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USTID WASTE DISLODGING AND CONVEYANCE
FY 1993 TECHNOLOGY DEVELOPMENT SUMMARY REPORT

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AUTHOR'S NOTE

The purpose of this document is to describe the testing and conclusions that resulted from the FY 1993 waste dislodging and conveyance technology development testing. The final FY 1993 reports from the various waste dislodging and conveyance technology development tasks are attached to this document as appendices.

EXECUTIVE SUMMARY

The FY 1993 testing of candidate single-shell tank waste removal technologies resulted in the following conclusions:

1. Waterjet-based waste dislodging technology appears to be capable of meeting the waste retrieval rates required by EM-30 at Hanford (i.e., 30 gpm waste removed) for both sludge and saltcake wasteforms, although more development is required to verify this.
2. A commercially-available air conveyance system (modified for wet use) was found to be capable of transporting simulated sludge under prototypic flow conditions (i.e., full-scale retrieval rates through expected actual vertical and horizontal distances). This achievement provides confidence that a modified pneumatic conveyance system should be capable of meeting a part of EM-30's retrieval system needs.
3. A hydraulically-driven jet pump has been developed as a possible alternative waste conveyance system. Jet pump and pneumatic conveyance systems each offer certain processing advantages over the other, so the development of both systems should continue in parallel.
4. Shear cutters and abrasive waterjet cutting devices should be suitable for the removal of in-tank hardware, however more development work is needed to determine how to handle the cut pipe.
5. An improved understanding of the jet cutting of sludge- and saltcake-like materials is needed to improve the confidence in the waste simulants used for testing.

The achievements and conclusions from each of the waste dislodging and conveyance technology development tasks are presented below.

SOFT-WASTE (SLUDGE) DISLODGING TOOL (WHC)

- Demonstrated integrated retrieval system (dislodging tool and air conveyance system) using sludge simulant. Sludge simulant retrieval rates exceeding 95 gpm were measured (for 15 sec. test).
- Determined that minimal water addition is required to dislodge the sludge simulant and convey it through the air conveyance system.
- Established that an air conveyance system will handle wet, sticky materials (clay-based sludge simulants) while conveying the material vertically over 60 feet.

MEDIUM-PRESSURE SCARIFIER (UMR)

- Experimentally determined how jet cut depth in saltcake simulant depends on jet pressure, nozzle diameter, and traverse speed.
- Demonstrated that 10 ksi jets will effectively remove saltcake simulant. Further, demonstrated ability of integrated medium-pressure scarifier and jet pump to remove saltcake simulant without the net addition of water to the tank.
- Extrapolated test data to predict that a scarifier could remove at least 30 gpm of saltcake and/or sludge using 10 ksi jets at a waterjet flow rate of 40 gpm.
- Demonstrated ability of modified, commercially-available jet pump to convey simulated dislodged saltcake at the expected full-scale flow rates and pressures.

HIGH PRESSURE SCARIFIER AND PNEUMATIC CONVEYANCE (PNL/QUEST)

- Designed and constructed near full-scale waste conveyance test facility to acquire parametric data for 3-phase flow testing of simulant.
- Completed scaling analysis and test plan for planned FY 1994 waste conveyance experiments.
- Completed single-jet experiments designed to determine the interactions between jets and waste simulants. Major conclusions are:

Removal efficiency increases with hydraulic horsepower, and water efficiency increases with jet pressure. The maximum material removal rate is obtained using a larger diameter jet at a higher pressure for both the round and fan jets.

Fan jets appear more effective than round jets for dislodging either saltcake or sludge simulants regardless of jet incidence angle, pressure, or velocity.

- Conducted multiple-jet experiments to investigate dislodging with more than one jet. Major conclusions developed thus far are:

Fan/fan-jet combination is superior for sludge dislodging.

For multiple passes, the average volume of material removed per pass was larger with multiple passes than with a single pass over a new surface. Second layer removal is likely to produce greater volumetric removal rates than those obtained in the first layer removed. The round/fan-jet and round/round-jet combinations show promise with a dislodger configuration that incorporates secondary motion.

The fan/fan-jet combination may prove acceptable in a system that does not have a secondary motion and may also perform relatively well in the presence of mixed waste.

