. Further evaluation and investigation showed that, based on project objectives and system constraints, either dewatering or drying the mixed-waste sludge were better selections than the solidification/stabilization option. Although LDR requirements will not be met by dewatering or drying the waste, volume reduction, removal of debris, and final placement of the waste in suitable containers will be achieved. Implementation of the solidification/stabilization option will meet LDR requirements, however, waste volume will be significantly increased. Constraints are placed in the model selection process to reject options which are not feasible. These constraints consists of waste-specific treatment trains, each specifically tailored to a different type of waste. The possible number of system combinations is dependent on the number of stages in the treatment train and the number of options available at each stage.

RESULTS AND DISCUSSION

With the K-25 waste-specific data and the cost constraint set at 105% (1.05) times the cost of the least cost solution resulted in eight alternatives (including the least cost solution). The alternatives are displayed in Figure 1. Any cost constraint percentages

(%) can be used to generate different numbers and sets of alternatives. This gives the decision maker the versatility of examining a variety of treatment and disposal combinations.

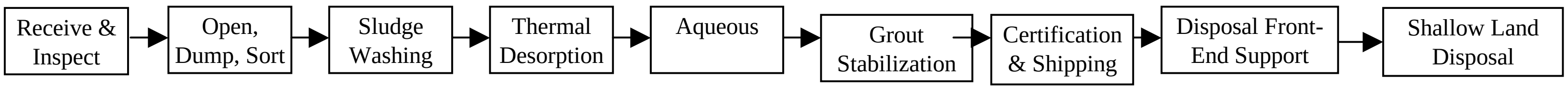
The least cost option is Alternative 8. The total life-cycle cost for this alternative is approximately $41,500/m^3. The eight alternatives depicted in Figure 1 represent not only the most cost efficient solutions with respect to the least-cost solution and user established constraints, but also the most different according to the pairwise difference technique. Locating the most cost-efficient solution is not necessarily difficult or unusual. However, locating the most different solutions that are within a competitive cost range to that of the low cost solution is unique to the model.

The alternatives in Figure 1 utilize only two primary treatment options, Thermal Desorption and Acid Digestion. Thermal Desorption uses a relatively high amount of electricity when compared to Acid Digestion. This factor makes Thermal Desorption the more costly of the two alternatives since control costs are approximately the same. Thermal Desorption is an older technology, and has a lower potential for waste volume reduction. Acid Digestion, on the other hand, is a relatively new treatment technology for LLMW. It's life-cycle costs are uncertain at the present time because of regulatory requirements and other factors. It does, however, have an excellent potential for volume reduction. Both of these treatment technologies have drawbacks that may limit their use in populated areas. Thermal Desorption is a thermal treatment option which has off-gas generation. It does not, however, generate the same level of effluents as an incinerator. Despite the higher control costs created by more stringent air quality standards, Thermal Desorption remains an effective and cost efficient treatment technology.

Alternatives Using Thermal Desorption

Seven of the eight alternatives shown in Figure 1 list Thermal Desorption as the primary treatment option. Only Alternative 4 uses Acid Digestion as a primary treatment option. The most cost-efficient solution, Alternative number 8, utilizes Thermal Desorption. This alternative is forced by model constraints to choose options at stages 1, 2, 7, and 8. Some flexibility, however, is offered in option selection in stages 3 (pre-treatment), 4 (primary treatment), 5 (secondary treatment), 6 (post-secondary), and 9 (disposal). Thermal Desorption utilizes a low temperature kiln to remove volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and metals from the waste. As indicated in Figure 1, the life cycle cost of Acid digestion is $21 million more than Thermal Desorption.

Alternative #1: Total Life-Cycle Cost = $43,879 /m^3.



Alternative #2: Total Life-Cycle Cost = $43,149 /m^3.

