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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830

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(a) Oak Ridge National Laboratory, Oak Ridge, Tennessee

Acknowledgments

The evaluation of technologies to enhance the dislodging and retrieval of radioactive waste stored in underground storage tanks that are confirmed or suspected to leak is a strategic initiative under direction of the US Department of Energy Office of Science and Technology, Tanks Focus Area. For this strategic task, Pete Gibbons, Retrieval Technology Integration Manager and Mike Rinker, Deputy Retrieval Technology Integration Manager provided TFA oversight. Special recognition is given to Jerry Cammann, CH2M Hill Hanford Group, for providing Hanford Site River Protection Project perspective and for providing guidance for application of technologies for retrieval of waste from leaking tanks throughout the course of the project. Also, support from Richard Harrington and assistant Robin Kummer is recognized for leading the technology prioritization workshop.

Summary

The need to identify and develop technologies applicable for remediation of tanks that are known or are suspected to leak was selected by the US Department of Energy (DOE) Environmental and Waste Management (EM) Tanks Focus Area (TFA) as a strategic initiative. The purpose of this task was to identify and evaluate technical options for single-shell tank (SST) waste retrieval that are applicable to retrieval of waste from potentially leaking tanks. Technologies that minimize leakage, retrieval technologies that use minimal water, and dry retrieval technologies were candidates for evaluation. This work was a collaborative effort between Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), and the River Protection Project (RPP) CH2M Hill Hanford Group (CHG).

The initial focus of the investigation was to identify and evaluate technical options for single-shell tank (SST) waste retrieval that were applicable to retrieval of waste from potentially leaking tanks. Safety, cost, authorization basis, and schedule risks were identified for each technology to provide RPP with adequate information to evaluate technical and programmatic risk. Based on this input, a two-day workshop was held by a team consisting of participants representing the US DOE EM-50 Tanks Focus Area, River Protection Project, Hanford Site projects and programs, and project collaborators from Pacific Northwest National Laboratory and Oak Ridge National Laboratory. During the workshop sessions, technology needs and solutions were identified based both on the approaches for retrieval of wastes from leaking tanks identified in this analysis and based on discussions of new technologies or novel arrangements of the technologies for remediation of leaking tanks among the workshop participants. These approaches grouped naturally into five categories: those related to waste dislodging (D), those related to waste conveyance (C), those related to both waste dislodging and conveyance (D&C), those related to the deployment platform (DP), and technologies related to leak detection, monitoring, and mitigation (LDMM).

Based on the technology ranking, six technologies were selected as potential candidates for further evaluation. These prioritized technologies include:

1 **Dislodging and Conveyance - Dry TORE® with jet pump combination.** The TORE® is a patented hydro transportation device with no moving parts that produces a precessing vortex core with the ability to convey solids at pre-determined slurry concentrations over great distances. The system moves from 1% to 70% or more solids by weight slurries. It consists of a concentric feed section having a central discharge tube, where a motive fluid such as water is used to displace the process material. The current TORE® design is based on developing a liquid-based precessing vortex core to mobilize and fluidize solids so they can be captured in the outlet pipe flow and removed from the vessel. The **dry TORE® concept** envisions using air to develop the precessing vortex core to fluidize dry solids. The TORE® outlet is coupled with a jet pump to transport the solids in a slurry transport line.

2 **Enhanced Dislodging - Sonic TORE® and Bulldozer (Vehicle) with Sonication.** The sonic TORE® concept envisions utilizing sonication to fracture and dislodge solids for entrainment in the TORE® precessing vortex core. The vehicle concept coupled with sonication envisions coupling sonication with the vehicle, perhaps through a plow blade, to fracture solids for transport to a conveyance system.

3 **Enhanced Dislodging - Sonication.** This technique envisions using ultrasonic energy to fracture and dislodge hard waste types such as salt cake and sludge.

4 **Deployment Platform - Long-reach Manipulator**. The purpose of this development is to investigate novel and cost effective approaches for long-reach manipulator technology.

5 **Deployment Platform - Next Generation Crawler Technology.** This development envisions a non-umbilical dislodger, possibly radio controlled and powered remotely to provide a deployment platform not affected by path, or the need to retrace steps. The crawler is envisioned as a deployment platform for any of the novel end effectors and conveyance techniques.

These five items were prioritized by the team into four technologies to recommend for further evaluation

- Air assisted TORE® for enhanced solids dislodging and mobilization
- Sonication for waste dislodging
- Novel long-reach manipulators
- Next generation crawler technology.

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Acronyms

AGA	alternate generation analysis
AM	amplitude modulation
C	conveyance
CHG	CH2M Hill Hanford Group
CODFM	coded orthogonal frequency division multiplexing
D	dislodging
D&C	dislodging and conveyance
DOE	Department of Energy
DOF	degrees of freedom
DP	deployment platform
DSP	digital signal processing
DTV	digital television
EM	Environmental Management
FFT	fast Fourier transform
FM	frequency modulation
GAAT	Gunite and Associated Tanks
HLW	high-level waste
LDMM	leak detection, monitoring, and mitigation
LDUA	light duty utility arm
MLDUA	modified light duty utility arm
NASA	National Aeronautics and Space Administration
OFDM	orthogonal frequency division multiplexing
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PVC	precessing vortex core
RPD&E	retrieval process development and enhancements
RPP	river protection project
SST	single-shell tank
TFA	Tanks Focus Area

1.0 Introduction

The purpose of this study is to identify and prioritize innovative approaches that can be used to enhance retrieval of waste stored in tanks that are confirmed or suspected to leak.

1.1 Background

Since 1961, Hanford has had 67 single-shell tanks (SSTs) that are confirmed or suspected of leaking waste into the environment. Hanford single-shell-tank waste will eventually be retrieved, and by the time waste removal from these tanks is completed, the average tank will have exceeded its design life by about 50 years. It can be assumed that more of the 149 SSTs that will leak over the time period required to complete waste retrieval.

A number of currently proposed techniques could be modified to be applicable for retrieval of waste from leaking tanks. Hanford has successfully demonstrated the use of past practice sluicing in Tank C-106. Also, the Hanford Tanks Initiative had begun to show credible costs for crawler-based technologies that could be deployed for heel retrieval (Berglin 1997). In the near future, Hanford retrieval programs will be demonstrating salt cake dissolution in tanks 241-U-107 and 241-S-112, pulse-jet mixing in tank 241-U-102, and a crawler based system in tank 241-C-104. These demonstrations do not specifically address the issue surrounding how to remove waste from the tanks that leak without exacerbating that leak. In the early and mid-1990s scarifier technologies were developed that used confined flow, ultra-high-pressure waterjets to fracture and dislodge waste coupled with concurrent retrieval. However, the technology implementation was deferred because of the high cost of the preferred arm-based approach for deployment. Therefore, enhanced methods for removing SST waste from an assumed-to-leak tank needed to be addressed for Hanford.

1.2 Scope

This study identified and evaluated technical options including mechanical, chemical, and fluidic processes for SST waste retrieval that are applicable to retrieval of waste from potentially leaking tanks. Technologies that minimize leakage, retrieval technologies that use minimal water, and dry retrieval technologies were candidates for evaluation. The details of these technologies are described in Sections 3.0 through 7.0. This work was conducted as a collaborative effort between PNNL, ORNL, and the River Protection Project, CH2M Hill Hanford Group (CHG). TFA and RPP jointly determined the technical approach to be taken for this problem, while RPP established the highest level requirements. A technology assessment was conducted to identify technologies that are available, nearly available, or are in early gates of technology development. The assessment addressed issues surrounding each technology to provide RPP with adequate information to evaluate technical and programmatic risk. A technology review workshop (summarized in the Appendix) was conducted to allow CHG, TFA, and the Hanford Site Technology Coordinating Group (STCG) an opportunity to review this work and select candidate technologies for further evaluation. The resulting documentation supports the Hanford SST Retrieval Program by providing data regarding candidate retrieval technologies for potentially leaking tanks for the Retrieval Alternate Generation Analysis (AGA) being developed by CHG in FY 2001.

The assessment addressed issues surrounding each technology to provide RPP with adequate information to evaluate technical and programmatic risk. Based upon feedback from RPP, recommendations were made regarding which technologies should be evaluated for potential application at Hanford. The tests will be designed to evaluate the technologies and to address the technical risks.

1.3 Waste and Tank Retrieval Priority

In FY 2000 the River Protection Project updated the single-shell tank waste retrieval sequence in the report RPP-7087, Rev. 0 *Single-Shell Tank Retrieval Sequence: Fiscal Year 2000 Update* (Garfield et al 2000). The retrieval sequence was developed incorporating three initial demonstrations of waste retrieval technology:

- Salt cake dissolution in tank 241-S-112
- Fluidic mixer technology demonstration in tank 241-S-102
- Confined sluicing/robotic technology in tank 241-C-104.

To determine the order of retrieval for the remaining tanks general criteria were developed:

- Focus on high-risk waste containing high Tc^{99} content in sound salt cake waste tanks
- Focus on sound tanks that contain mixed sludge and salt cake wastes
- Focus on tanks that have leaked or are assumed to have leaked.

Ten categories of waste, listed in Table 1.1, were established based these criteria and other logistics. These categories were used to guide the development of the retrieval sequence. The complete tank retrieval sequence is provided in RPP-7087. The priority listing shows that leaking tanks are priority 7 through 10. This sequence permits the site to gain experience retrieving waste from non-leaking tanks prior to tackling the potentially more difficult to retrieve waste from leaking tanks. This strategic task investigates methods to employ when waste from leaking tanks or potentially leaking tanks is being retrieved.

Table 1.1 Single-shell tank waste retrieval categories in order of retrieval priority

Retrieval Priority	Category	Descriptor
1	1	Sound salt cake tanks with elevated levels of Tc^{99}
2	2	Sound sludge tanks with less than 1.83 m of sludge
3	3	Sound salt cake tanks with lower levels of Tc^{99}
4	4	Sound sludge/sludge mixed tanks with less than 1.83 m of sludge
5	5	Sound sludge tanks with more than 1.83 m of sludge
6	6	Sound sludge/sludge mixed tanks
7	7	Leaking sludge tanks
8	8	Leaking sludge/sludge mixed tanks
9	9	Leaking sludge tanks with less than 1.83 m of sludge
10	10	Leaking sludge tanks with more than 1.83 m of sludge

1.4 Workshop

A two day workshop was conducted to assess the applicability of technologies proposed for enhancing retrieval of waste from leaking or tanks suspected to be leaking. The workshop team consisted of participants representing the US DOE EM-50 Tanks Focus Area, Hanford Site projects and programs, and project collaborators from Pacific Northwest National Laboratory and Oak Ridge National Laboratory. Workshop attendees and affiliation are listed in Table 1.1. The workshop results are presented in the Appendix. Specific recommendations and prioritizations from this workshop are presented in Section 2. Detailed descriptions of the technologies are provided in Sections 3 through 7.

Table 1.1 Workshop attendees

Attendee	July 23	July 24	Affiliation
Judith Bamberger	+	+	Pacific Northwest National Laboratory
Brian Hatchell	+	+	Pacific Northwest National Laboratory
Harry Smith	+	+	Pacific Northwest National Laboratory
Ben Lewis	+	+	Oak Ridge National Laboratory
John Randolph	+	+	Oak Ridge National Laboratory
Jerry Cammann	+	+	CH2M Hill Hanford Group
Keith Carpenter	+	+	CH2M Hill Hanford Group
Dave Vladimiroff	+		CH2M Hill Hanford Group
Richard Harrington	+	+	Facilitator - CH2M Hill Hanford Group
Robin Kummer	+	+	Assistant - CH2M Hill Hanford Group
Shafik Rifaey	+	+	CH2M Hill Hanford Group
James L Huckaby	+		Pacific Northwest National Laboratory
Pete Gibbons	+	+	Tanks Focus Area - CH2M Hill Hanford Group
Richard Wojtasek	+		CH2M Hill Hanford Group
Gary Josephson	+	+	Tanks Focus Area - Pacific Northwest National Laboratory

2.0 Workshop Conclusions and Recommendations

Conclusions and recommendations regarding innovative approaches for dislodging and retrieving waste from tanks that are known or suspected to leak were developed during this evaluation and workshop. The prioritized results from this workshop along with recommendations for a research path forward are presented in section 2.1.

2.1 Conclusions

During the workshop sessions, technology needs and solutions were identified based both on the approaches for retrieval of wastes from leaking tanks described in Sections 3, 4, and 5, and based on discussions of new technologies or novel arrangements of the technologies for remediation of leaking tanks among the workshop participants. These approaches grouped naturally into five categories: those related to waste dislodging (D), those related to waste conveyance (C), those related to both waste dislodging and conveyance (D&C), those related to the deployment platform (DP), and technologies related to leak detection, monitoring, and mitigation (LDMM). Of the twelve technologies discussed, the first five listed in Table 2.1 were recommended by the team for future evaluation, potentially in FY-2002. Recommendations for items six through 12 in Table 2.1 were presented to permit readers to ascertain the group consensus regarding additional development. Some items related to leak detection monitoring and mitigation were recommended for transfer to the Tanks Focus Area task in that area. Other items were deemed technically mature and other items were deemed basic research in scope and should be considered for funding by the EMSP (Environmental Management Science Program). Items identified for future funding in out years are listed in Table 2.2 as well as are the items recommended for transfer to the Leak Detection, Monitoring and Mitigation (LDMM) program.

Table 2.1 Technologies ranked for further evaluation

Rank	Technology	Category	Recommendations for FY 2002 Evaluation
1	Dry TORE® with jet pump combination	C	Yes
2	Sonic TORE® and vehicle with sonication	D	Yes
3	Sonication	D	Yes
4	Long reach manipulator - Novel and cost effective	DP	Yes
5	Next generation crawler technology: Radio controlled, non-umbilical dislodger. Consider applying a crawler to any of aforementioned technologies.	DP	Yes
6	Shop-vacuum to in-tank collection container	C	Group with Multi-phase flow
7	Multi-phase flow	C	Consider alternate funding for research
8	Drying absorbent (e.g., micro cell E)	LDMM	Transfer to TFA Leak Detection Monitoring and Mitigation scope
9	Hose management	DP	Develop as a part of long reach manipulator and next generation crawler technology
10	Modified stationary guzzler (i.e. trencher; vacuum conveyance)	C	Technically mature, no FY2002 funding required for TFA retrieval scope
11	Small diameter dislodger/conveyor (borehole miner)	D&C	Technically mature, no FY2002 funding required for TFA retrieval scope
12	Controlled rapid solidification with crawler, manipulator, and others	LDMM	Transfer to TFA Leak Detection Monitoring and Mitigation scope

D = Dislodging
C = Conveyance
DP = Deployment Platform
LDMM = Leak Detection Monitoring and Mitigation

Table 2.2 Technologies identified for future consideration or transferred to leak detection monitoring and mitigation scope

Rank	Items for Future Consideration
1	Debris management system
2	Integrated mixer mobilization pump on a crawler based system (e.g., mud pump moving around on a tether system)
3	Alternate dislodging fluids leak inhibitor, e.g., Bentonite clay
4	A phosphate based concrete and/or grout (low strength)
5	Acoustic levitation
	Items transferred to Leak Detection Monitoring and Mitigation
	Apatite in tank
	In tank inspection; integrity viewing/mapping
	Fluid reactive with sand or concrete
	Ultrasonic transmission to identify leaks
	Controlled rapid solidification with crawler, manipulator, and others
	Drying absorbent (e.g., micro cell E)

In Table 2.1, the technologies identified during the workshop are ranked in terms of priority for development. A brief description of the technology and the proposed path forward for each technology follows.

1. **Dry TORE® with jet pump combination.** The current TORE® design (see Section 4.2) is based on developing a liquid-based precessing vortex core to mobilize and fluidize solids so they can be captured by the outlet flow and removed from the vessel. The dry TORE® concept envisions using air to develop the precessing vortex core to fluidize solids coupled with a jet pump to transport the solids in a slurry.

2. **Sonic TORE® and vehicle with sonication.** The sonic TORE® concept (see Section 4.2) envisions utilizing sonication (see Section 4.1) to fracture and dislodge solids for entrainment in the TORE® precessing vortex core. The vehicle with sonication envisions coupling sonication with the vehicle, perhaps through a plow blade, to fracture solids for transport to a conveyance system.

