INNOVATIVE TECHNOLOGIES AND UNIT OPERATIONS AVAILABLE FOR POTENTIAL IN SITU AND EX SITU TREATMENT OF WASTE AND RESIDUALS FOR HANFORD SINGLE-SHELL TANKS

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ABSTRACT

In July 1990, the "Third Party Technical Workshop - Hanford Site Single-Shell Tank Waste and Residuals" was held in Spokane, Washington. The objective of the workshop was to identify, discuss, and rate innovative technologies that have not been seriously explored for treatment of single-shell tank waste and residuals.

Ten nationally-recognized waste management experts were asked to attend the workshop and to bring their ideas on how to treat this unique waste stream either 'in situ' (treat in place) or 'ex situ' (remove and treat). The long-term objective of this initiative was to assist the U.S. Department of Energy-Richland Operations Office and Westinghouse Hanford Company in partially fulfilling a milestone to identify an appropriate means of disposing of waste, tanks, contaminated piping and soils by January 1999.

A total of 11 ex situ and 11 in situ applied technologies with potential applicability to single-shell tank waste and residuals were identified and discussed in the workshop. An additional 12 nonapplied, innovative (brainstormed) technologies were also identified.

INTRODUCTION

There are 149 single-shell tanks (SSTs) located in 12 underground 'tank farms' in the 200 East and 200 West Separations Areas at the Hanford Site in southeastern Washington State (Fig. 1). Each tank farm contains 4 to 18 tanks.

In July 1990, the "Third Party Technical Workshop - Hanford Single-Shell Tank Waste and Residuals" was hosted in Spokane, Washington, by Bovay Northwest Inc. under contract to the Westinghouse Hanford Company (1). The objective of this workshop was to identify potentially applicable technologies for obtaining closure of the SSTs, associated equipment, and contaminated soils. The identification of these technologies represent an initial step toward meeting the "Hanford Federal Facility Agreement and Consent Order" (Tri-Party Agreement) milestones requiring the identification of appropriate disposal mechanisms for SST waste, contaminated piping and soils by January 1999 and demonstration of a full-scale, SST closure to be completed by June 2004 (2).

Objective and Scope

The primary objective of the workshop was to identify, discuss, and rate technologies and/or unit operations with potential applicability for the treatment and/or remediation of SST waste itself; residuals left after any retrieval operations; and/or contaminated soils adjacent and below the SSTs.

The long-term objectives of the SST treatment program are to select, design, test, and install a final waste form technology in a credible and defendable manner. The following ground rules were established early in the workshop planning process:

- Sessions must facilitate open and honest interchanges.
- Brainstorming is acceptable if technologies can be applied to this difficult-to-treat waste stream.
- Conflict of interest must be minimized.
- Whatever technology is selected or rejected, a solid, technically defensible rationale for its selection or rejection must be identified.

A few technologies were deemed to be out of the workshop's scope because they are supported by ongoing programs, thus they were not discussed at the workshop (3). These technologies were in situ vitrification and vitrification (borosilicate glass). Additionally, technologies dealing strictly with retrieval or interim treatment of SST waste or residuals were deemed out of scope.

Planning

The identification of innovative technologies and unit operations for the treatment of SST waste and residuals was

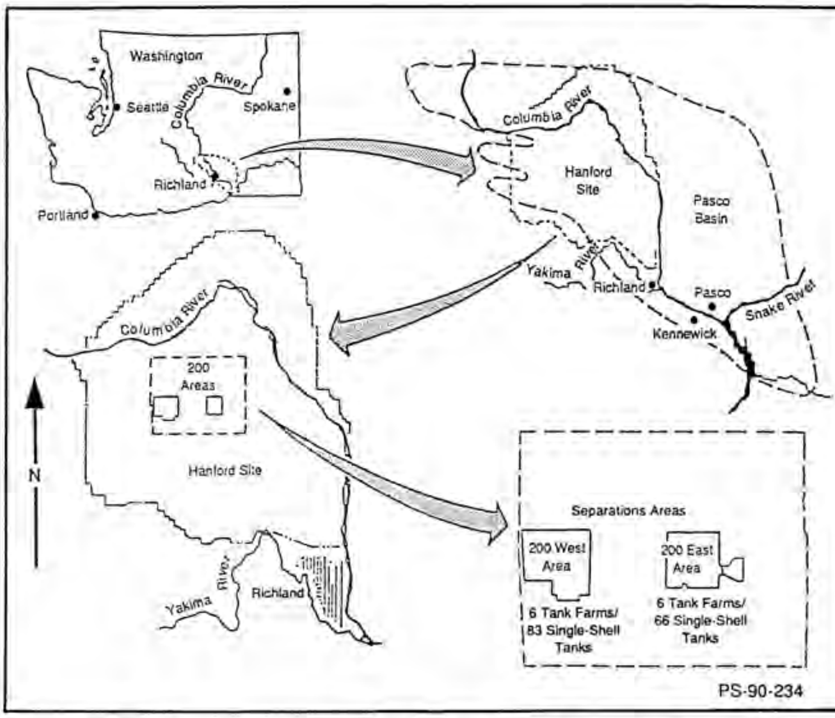

Fig. 1. Locations of the Hanford Site and the separations areas.