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Thermal Desorption has the capability to remove a variety of contaminants. Using the proper temperatures, even metals such as mercury can be removed to safe limits. Contaminants such as Benzene and Toluene, VOCs present in the K-25 sludge, can be reduced from concentrations of 1,000 and 24,000 ppb respectively, to 5.2 ppb. Tests using Thermal Desorption to remove mercury and other contaminants were performed by Seaview Thermal Systems at the U.S. DOE, Oak Ridge, Tennessee, Y-12 plant. Performance data from the tests lists initial mercury concentrations in the test matrix as 1140 mg/kg. The mercury was removed to concentrations of 0.19 mg/kg with a detection limit of 0.03 mg/kg (19). A pilot-scale demonstration with remediation capacity of 2.1 tons per hour was performed at the Anderson Development Company (ADC) Superfund site in Adrian, Michigan using a Low Temperature Thermal Treatment (LT^3) system. Approximately 80 tons of VOC and SVOC contaminated sludge (concentrations ranging from 35 to 25,000 μg/kg) were treated using six 6-hour tests. After treatment, VOC concentrations were below detection limits of 60 μg/kg. SVOC concentrations also decreased. Another study in 1991 was performed at the Waukegan Harbor Superfund site in Waukegan Harbor, IL. This site was primarily contaminated with PCBs, VOCs, SVOCs, and metals. PCB levels were 9,173 mg/kg before treatment and averaged 2 mg/kg after treatment. Initial VOC concentrations totaled 17 mg/kg, while in the treated soil concentrations averaged 0.03 mg/kg. In this particular study, metal concentrations were approximately the same before and after the treatment. This was the result of the systems lower operating temperatures failing to significantly remove metals.

While not providing the same volume reduction as Acid Digestion, Thermal Desorption does offer a reduction of approximately 5% (14). This disadvantage may be offset, however, by the higher cost of Acid Digestion. The life-cycle cost of Acid Digestion for the 9,850 m^3 of K-25 waste is estimated at \$4,675/m^3, approximately 87% higher than that of Thermal Desorption which is \$2,500/m^3. Acid Digestion has a higher unit life-cycle cost than Thermal Desorption, but it also has a greater tradeoff in volume reduction. The removal of target contaminants is a critical consideration when considering either Thermal Desorption or Acid Digestion as a primary treatment option. Either is capable of performing organic contaminant removal in accordance with LDR treatment standards. However, Thermal Desorption costs less than Acid Digestion. Thermal Desorption also lacks the inherent dangers of the chemical treatment used in Acid Digestion and the difficulty in obtaining operating permits.

In stage 3 of Alternative 8, Filtration is chosen as a pretreatment option. This option has an estimated life-cycle cost of \$1.20/kg. Using Filtration to treat the entire 9,850 m^3 (12,302,500 kg) of LLMW has an estimated life-cycle cost of \$14,763,000. Filtration is chosen by the model for five of the eight alternatives in Figure 1. Sludge Washing is chosen for the other three. Sludge Washing costs slightly more than Filtration, at \$2.20/kg. This translates into a life-cycle cost of \$27,065,500 for Sludge Washing, a difference of \$11,072,250. Filtration uses a rather simple system to remove solids from liquids. It also serves to remove larger debris from the waste. It has a solids removal efficiency with the K-25 waste of approximately 25%. This simple type of solids removal system may be suitable for some types of LLMW, but not for others. Sludge washing, on the other hand, uses a more complex assembly of components that may be more advantageous when dealing with waste like the K-25 waste. Sludge Washing has a removal efficiency of approximately 35%. The Sludge Washing treatment system is comprised of a feed preparation system, extraction/gravity settling system, a treated solids filtration system, a solvent recovery system, and associated utility and reagent systems (Feizollahi and Shropshire, 1994). Some of the metals present in the K-25 waste could pass through a filtration device used in the Filtration treatment option. However, the extraction/gravity settling system found in Sludge Washing uses entrapment in a flocculent mass or adsorption to more efficiently remove the contaminants. The sludge is stored in temporary day tanks when it enters the feed preparation system. Once it leaves the day tanks, the sludge is screened and passed into the feed hopper, then into the solvent extraction system.