3. **Sonication.** This technique envisions using ultrasonic energy (see Section 4.1) to fracture and dislodge hard waste types such as sludge and sludge.

4. **Long reach manipulator**. The purpose of this item is to investigate novel and cost effective approaches for long-reach manipulator technology (see Section 6).

5. **Next generation crawler technology.** This item envisions a non-umbilical dislodger, possibly radio controlled and powered remotely to provide a deployment platform not affected by path, or the need

to retrace steps (see Section 7). The crawler is envisioned as a deployment platform for any of the novel end effectors and techniques.

6. **Shop-vacuum to in-tank collection container.** This concept is based on using a low pressure drop vacuum to transfer dislodged waste to an in-tank collector.

7. **Multi-phase flow.** This conveyance mode uses either air or water as the carrier fluid, entraining dry or wet solids.

8. **Drying absorbent (e.g., micro cell E).** This concept envisioned adding an absorbent to the waste to bind the liquid into a dry solid that could be dislodged and conveyed using methods applicable to dry solids.

9. **Hose management.** More effective ways to route and deploy hoses for delivery of fluid, power or other utilities or for conveyance have the ability to greatly improve dislodging and retrieval efficiency.

10. **Modified stationary guzzler (i.e. trencher; vacuum conveyance)**. The guzzler is a tool to dislodge waste and convey it pneumatically to a collector such as a drum.

11. **Small diameter dislodger/conveyor (borehole miner).** The borehole miner (see Section 4.3) incorporates both dislodging and conveyance and can be deployed through a 30-cm- 12-in.- diameter riser. The extendible, erectable nozzle provides a high-pressure, low-flow rate fluid jet to fracture and dislodge waste; the jet pump with in-line crusher removes waste as it is slurried to the inlet. The extendible nozzle reduces the jet stand-off distance and provides enhanced dislodging.

12. **Controlled rapid solidification with crawler, manipulator, or other deployment method**. Rapid solidification (see Section 3.1) provides a method to seal tank surfaces to reduce leakage outside of the tank shell.

2.2 Recommendations

The team presented recommendations to the TFA review team for near-term development for the following four technologies:

- Air-assisted TORE®
- Sonication for enhanced solids dislodging
- Novel manipulator approaches
- Next generation crawler technology.

Details of the proposed technical approaches are provided in Section 8.

3.0 Novel Leak Reduction Technique

Methods to physically alter the ability of a fluid to flow could play a useful role in stabilizing liquids in leaky tanks. By altering the fluid viscosity to that of a gel, the potential exists for the fluid to enter potential cracks in the tank wall and surrounding concrete to form a seal that would prevent contamination from flowing into the environment.

3.1 Sol-Gel and Rapid Solidification Technology for Enhancing Tank Integrity

Sol-gel processing is a chemical synthesis technique by which liquids are controllably reacted to produce gel, solid, or solid-like matrices. Inorganic fluids that rapidly solidify upon application can be used to enhance integrity of potentially leaking tanks by infiltrating areas that leak to reduce the size of the penetration or seal the leak. During application this process has the ability to convert from a free flowing fluid to a solid within minutes of application. In addition, the process can incorporate aqueous liquids and solids into a solid glass object at room temperature using no heat at a very fast rate. These conversions are non-reversible and embody a high state of integrity for extended periods of time. The chemistry associated with this solidification process is inorganic and may be compatible with vitrification.

3.1.1 Super Rapid Solidification

- Chemical reaction causes permanent formation of crystalline glass at ambient temperatures
  - Components are aqueous liquids
  - After combination the mixture crystallizes
- Cold-formed glass has many attributes of hot melter-formed borosilicate glass
  - Resistant to corrosives
  - Stable for long periods of time
- Cold formed glass differs from hot melter glass
  - Can incorporate water or liquids into its crystalline structure –from 0.5 to 30%
  - Used to solidify free liquids and trap particles in the matrix

3.1.2 Pros

- Can be applied locally to tank areas that may be prone to leakage such as the interface between the fluid layer and atmosphere or at the weld between the knuckle and tank wall.
- Can be applied either from the inside of the tank or from the outside of the tank.
- Components contain only inorganics such as silica and no organics are added to the tank.
- Small quantities of sealant can be applied with little increase in volume of waste.
- Any sealant removed during retrieval is acceptable as a feed for vitrification.

3.1.3 Cons

- Fluid must be locally applied using an arm and local deployment system.
- Ability to seal simulated penetrations in tanks must be confirmed.

- Ability to incorporate fluids and solids such as supernatant liquid, salt cakes, and sludges must be demonstrated.
- Ability to maintain integrity while subject to operation of waste retrieval technologies must be verified.

4.0 Dry or Controlled Fluid Addition Dislodging and Retrieval

Waste dislodging methods that use no or little liquid addition are attractive for retrieval of waste from leaky tanks because no fluid layer or associated hydrostatic head is formed that could force waste from the tank. Four dislodging approaches are discussed.

- Sonication, which uses ultrasonic energy to fracture and dislodge solids with no fluid addition.
- Scarifiers, which use medium to high pressure low flow rate confined jets to dislodge solids coupled with integral retrieval.
- TORE®, which uses an air-based precessing vortex core to entrain dislodged solids coupled with integral retrieval.
- Borehole miner, which uses a low flow rate, high-pressure jet for bulk dislodging and mobilization combined with integrated retrieval.

4.1 Sonication for Waste Dislodging without Fluid Addition

Ultrasonic dislodging and fracture is caused by cavitation, the rapid formation and violent collapse of minute bubbles. Cavitation is produced by introducing high-frequency (ultrasonic) high-intensity sound waves into the waste. The agitation caused by intense imploding bubbles creates a highly effective scrubbing of both exposed and hidden surfaces.

The ultrasonic system includes the transducer and the ultrasonic generator that produces the high frequency electrical signal. Ultrasonic energy is a series of pressure points, a series of compressions and rarefactions. If the sound energy is of sufficient intensity, the liquid will actually be pulled apart at the rarefaction stage and small bubbles or cavities will be formed. With the following compression stage, the bubbles collapse or implode throughout the liquid, creating an extremely effective force (cavitation) uniquely suited for dislodging and fracturing waste. The energy released from a single cavitation bubble is very small, but many millions of bubbles collapse every second. Cumulatively the effect is very intense and produces intense scrubbing and fracturing action on the surface of the waste that is characteristic of all ultrasonic cleaning.

Ultrasonic transducers are being developed and deployed at PNNL in a variety of configurations, shown in Figure 4.1 that could be used as end effectors or "plow blades" on a crawler or integrated with manipulators. In addition recent technology advances show that transducers can be formed in flexible transducer sheets on the order of ~15 cm x 61 cm (6 in. x 2 ft). These larger configurations may make in-tank deployment feasible.

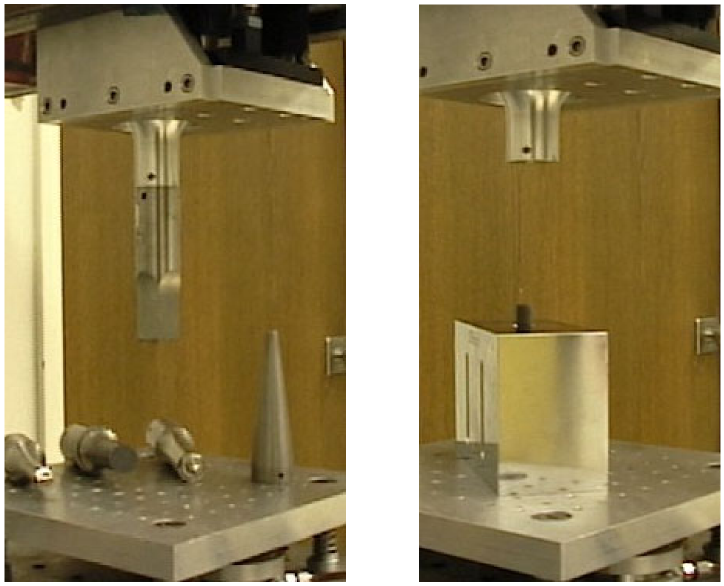

Figure 4.1 Ultrasonic transducers of a range of shapes can be designed for deployment on crawlers

Two university student teams investigated ultrasonic dislodging of waste simulants at the 2001 WERC[a] Design competition. The teams showed that at a small-scale ultrasound effectively dislodged the salt cake and sludge simulants as shown in Figure 4.2.

Figure 4.2 Sonicator system and dislodging of salt cake and sludge simulant

The systems shown above demonstrate sonicator fracture and dislodging of waste simulants using small-diameter sonic horns. In Figure 4.2 (right) surfactant was added to the waste, transforming it into a more foamy mixture that resisted fluid flow. These techniques can be deployed at larger scale. Staff at PNNL have applied larger area horns (7 cm x 18 cm [3 in. x 7 in.]) for solids treatment. Also in development are larger transducer sheets, several cm (in.) in width by a meter (several feet) in length. These

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[a] WERC a consortium for environmental education and technology development, New Mexico State University, Las Cruces, New Mexico. http://www.werc.net/.

configurations can be readily adapted for larger scale dislodging and deployment via manipulator or crawler.

4.1.1 Pros

- Dislodges waste without fluid addition.
- Focused energy distributed to areas of greatest need.
- Effective for dislodging and crumbling hard salt cakes and sludges.
- Can be used for cleaning walls and surfaces of in-tank equipment.
- Currently most units operate at 20 kHz; decreases in frequency may increase the area of signal influence and depth of penetration.
- Sonicator horn size can be sized for tank deployment.
- Sonicator tool can be incorporated into various deployment platforms such as a crawler or an arm.

4.1.2 Cons

- Deployed by an arm or crawler.
- Only demonstrated at laboratory scale.

4.2 Scarifiers

Scarifers use high-pressure, low-flow rate fluid, cryogenic, or air jets to fracture and dislodge solidified salt cake and sludge wastes. PNNL has developed scarifier end effectors that operate at up to 350 MPa (50,000 psi) at flow rates as low as $3x10^{-4}$ m^3/s (5 gpm) per cutting jet (Bamberger et al 1995). Other end effectors operate at lower pressures. Figure 4.3 depicts two scarifier technologies. In addition, scarifiers that use liquid nitrogen and CO_2 pellets can dislodge waste with no accumulation of cutting fluid in the tank. PNNL investigated coupling scarifiers with air conveyance (Liljegren et al. 1995) and assisted ORNL in the deployment of confined sluicing and jet-pump conveyance for use in tank waste retrieval operations at ORNL.

4.2.1 Pros

- Effectively dislodges very high strength waste.
- Adds little or no fluid to the tank.
- Cryogenic and air-based cutting are dry.

4.2.2 Cons

- Deployed by a crawler or manipulator.
- Requires an integrated conveyance system for waste retrieval.

Figure 4.3 High-pressure scarifier and air conveyance (left) and confined sluicing end-effector and jet pump conveyance (right)

4.3 Merpro TORE® for Enhanced Conveyance

The TORE® is a patented hydro transportation device with no moving parts with the ability to convey solids at pre-determined slurry concentrations over great distances.[a] The system moves from 1% to 70% or more solids by weight slurries. The device contains no parts to wear out and simply requires fluid to be pumped.

The TORE® is a hydraulic conveyor of solids that contains no moving parts. It consists of a concentric feed section having a central discharge tube, where a motive fluid such as water is used to displace the process material, depicted in Figure 4.4. The TORE® can be installed in any orientation to ensure it is buried in solids. A phenomenon known as a precessing vortex core (PVC) occurs beneath the foot of the TORE® central tube and is responsible for fluidization of solids, leading to their subsequent transport (Chard et al 1996). A PVC is an unstable, time dependent, three-dimensional vortex core, which

[a] Dave Smet, CH2MHill Hanford Group, identified Merpro, Ltd. and their TORE® technology as a potential method for enhancing waste retrieval. He led a workshop July 16-17, 2001 to introduce others at Hanford to the Merpro Ltd. team and the potential applications of this technology.

precesses about the geometrical center. Its occurrence results from shear between the driving vortex (swirling flow exiting the TORE® into the vessel) and the forced vortex (swirling flow entering the TORE® via the inner tube). The pressure drop across the TORE® is minimal.

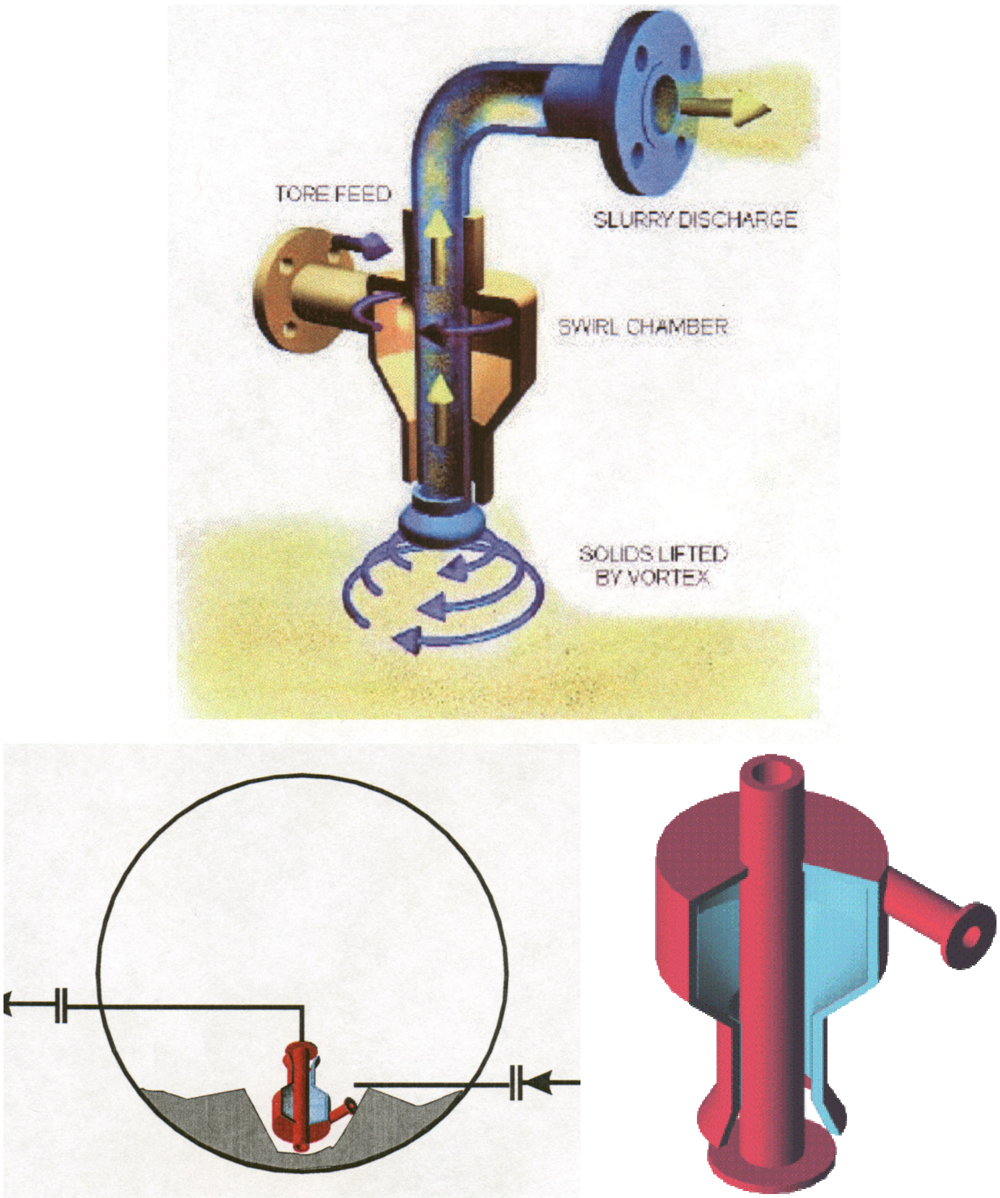

Figure 4.4 TORE® configuration for solids suspension and retrieval

The TORE® must be installed as part of a system and motive pressure for transporting the solids must be provided by another source. Currently, the TORE®, by nature of its operation, is best suited to applications in which it is placed in a pressure vessel (Faram et al 1996). For TORE®s installed internally/externally in a pressure vessel the motive pressure is due to the operating pressure of the vessel. For TORE®s installed in atmospheric vessels compressed air or a jet pump must be installed in the TORE® inlet line to provide the motive pressure. The flow in the discharge line is provided by a jet pump or other pump. In each case the discharge flow rate from the TORE® should be controlled to ensure that the slurry velocity does not exceed the erosional limits of the materials used to construct the piping.