WATER CANNON (LLNL)

- Experimentally determined that varying the stand-off distance between 1" and 12" does not affect performance of the hydraulic impact end effector.
- Evaluated several removal patterns and the results indicate that the actual pattern is not as important as the spacing between firings in controlling the resulting fragment size. With a spacing between shots of less than two inches, the resulting fragments were all less than two inches.
- Enhanced the fracturing of the saltcake simulant significantly by increasing the pressure from 40 to 50 ksi. The increase in pressure increases the shock energy of the hydraulic impact.
- Demonstrated that the number and dimension of fragments can be controlled by varying the nozzle design, operating pressure, and standoff distance.

IN-TANK HARDWARE REMOVAL (SNL)

- Examined wide variety of potential technologies and determined shear cutters and abrasive waterjet to be best options.
- Demonstrated autonomous docking and cutting of steel pipes under robotic control using shear cutters.
- Determined that abrasive waterjet cutting is feasible within the positioning and stability limits of a robotic control system
- Determined that up to 8" pipe can likely be cut using shear cutters weighing less than 400 pounds. Cutting larger pipes (8"-12") will likely require a cutter weighing between 400 and 600 pounds.

CONTENTS

AUTHOR'S NOTE	iii
EXECUTIVE SUMMARY	v
1.0 INTRODUCTION	1
2.0 CONCLUSIONS AND RECOMMENDATIONS	2
3.0 FY 1993 TESTING AND CONCLUSIONS	7
3.1 SOFT WASTE DISLODGING UNIT (WHC)	7
3.2 MEDIUM-PRESSURE SHROUDED WATERJET EXTRACTOR (UMR)	9
3.3 HIGH-PRESSURE SCARIFIER AND PNEUMATIC CONVEYANCE (PNL/QUEST)	11
3.3.1 Scarifier Development	12
3.3.2 Pneumatic Conveyance Development	15
3.4 WASTE SIMULANT DEVELOPMENT	16
3.5 WATER CANNON DEVELOPMENT (LLNL)	19
3.6 IN-TANK HARDWARE REMOVAL END EFFECTOR DEVELOPMENT (SNL/SPEEDWAY HYDRAULICS/QUEST)	20
APPENDIX A: SINGLE-SHELL TANK SOFT WASTE DISLODGING AND CONVEYANCE SYSTEM DEVELOPMENT TEST FINAL REPORT (WHC-SD-WM-TRP-171, Rev. 0)	
APPENDIX B: DEVELOPMENT OF MULTI-FUNCTIONAL SCARIFIER DISLODGER WITH AN INTEGRAL PNEUMATIC CONVEYANCE RETRIEVAL SYSTEM FOR SINGLE-SHELL TANK REMEDIATION (PNL-8901)	
APPENDIX C: HYDRAULIC IMPACT END EFFECTOR FINAL TEST REPORT (UCRL-ID-116220)	
APPENDIX D: TECHNOLOGY DEVELOPMENT OF INTERNAL TANK HARDWARE END EFFECTORS (SAND 94-1579)	

1.0 INTRODUCTION

The Hanford single-shell tanks contain over 37 million gallons of radioactive waste generated as part of the production of nuclear materials for the nation's defense. The consistency of the waste varies from liquid, to paste-like sludge, to very hard, brittle saltcake. Removal of these wastes from single-shell tanks is necessary to minimize contamination of the soil surrounding the tanks that results when the tanks leak. Many of the tanks are either known or suspected to leak. Because of this problem, it is desirable that the technologies used to retrieve the waste from the leaking single-shell tanks be designed specifically to reduce the potential for leakage of waste. Waste retrieval methods used in the past require that large volumes of water be pumped into the tank and the resulting waste slurry pumped out. This technique cannot be used in the leaking single-shell tanks.

It is the goal of the Underground Storage Tank Integrated Demonstration (USTID) waste dislodging and conveyance development efforts to generate the data necessary to both allow potential retrieval system vendors to design a successful retrieval system and to provide EM-30 representatives with the data to select the most probably successful of the vendor-proposed retrieval systems. Extensive reviews were conducted of the available technologies that might be applied to single-shell tank waste retrieval. The most promising technologies were identified and, during FY 1993, a series of scoping tests were performed. The conclusions and recommendations drawn from this testing are provided in this report.

The purpose of this report is to provide an overview of the waste dislodging and conveyance testing conducted during FY 1993. Based on the testing, recommendations for future work were developed with input from those involved in the testing as well as EM-30 representatives. It is not the purpose of this report to replace the detailed reports prepared by the individual waste dislodging and conveyance technology tasks. For detailed information, the reader is referred to these individual reports included as appendices to this document.