a challenging process. The ideal technology would be one that had been extensively applied in the treatment of a nonradioactive waste stream analogous to the waste currently in storage in SSTs.

The process used to select technologies began with an extensive literature search. The list of several dozen potential technologies was narrowed by screening out technologies that did not have a potential for treating SST waste and residuals.

The next step in the process determined if any of the applicable technologies had been applied to waste streams analogous to SSTs; because no technologies could be identified that had been applied to a waste stream analogous to SSTs, the list was further screened by assessing the potential of applying the technology to the waste stream. If no such potential existed, the technology was dropped from further consideration. An example of existing technologies currently in use for an analogous waste stream are lagooning and solar evaporation of high-salt brines in Death Valley, California, subsequent to mineral extraction. These technologies were not considered because of environmental, public health, and safety considerations associated with lagooning radioactive materials.

Screened technologies were further refined by contacting the author(s) or vendor(s) of the reviewed literature. Discussions were held regarding their level of interest in participating in the workshop. In some instances, the author or vendor could not attend the workshop because of conflicting schedule problems; in those cases, permission was granted to have their technology represented through another expert.

Through this process, 10 technical experts were chosen to participate in the workshop. To facilitate concurrent workshops, experts were segregated into ex situ and in situ categories depending upon their expertise. In situ technologies are those in which SSTs, associated equipment, and/or residuals are treated in place. Ex situ technologies involve those in which the waste, equipment, and/or residuals are removed before treatment.

SINGLE-SHELL TANK CHARACTERISTICS

A brief explanation of the construction details of the 149 SSTs is given in following paragraphs. All of the tanks consist of a single carbon-steel liner within a reinforced concrete shell and can be categorized into one of four different types based on size and construction. Three of the four different tank types are 22.9 m in diameter, have a domed top constructed of reinforced concrete, and can hold volumes of 2,000 m^3, 2,900 m^3, or 3,800 m^3. The fourth type of tank is 6.1 m in diameter, has a flat reinforced-concrete top, and can hold a volume of 210 m^3. There are 16, 210-m^3 tanks; 60, 2,000-m^3 tanks; 48, 2,900-m^3 tanks; and 25, 3,800-m^3 tanks.

Waste from reprocessing and waste management operations on the Hanford Site was discharged into SSTs from 1945 to 1980. The waste consisted of the high-activity waste fractions generated from fuel reprocessing operations used to recover special nuclear materials. Additionally, waste was removed from some of the tanks to recover enriched uranium and remove some fission products; the processed waste was then placed back into the SST system. Several different processes and facilities discharged waste into the SST system during their operational life including the bismuth phosphate ($BiPO_4$), reduction/oxidation (REDOX), and the plutonium/uranium extraction (PUREX) processes.

Currently, the SST waste consists of about 140,000 m^3 of solids and about 23,000 m^3 of interstitial liquid and supernatant. A program is underway to reduce the collective volume of liquid to about 4,000 m^3 by 1996. The solids in the tanks consist of about 90,000 m^3 of salt cake and 50,000 m^3 of sludge. Approximately 50% of the sludge volume is intermixed with salt cake. This waste volume consists of about 200,000 MT of chemical waste and about 2.2 EBq (2.2×10^{18} Bq) (approximately 1,400 MT) of radionuclides (decayed through January 1995).

About 93 wt% of the salt cake consists of sodium nitrate and sodium nitrite salts. The non-salt-cake portions of the waste sludge are primarily metal oxides and metal hydroxides precipitated from the caustic SST solutions. About 98% (by activity) of the radionuclide content is ^{90}Sr (1.7 EBq) and ^{137}Cs (0.4 EBq). The physical properties of the SST waste ranges from hard, dry crystalline solids to wet solids. The bulk density ranges from 1.2 to 1.9 g/cm^3.