It is favorable to install a TORE® in a vessel which concentrates the solids within the TORE®s zone of influence but this may not always be practical, especially for retrofits (Parkinson and Delves 1999). For cases where the TORE® is installed in large diameter vessels the degree of solids removal can be calculated using a series of cones, with a suitable angle of repose, extending from the edge of the TORE®s maximum zone of influence. For general design the zone of influence is considered as six times the TORE® discharge pipe diameter.

4.3.1 Pros

- TORE® can be used to fluidize settled solids for transport out of the tank.
- No water addition to the tank is required for solids removal.

4.3.2 Cons

- A jet-pump, blower or other pump must be installed to power the TORE®.
- The sphere of influence is limited to its zone of influence, based on the angle of repose of the solids.
- May require multiple units to reach solids throughout the tank.

4.4 Borehole Miner and Integrated Conveyance

The borehole miner uses an extendible, erectable low flow, medium pressure jet to fracture and dislodge solids that are retrieved from the tank using a jet pump located at the base of the extendible nozzle mast. This technique was developed for excavating and removing solids from boreholes using a single device deployed through one borehole. An extendible nozzle system without the jet pump retrieval system was deployed sequentially in four tanks at ORNL to remediate the horizontal underground storage tanks at the Old Hydrofracture Facility as shown in Figures 4.5 and 4.6 (Bamberger et al 1999).

4.4.1 Pros

- Deployed through one 31-cm- (12-in.-) diameter riser.
- Low flow rate 0.002 m^3/s (~ 30 gpm) at pressures up to 14 MPa (2000 psi).
- Retrieval rate balanced with input inhibit fluid accumulation.
- Positionable extendible nozzle decreases nozzle stand-off distance and is more effective for dislodging.
- Relatively rapid dislodging and conveyance. Tanks at ORNL cleaned out in <24 hrs.
- Can operate with recycled supernatant liquid.
- Integrated jet pump and crusher reduces size of any remaining solids prior to removal.

4.4.2 Cons

- Some fluid accumulation in the tank.

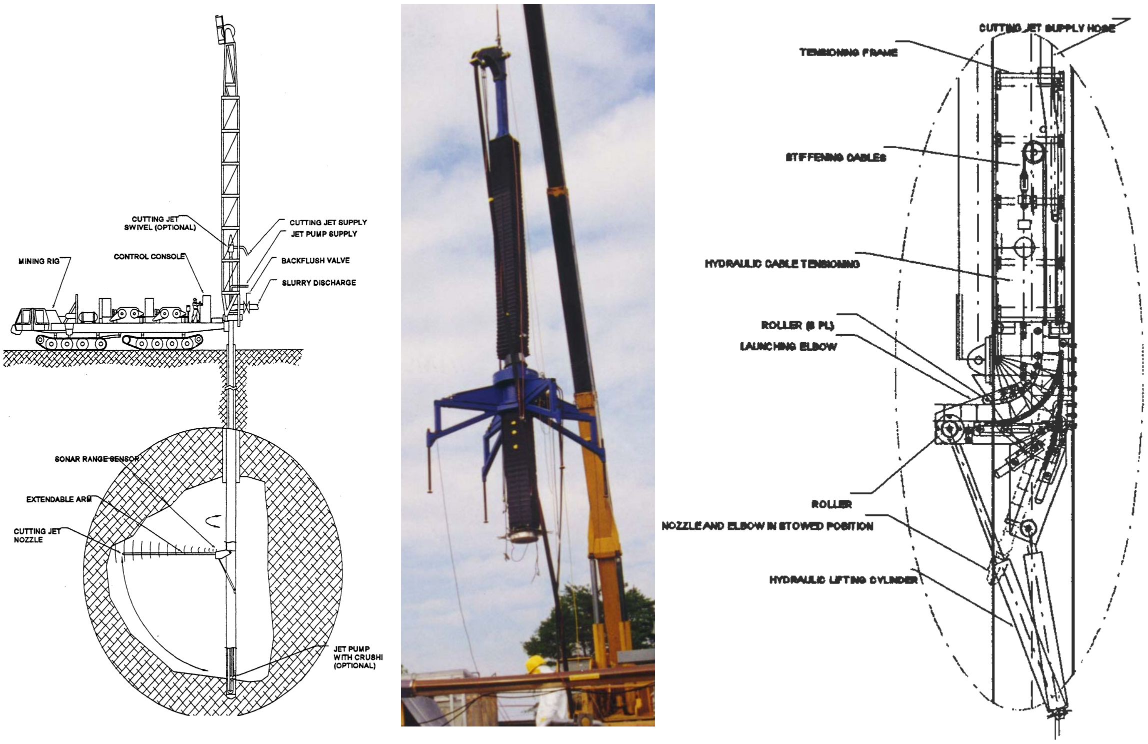

Figure 4.5 Borehole miner showing (a) integrated dislodging and conveyance, (b) deployment at ORNL, and (c) arm linkage for changing angle of arm

Figure 4.6 Testing of the borehole miner showing the focused movable nozzle and linked arm

5.0 Fluid-Based Retrieval Techniques

Fluid-based retrieval is the conventional method for waste retrieval from intact tanks. Several approaches are described and evaluated with respect to applicability for use in retrieval of waste from leaky tanks.

5.1 Conventional Pump with Mixer System for Bulk Sludge Retrieval

For tanks with significant amounts of supernatant, the use of a mixer system to mobilize the sludge and a conventional pump (long shaft, diaphragm, or submersible) for bulk retrieval of the waste is feasible. Mixer systems such as the Russian Pulsating Mixer Pump, Pulsed Air, Pulsed Jet Fluidic Mixer, and Flygt mixers have all been demonstrated and deployed at Oak Ridge. Figures 5.1 and 5.2 show the various mixer systems used in tank waste retrieval operations at Oak Ridge National Laboratory.

Figure 5.1 View of Russian pulsating mixer pump in tank TH-4 (left) and Flygt mixers on top of tank W-5 (right) before deployment

Figure 5.2 View of Pulse-Air mixer before deployment in tank W-9 and pulsed jet fluidic mixer at Bethel Valley Evaporator Service Tanks

Conventional waste retrieval pumps such as long shaft pump, submersible pump, and other sludge handling system can be used as a fixed-point retrieval system in bulk sludge retrieval operations. Retrieval of residual sludge from the tank floor must be accomplished using retrieval systems that are more mobile. The pros and cons for this type of retrieval system are as follows.

5.1.1 Pros

- Inexpensive.
- Proven effective in bulk sludge removal operations.
- Adds no liquids to the tanks.

5.1.2 Cons

- Requires a significant amount of supernatant liquid to be present (amount varies depending on mixer type).
- Some development required for large diameter tank applications.
- May require large diameter opening (56 cm [22 in.] or more) for installation of mixers.

5.2 Comparison of Jet-Based Dislodging Approaches

To permit comparison between the jet-based dislodging technologies, their physical and operating characteristics have been summarized in Table 5.1 (Bamberger 2000, Bamberger et al 1996, 1992). Items addressed include the operating principal, ability to dislodge waste forms, and other operating characteristics. The technologies are ordered by jet pressure from low to high pressure; the Flygt mixer is listed after the fluid jet technologies. The results in this table also evaluate the ability of the system to operate using recycled supernatant to reduce water usage and the need for significant levels of fluid to be present in the tank. If supernatant recycle is not considered, each technique will generate slurry at the device operating flow rate.

- Four of these techniques: the Hanford tank C-106 sluicer, borehole miner, pulsating mixer pump and fluidic pulse-jet mixing will readily fit through a 31-cm- (12-in.-) diameter riser.
- The borehole-miner extendible-nozzle can clean walls, embedded piping, and mobilize extremely hard waste throughout the tank. The arm extension of 3 m (10 ft), and its ability to move back and forth can be used to sweep waste from collection piles deposited by the mixer pump back into the mixer pump path or toward the retrieval pump inlet.
- The pulsating mixer pump and fluidic pulse-jet mixer can provide slurry mobilization; however, they are not acceptable for wall cleaning.
- Four of these jet-based dislodging techniques: sluicer, borehole miner, waste retrieval end effector and high-pressure scarifier do not require standing water in the tank to facilitate operation.

Table 5.1 Comparison of waste mobilization technologies

Criteria	Pulsed-Air	Pulsating Mixer Pump	Fluidic Pulse-Jet Mixing	C-106 Sluicer	Borehole-Miner Extendible-Nozzle	Waste-Retrieval End Effector	High-Pressure Scarifier	Flygt Mixer	Mixer Pump
Technique	compressed air pulses	compressed air propels slurry jet	compressed air propels slurry jet	water or fluid jet	water or fluid jet	water jet	water jet	propeller creates a fluid jet	high-volume oscillatory fluid jets
Jet pressure	0.35 to 0.69 MPa (5 to 100 psi) air	0 to 0.69 MPa (0 to 100 psi)	0 to 0.69 MPa (0 to 100 psi)	to 2.07 MPa (300 psi)	0 to 20.7 MPa (0 to 3000 psi)	0 to 69 or 207 MPa (0 to 10,000 or 30,000 psi)	379 MPa (55,000 psi)		up to 2.8 MPa (400 psi) liquid
Flow rate	0.005 standard m^3/s (10 scfm) air per plate	0.014 m^3/s 850 l/min (224 gal/min)	tbd	0.022 m^3/s (350 gal/min)	0 to 0.0095 m^3/s (0 to 150 gal/min)	0.0063 m^3/s (10 gal/min) /jet	0.00038 m^3/s (6 gal/min) /jet	1.1 m^3/s (17,500 gal/min)	up to 0.315 m^3/s (5000 gal/min) /jet
Enhances dissolution	tbd	yes	yes	yes	yes	yes	yes	yes	yes
Mixes viscous liquids	yes	yes	yes	yes	yes	yes	yes	yes	yes
Mixes slurries	yes	yes	yes	yes	yes	yes	yes	yes	yes
Mobilizes settled solids	to some extent	to some extent	to some extent	to some extent	yes	yes	yes	to some extent	yes
Dislodges solid heels	no	no	no	perhaps	yes	yes	yes	no	if close to mixer pump
Power	7.5 to 15 kW (10 to 20 hp)	tbd	tbd	186 kW (250 hp)	149 kW (200 hp)	tbd	tbd	37 kW (50 hp)	224 kW (300 hp)

Criteria	Pulsed-Air	Pulsating Mixer Pump	Fluidic Pulse-Jet Mixing	C-106 Sluicer	Borehole-Miner Extendible-Nozzle	Waste-Retrieval End Effector	High-Pressure Scarifier	Flygt Mixer	Mixer Pump
Operating limits	functions at all liquid levels, plates located <2.54 cm (1 in.) above the tank floor	functions at all liquid levels, nozzle located <2.54 cm (1 in.) from floor	functions at all liquid levels, nozzle located <15.2 cm (6 in.) from floor	functions at all liquid levels	functions at all liquid levels	functions at all liquid levels	functions at all liquid levels	functions when submerged. Mixer is 51 cm (20 in.) in diameter and was installed 20.5 cm (8 in.) above tank floor. Minimum fluid depth is 51 cm (20 in.)	~1.2 m (4 ft) head required for maximum power. Nozzle centerline ~0.3 to 0.46 m (1 to 1.5 ft) from tank bottom
Fluid level required for operation	fluid to cover plates required. Functions best in > 1 m of fluid	requires fluid level above inlet to function	requires fluid level above nozzle to function	no fluid accumulation in tank required for operation	no fluid accumulation in tank required for operation	no fluid accumulation in tank required for operation	no fluid accumulation in tank required for operation	requires fluid to submerge mixer.	requires a minimum of 1.2 m head for operation
Percent secondary waste generated using supernatant recycle	0%	0%	0%	0%	0%	0%	0.00038 m^3/s (6 gal/min) /jet	0%	>0% (some seal lubrication water added)
Deploy-ment	riser mast, system unfolds	riser mast	riser mast	riser mast	riser arm	arm or remote vehicle	arm or remote vehicle	riser mast, system unfolds	riser mast, system remains under riser
Remotely deployed	yes	yes	yes	yes	yes	yes	yes	yes	yes

Criteria	Pulsed-Air	Pulsating Mixer Pump	Fluidic Pulse-Jet Mixing	C-106 Sluicer	Borehole-Miner Extendible-Nozzle	Waste-Retrieval End Effector	High-Pressure Scarifier	Flygt Mixer	Mixer Pump
Maintain-ability	compressor located outside the tank, plates submerged in waste	valves and compressor located outside tank	valves and compressor located outside tank	pump located outside of tank, pump may be contaminated based on source of fluid	pump located outside of tank, pump may be contaminated based on source of fluid	pump located outside of tank, arm or vehicle inside tank, pump may be contaminated based on source of fluid	pump located outside of tank arm or vehicle inside tank	entire mixer including motor is submerged	pump motor located above the tank riser, pump internals submerged in waste
Removal	system must be collapsed prior to removal	system removed through riser	system removed through riser	system removed through riser	system removed through riser	system removed through riser	system removed through riser	system must be collapsed prior to removal	system removed through riser

5.3 Conventional Pump with Remotely Operated Vehicle

The most direct method of pumping the waste from waste tanks is the use of a conventional pump (long shaft or submersible) with the suction inlet at the bottom of the tank. This concept s illustrated in the Figure 5.3.

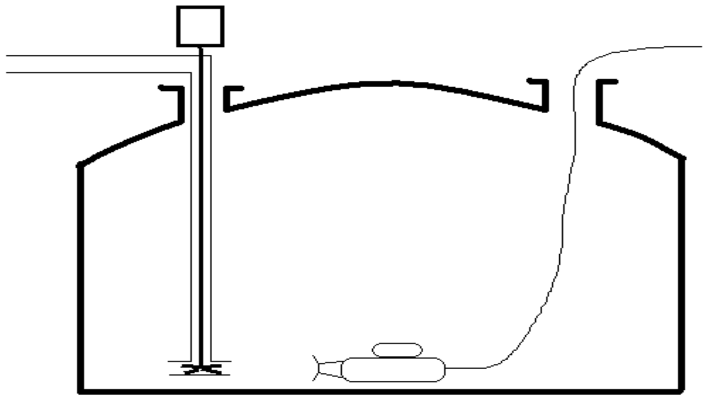

Figure 5.3 Conventional pump with remotely operated vehicle

In this example, waste is moved to the pump inlet using a small remotely operated vehicle, such as a Redzone Houdini-type system. Although this pump system could be designed to have a very large flow rate, the flow rate limitation of the overall system will be the rate at which the vehicle can plow waste to the pump. The pros and cons of this system are listed below.

5.3.1 Pros

- Simple, proven, cost effective pump.
- Available DOE experience with in-tank vehicles.
- Vehicle can effectively break up sludge and salt cake by plowing and driving over waste.
- Rapid removal of liquids.

5.3.2 Cons

- Vehicle may get stuck in deep sludge.
- Limited removal rate using plow.
- Difficult to plow over obstacles in tank such as pipes, hoses, cables, and tapes.
- Extensive contact with sludge reduces reliability of vehicle.
- Difficult storage of long and contaminated pump line afterwards.
- Mainly for pumping liquids, will not pump dry powders such as crushed salt cake.
- Pump may periodically run dry during heel retrieval.

5.4 Conventional Pump with Flexible Hose

To overcome the difficulty of plowing the waste around the bottom of the tank, a flexible hose can be attached to the pump inlet. The hose can be carried by a remotely operated vehicle or a large robotic arm as shown in Figure 5.4.