Freeze Crystalization is selected by the model at stage 5 to treat the liquid portion of the K-25 sludge. Freeze crystalization is a promising innovative technology. It is assumed to be as efficient at meeting both LDRs and DOE disposal requirements as Aqueous Treatment. The approximate total life-cycle cost for this alternative is $35,677,250. The life-cycle cost of Aqueous Treatment for the 32,000 drums of K-25 waste is $41,828,500, which represents a 17.2% increase over that of Freeze Crystalization. Freeze Crystalization separates pure solvents such as water from dissolved solids, undissolved solids, and organic contaminants (6). The process operates at temperatures low enough to prevent volatile organics from vaporizing. This has the effect of reducing the need for off-gas systems that are often required in traditional aqueous treatments. In many applications, water is used as the solvent. Freeze crystallization separates water from wastes by lowering the wastes temperature until ice crystals form. The resulting ice crystals are less dense than the solution causing the crystals to separate by gravity. Due to the simplicity of operation and the reduced life-cycle cost when compared with Aqueous Treatment, Freeze Crystalization is definitely worth further consideration and testing as a secondary treatment option.

The pre-disposal treatment selection, Grout Stabilization, is chosen in stage 6. This option is the least expensive of the four options at this particular stage. The per-unit life-cycle cost for Grout Stabilization is $3.50/kg. Implementation of the solidification/stabilization option will meet LDR requirements, however, waste volume will be significantly increased. Comparing the life-cycle costs of Grout Stabilization with the life-cycle costs of the three other treatment alternatives available at this stage, Vitrification, Polymer Stabilization, and Macroencapsulation, reveals that they are 271%, 414%, and 440% higher respectively. Grout stabilization, as mentioned above, processes noncombustible waste to form a solid mass. Grout stabilization offers an advantage over vitrification when considering energy consumption. Vitrification, however, may offer an advantage over grout stabilization when considering the final volume of disposed waste. The stabilization processes increase the waste output by approximately 130%.

Stabilization also reduces the mobility of contaminants by securely containing them. This is accomplished by chemical reactions that occur between the stabilizing agent and contaminants. Solidification locks the waste into a uniform solid of high-structural integrity. It prepares the treated waste for disposal, and is necessary to ensure containment. Several popular solidification materials are concrete, asphalt, and polyethlyene. One of the most popular materials is concrete.

The waste and concrete are mixed together and poured into secure containers or drums where it solidifies. Any remaining water that is left in the waste is taken up by the concrete as it sets. The possibility of using recycled materials for the solidification process is an option that can help reduce life-cycle costs. It is possible to produce concrete from recycled aggregate and fly ash from power plants. Using fly ash as an additive has the effect of reducing the cost of the concrete by using a recycled material as well as providing a disposal outlet for power plant waste. Fly ash, or pozzolan, can readily be substituted for 15% to 25% of the cement in concrete mixes (20).

The combined effects of pre-, primary, and post-treatment options affords Alternative 8 a final volume of waste for disposal of approximately 6,800 m^3. The life-cycle cost for Alternative 8 is approximately $41,500/$m^3$. This alternative offers the lowest cost when compared to the other alternatives. This factor alone may make it the most attractive selection from a group of alternatives when searching for treatment trains for inorganic sludge. However, the differences between the final volumes of waste for disposal for the various alternatives are significant. This may lead decision makers to consider alternatives with slightly higher costs, but with considerately less final waste volume.

Alternatives 6 and 7 have final waste volumes of approximately 7,300 m^3 and life-cycle costs of approximately $44,184 and $43,543 per cubic meter respectively. Both of these alternatives utilize Aqueous Treatment at stage 5 which has a slightly higher unit life-cycle cost than Freeze Crystalization. They also utilize Filtration at stage 3, which has a lower volume reduction potential than other options. Alternative 6, however, utilizes Engineered Disposal instead of the less expensive Shallow Land Disposal. This accounts for Alternative 6 having the highest life-cycle cost. Both of these alternatives are identical with respect to final waste disposal volume. Neither of these alternatives offer optimum disposal space usage.