In addition to the reprocessing waste inventory, some unique materials have been added to a few of the tanks for various purposes since the tank operations began. The materials include diatomaceous earth, portland cement, organic ion-exchange resins, experimental fuel elements, and other liquid and solid wastes.

Of the 149 SSTs, 68 have been confirmed to have leaked liquid contents to the surrounding soils. Estimates indicate that about 2,800 m^3 of liquid waste have leaked from these tanks. When active operations were ceased, a program was initiated to remove the pumpable liquid from the tanks to reduce potential for further leakage (4).

THE WORKSHOP PROCESS

The workshop was organized into two concurrent sessions each consisting of a panel of four to six technical experts in each session. The technical experts were chosen so that a broad spectrum of backgrounds would be represented at workshop. The concurrent sessions were centered around two general types of technologies: in situ and ex situ.

Technical Expert Panel

Technical experts on the panel were selected on the basis of their expertise in the areas of technology with some potential applicability to the SST waste or residuals. Priority was given to those experts who have knowledge of a treatment system or process for a nonradioactive analog to SST waste.

The 10 experts were chosen from an initial list of 35 individuals. The experts grouped into their participant session (i.e., ex situ or in situ) are listed in Table I.

The Workshop Process

In each workshop session (i.e., ex situ and in situ), the technical experts made a brief presentation of technologies that may be applicable to the SST waste stream and/or residuals. After this presentation, the technology was discussed in an open forum by the panel of experts and other session attendees. During this discussion the potential applicability of the technology to SST waste and residuals, and the advantages and disadvantages were discussed.

After all technologies were presented and discussed, the technical experts from each session rated each technology. Technologies were rated based on their potential feasibility, potential application to the SST waste and residuals problem, and on the opinions of the experts.

In addition to the technologies presented by the experts, the participants were asked to identify other technologies (regardless of whether they were applied technologies or not) that had not been discussed previously during the workshop. Some of these technologies could be considered innovative concepts and with modification and additional refinement these technologies could merit further consideration. The goal of this process was to ensure that all possible technologies with even a remote possibility of application to the SST waste and residuals were discussed.

TECHNOLOGIES IDENTIFIED

The technical experts presented, discussed, and rated 11 ex situ and 11 in situ technologies. In addition 12 brainstormed technologies were identified by the technical experts and other workshop participants. A brief description of these technologies (presented in no particular order) and one graphic example of each ex situ, in situ, and brainstormed technologies are presented in following sections.

Ex Situ Technologies

Eleven ex situ technologies were identified and discussed in the workshop. Each technology is described in following sections. The following is a list of those technologies:

TABLE I

Panel of Technical Experts

Ex Situ Technical Experts

Expert	Affiliation	Expertise
Lloyd Andrews	Chem-Nuclear Systems	Nuclear and chemical waste cleanup
Nathan Burbank, Jr.	Consultant	Industrial waste treatment
Peter Colombo	Brookhaven National Laboratory	Waste solidification
Neal Egan	MSE, Inc.	High-temperature plasma melting
John Rusin	Consultant	Nuclear waste form development
Wallace Schulz	Consultant	Nuclear separations chemistry and processes

In Situ Technical Experts

Expert	Affiliation	Expertise
Willy Abeele	Consultant	Geohydrology and geotechnical engineering
Paul Scott	Pacific Northwest Laboratory	In situ solidification
Michael Skriba	Fluor Daniel	Radioactive and hazardous waste management
Russell Treat	Ebasco Services Inc.	Radioactive and hazardous waste treatment technologies

- Complete partitioning of SST waste
- Encapsulation of SST waste using low-density polyethylene (LDPE)
- Centrifugation of salt cake and liquid slurries
- Water treatment technologies
- Plasma arc furnace
- Encapsulation via ceramics
- Encapsulation via borosilicate glass
- Encapsulation via glass ceramic
- Elutriation of SST sludges followed by ion exchange
- X*TRAX™*
- Encapsulation of SST waste using modified sulfur cement.

Complete partitioning of single-shell tank waste--this approach involves the use of existing technology, or in some instances modification of an existing separation technology, to completely partition the mixed waste in the SSTs into two major fractions: radioactive and nonradioactive. The partitioning technologies proposed include the transuranic extraction (TRUEX) and strontium extraction (SREX) processes and precipitation and ion exchange processes. The various waste streams would then be encapsulated or destroyed for long-term waste management purposes.

Encapsulation of SST waste using LDPE--this technology involves mixing of dried waste with LDPE in a twin-screw auger producing a flowable product that sets up into a solid polyethylene matrix encapsulating the waste.