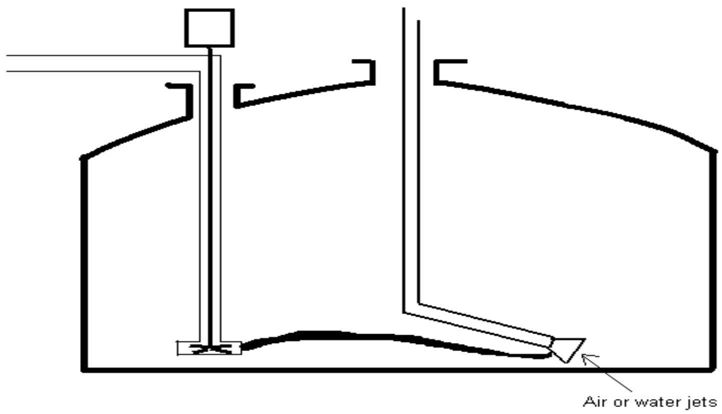

Figure 5.4 Conventional pump and flexible hose

With this concept, break up of the sludge and salt cake will be performed by air or water jets in the end-effector rather than a plow blade on a remotely operated vehicle. Air or water jets will be used to break up the sludge. Air is preferred to minimize water addition to potentially leaking tanks, but may present difficulties for the transfer system. The pros and cons of this system are listed below.

5.4.1 Pros

- Higher throughput since waste is pumped from its original location in tank rather than being plowed to the pump inlet.
- Waste will not have to be plowed over obstacles in tank.
- Very deep sludges are not a concern.
- Water or air jets may offer advantages in breaking up sludge. The potential to damage the tank floor would be less.

5.4.2 Cons

- A vacuum system will be needed to prime the pump through the hose. A simple jet pump could be used for this.
- A method of deploying and carrying the hose will be required, either via a remotely operated vehicle or a long reach robotic arm inserted into the tank.
- Air and water jets may not be effective on hard sludges.
- Additional air or water may be added to the tank via the end effector.
- Difficult storage of long and contaminated pump line afterwards.
- Will not pump dry powders, although a water driven jet pump could assist.
- Conventional pumps may loose prime if air is used to dislodge sludge.

5.5 Vacuum System with Jet Pump Assist

Vacuum systems can be very simple and can offer several advantages over a conventional pump, such as the ability to pump powders and handle intermittent slug flow. The major disadvantage to vacuum systems is that they are limited to a maximum suction lift of 10 m (~33 ft). To overcome this limitation, a jet pump can be added near the inlet of the retrieval system as shown in Figure 5.5.

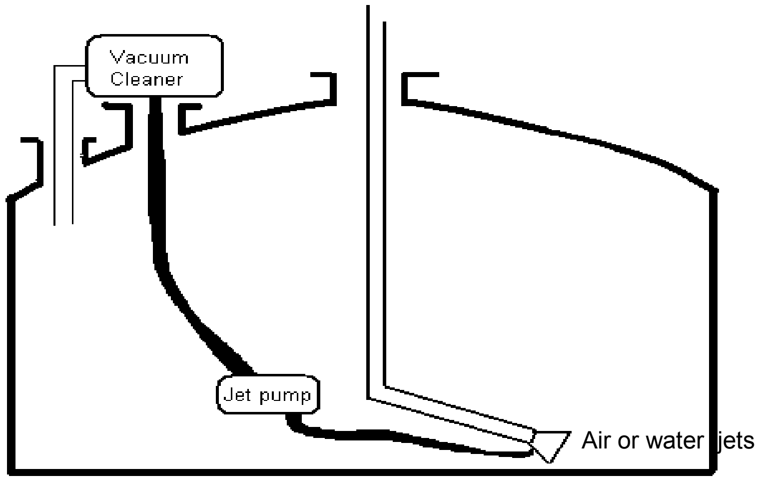

Figure 5.5 Vacuum system with jet pump assist

The vacuum system consists of a small holding tank, filter, air pump, and a return pipe used to exhaust filtered air back into the tank. The jet pump can be driven by water, air, or steam. Use of an air motivated jet pump would not be as efficient as the other alternatives. A water-driven jet pump has the advantage of being able to rinse the inside of the transfer line. In some cases, such as pumping powders, the jet pump is not needed but can still be left in the line with no pumping fluid applied. Air or water jets positioned at the inlet to the suction line will be used with an end effector to mobilize the sludge. The pros and cons of this system are listed below.

5.5.1 Pros

- Capable of pumping a wide variety of liquids, powders, gas, sludge, and small rocks.
- Uses hose instead of pipe so the contaminated equipment can be rolled up, stored, or discarded relatively easily.
- Good throughput.
- Waste will not have to be plowed over obstacles in tank.
- Very deep sludge is not a concern.
- Water or air jets at suction inlet may offer advantages over plowing in breaking up sludge through reduced potential for damage of the tank floor.
- The in-line jet pump will not add water to tank.

5.5.2 Cons

- A method of deploying and carrying the hose will be required such as a stand alone hose management system, a remotely operated vehicle ,or a long reach robotic arm inserted into the tank.
- Air and water jets may not be as effective as plowing in breaking up hard sludges.
- Additional air or water may be added to the tank via the end effector.

5.6 Vacuum System with Intermediate Tank

This concept uses an intermediate collection reservoir inside the waste tank as a feed tank for the transfer system. Figure 5.6 illustrates the concept.

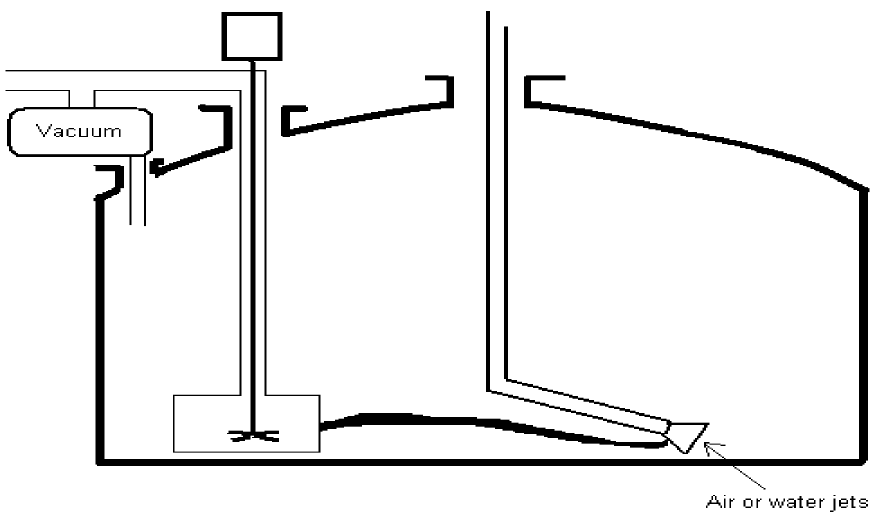

Figure 5.6 Vacuum system with intermediate tank

A vacuum system is used to transfer liquids, sludges and powders into a small intermediate tank located inside the waste tank. The waste is then pumped out of the intermediate tank with a conventional (long shaft or submersible) pump. Water can be added to the intermediate tank to improve the transfer of powders and sludges, plus the slurry can be diluted so it can be pumped long distances. A side benefit is that little radioactive material is stored outside the waste tank, therefore radioactive exposure is reduced. The pros and cons of this system are listed below.

5.6.1 Pros

- Capable of pumping a wide variety of liquids, powders, gas, sludge, and small rocks.
- Has high throughput, probably better than a jet pump.
- Conventional pumps are capable of very high discharge heads.
- Waste will not have to be plowed over obstacles in the tank.
- Very deep sludge is not a concern.
- Water or air jets at suction inlet may offer advantages over plowing in breaking up sludge through reduced potential for damage of the tank floor.

- Can dilute wastes for pumping long distances.
- Less radiation exposure to the outside.

5.6.2 Cons

- Larger riser opening may be needed for insertion of intermediate tank.
- Difficulty in storing contaminated pump line and intermediate tank.
- A method of deploying and carrying the hose will be required, either as a stand alone system or via a remotely operated vehicle or a long reach robotic arm inserted into the tank.
- Air and water jets may not be as effective as plowing in breaking up hard sludges.
- Additional air or water may be added to the tank via the end effector.

6.0 Arm-Based Retrieval Techniques

Deployment of end-effectors, retrieval systems and other remediation hardware can be enhanced by arm-based retrieval. Three techniques including two novel approaches developed by ORNL are presented.

Oak Ridge National Laboratory (ORNL) has proposed a new robotic arm for use in cleaning the single-shell tanks at Hanford. To make the arm storage compact and convenient, an arm based on a series of links similar to roll up cable trays was envisioned. This 30-m- (100-ft-) long arm could be rolled up onto a reel roughly 2.4 m (8 ft) in diameter. Compared to previous arms that were stored in tall tower-like boxes, the compact reel will not have any of the safety and wind-loading problems associated with towers, and will be easy to transport to other work sites.

In the process of developing the concept, two separate variations emerged – the Folding-Link Arm and the Roll-Up Arm. These deployment concepts are similar to a link-arm concept described by Krieg et al. (1992). The key differences between the variations are whether the arm actuation should be contained within the arm or provided by an external structure. Selecting between the variations will be based on deciding what the most important features are for arms deployed in the Hanford tanks. Desired features for the arm are sufficient capacity and reach, insertion into existing 31-cm- (12-in-) diameter risers, reliable and safe operation, reasonable cost, minimal radiation exposure, and effective contamination control. Sections 6.2 and 6.3 provide brief descriptions of the ORNL arm concepts and Section 6.4 provides a comparison between the two concepts.

6.1 Hose Embedded Long Reach Manipulator

The following figure shows a concept for an integrated system with the waste transfer hose embedded in a long reach arm. The performance of this system is the same as the Vacuum System with Jet Pump Assist.

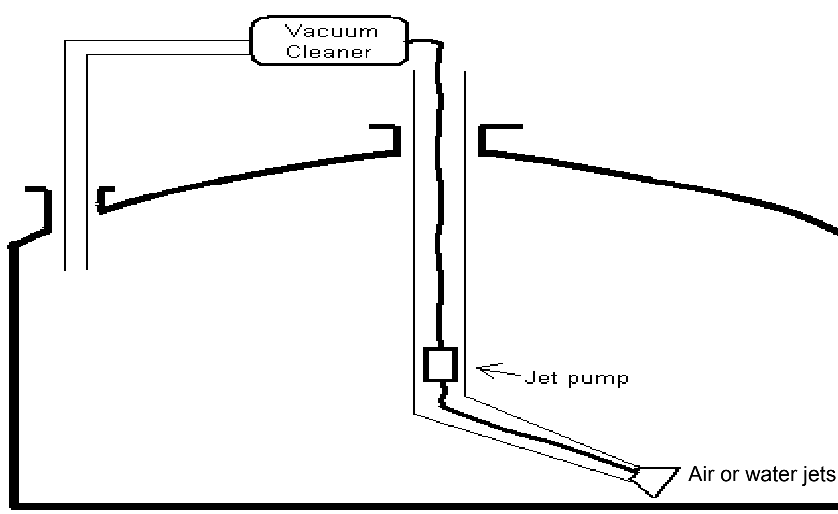

Figure 6.1 Hose embedded long reach arm

The vacuum system consists of a small accumulator tank, filter, air pump, and a return pipe to exhaust filtered air back into the tank. The jet pump can be driven by water, air, or steam and is integrated into the long reach arm. Air or water jets positioned at the inlet to the suction line will be used with an end effector to mobilize the sludge. The pros and cons for this system are listed below.

6.1.1 Pros

- Requires only two 31-cm (12-in) risers.
- If using the ORNL "roll up" arm, the system can be washed off and rolled up onto a relatively compact reel for transport to the next tank.
- Use of only one deployment system rather than a separate pump and arm/vehicle deployment system will save costs.
- Capable of pumping a wide variety of liquids, powders, gas, sludge, and small rocks.
- Good throughput.
- Waste will not have to be plowed over obstacles in tank.
- Very deep sludge is not a concern.
- Water or air jets at suction inlet may offer advantages over plowing in breaking up sludge through reduced potential for damage of the tank floor.

6.1.2 Cons

- A stand alone system or a long reach manipulator would have to be developed. The new arm design is unproven and thus will need thorough testing.
- The pumping head will be higher to reach the top of the arm reel, 21 m (70 ft) instead of 15 m (50 ft).
- Jet pump may introduce some water, although not really a problem since water is not released into tank.
- Air and water jets may not be as effective as plowing in mobilizing hard sludges.
- Additional air or water may be added to the tank via the end effector.

6.2 Long Reach Folding Link Manipulator Concept

The Folding Link Manipulator emphasizes the theme of making the arm itself as simple as possible by using an external sleeve to provide elbow actuation. No actuators and their associated wires and hoses would be contained within the arm. Furthermore, the actuator that controls the elbow movement sleeve is in the deployment container and not the tank, which would make actuator failure recovery a relatively simple matter. As shown in the Figure 6.2, the elbow movement sleeve encloses the arm while it is in the riser and for a few feet into the tank. The last segment of the sleeve is hinged to bend the arm and provide the elbow actuation.

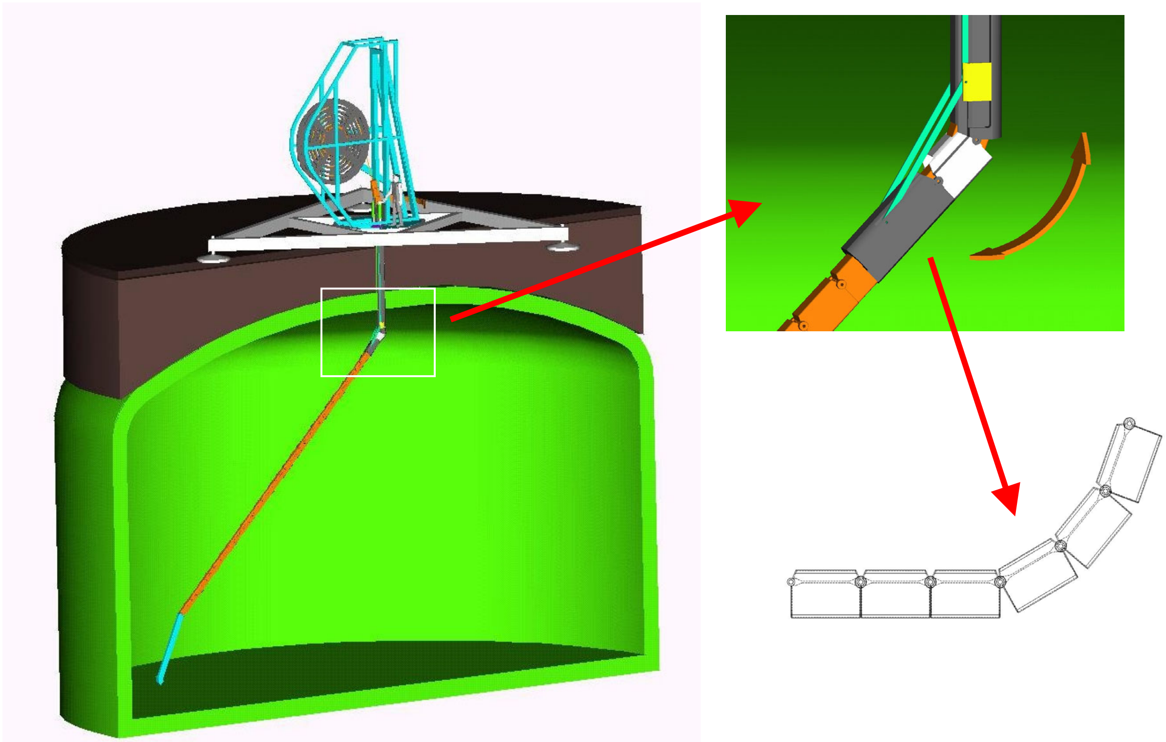

Figure 6.2 Long reach folding link manipulator concept

Contact between the arm and the sleeve is through a series of rollers on the arm as shown in the Figure 6.3. The potential for jamming of these rollers in their slot is a concern since gritty sludge may be splashed onto the arm during operation. Figure 6.3 also shows a cross section of the sleeve mechanism.