Alternative 5 has the combined benefit of a low life-cycle cost ($42,933/$m^3$) and a low final volume of waste for disposal. This alternative utilizes Sludge Washing for pretreatment instead of Filtration. The final volume of disposable waste for this alternative is approximately 5,900 m^3, slightly less than the alternatives that utilize Filtration. As previously discussed, Sludge Washing has the potential to reduce the overall volume of waste to a greater degree than does Filtration. Sludge Washing does have a higher life-cycle cost than Filtration, but the higher cost is offset by the lower life-cycle costs of Freeze Crystalization (stage 5) and Shallow Land Disposal (stage 9). Freeze Crystalization has the potential to lower the final volume of waste more than Aqueous Treatment. Shallow Land Disposal is selected by the model as the disposal option for this alternative. This alternative has the lowest final waste disposal volume of any alternative that utilizes Thermal Desorption. It is also the second most cost efficient among the eight alternatives depicted in Figure 1.

Alternatives 3 and 5 offer the most efficient waste reduction among the seven alternatives that use Thermal Desorption as a primary treatment option. Alternative 3 is similar to Alternative 5 except for the selection of disposal options. Alternative 3 uses Engineered Disposal, which is slightly higher than the Shallow Land Disposal option chosen in Alternative 5. The final waste volume is the same for both alternatives. Alternative 3 is cost competitive (within 105% of the least cost solution) when compared to Alternative 5. If the waste demands a greater degree of protection due to unstable soil conditions (i.e., clay), Engineered Disposal is the better option, regardless of the slightly higher cost.

Alternatives 1 and 2 are similar to each other in regard to the final volume of waste and life-cycle cost. Both of these alternatives have life-cycle costs that are very similar to Alternatives 6 and 7. The final volume of waste for disposal in Alternatives 1 and 2 are approximately 6,330 and 6,840 m^3 respectively. The final volume of waste produced is approximately the same as Alternative 8, the least-cost alternative. However, the life-cycle costs of Alternatives 1 and 2 are approximately \$2,000/m^3 higher. Alternative 1 uses Sludge Washing in stage 3 and Aqueous Treatment in stage 5. This combination offers higher degree of waste reduction than the Filtration/Freeze Crystalization combination used in Alternative 2. Alternative 1 has a slightly higher total life-cycle cost than Alternative 2, even though Alternative 2 uses Engineered Disposal.

Alternatives Using Acid Digestion

One of the most efficient alternatives with respect to life-cycle cost and final waste volume is Alternative 4. If disposal space is limited, or if energy costs are high, then Alternative 4 may be a good choice. This alternative utilizes Acid Digestion as the primary treatment option instead of the higher energy consumer, Thermal Desorption. Acid Digestion is an innovative treatment for LLMW which reduces the amount of land required for disposal by reducing the final waste volume. Only one of the eight alternatives shown in Figure 1 (Alternative 4) lists Acid Digestion as the primary treatment option. The most cost-efficient solution, Alternative number 8, utilizes Thermal Desorption. Alternative 8 is not, however, the most efficient at reducing the overall volume of waste. The second most cost-efficient solution is Alternative 4. Acid Digestion has the potential to remove a variety of contaminants, including metals. Nickel is one of the chief metals present in the K-25 sludge. The LDR concentration limit for land disposal is 11 mg/L leachate concentration using the Toxicity Characteristic Leaching Procedure (TCLP) (40 CFR 268, LDR Treatment standards), while the concentration of Nickel in the K-25 sludge is approximately 4.0 mg/l TCLP. Several types of acid are available for use in this treatment technology.

Using sulfuric acid as an extraction agent offers certain advantages over other types of acid. Sulfuric acid cuts cost, reduces fumes, and lessens the degree of corrosivity when compared to that of hydrochloric and nitric acids. Time, temperature, acid concentration, and the solvent/matrix ratio are parameters that control the rate and amount of contaminant removal. Using a 2% sulfuric acid concentration for one hour at 95^{o}C with a 75:1 v:w ratio results in approximately a 95% removal rate (23). This has the effect of reducing the concentration of Nickel in the K-25 sludge to approximately 0.20 mg/L, or 0.12 mg/L below the LDR disposal limit. Depending on the concentration and number of metals present, Acid Digestion can reduce the matrix weight by approximately 50%.

The secondary treatment that is selected for Alternative 4, Grout Stabilization, slightly counteracts the volume reducing effects of Acid Digestion. If the waste volume after Filtration is considered to be approximately 7,400 m^3, the volume after Acid Digestion would be approximately half this amount, or 3,700 m^3. Grout stabilization would increase this to approximately 4,800 m^3, or, 130% of the volume before secondary treatment. Alternative 4 costs \$545/m^3 (1.3 %) more than the least cost alternative. It has the greatest volume reduction potential of all the alternatives. Since this alternative is cost efficient (within 105% of the least cost solution) the benefits of volume reduction may outweigh and justify the slight cost difference.