Centrifugation of salt cake and liquid slurries--this technology could be used as one unit operation to separate the liquid phase from the insoluble salts (after retrieval from the tanks) resulting in a concentrated salt cake slurry. Several types of centrifuges have been used for a salt cake application; these include a screen-based centrifuge or a concurrent-flow centrifuge for continuous operation and a basket centrifuge for batch operation.

* X*TRAX™

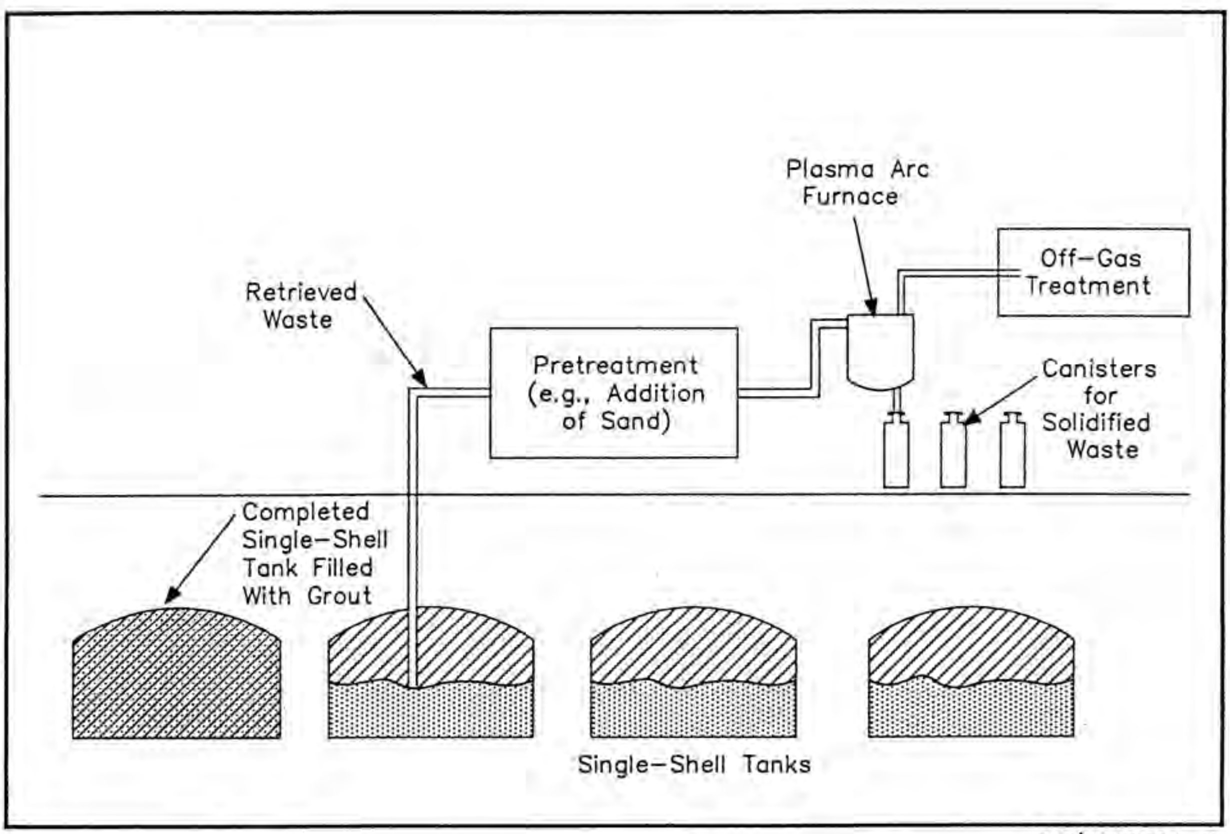

Fig. 2. Conceptualization of the use of a plasma arc furnace.

Water treatment technologies--this technology involves the relatively straight-forward use of existing municipal and industrial waste water treatment technologies, such as the standard lime- softening process, in the demineralization of sludges, salts, and salt cakes. A variation on the typical equipment uses contact with a previously coagulated stream to enhance precipitation and flocculation.

Plasma arc furnace--this technology uses a plasma torch to produce very high localized temperatures (up to 1700°C) in a waste or waste matrix. The process can destroy organics and some inorganics (e.g., nitrates) and melts and solidifies the remaining material in a durable glasseous product. Potentially, little or no pretreatment would be necessary to handle the SST waste using this technology. As a representative of an ex situ technology, Fig. 2 presents a conceptualization of this technology as applied to SST Waste.