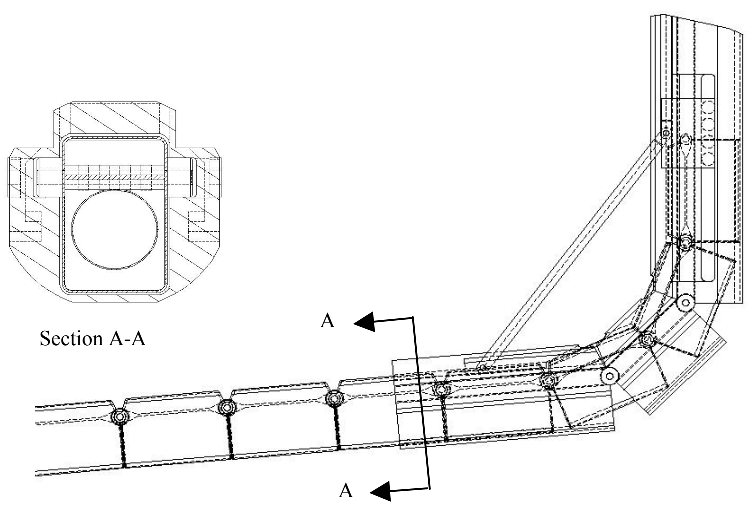

Figure 6.3 Folding manipulator roller and sleeve sketch

The arm will usually have an end-effector attached to the end, such as a sluicing spray nozzle and/or vacuum attachment. It is likely that most of the typical end-effectors will not fit through the sleeve and thus the sleeve will usually need to be withdrawn any time the arm is completely withdrawn from the tank.

The manipulator links are deployed from the take-up reel vertically through the vertical guide and through the distal guide element, which is used to control the elevation of the tip of the arm from vertical to horizontal. The take-up reel, support mast, vertical guide, and distal guide rotate to control the azimuth. The links are hinged together and pined. Guide rollers on each end of the hinge pins guide the links through the vertical and distal guide elements. The extended links remain straight by gravity and can be extended to 13 m (42 ft) or more. The links have a 10-cm- (4-in-) diameter utility passage through the center for insertion of hoses and cables. The pros and cons of this system are listed below.

6.2.1 Pros

- Simple tank entry and insertion.
- Three DOF (degrees of freedom) available with large workspace (13 m [42 ft] horizontal extension or more).
- Large link cross-section relative to riser size (no over-lapping or folded links in riser).
- Fits through 31-cm- (12-in-) diameter riser with a 36 kg (100 lbm) payload (230 kg [500 lbm] payload for 0.6 m [24-in] riser model).
- Simple control (Extension, Elevation, Azimuth) lends itself to tele operation.
- Straight-line extension can avoid internal tank obstructions.
- Low cost potential.
- Low above ground height (no tall towers).
- All manipulator actuators located above ground.
- Convenient access to manipulator tip can be provided.
- Can be deployed into full tanks.

6.2.2 Cons

- Links may become fouled and require scrubber/spray heads prior to retraction.
- May require active controls or stabilization off tank floor to damp resonance at long reaches.
- Must rely on limited lateral motion of end-effectors to reach around objects.
- Requires additional development and testing.

6.3 Long Reach Roll-Up Manipulator Concept

The roll up manipulator performs elbow actuation within the arm links itself. Because some of the Hanford tanks are short in height yet large in diameter, the arm will require two elbows to obtain adequate reach inside the tanks. Appropriate control lines (wires, hoses) will be run down the center of the arm to the actuators. A preliminary design has been developed based on hydraulic cylinders to actuate the elbows. This design is reasonable in complexity and has sufficient torque at reasonable hydraulic pressures of 21 MPa (3000 psi). Figure 6.4 shows the general layout for the roll up arm concept. Its primary advantage is its ability to be rolled up onto a reel for compact storage. The simple chain design should also be reliable, moderate in cost, and have a long operating life.

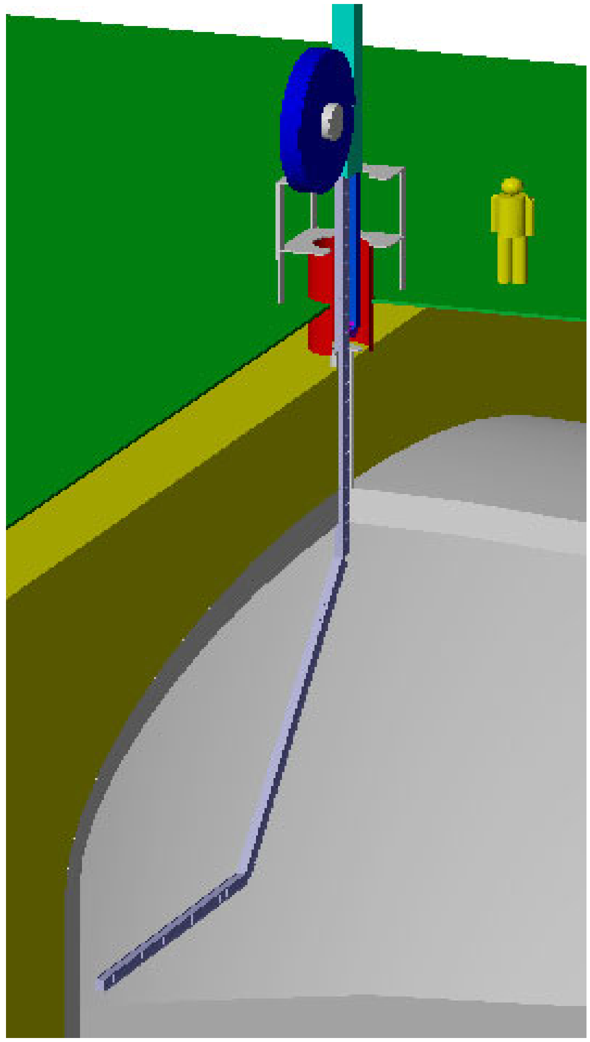

Figure 6.4 Long reach roll up manipulator concept

Figure 6.5 shows an example of two of the non-actuated links and shows the simple appearance of the links. Note that this variation does not use the rollers for the sleeve.

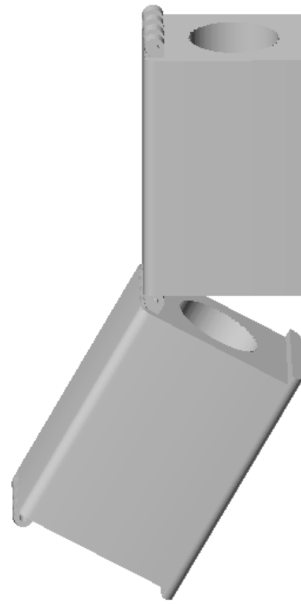

Figure 6.5 Typical non-actuated roll-up manipulator links

The base rotation joints and the reel will be powered by electric motors, and the two rotary joints within the arm will be powered by integral water-based hydraulics. By using the hollow arm to carry the waste conveyance system hoses, the deployment system for the conveyance system can be eliminated. The arm is deployed through a glove box for convenient maintenance of the arm, decontamination, and changing end effectors. In the glove box, links can be removed and replaced to repair the arm and shorten it for special circumstances.

The roll up arm has a layout that is similar to the Spar Modified Light Duty Utility Arm (MLDUA) that was used at the ORNL Gunite and Associated Tanks (GAAT) project. The roll up arm uses internal actuators similar to the MLDUA and accommodates a large MLDUA-style plastic boot as shown in Figure 6.6. The containment box and glove box are also similar and convenient for technicians standing on the platform deck.

The pros and cons of this system are listed below.

6.3.1 Pros

- Arm and waste conveyance system can be deployed through a single 31-cm- (12-in-) diameter riser.
- Load capacity of 46 kg (100 lbm)
- Cost similar to the Folding Link arm concept.
- Compact storage of arm on take-up reel.
- Reaches entire floor and walls, plus part of ceiling for 23-m- (75-ft-) diameter tanks.
- Can be covered with a boot similar to the LDUA for contamination control.
- Tolerant of moderate amounts of sludge accumulation on arm.

- The hollow arm can accommodate suction and cleaning hoses for waste retrieval system.

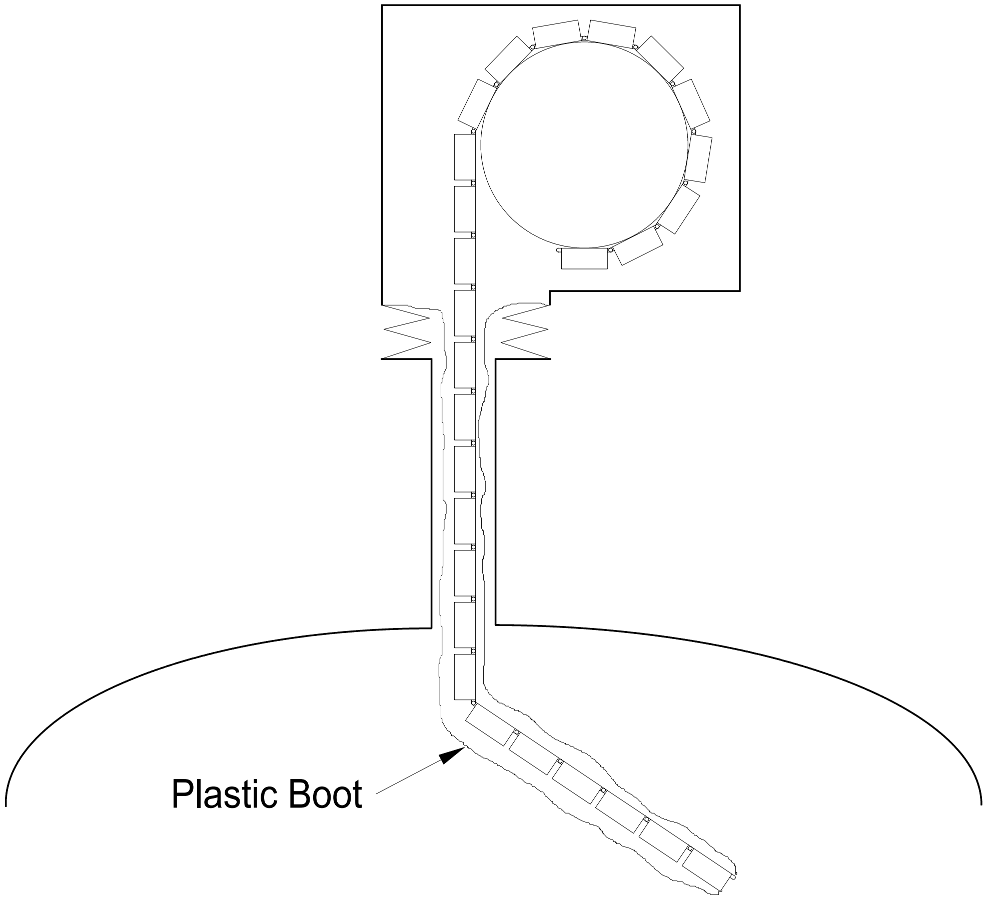

Figure 6.6 Illustration of boot application for roll-up manipulator

6.3.2 Cons

- Requires additional development and testing.
- Significant compliance [up to 0.6-m (2-ft) deflection under full load].
- Mechanical resonances may require active dampening.
- No redundant degrees of freedom to reach around obstacles beyond limited lateral motion of end-effector.
- Joints will tend to trap contamination, but arm will still function.
- May be necessary to shorten arm for deployment in tanks full of waste.

6.4 Comparison Discussions between the Two Manipulator Concepts

The selection between the two arm variations will be based on how each system handles specific concerns during deployment. Furthermore, whether or not some of these concerns are a real problem will depend on how the customer will use the arm and under what conditions. The team that makes the final decision should consist of the designers, operators with prior experience in tank waste retrieval operations and similar projects, and Hanford operations personnel. The major issues for consideration are described in Sections 6.4.1 through 6.4.7

6.4.1 Structural Issues

The structural design of the arm will be challenged to accommodate both small diameter and long reach. For a fixed diameter, a longer arm will support less load than a shorter arm. The roll up variation would be considered a somewhat longer arm since it fastens to its base near the take up reel, whereas the folding link variation is considered fastened at the sleeve. However, the cross-sectional size of the folding link version may be compromised because extra clearance is required for the sleeve. The full weight of the folding link arm will also have to ride on essentially four of the link rollers. At this time neither method appears to have a strong structural advantage over the other, however during the detailed design process for the arm, a clear advantage for one or the other may emerge.

6.4.2 Clearance Issues

The arm will be a close fit in a 31-cm- (12-in-) diameter riser, and the sleeve required for the folding link arm will further complicate this situation. The roll up arm may require an alignment strut due to the links tilting slightly to the side because of center-of-gravity effects, however this strut is anticipated to be very small and lightweight.

6.4.3 Sludge Coating Effects

The effects of sludge will be highly dependent on how the arm is used. If the arm were used to deploy a mobilization device that may scatter sludge, the arm would be coated with tank waste that may jam mechanisms in the arm. For the roll up arm, the only moving links are the two powered elbow joints, and they could be covered with a small boot as illustrated in Figure 6.6. Sludge could be washed from the arm as it is pulled through the glove box so sludge would not remain on the arm as it is rolled up on the reel. Normally the only time the passive links move is when the arm is withdrawn onto the reel. Furthermore, a technician in the glove box could tape the links at their joints to keep sludge completely out of the joints. And finally, similar to the MLDUA at ORNL, a large plastic boot could cover the entire arm to keep the arm mechanism free from sludge. For the folding link arm, none of these sludge covers could be used since all of the links bend in the sleeve elbow and no bag could pass between the links and the sleeve because of the rollers. A large overall boot could cover the arm/sleeve assembly, but the clearance between the sleeve and tank riser would be tight. It would also be possible to have a water spray ring wash off the links as the arm is pulled into the sleeve. Sludge on the arm could cause significant problems because it would jam the rollers traveling in the sleeve and would foul the joints as they turned in the sleeve elbow. Methods to mitigate these problems would have been evaluated during the design phase and with follow-on testing.

6.4.4 Decontamination Issues

Decontamination needs will also be highly dependent on how the arm is used and on the cleanliness expectations of the tank operations personnel. The issues are similar to the sludge coating effects mentioned in Sect. 6.4.2. The majority of the sludge can be washed off, however there may be issues with sludge being 'ground into' the metal surfaces from metal to metal contact. This is of particular concern for the folding link arm since waste may be squeezed between the link rollers and the sleeve slots. There is also a concern that the many links on the arm will trap pockets of contamination and make decontamination very difficult. The ability to tape the link joints on the roll up arm will help reduce this problem.

6.4.5 Reliability and Failure Recovery

As with any remote system, the arm should be recoverable if any of the components fail. Obviously some components are more likely to fail than others, and active components, such as actuators and their associated wire and hoses, are more likely to fail than passive components, such as joints and rollers. This would encourage placing active components outside the tank where they could be easily accessed for repair. This is a strong point for the folding link arm design since all of its actuators are outside the tank. The roll up arm design would be at risk if one of the elbows stuck in a bent position. In this case, the arm could not be withdrawn for repair. The only option in this case would be to cut the arm off and leave it in the tank. However, through careful design the roll up arm elbows could be designed to fail to a passive mode where they would relax straight due to gravity, thus enabling the arm to be withdrawn. This technique was used on the MLDUA with good results, and the roll up arm joint will be much simpler than the MLDUA.

Under heavy sludge conditions, the passive rollers on the folding link arm may become unreliable and jam. In this case, the arm would also have to be left in the tank. Also, this system would be dependent on proper operation of the spray ring on the end of the sleeve to wash the arm. The hoses and nozzles associated with the spray ring could also possibly clog or burst.

6.4.6 Area of Reach

The roll up arm does have some reach limitations because of the elbow arrangement. The end of the arm cannot approach straight up since gravity would not be able to hold the arm straight, therefore only the outer rim of the ceiling will be reachable. Whether this is an issue will depend on the customer's needs. The folding link arm will be able to cover the entire tank inside.

6.4.7 Full Tank Issues

The elbow arrangement for the roll up arm causes problems if the tank is very full. The arm will need to be inserted far enough into the tank so that it can bend its elbow, however this would require dipping the arm in sludge for full tanks. There may be work-around solutions to this problem by shortening the arm by removing some links, however preliminary statements from the customer indicate that all the tanks will be mostly emptied using conventional pumps and agitators before an arm is inserted. Usually the arm is used to recover unpumpable sludge on the bottom. In contrast, the folding link arm can be deployed in essentially full tanks.

6.5 AEA Technology ARTISAN™ Manipulator

The ARTISAN™[a] is a heavy-duty manipulator, which can be tailored to meet a variety of needs. The ARTISAN™ Tank Manipulator is simple in concept and is constructed with four degrees of freedom using four main modules to suit the specific target application. A typical ARTISAN™ configuration is in Figure 6.7.