2.0 CONCLUSIONS AND RECOMMENDATIONS

The FY 1993 testing of candidate waste dislodging and conveyance technologies has substantially advanced the understanding of the processes required to remove waste from tanks. Previous studies directed the focus of the FY 1993 efforts on waterjet-based waste dislodging systems for saltcake waste, which appears to present the greatest challenge for waste dislodging. During FY 1993, scoping tests were conducted to determine which of the candidate technologies are likely to be capable of meeting EM-30's waste retrieval needs at Hanford (e.g., average of 30 gpm waste removed for sludge and saltcake).

The FY 1993 work demonstrated that waterjet-based retrieval systems should meet EM-30's needs provided that certain operational constraints can be met. Further, preliminary examinations were conducted of two types of waste conveyance systems (jet pump and blower-powered conveyance systems) and both were found to offer certain advantages. Finally, the viability of shear cutters and abrasive waterjets for the removal in-tank hardware was demonstrated, and the ability of a hydraulic impact device (water cannon) to dislodge saltcake simulant was also shown.

Based on the University of Missouri-Rolla (UMR) and Pacific Northwest Laboratory (PNL)/Quest Integrated, Inc. (Quest) studies of the depth of waterjet cut into saltcake simulant as a function of jet pressure, nozzle diameter, and traverse speed, it appears likely that a waterjet-based retrieval system can be designed to meet the EM-30 target of 30 gpm average waste removal rate. The UMR data predict that a saltcake removal rate of 30 gpm could be attained using 10 ksi, 40 gpm waterjets. The PNL/Quest team is evaluating higher-pressure jets (about 50 ksi) and their data predict that the 30 gpm target can be met using 50 ksi jets at a flow rate of less than 40 gpm water (possibly as low as 5-10 gpm). It must be stressed that these predictions are based on preliminary data and may change as more data are generated.

As part of the development of the soft waste dislodging unit, Westinghouse Hanford Company (WHC) engineers utilized a blower-powered waste conveyance system modified to transport the dislodged sludge simulant. The

dislodged clay-based sludge simulant chunks were conveyed at prototypic flow rates through a 60-foot vertical rise as well as through a horizontal run to simulate the flow conditions expected during SST retrieval. Previous testing of this type of air conveyance system demonstrated that unless water was added along with the sludge simulant, the conveyance line would accumulate sludge simulant and plug.

The WHC team demonstrated the ability of their integrated soft waste dislodging unit and air conveyance system to mobilize and convey sludge simulant at approximately 95 gpm with a water flow rate of less than 7.5 gpm. These high retrieval rates were sustained for only about 15 seconds due to the small size of the test bed. Further testing is required to determine whether these high retrieval rates can be sustained for long-term, steady-state waste removal operations. During the testing, the conveyance line was observed to flex and jump as pieces of sludge simulant were sucked through. Quantifying the magnitude of the forces that might be applied to the robotic arm as a result of this conveyance line movement is a recommendation for future development work.

An alternative conveyance system for dislodged waste is being developed by the UMR team. This system utilizes a modified version of a commercially-available jet pump to provide the suction that lifts the dislodged waste from the tank. Once the dislodged waste is entrained in the air entering the jet pump, it passes only a short distance through the conveyance line before flowing through the jet pump throat. Several 10 ksi waterjets are focused through the jet pump throat, and these waterjets will cut up any pieces of sludge or saltcake large enough to become lodged in the pump throat. The resulting gas/slurry/solid mixture is pushed up through a 2-inch diameter conveyance line. The ability of this modified jet pump to produce the required pressure and flow rates was demonstrated by the UMR team in FY 1993. It is not yet known how the jet pump conveyance system compares to the blower-powered system in terms of entrained air flow rate or reaction forces on the robotic arm. The jet pump system offers the benefits of a small conveyance line (compared with 6" line required for blower system) and the avoidance of contaminated machinery (outside the tank); in the blower-powered system the

blower internals are likely to become contaminated from exposure to radioactive aerosols.

After an extensive review of the technologies available for the removal of in-tank hardware, researchers at Sandia National Laboratory (SNL) selected shear cutters and abrasive waterjet cutters as being most promising. The ability of shear cutters to cut steel pipes of small diameter while under robotic control was verified. It was determined that a shear cutter weighing between 400 and 600 pounds would likely be required to cut pipes larger than 8 inches in diameter. Because of the weight restrictions on the robotic arm, an alternative technology may be required to cut the larger-diameter pipes. The SNL/Speedway Hydraulics/Quest team investigated the potential of abrasive waterjets for the cutting of larger pipes. While considerably more development is needed, abrasive waterjets appear to be promising for this application.