Encapsulation via ceramics, borosilicate glass, and/or glass-ceramic (three technologies). This group of three technologies would solidify and encapsulate the retrieved waste using either one or a combination of several solidification techniques that include ceramics, borosilicate glass, or glass-ceramic. Some type of waste pretreatment would probably be necessary before solidification.

Encapsulation of SST waste using modified sulfur cement--this technology, developed by the U.S. Bureau of Mines, uses a modified sulfur cement to solidify and encapsulate waste species. The sulfur cement is modified by adding approximately 5 wt% dicyclopentadiene (polymer) to prevent a phase change in the sulfur matrix that can weaken the final cement. A sulfur compound is added to some formulations to reduce leachability of some waste species. The sulfur, polymer, and waste are mixed and heated, resulting in a thermoplastic that solidifies in a matter of hours.

Elutriation of SST sludges followed by ion exchange--this technology involves the washing of sludges with either water or aqueous solutions of salts to remove various waste species from the sludges. The elutriant is then treated by ion exchange.

X*TRAX™ --this process utilizes a patented, low-temperature thermal separation system for separating chemical components from radioactive components found in contaminated soils and dewatered solids such as sludges. The process uses an indirectly-fired rotary dryer to volatilize certain contaminants. The resulting contaminated off-gas stream is treated to remove particulates and vapors previously removed from the sediments. The process has been tested in nuclear operations at the Barnwell and the Oak Ridge Gaseous Diffusion plants.

In Situ Technologies

Eleven in situ technologies were identified and discussed in the workshop. Each technology is described in following sections. A listing of the technologies is as follows:

- Sequestering agents
- Wicks coupled with collector drains
- Rheologically formulated treatment-liquids and solids
- Solution mining coupled with horizontal drilling
- Electrosmosis coupled with a fine clay barrier
- Jet (injection) grouting of soils
- Grouting (all grouting except injection)
- Cryogenics (in conjunction with other ex situ techniques)
- Grouting--dome fill
- Biological treatment
- Bentonite biobarriers.

Sequestering agents--this 'active zone' concept takes advantage of known properties for a host of sequestering agents (such as activated carbon or ion exchange media) to adhere, contain, and isolate contaminants of concern once injected as a slurry into soils. This is not an in situ treatment alternative that is applicable to waste residuals inside SSTs.

Coupled with horizontal drilling, an 'active floor' could be placed under the tanks by drilling a horizontal grid and filling it with ion exchange as a sequestering agent.

Wicks coupled in conjunction with collector drains--large-scale lateral-flow tests have been performed in a fine-textured material overlying a coarser medium. The interface is an effective barrier, because suction predominates over the forces of gravity. The percolating liquid will penetrate the coarser material only after the overlying finer material nears saturation. Consequently, the structure (i.e., the waste) that is enclosed in the coarser material, remains dry. As long as the pressure at the coarse/fine interface remains negative, water infiltrating the finer layer will not cross the interface; instead, it will flow along the sloped interface.

Rheologically formulated treatment-liquid and solid--this technology couples directed acoustics with high-shear strength muds, grout, and gels to provide a protective barrier.

Solution mining coupled with horizontal drilling--this technology has been used in the uranium mining industry to extract uranium from soils in situ through a series of injection and recovery wells. By design it mobilizes constituents and is normally used in situations where contamination of