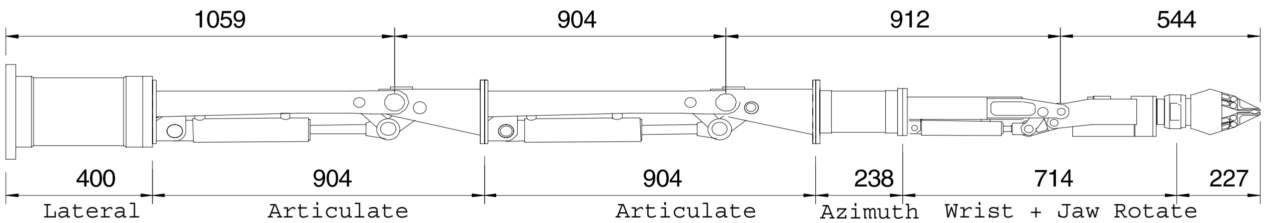

Figure 6.7 ARTISAN™ manipulator configuration

The manipulator is lowered vertically into a tank or vault through an available access port and is secured into position using spreader plates. AEA Technology shows a typical ceiling and wall mounted configurations in Figure 6.8:

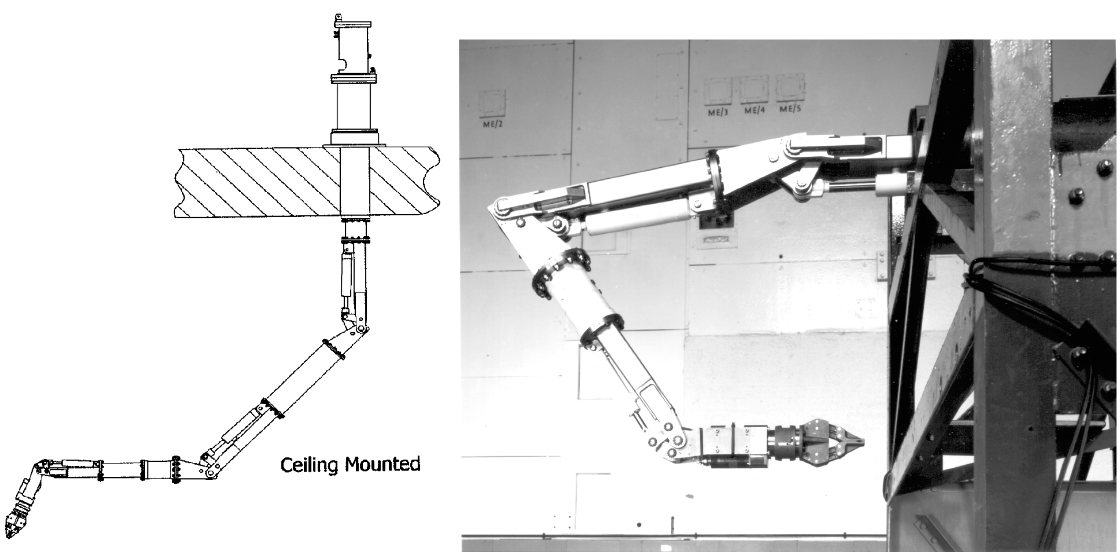

Figure 6.8 Arm ceiling and wall-mounted deployment configurations

All configurations are constructed from standard parts for greater flexibility and reliability. Discreet modules can be used to produce a long reach, high payload manipulator that can be installed through the

[a] AEA Technology Products & Systems. Abingdon, Oxfordshire, United Kingdom, Tel: +44 (0)1235 463405. ARTISAN(TM) Manipulator System - Specification, AVS/DOC/1338, January 1999. http://www.aeat-prodsys.com/prodsys/subdivisions-div/ART1.html

small access ports. Each of the ARTISAN™ Tank Manipulator joints consists of a hydraulic drive actuator. The arm is designed for ease of decontamination and maintenance. The standard version of the ARTSIAN™ Tank Manipulator has a maximum radiation tolerance of 30 kGy with high tolerant systems available. In addition to the manipulator arm the complete system also includes (1) a hydraulic power pack and manifold block for hydraulic fluid distribution and (2) a control station, which consists of a telerobotic controller, control panel, and operator control station.

6.5.1 Pros

- Commercially available proven technology.
- Configurable to customer needs.
- At least four DOF.
- Rigid construction.
- Capacity to reach around obstructions.

6.5.2 Cons

- May require significant headroom to deploy and/or retract fully assembled unit.
- Hydraulic and power cables pass down center of arm modules, which does not appear to leave room for waste retrieval hoses.

7.0 Next Generation Vehicles

One of the most useful tools for removing sludge from radioactive waste tanks is a small remotely operated vehicle, such as the Redzone Robotics[a] Houdini system. In anticipation of using such vehicles at Hanford, there is a need to make these good tools even better; therefore, potential improvements are being identified for in-tank vehicles. One of the most desirable new features is tetherless operation. Achieving this mode of operation would require developing new on-board power supplies and communications links to the vehicle. This section will focus on these two areas.

7.1 Power Supply System Considerations for a Tetherless Vehicle

The most obvious power source for a tetherless vehicle is batteries, however alternative power sources such as the use of fuel cells which could potentially provide benefits of lighter weight, smaller volume, longer life, and quicker recharge or refueling time should be investigated. There are several compatibility issues with the use of fuel cells in waste tanks since more traditional fuels, such as hydrogen, gasoline, or methanol, would be considered safety hazards. However, recently a new type of fuel cell based on zinc-air technology has been developed that performs well and is relatively safe. The zinc-air system was designed to replace gas generators to allow electric generator to be safely used indoors. The zinc-air fuel cell is anticipated to perform well in the environment inside of waste tanks. The fuel cell would also not wear out like batteries.

The overall use of the system is shown in the Figure 7.1. The vehicle shown in Figure 7.1 is tetherless and is powered by fuel cells. Communication to and from the vehicle will be accomplished with improved radios. A temporary tether will be available for re-fueling the vehicle and for emergency withdrawal.

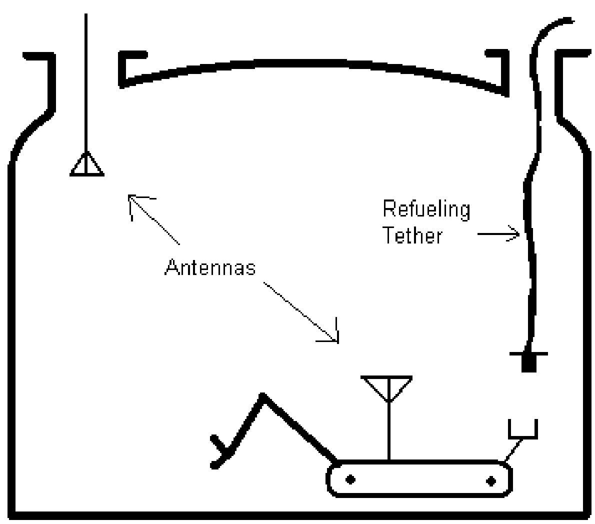

Figure 7.1 Tetherless vehicle schematic

[a] Redzone Robotics, Inc. 412, 476-8980, Homestead, Pennsylvania. http://redzone.com/pages/ser_port-pro-houdini.html

7.1.1 The Zinc-Air Fuel Cell

This technology is being developed by the Metallic Power, Inc.[a] . The fuel cell uses zinc metal in the form of small pellets and combines it with oxygen from the air to form zinc oxide, which can be regenerated (recycled) into zinc pellet fuel again. A lawn mower size unit produces about 2000 watts. This size should provide sufficient power to run a vehicle if power consumption is minimized and a small battery or super capacitor is used to temporarily supply peak power needs. During fuel cell operation zinc pellets are continuously fed from a feed tank into the cell and combined with oxygen from the air. The zinc oxide byproduct is in a potassium hydroxide solution, which is collected in a second tank. To refuel, the vehicle finds the refueling tether and connects to it. This tether simultaneously pumps the zinc oxide solution out while receiving new zinc pellets. The capacity of the fuel tanks should allow a one-day operating time; the refueling operation would take only a few minutes. Metallic Power is still in the development stage for their fuel cells and expects to have a commercial product next year. Investigation of delivery techniques, power output, materials compatibility, sealing systems, and withdrawal techniques should be further investigated.

7.1.2 Using the Fuel Cell in a Waste Tank

Although there may be other compatibility problems, the zinc-air fuel has a distinct safety advantage. For most other power systems, the hydrogen, gasoline, or methanol fuel would be considered an explosion hazard, plus batteries typically have toxic waste problems because of their lead or cadmium based chemistries. The zinc fuel cell system does use potassium hydroxide, however most of the Hanford tanks already contain alkali solutions. The fuel cell operates at room temperature and there are no high pressures chambers that could lead to an explosion.

Some of the compatibility problems that the fuel cell might encounter involve nuclear radiation and the presence of other gases inside the waste tank. Radiation hardening is always an issue with remote systems, and there have been no studies on whether zinc fuel cells can withstand radiation exposure. Hydrogen fuel cells have been used in moderate radioactive environments for NASA (National Aeronautics and Space Administration), but this does not necessarily imply success for zinc fuel cells. The fuel itself is metallic zinc, which is radiation tolerant since there are no chemical bonds or organic materials that could be broken in the fuel. The potassium hydroxide solution system is stable in radiation since this chemistry has been used extensively for processing spent nuclear fuel. The remaining question is the membranes used in the fuel cell itself. Since the bulk of the fuel cell/fuel tank system is inside the waste tank, it may be practical to shield the fuel cell itself and not shield the fuel tanks. Another concern is that compared to hydraulic systems, electrically powered systems are more sensitive to radiation requiring the extensive use of radiation sensitive semiconductors. Appropriate combinations of shielding and radiation hardened electrical components must be determined.

Another issue is that of contamination potentially carried by the spent fuel from the fuel cell. If the zinc oxide spent fuel solution is pumped out of the waste tank for regeneration, this fuel may be considered suspect because it was once inside the waste tank and may be contaminated. A similar concern was expressed at ORNL for the GAAT project when hydraulic fluid for the MLDUA and Houdini was

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[a] Metallic Power, Inc., 760 476-8000, Carlsbad, California. http://metallicpower.com/technology.htm.

recirculated in and out of the tanks to operate the machinery. For this situation, administrative controls were in place to consider the hydraulic pumps contaminated even though they were not inside any tanks. This method could also be used for the zinc regeneration system. Alternatively, the zinc regeneration system is a small unit that could be located inside the waste tank just inside a tank riser.

Some of the Hanford tanks may also have other gasses in the headspace above the waste that may interfere with the operation of the fuel cell. A variety of volatile chemicals are in these tanks, some of which may corrode the fuel cells. Gaseous hydrogen is also present in some of the tanks. It may be possible to flush fresh air through the tanks to reduce the presence of the undesired chemicals. Evaluation of the impacts of headspace gasses on fuel cell operation is needed.

There are also practical considerations for getting the fuel line connected to the vehicle. The vehicle would presumably find the fuel line and connect itself, therefore the vehicle would require a manipulator. Plow blade only (no manipulator) vehicles would require some other mechanism to attach the hose such as a long reach manipulator arm. Also any other problem, such as the vehicle getting stuck, the arm or wheels failing, or running out of fuel, could prevent the vehicle from connecting to the hose. Backup provisions for emergency withdrawal of the system should be investigated.

Important design considerations for the fuel cell will be power requirements, physical size, reliability, lifetime, and radiation hardening. For the overall system, radiation hardening, physical size compared to riser diameter, ruggedness, mobility, fuel line design, and reliability will all need to be addressed.

7.2 Wireless Communications inside Waste Tanks

Although the communications links might be considered off-the-shelf items, high-bandwidth radios inside waste tanks have severe problems because of the reflective environment caused by the steel tanks walls. In most cases video radio links from the vehicle to an antenna at a tank riser would have unacceptable performance. However, a new method of modulation based on dividing the signals into many separate carrier frequencies called Orthogonal Frequency Division Multiplexing (OFDM) has been developed. This method has much better performance in reflective environments and could be adapted for in-tank tetherless vehicle applications.

Wireless video radios that are used with mobile robotics are essentially the same technology as household televisions except they may use FM (frequency modulation) in a different frequency band. Similar to the difficulty of receiving broadcast television in a moving car, the video radios for mobile applications have had difficulty sending good signals back to the base station. The problem is even worse indoors because of the reflections off the metal building walls. An interesting question is why other types of radios, such as pagers and walkie-talkies, rarely have any trouble in the same locations. The reason why pagers work and video does not is because of the high bandwidth required for video. To explain this effect, consider Figure 7.2, which is an example of a digital signal versus time being received by a radio.

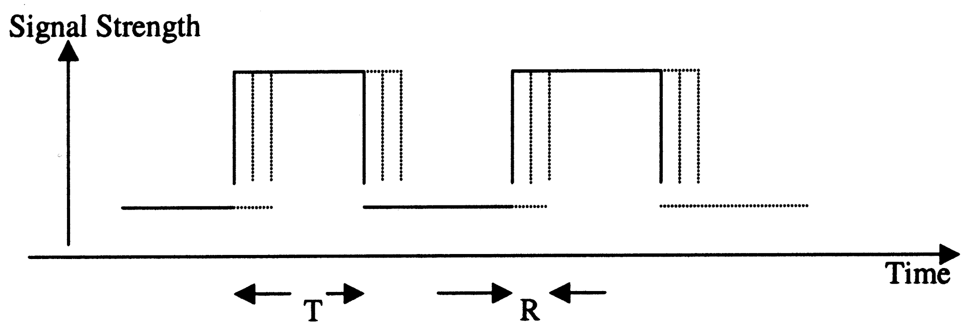

Figure 7.2 Example of a digital signal versus time being received by a radio

The dotted lines represent signals that do not come directly from the transmitter, but arrive in a round about fashion after reflecting off other objects. Due to the speed of light, the signals that take a longer path arrive at a later time as represented by R in the figure. This effect is called “multipath distortion”. Whether this is a problem or not is highly dependent on the period of the pulse T. R is a fixed quantity that depends on the terrain and other reflective objects. For voice radios, T is much longer than R and thus can be smoothed out. For high-bandwidth video signals, R is comparable to T, thus the multipath distortion cannot be filtered out. If this multipath distortion problem could somehow be solved, video performance could be dramatically improved.

7.2.1 Multiple Carrier Radios

A question to ask is, if walkie-talkies work so well in all environments, would it be possible to combine several walkie-talkies together to get an overall high bandwidth signal. This is indeed possible with the best example being Orthogonal Frequency Division Multiplexing (OFDM). If you had a high bandwidth signal that required 8 MHz for example, a normal AM (amplitude modulation) signal spectrum would look like that shown in Figure 7.3. Using OFDM, you could instead use eight separate AM signals, each with 1 MHz bandwidth as shown in Figure 7.4.

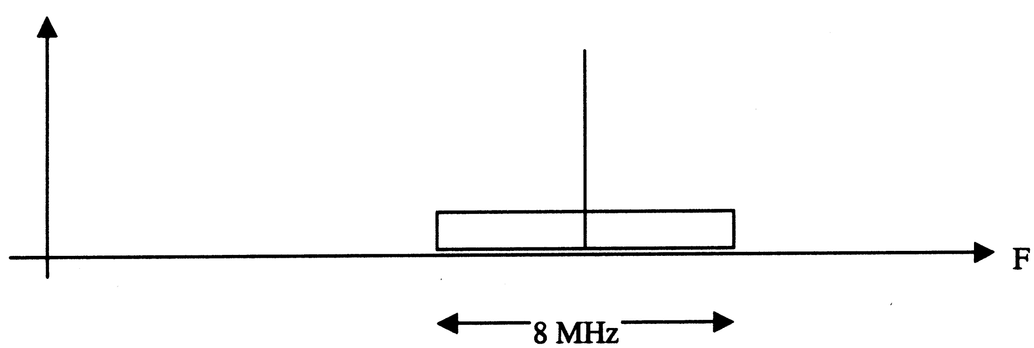

Figure 7.3 Typical 8 MHz signal spectrum

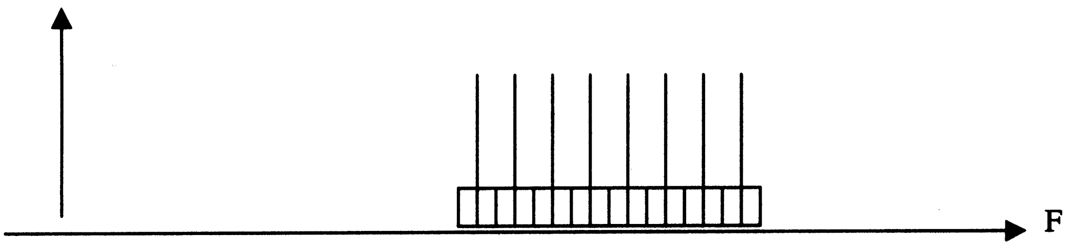

Figure 7.4 Orthogonal frequency division multiplexing signal

The total bandwidth and total power are the same for both cases. The separate AM signals can be transmitted and received as if they were completely separate radios. If the bandwidth for the separate signals is small enough, then the signals will have good reception similar to walkie-talkies. Thus, this system offers good reception advantages and no disadvantages other than the circuitry required to implement the several small radios. Unlike the radical bandwidth characteristics of advanced schemes such as spread spectrum, OFDM is very similar to standard AM and FM in regards to power and bandwidth.