Land disposal is used almost exclusively for treated LLMW. For many years, there were insufficient treatment technologies to allow LLMW to be land disposed. This has changed because of the advent of new technologies which effectively reduce the hazardous constituents of the waste, and safely contain the radioactive This contaminants. Final disposal is usually accomplished by transporting the treated waste to a disposal site located a safe distance from surrounding populations. Although land prices are usually more economical in remote areas, disposal is still relatively expensive. By utilizing treatment technologies which reduce the final volume of waste, land space is conserved and disposal costs are reduced. There are four basic disposal technologies considered in this model. These are: 1) Engineered Disposal; 2) Shallow Land Disposal; 3) Silo Disposal; and 4) Bore Hole Disposal. Bore Hole Disposal, the fourth option, is the least cost-efficient disposal alternative for large volumes of waste. However, since the model is configured to allow the user to input the volume of waste, this option may be considered as a viable alternative in certain circumstances. Silo Disposal has the second highest disposal cost of the four alternatives. In cases where disposal space is limited, Silo Disposal may be the most useful option. Two disposal options are initially chosen by the model as the most cost efficient for the eight alternatives in Figure 1. These are Engineered Disposal and Shallow Land Disposal. Both of these share a common characteristic: they involve the use of a shallow land disposal site that must be monitored for extended periods of time.

Shallow land disposal is the disposal option selected at stage 9 for Alternative 8. Shallow land disposal consists of shallow trenches but lacks the engineered features found in engineered disposal. An important issue in the use of Shallow Land Disposal is the establishment of waste acceptance criteria that will ensure a low risk to humans and the environment. The International Atomic Energy Agency (IAEA) basic criteria has been used mainly in the USA, Canada, and the United Kingdom (21)." The NEA approach consists in giving generic reference levels and providing guidance on the methods which could be used by national authorities to derive site specific waste acceptance criteria. The NEA approach lists three types of waste acceptance criteria: 1) Limits on the concentrations of radionuclides in wastes; 2) Limits on the total activity of radionuclides to be disposed of at a given facility; and 3) Performance standards for waste forms and waste packages (22). The assessment of risks relating to radiological exposure is performed by models which consider the properties and stability of the various soil barriers and the rates of radionuclide migration through the barriers. Shallow Land Disposal deals primarily with short-lived isotopes which require shorter disposal periods than required for deep geological disposal. Engineered Disposal uses Shallow Land Disposal with the addition of engineered structures such as concrete lined trenches or vaults. If these features are not of primary importance or necessary to ensure site integrity, shallow land disposal is the most economical disposal option among those that were selected by the model. Both options have the versatility of offering waste retrieval if this becomes absolutely necessary.

CONCLUSIONS

A life-cycle model was developed that generates Low Level Mixed Waste alternatives using life-cycle cost and ranking techniques. The model generated a set of cost efficient treatment and disposal alternatives. Two primary treatment techniques emerged as the most cost efficient; (1) Thermal Desorption; and (2) Acid Digestion. Although Thermal Desorption is the most cost efficient, Acid Digestion is the most efficient at reducing the waste volume. This is an effective tool that can assist engineers and decision makers in planning effective, cost efficient treatment designs for Low Level Mixed Waste Management.

Developing and establishing life-cycle costs involves possessing familiarity with high technology treatment equipment that are extremely complicated. Many of these systems have only been operational a short time because of the newly developing technologies for low level mixed waste. Therefore, obtaining information about them and their costs may be difficult, especially when life-cycle cost information is desired. Fluctuations in this cost data may alter the final selection of treatment technologies, and hence, the total life-cycle cost.

A decision maker will probably have more technologies to choose from than those available at this particular time. It is very difficult for a decision maker to examine all of the possibilities and the way that they relate to technical and economic issues. The model can examine a large number of alternatives and provide results based on user-provided cost constraints.

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