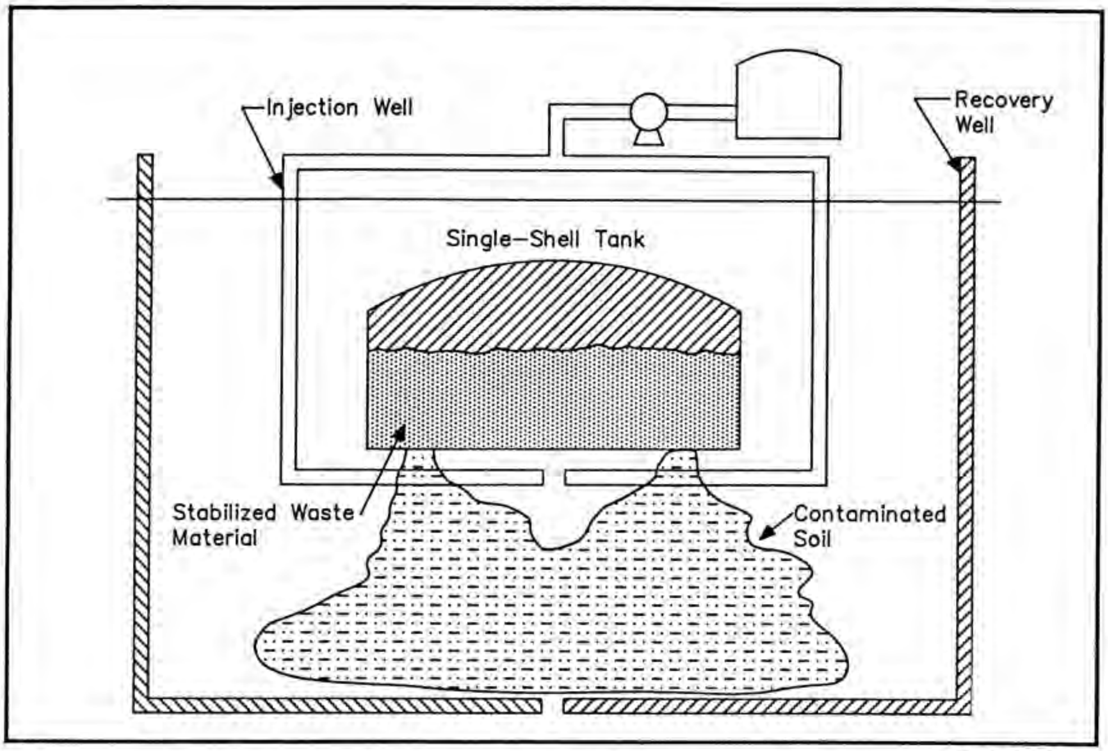

Fig. 3. Conceptualization of solution minimg technology.

other geohydrologic zones can be minimized. A graphic conceptualization of this technology can be found in Fig. 3.

Electrosmosis coupled with a fine clay barrier--this technology couples the injection of fine clay adjacent, outside, and beneath SST walls with an electrical potential (direct current) to force the migration of moisture to a collection point for recovery and processing.

Jet (injection) grouting of soils--this technology calls for injecting grout (possibly via 'lancing' to create mounds or 'pillows' of grout) under high pressure into soils to act as a barrier to further migration. The lancing technology is a patent of the Italians and is used extensively for applications related to strengthening subsoils under building foundations.

Grouting (all grouting except injection)--the technologies related to grouting involve either the placement of grout curtains in soils adjacent to SSTs, mixing grout formers and wastes together in the tanks, or the filling of the tanks void space ('dome fill'). Either an inorganic or an organic grout can be used. Organic grouts may not be acceptable because they are very sensitive to changes in the waste makeup and contain hazardous and flammable materials such as vinyl chloride.

Cryogenics (in conjunction with other ex situ techniques)--this technology provides an interim barrier to prevent the migration of contaminants by injecting a cryogenic fluid (e.g., liquid nitrogen) into soils external to the SST walls. In this manner, the soils adjacent to the tanks are frozen thus preventing further migration.

Biological treatment--this technology would introduce biological organisms to soils to destroy and convert certain contaminants to harmless materials. The technology is currently under investigation for a host of hazardous waste applications and has been proven effective in certain situations.

Bentonite biobarriers--this technology takes advantage of the natural properties of bentonite and other natural geologic media to contain and isolate hazardous wastes when applied as a land disposal option. Soil and a maximum of 14% bentonite are mixed to form a barrier. The concept also utilizes the concept of wicking by allowing a sponge-like effect to occur followed by direction of leached material to a collection point for treatment and disposal.

Brainstormed Technologies

Twelve brainstormed technologies were identified during the workshop. Each technology is described in following sections. These brainstormed technologies are as follows:

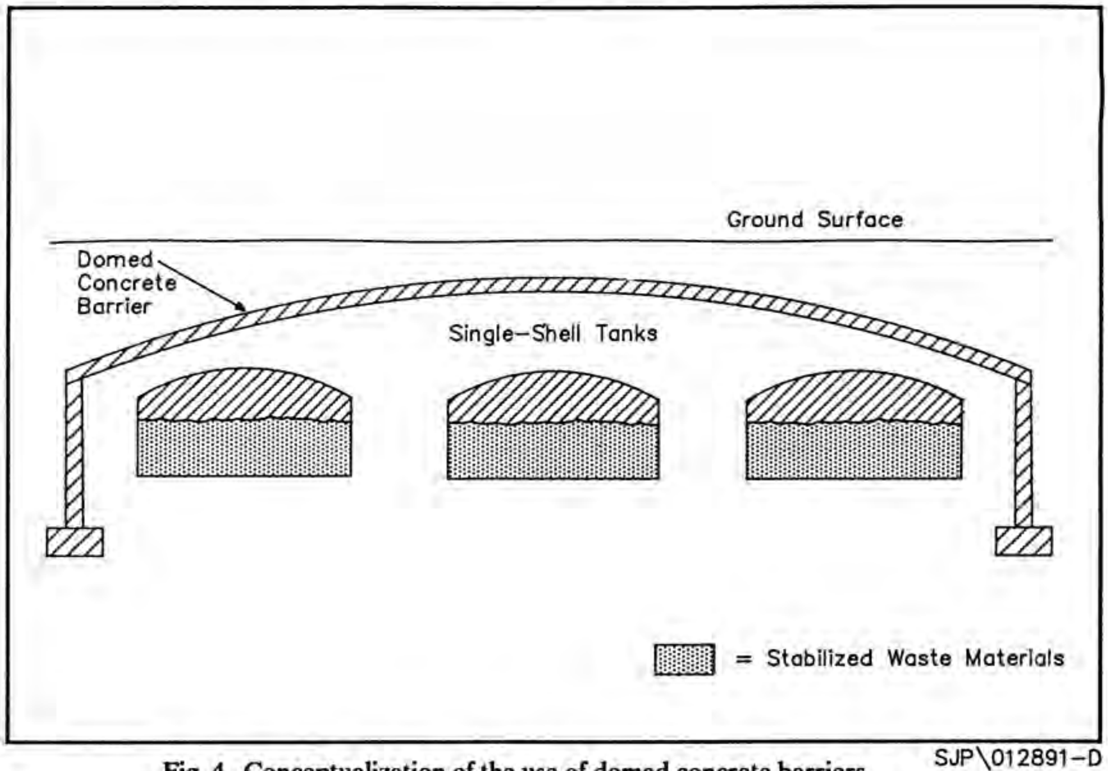

Fig. 4. Conceptualization of the use of domed concrete barriers.

- High-density media isolation and retrieval
- In situ mixing and treatment
- In situ encapsulation
- Domed barriers
- Miniaturization of ex situ techniques
- Gas-phase reaction technique
- In situ polymerization
- Selective cropping
- Water channeling
- Molten salt and nonaqueous waste separation
- High-velocity jets for cleaning of sheet steel
- Freeze barriers or cells.

High density media isolation/retrieval--this idea would utilize a high-density material to float out sludges and salt cake from the SSTs. Ideally, the media would set up and/or sequester remaining residuals. It would be used in conjunction with an in situ leak prevention technology and an ex situ full-treatment plan.

In situ mixing and treatment--this idea would recover and mix SST waste in situ using one auger to mine the waste from the tank bottom and side. This auger would feed into a twin auger where it would be mixed with a sequestering and/or an encapsulating agent and fed back into a portion of the tank. This technology represents using an ex situ treatment technique in tank or in situ. Some possible encapsulating agents include a low-temperature glass, low-temperature ceramic forming agent, or LDPE.

In situ encapsulation--this idea would use encapsulation materials such as polyethylene that would be injected into zones of contaminated soils to tie up contaminants thus preventing migration.

Domed barriers--massive concrete domes could be constructed over the tanks to provide a solution to the potential for compromising barrier integrity by tank collapse or expansion. Concrete materials have had a several thousand-year history as massive structures. Fig. 4 presents a graphic conceptualization of this brainstormed technology.

Miniaturization of ex situ techniques--this generic idea would simply install ex situ techniques within the confines of SSTs (e.g., plasma or other melter technologies).

Gas-phase reaction technique--this idea would introduce agents that would induce a gas-phased reaction over a long period of time to render SST species harmless.

In situ polymerization--this idea would inject one or several monomers into the soils adjacent to tanks, mixing with existing substrate and contaminants. Once satisfied that a relatively homogenous mix has been obtained, an agent to initialize polymerization of the added monomers would be injected. The resulting in situ polymerization would encapsulate and isolate the SST contaminants.

Selective cropping--this idea (first proposed by the Russians) would introduce deep-rooted crops above contaminated areas to selectively uptake contaminants. The crops would then be harvested and treated.

Water channeling--this idea (as previously proposed by Pacific Northwest Laboratory) would engineer structures to channel advecting water between the tanks thus not allowing the moisture to dissolve waste and transport it to the aquifer. Or, coupled with engineered barriers, the channels act as conduits for wicked or leached material that could be collected and treated to remove contaminants.

Molten salt and nonaqueous waste separation--this idea would use a molten salt phase to separate various waste species from non-water-soluble SST wastes, such as sludges and some fractions of the salt cake.

High-velocity jets for cleaning of sheet steel--spray pumps capable of delivering streams of water (or other liquids) with scouring velocities approaching several 30 m/s could be used to clean the sheet steel making up the sides and bottoms of the SSTs.