The multi-carrier concept can be used for analog or digital signals. An example analog system for video would have roughly 30 kHz of bandwidth for each carrier, which is the same bandwidth as a typical voice radio. However, this would require 250 carriers! Building 250 small radios is certainly not practical, however such a system can be synthesized using modern DSP (digital signal processing) techniques and the Fast Fourier Transform (FFT). An example of how this is done is shown in the next section.

There are several examples of OFDM that are in use today. The high-speed Digital Subscriber Line connections that run 6 mega baud internet signals to your home over regular phone lines are based on OFDM. The new digital television (DTV) system now in use in England is based on Coded OFDM (COFDM), which is OFDM with some redundant coding added to improve robustness. The British DTV system has generated great interest because of its superior reception over analog television. Viewers have been able to get good reception under adverse conditions, such as basements with just plain rabbit-ear antennas and cars traveling down the highway. OFDM is also being considered for other wireless digital systems, such as microwave high speed Internet into the home.

7.2.2 Proposed Analog System

A system that is appropriate for commercial broadcast is not necessarily the best choice for mobile robotics. Broadcast systems are designed to minimize bandwidth so more channels can be delivered, but this may not be necessary with the channels allocated for robot use. Broadcast systems use MPEG II (music photographic experts group) video compression, which requires large, sophisticated, and power hungry circuits that are not desirable on small mobile robots. Digital systems always require a signal of a minimum quality in order to work, whereas analog systems are sometimes more tolerant.

The proposed analog system is the same as the example above with 256 carriers and 8 MHz total bandwidth. An example of a system to implement this is shown in Figure 7.5.

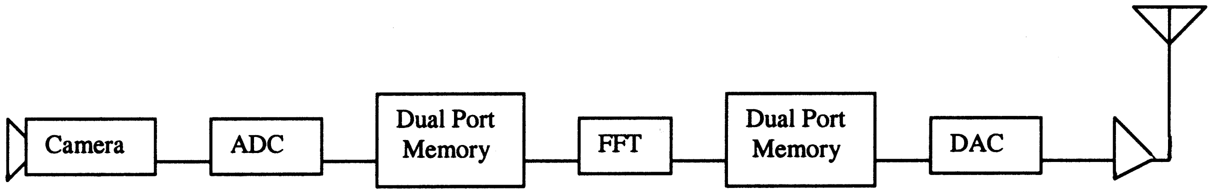

Figure 7.5 Prototype OFDM system schematic

In addition, the carriers are chosen such that they correspond to specific lines on the television screen. A normal TV screen is scanned horizontally (the dotted lines represent the retrace) as illustrated in Figure 7.6.

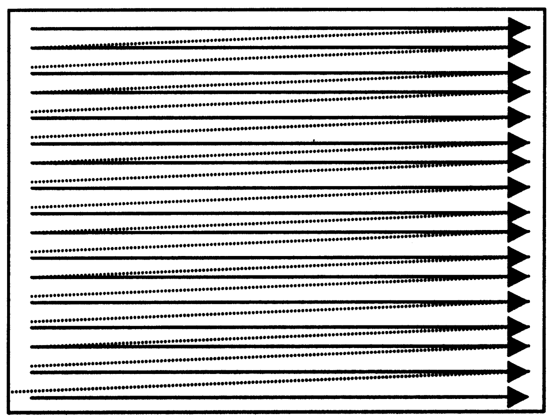

Figure 7.6 Illustration of a normal TV screen scan

The ADC and FFT is synchronized with the scanning such that the screen is now represented as columns, with each column corresponding to one of the AM carriers. The carriers would correspond as illustrated in Figure 7.7.

The advantage of this system is that for horizontal synchronization, the pixel location is known from the carrier frequency, and thus no sync signal is required. This significantly improves the robustness of the signal since maintaining sync is one of the most troublesome aspect of weak signals. For vertical sync, one of the carriers could be dedicated for synchronization, however a robust system similar to the horizontal sync is also being investigated. Compared to a full MPEG II system, this method is much simpler and could be built from just a few integrated circuits.

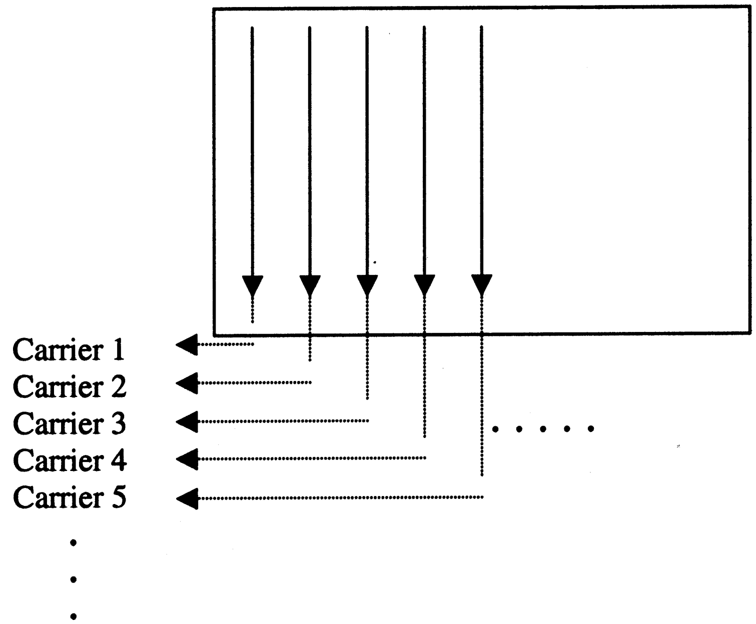

Figure 7.7 Illustration of how carriers correspond to scan lines

8.0 Recommendations for Development

To facilitate the TFA's Strategic Projects Review held in September, 2001, a detailed technical approach was developed for the three highest ranked alternatives. This section summarizes the incentives, economic drivers, technical risk, and technical approach for air-assisted TORE®, sonication for enhanced solids dislodging, and novel manipulator approaches.

8.1 Air-Assisted TORE® for Enhanced Solids Mobilization and Retrieval

The TORE® is a patented hydrotransportation device with no moving parts with the ability to convey solids at pre-determined slurry concentrations (up to 70 wt% solids) over great distances. The TORE® operates by developing a fluid-based precessing vortex core to mobilize and fluidize solids so they can be captured in the outlet pipe flow and removed from the vessel. The dry TORE® concept will use air (instead of water) to develop the precessing vortex core to fluidize and entrain dry solids. The TORE® outlet is coupled with a jet pump to transport the entrained solids.

The objective of this study is to evaluate the ability of the TORE® to mobilize waste during retrieval without addition of fluids to the waste in the tank. Using a TORE® specifically optimized for air, bench-scale and lab-scale tests will be conducted to evaluate the TORE® zone of influence. Waste simulant recipes will be based on previously developed recipes. Test results will be reviewed to assess the benefit of technology for solids entrainment and dry retrieval and to make recommendations for range of applicability with respect to waste type.

8.1.1 Incentives and Impact on DOE HLW (High Level Waste)Mission

The following are potential economic drivers for use of the air-assisted TORE® for solids fluidization and entrainment:

- Provides a dry method of fluidizing and entraining solids for retrieval with the ability to extend the zone of influence by incorporating a precessing vortex to entrain solids into the retrieval inlet.
- Eliminates the need for fluid addition to pump dislodged solids from the tank as a slurry.
- Permits dry retrieval of waste from suspected leaking tanks.

Dry retrieval permits retrieval of waste from suspected leaking tanks without addition of costly ex-tank barriers, or specific in-tank stabilization of tank areas expected to leak. Dry solids removal reduces the amount of fluid addition to that required for slurry transport, thereby reducing tank space required for storage of the retrieved slurry and reducing need for excess fluid evaporation.

8.1.2 Technical Approach

This work will be conducted in the following phases.

Applications Assessment

- Consult with vendor (Merpro Ltd) and users regarding applications for air-assisted entrainment and reduced fluid entrainment applications. Compile a relevant list of deployments similar to waste retrieval.

Bench-scale Tests - Entrainment Range of Influence

- Conduct tests using vendor-supplied operating conditions to measure the airflow velocity profiles. From this data make predictions of the region of TORE® influence for mobilizing and entrainment of dry solids, wet solids, and sludges.
- Conduct parametric tests evaluating performance of solids entrainment over a range of simulant types and particle size distributions. The tests will include dry sand and gravel, dry salt cake, and moist sludge. The quantity of solids removed and the displacement pattern will be evaluated.
- Develop recommendations for air-assisted TORE® for solids entrainment and retrieval.

Integrated Tests - Entrainment and Retrieval

- Use an integrated TORE® configuration with suction to evaluate combined entrainment and retrieval of dry solids, moist solids, and sludges. Some of these simulants will already have been "fractured" ultrasonically as a part of task 1.2.

Tool Configurations

- A variety of tool configurations for air-assisted TORE® technology for single-shell tanks at Hanford will be devised. The general operating envelope, power requirements, flow diagrams, potential safety concerns, and operating scenarios for practical application of this system in waste retrieval operations will be investigated.

8.2 Sonication for Enhanced Solids Dislodging and Mobilization

High-frequency ultrasonic energy applied to solidified salt cake and sludge wastes can provide sufficient energy to fracture and dislodge solids to enhance dry retrieval. The objective of this study is to evaluate the use of high-frequency ultrasonic energy applied to solidified salt cake and sludge wastes to rapidly fracture and dislodge solids to enhance dry retrieval. Existing PNNL sonication equipment will be used to conduct specific bench-scale tests targeting dislodging of salt cake and sludge wastes. The tests will evaluate transducer configurations compatible with waste fracture and dislodging and quantify the effects of frequency using a range of sludge and salt cake simulants. Ultrasonic system configurations will be designed for bulk dislodging. This task will also develop conceptual designs for transducers that could be readily used on crawlers or manipulators for use on both salt cake and sludge-based wastes.

8.2.1 Incentives and Impact on DOE HLW Mission

The following are potential economic drivers for using sonication for solids fracture, dislodging, and mobilization to enhance dry retrieval.

- Provides an efficient method to rapidly fracture and dislodge solidified waste.
- Eliminates the need for fluid addition for solids dislodging.
- Permits dry retrieval of waste from suspected leaking tanks.

Using sonication to fracture and dislodge waste eliminates the need for water jet based dislodging. This method for dislodging permits dry retrieval which reduces the risk of retrieving waste from leaking or suspected to be leaking tanks by eliminating addition of fluid that could transport waste through penetrations in the tank into the ground beneath the tank.

8.2.2 Technical Approach

This work will be conducted in the following phases.

Equipment and Applications Assessment

- Consult with ultrasonic equipment manufactures regarding bulk solids fracture applications and remote deployment equipment configurations. Compile information relevant to waste retrieval in Hanford SST's.

Bench-scale Tests

- Tests will be conducted to evaluate dislodger tool operating conditions and configurations. Parameters to be evaluated include frequency, pulse type, tool configuration and the presence or absence of coupling agents (dry versus wet probe operation). Both large and small tool sizes will be evaluated.
- Parametric tests will be conducted to evaluate solids dislodging using tools selected during bench scale tests. These tests will be conducted using a range of simulants including salt cakes and sludges. The dislodging ability of the tools will be quantified. The dislodged simulants will be used to evaluate TORE® ability to entrain them as testing described above
- Recommendations for applying sonication for dry waste dislodging will be developed.

Tool Configurations

- A variety of tool configurations for sonication in single-shell tanks at Hanford will be designed. The general operating envelope, power requirements, flow diagrams, potential safety concerns, and operating scenarios for practical application of this technology in waste retrieval operations will be investigated. Component approaches for using sonication equipment on a crawler or manipulator, including plow blades, vibrating suctions inlets, vibrating tracks, etc. will be developed.

8.3 Long Reach Manipulator

Deployment of end-effectors, retrieval systems and other remediation hardware can be enhanced by arm-based retrieval. To make the arm storage compact and convenient, an arm based on a series of links similar to roll up cable trays is envisioned. Compared to previous arms that were stored in tall tower-like boxes, the compact reel will not have any of the safety and wind-loading problems associated with towers, and will be easy to transport to other work sites.

Desired features for the arm are sufficient capacity and reach, insertion into existing 31-cm- (12-in-) diameter risers, reliable and safe operation, reasonable cost, minimal radiation exposure, and effective contamination control. The novel long reach manipulator can be incorporated into baseline retrieval plans for potentially leaking tanks with no major facility retrofits.

8.3.1 Incentives – Impact on DOE HLW Mission:

The following are potential economic drivers for use of the novel long reach manipulator:

- Facilitate and reduce the cost of retrieval of wastes from Hanford Single Shell Tanks (SSTs).
- Eliminates the need to install large diameter risers in SSTs to accommodate costly manipulator arms.
- Provide a means of tool deployment and integration of hose management in a single low cost, minimal exterior height, manipulator arm.

Use of this technology would eliminate the necessity of installation of large diameter risers in SSTs. Existing 31-cm- (12-in.-) diameter risers could be used for deployment of the novel long-reach manipulator arm.

8.3.2 Technical Approach

This work will be conducted in the following phases.

- Complete conceptual design for novel long-reach manipulator after down selection of joint and guide concepts.
- Fabricate subcomponents and perform limited functionality tests.
- Modify design based on the functionality test results and determine cost estimate for fabrication of prototype arm.
- Fabricate prototype arm and test under simulated SST operating conditions.
- Finalize design based on prototype test results.
- Fabricate hot deployment arm and deploy in SST cleanup operations.

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10.0 Appendix Workshop Notes

TECHNOLOGY PRIORITIZATION: RETRIEVAL FROM POTENTIAL LEAKING TANKS

July 23-24, 2001

HTC, Multnomah Falls Room

TABLE OF CONTENTS

ACTIONS

WHAT	WHO	WHEN
1. Link FY02 work plan to the CHG Level 1 logic (P3 schedule)	Judith Bamberger/ Jerry Cammann	TBA
2. Obtain multi-phase flow test “alternate funding”	Keith Carpenter/ Peter Gibbons	TBA
3. Develop FY02 Retrieval TFA work plan and obtain endorsement from balance of TFA and SST Retrieval Team	Judith Bamberger/ Ben Lewis	8/25/01
4. Submit any specific research needs, within the priority six areas, to Judith Bamberger via e-mail	Workshop team members	7/27/01
5. Issue workshop results • Issue Executive Summary Facilitators letter by 7/31/01	Richard Harrington/ Robin Kummer	7/25/01

TBA = To Be Arranged

POTENTIAL FY02 TFA/SST TECHNOLOGIES

Item No.	Ranking No.	Technology	Category
1.	3	Sonication	D
2.	2	Sonic TORE® and bulldozer with sonication	D
3.	10	Modified stationary guzzler (trencher; vacuum conveyance)	C
4.	1	Dry TORE® with jet pump combination	C
5.	7	Multi-phase flow	C
6.	6	Shop-vac to in-tank collection container	C
7.	11	Small diameter dislodger/conveyor (borehole miner)	D&C
8.	4	Long reach manipulator • Novel and cost effective	DP
9.	5	Next generation crawler technology • Radio controlled, non-umbilical dislodger • Consider applying a crawler to any of aforementioned technologies	DP
10.	9	Hose management	DP
11.	12	Controlled rapid solidification with crawler, manipulator, and others	LDMM
12.	8	Drying absorbent (e.g., micro cell E)	LDMM

D = Dislodging
C = Conveyance
DP = Deployment Platform
LDMM = Leak Detection Monitoring and Mitigation

OTHER POTENTIAL TFA/SST TECHNOLOGIES

Item	Rank	Technology
F1.	4	A phosphate based concrete and/or grout (low strength)
F2.	1	Debris management system
F3.	2	Integrated mixer mobilization pump on a crawler based system (e.g., mud pump moving around on a tether system)
F4.	5	Acoustic levitation
F5.	3	Alternate dislodging fluids leak inhibitor, e.g., Bentonite clay
LDMM		Apatite in tank
LDMM		In tank inspection; integrity viewing/mapping
LDMM		Fluid reactive with sand or concrete
LDMM		Ultrasonic transmission to identify leaks
LDMM		Controlled rapid solidification with crawler, manipulator, and others
LDMM		Drying absorbent (e.g., micro cell E)

F = Future consideration (beyond FY02 Scope)
LDMM = Transfer/Assign to LDMM TFA team

NOMINAL GROUP TECHNIQUE (NGT)

Item No.	Votes/Points	TOTAL Votes	TOTAL Points	New Rank
1	5,2,6,2,4,3,7,4	8	33	3
2	5,7,6,6,3,6,3,7	8	43	2
3	4,1,2,1	4	8	10
4	1,5,7,6,5,7,5,6,6	9	48	1
5	7,1,7,1	4	16	7
6	4,3,2,3,1,1	6	14	6
7	7,3	2	10	11
8	5,5,5,2,4,4,3	7	28	4
9	6,2,6,1,5	5	20	5
10	2,3,3,1	4	9	9
11	4	1	4	12
12	1,2,4,4,2	5	13	8
	Total	63		

NGT COMMENTS

- Items 11/12, "Controlled rapid solidification with crawler, manipulator, and others," and 12/8, "Drying absorbent (e.g., micro cell E):" moves to the LDMM TFA team
- Items 7/11, "Small diameter dislodger/conveyor (borehole miner)," and 3/10, "Modified stationary guzzler (trencher; vacuum conveyance):" are technically mature enough that no additional work is needed in the FY02 retrieval TFA scope
- Item 10/9, "Hose management," will be developed as part of 8/4, "Long reach manipulator," and 9/5, "Next generation crawler technology"
- Item 5/7, "Multi-phase flow," consider alternate funding for research – See Action Item #2

WEIGHTED EVALUATION CRITERIA

1.	Minimize leakable liquid	33.9%
2.	Timeliness; meet schedule	25%
	• Retrieval rate; duration and operational effectiveness	
3.	Ease of O&M	21.4%
	• Including ALARA	
4.	Cost effectiveness	10.7%
	• Life cycle cost	
	• Maximize re-use	
5.	Ease of licensing/permitting	5.4%
	• Authorization basis	
6.	Maximize 99% retrieval	3.6%
		100%

"PAIRED COMPARISON"

	B	C	D	E	F	G		TOTAL	NEW RANK
A	A3	A4	A3	A3	A4	A2		19	1
	B	C1	D2	E2	B2	G2		2	6
		C	D3	C2	C3	G3		6	4
			D	D3	D4	G3		12	3
				E	E1	G4		3	5
					F	G4		0	
						G		14	2
								56	

Scale

0 = No difference
1 = Very slight difference
2 = Slightly more important
3 = Reasonably more important
4 = Much more important
5 = Extremely more important

CRITERIA PRIOR TO PAIRED COMPARISON

A Minimize leakable liquid
B Maximize 99% retrieval
C Cost effectiveness
- Life-cycle cost
- Maximize re-use: Within same tank; more than one tank, and/or farm

D Ease of O&M
- Including ALARA

E Ease of licensing/permitting
- Authorization basis

F Facilitate use on multiple waste types (e.g., salt cake, sludge, etc.)
G Timeliness; meet schedule
- "Retrieval rate; duration; operational effectiveness"

REVIEW OF PAIRED COMPARISON RESULTS

- Minimize leakable liquid
  - Supports the goal of minimizing waste volume (e.g., water addition, compounds/absorbents

- Supports efforts to develop dry retrieval technologies

- While maximizing 99% retrieval is a goal, it was ranked last. However, the criteria are important and included in the overall 100% scope.

EVALUATION OF BRAINSTORM TECHNOLOGIES

- Evaluation Guidelines
  - Read all ideas
  - Eliminate the possible, but improbable
  - Keep ideas that are potential FY02
  - Consider categories, e.g., future considerations (beyond FY02) for out-years and/or backup for FY02
  - Add new ideas, as appropriate, i.e., consider combining ideas for benefit of FY02 work
  - Use criteria to facilitate decision points

CATEGORIES

F = Future considerations (beyond FY02) but can serve as backup to FY02 and/or areas for out-year

LDMM = LDMM areas to be carried over into the LDMM TFA scope

D = Dislodging

C = Conveyance

DP = Deployment Platform

BRAINSTORM POTENTIAL SST TECHNOLOGIES

(Tests and/or Research)

D Sonication

~~- TORE® Vortex~~

DP Long reach manipulator

- Novel cost effective

\- Controlled "Rapid solidification" with crawler or manipulator, or others

\- Drying absorbent (e.g., Microcell E)

~~- Bulldozer~~

~~- Street cleaner~~

~~- Radio controlled robot~~

- ~~Non-umbilical dislodger~~

~~- Rototiller on end of crawler~~

D&C Small diameter dislodger/conveyor ("borehole miner")

C Modified stationary guzzler (trencher; vacuum conveyance)

C Dry TORE® with Jet pump combination

LDMM In-tank inspection; integrity viewing/mapping

~~- Phosphate glass system~~

LDMM Apatite in-tank

F A phosphate based concrete and/or grout (low strength)

~~- Liquid based system~~

- Pulsating mixer pump; AEAT

\- ~~Sonic TORE® and bulldozer with sonication~~ "combined with modular crawler"

~~- Burnout of tank with laser~~

LDMM Fluid reactive with sand or concrete

F Debris management system

DP Hose management

\- ~~Three-phase flow~~ Covered in multi-phase

C Multi-phase ~~liquid base~~ flow

BRAINSTORM POTENTIAL SST TECHNOLOGIES

(Tests and/or Research)

DP Next generation crawler technology

- Radio controlled, non-umbilical dislodger
- Consider applying a crawler to any of aforementioned technology

~~- Total tank excavation (i.e., yank a tank)~~

LDMM Ultrasonic transmission to identify leaks

~~- Modular crawler system tools~~

D Sonic TORE® and bulldozer with sonication

F Integrated mixer mobilization pump on a crawler based system (e.g., mud pump moving around on a tether system)

F Acoustic levitation

C "Shop-vac to in-tank collection container

F Alternate dislodging fluids – leak inhibitor (e.g., Bentonite clay)

TFA OVERVIEW

- Presentation
  - Reviewed TFA project scope, current dislodging and retrieval/removal techniques
  - Clarified additives considered
  - Identified efforts on-going with sol-gel and rapid solidification technology to enhance tank integrity; including:
    - Sonication for waste dislodging without fluid addition
    - Scarifying end effectors
    - TORE®-vortex
    - Borehole miner
    - Fluid-based mobilization and retrieval
    - Conventional pump and remote operated vehicle (i.e., bulldozer)
- Consider mix/match these technologies

MEMORIES

AI = Action Item

✓ Misting technologies

~~- Priority waste form sludge vs. salt cake~~

✓ Dry retrieval (no liquid addition)

✓ Cryogenic cooling of the tank structure (i.e., reducing the temperature below the nil ductility)

AI #1 Path forward needs to show a link to CHG Level 1 logic

- Consider funding links in P3

✓ Focus on volume and curies removed (See Criteria #1: Maximize 99% retrieval)

SST SCHEDULE PRIORITIES

Focus is on retrieval first, then how to deal with potential leaks

- Drier we can make any retrieval is favorable (i.e., minimize water)
- "We don't have anything on mitigation" (i.e., mitigate leaks)

We <u>always</u> want Best Advanced Technologies

Using a retrieval performance base methodology which is a risk based approach

Table 2.2 and 2.3

- First assumed leaker is 241-TX-105 scheduled for 12/25

Interim Stabilization will be completed by 9/30/04 (under Consent Decree) <u>three criteria</u>

1. 5 Kgal of free liquids/supernatant left
2. 50 Kgal interstitial
3. .05 gal pump rate

⚐ Priority needs are on those tanks that have confined space and/or limited/restricted access (e.g., C-107 through C-112, etc.)

- *The focus boils down to the "<u>size, location, and number of risers available</u>" tend to dictate our approach
- *Then, we have in-tank obstructions (e.g., thermocouple trees, air lift circulators, steam coils, failed pumps, etc.)
- Tank dome limits: 100 tons

67 of the 149 SST, are known/suspected leakers

- May want to consider all SSTs as known/suspected leakers

⚐ Today we are focused on

1. Salt cake (S-112)
2. Sludge (C-104)
3. Combined salt cake and sludge (S-102)

⚐ Level 1 logic

- Confined and limited access tanks
- Dry retrieval
- Retrieval from IMUSTS (incidental miscellaneous underground storage tanks)

*Constraints

SST SCHEDULE PRIORITIES

⚐ "Key programmatic focus is to cover salt cake, sludge, and combined in confined/limited access tanks and dry retrieval"
The waste focus will be combined salt cake and sludge

SST PROJECT NEEDS

- Technology: One size does not fit all; need a tool bag of technologies

⚐ Leak Detection Monitoring and Mitigation (LDMM)

- Develop technology sensitive to leaks
- Volumes to detect are risk based
  - Total volume number
  - Target rate: reliably detect "x" gallons (e.g., C-104 can leak ~10 Kg; S-112 cannot leak <2 g "how can we measure that?"
- August 2001 begin a LDMM technology demonstration (a.k.a., "bake-off")
  - Current techniques can resolve +/- 8 Kg of leak
    - Today we rely on in-tank mass and material balance
    - Out of tank we rely on high resolution spectral gamma

  ⚐ Focus, in August, is on ex-tank technologies
  - Looking at volume integrating technologies
  - Will <u>demonstrate six</u>
    1. Tracer technique
    2-4. Electrical technique
    5. Radar technique
    6. Seismic technique
  - Looking to resolve between 500 and 1Kgal of leakage
- The August bake-off
  - Using 36% solution of sodium ($Na_2S_2O_3$)
  - A series of four injections varying in volume
  - Test site is a 2/3 scale mock-up

- In-tank areas are being done within the projects
  - One global F&R document
  - Some specific project F&Rs on LDMM
- Leak monitoring quantifies the leak
- Leak mitigation minimizes leaks within a range from do nothing to subsurface or in-tank barriers

⚐ Key is to estimate volume and location of the leak

- Current SST technologies planned for use
  - Contract with Savannah National Laboratory for development of apatite reactive zone vs. a barrier
    - Like a purification system for water
    - Will do bench scale testing of apatite reactive zone on uranium and Tc^{99}
      - FY-02 will then do field tests

⚐ NOTE: "The key challenge is demonstrating irreversibility of this absorption process."

- Current planned SST retrieval technologies

Planned Technologies	Tank(s)	TFA Additional Needs/Second Generation?
1. Fluidic System	S-102	TBD
2. Low Volume Density Gradient Volume Salt Cake Dissolution	S-112/ U-107	TBD
3. Sludge Retrieval Crawler	C-104	TBD
4. In-tank Mass and Material Balance	Most SSTs	TBD
5. High Resolution Spectral- Gamma For Ex-Tank	Most SSTs	TBD

NOTE: There are several mitigating actions in process on the five mentioned technologies.

PURPOSE

- To select (prioritize/rank) those processes that the SST Project needs new information and/or tests performed in FY02 to support the retrieval mission (long term: 2006-2018)
  - In addition, to develop a rank criteria for application/use in future efforts.

NOTE: The results of this workshop will be integrated into "TFA's FY02 work plan"

DEFINITIONS

- FY02 Scope
  - Those areas that require effort/work to be done in support of potential deployment in FY06 and beyond

WIN/WIN OPPORTUNITY

- SST PROJECTS
  - *Obtain data and/or testing on existing, and/or hybrid, and/or new technology to facilitate retrieval from potentially leaking tanks with little or no money from the projects

- TFA
  - *Obtain needed SST data and/or tests to facilitate development and deployment of required technologies to facilitate retrieval from potentially leaking tanks

*Consider additional areas (technology) for future selection

OPENING REMARKS

- This task is strategic
  - This is indirect support; while some direct support is on various tanks (S-112, C-104, etc.)
- Looking for the opportunity to develop and deploy technologies for future SST retrieval
  - TFA has a small (~$250K) amount of $ to look at scope that RPP thinks is worthwhile to develop
    - If additional work is needed then it will be prioritized in the out-years
    - Don't want to duplicate project work; want to support your need

⚐ Specifically, what tests do you need conducted and/or technology research you need done next year to support future needs

- Background:
  - Will overview the current technologies being worked
    - See handout

  ⚐ Again, what tests do you need performed and/or development work in the next fiscal year
- Need to look at our needs from a science-fair perspective
  - We have looked at areas that minimize the use of water
    - Process focus vs. Project
- SST projects are definite
  - Looking for those areas that add value

  ⚐ Via TPA: LDMM technologies are a priority

TECHNOLOGY PRIORITIZATION:
RETRIEVAL FROM POTENTIAL LEAKING TANKS
HTC, Multnomah Falls Room
July 23-24, 2001

AGENDA

Day 1, Monday, July 23, 2001

7:15 - Welcome/Purpose, Safety Topic, & Introductions
- Review Agenda, Guidelines and Expectations
- Opening Remarks

7:45 - Review/clarify 2003-2006 SST Demo/Retrieval Schedule
- Identify SSTs, schedule, leak potential, and technology plans
- Utilize parking-lot information sheets, as required

9:30 - **BREAK**

9:45 - Finalize 2003-2006 SST Demo/Retrieval Schedule
- Solidify matrix of information by SST
- Status on-going technology activities

10:45 - Overview Potential Technology Candidates
- Review/clarify TFA candidates
- Identify potential TFA and SST benefits

11:30 - **LUNCH**

12:30 - Finalize Potential Technology Candidate List
- Identify existing and/or planned technologies
- Brainstorm potential new candidates

2:30 - **BREAK**

2:45 - Develop Technology Evaluation Criteria
- Identify and define the criteria list
- Solidify/select final criteria list

4:15 - Finish Day 1 with Wrap-up Review of Status and Day 2 Agenda

TECHNOLOGY PRIORITIZATION:
RETRIEVAL FROM POTENTIAL LEAKING TANKS
HTC, Multnomah Falls Room
July 23-24, 2001

AGENDA

Day 2, Tuesday, July 24, 2001

7:15 - Review Agenda, Purpose, and Status from Day 1

7:30 - Finalize Technology Evaluation Criteria
- Rank criteria with applied weighting
- Update criteria definitions, as required

9:30 - **BREAK**

9:45 - Prioritize/Rank Technologies
- Evaluate using weighted criteria
- Eliminate the possible, but improbable

11:30 - **LUNCH**

12:30 - Complete Technology Rankings
- Document/baseline selection rationale
- Select the best technologies for TFA investigations

2:30 - **BREAK**

2:45 - Develop Path Forward
- Validate parking-lot information sheets
- Determine actions and/or interfaces required to proceed

4:15 - Finish Session with a Round-Robin Closeout
- Last minute items
- Meeting utility

GUIDELINES AND EXPECTATIONS

- Opportunity is knocking!
  - Align TFA funded work to meet SST needs
- Need to know what SST technology needs are and when
  - Identify near term techniques already planned/confirmed
  - Identify/focus those additional technologies that may be needed (focus on areas of weakness and/or lack maturity)
- Will <u>not</u> attempt to change any near-term confirmations
- <u>Will</u> focus on 2003 - ? needs
- Open and honest communication
  - Active licensing: seek first to understand
- Wear two hats: you decide when
- Roles: facilitator and you
- Keys to success
  - Communication/teamwork
  - Strive only for win/win (SST & TFA)
  - Make a difference ☺

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