Although out of the workshop's scope, this technology could be used to retrieve the waste from the tanks. The high-velocity jets would be used to homogenize the salt cake and/or sludge into a pumpable slurry which could then be removed from the tanks.

Freeze barriers/cells--conventional ground drilling, refrigeration, and water circulation can be used to create ice barriers in soil to prevent contaminant migration. These techniques can be modified to freeze a solid block of ground which then can be removed. The barrier application is patented technology and is being evaluated by the U.S. Department of Energy (DOE). The freeze cell technology is being patented and is being considered by the DOE for further evaluation.

RECOMMENDATIONS

At the conclusion of the workshop, participants were asked for their recommendations. The following discusses those recommendations by subject matter.

Institutional

A technical review panel should be established to review the SST treatment program from 'cradle to grave'. In addition, the public, or it's representative, should be included in the technology selection process.

The Workshop Concept

The open and honest communication that occurs in a small workshop process can be an effective mechanism to solicit information, exchange ideas, brainstorm new ideas, and interact between those with the problem and those with solutions. It may be equally effective when applied to a smaller subset of technologies studied in depth. The workshop process is also effective in sorting and ranking different technologies as to their viability in treating unique waste streams.

Treatment Systems Engineering

Considerable research has already been done on a limited number of SST treatment technologies. We should learn as much as possible from the past to avoid repetition and waste of limited resources. Small demonstration projects should be pursued as soon as possible to allow time to react to lessons learned in time for the full-scale technology field-scale demonstration. This will build our confidence levels with interested parties and peers. No single treatment system may be available to treat this waste stream; coupling may be required.

Ex Situ Technologies

Of 11 ex situ technologies and unit operations explored, the following warrant further investigation for treatment of SST waste and residuals: partitioning, plasma arc furnace, LDPE encapsulation, and sulfur cement encapsulation. In addition, upon further investigation, the following technologies and unit operations may warrant further investigation: X*TRAX™, centrifugation of salt cake and slurries; traditional water treatment technologies, and glass-ceramic encapsulation. The technologies and unit operations that warrant further study were recommended by the technical experts. Those recommendations were based primarily on the potential applicablity to the SST waste and residuals.

In Situ Technologies

After reviewing 11 in situ technologies and unit operations, the following were determined to warrant further investigation: X*TRAX™ solution mining coupled with horizontal drilling, use of sequestering agents, cryogenics (interim solution), and grouting (for dome fill only).

Upon further investigation, the following may warrant further investigation: jet grouting (of soils), electrosmosis coupled with a fine clay barrier, and the use of wicks coupled with collector drains. The technologies and unit operations that warrant further study were recommended by the technical experts. Those recommendations were based primarily on the potential applicablity to the SST waste and residuals.

Brainstormed Technologies

After reviewing 12 brainstormed technologies, the following may warrant further investigation: in situ encapsulation, miniaturization of ex situ techniques, gas-phase reaction techniques, in situ polymerization, water channeling, and molten salt and nonaqueous waste separation.

Selection Criteria

The selection of a final technology or unit operation(s) to treat SST waste and residuals is the cornerstone to solving this problem. Performance and engineering objectives should be established. The ultimate disposal of SST waste and residuals may dominate the selection process. In selecting a technology, consideration should be given to the resources required to decommission and dispose of the waste treatment facilities themselves. Secondary waste streams should also be considered when selecting the treatment technology. Additionally, consideration should be given to ultimate disposal of treated SST waste/residuals in the 'same hole' from where they were removed.

Future Workshops

Future workshops should be held to solicit and evaluate more definitive technology information in concert with involving the public sector and regulators.

Subjects that could be addressed by future workshops include the following:

- The long-term SST treatment road map
- The technology selection process
- Partitioning technologies
- Solidification and detoxification of $NaNO_3$ operations
- Additional SST residual characterization information.

SUMMARY

The objectives of the July 1990 "Third Party Technical Workshop - Hanford Single-Shell Tank Waste and Residuals" were met. A total of 22 applied technologies not previously discussed as solutions to treatment of SST waste and residuals were identified, eight of which warrant further investigation. In addition, 12 brainstormed ideas may warrant further investigation.

A review of the literature did not reveal any existing applied technologies in use on analog waste streams. There may be a number of technologies or groups of technologies that may work; however, the degree of treatment effectiveness has not been determined.

There was no consensus regarding the potential application of any one in situ or ex situ technology. However, the use of ex situ and some in situ technologies definitely warrant further investigation. In situ technologies may be best suited when coupled with ex situ treatment options.

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