Researchers at Lawrence Livermore National Laboratory (LLNL) worked with representatives from Quest to investigate the use of a pulsed high pressure waterjet to selectively remove saltcake waste from pieces of in-tank hardware. Known as the hydraulic impact end effector, or water cannon, the device directs a focused, pulsed beam of high pressure water onto the waste surface. The LLNL/Quest team found that the size and number of pieces of dislodged saltcake simulant could be controlled by varying nozzle design, water pressure, standoff distance, and the spacing of successive water pulses.

Because the near-term needs of the EM-30 retrieval program are focused on the retrieval of a tank that contains relatively little in-tank hardware (241-C-106), a programmatic decision was made to delay further development of the shear cutter, abrasive waterjet cutter, and the water cannon. These technologies will be needed for the retrieval of waste from tanks beyond C-106 (known as second-generation retrieval system deployment), but in preparation for C-106 waste retrieval the waste dislodging and conveyance development efforts have been directed toward providing EM-30 and potential vendors with the information needed to successfully design and operate the C-106 retrieval system. The development of the other waste dislodging and conveyance systems will continue as these efforts directly support C-106 retrieval.

The identification of the waste dislodging and conveyance issues to be examined in FY 1994 was a cooperative effort between EM-30 representatives and all of the researchers conducting FY 1994 work. In general, it was agreed that the development of both the UMR medium-pressure scarifier and the PNL/Quest high pressure scarifier should continue in parallel. Both systems offer certain advantages over the other and, based on the current data, both are likely to result in successful retrieval systems. It is likely that both medium- and high- pressure jets would be deployed in a single retrieval operation due to the advantages that each has in specific operational situations. In FY 1994, waste dislodging and conveyance will focus on the 7 major issues listed below.

- Consideration must be given to the strategy to be followed as the waste is removed from the tank. For example, should the waste level be lowered uniformly by a couple inches each pass, or should several feet of waste be removed from a given area before continuing to the next area? These types of issues have an impact on the allowable designs of the waste dislodging tools, and a profound impact on the designs of the sensors and control systems of the EM-30 manipulator system.
- What are the forces likely to be applied to the robotic arm and how will the arm's response affect the efficiency of the waste dislodging tool and conveyance system? Some of the most important data needed by the designers of the long reach arm are the dynamic and static loads the arm will be subjected to and what the arm's allowable deflection is in response to those loads. Some of the FY 1993 waste dislodging and conveyance development work has resulted in estimates for the dynamic and static loads imposed on the arm by the dislodging tools, but these data must be refined. More importantly, though, is the lack of data pertaining to the dynamic loads produced by the conveyance systems. The WHC team observed the 6-inch air conveyance line being flexed and jolted as pieces of dislodged sludge simulant were conveyed through the line. Judging by the severity of these jolts, it is suspected that the dynamic loads produced by the conveyance system might be at least as large as those produced by the waste dislodging tools.
- The effect of variations in standoff distance in the rate of waste removal must be quantified so that estimates for the required long reach arm stiffness can be made. If the waste dislodging tools can withstand positional oscillations with amplitudes of several inches without the loss of retrieval rate, then the long reach arm can be built to less stringent stiffness requirements than if positional stabilities on the order of ± 0.5 inches are required to maintain acceptable retrieval rates.
- Whether a uniform waste surface can be maintained must be examined. The action of the waterjets on the waste surface topography will be examined.

to determine whether it can be expected that the waste surface can be lowered uniformly and maintained flat. If not, waste retrieval tools must be designed that can avoid water loss as the result of the lack of a good seal against the waste surface.

- Some level of testing is required to determine whether the single-shell tank walls will sustain significant damage when impacted by waterjets of varying pressures (i.e., is a 10 ksi 10 gpm waterjet more or less damaging to a corroded tank wall than a 50 ksi 1 gpm waterjet?). A knowledge of the susceptibility of the tank walls to damage will also play a role in the selection of the strategy for waste removal.
- All aspects of the waste dislodging and conveyance system testing are heavily dependent on the quality of the wasteform simulants. Improvements to the waste simulants are currently limited by the lack of understanding of which physical properties of the waste provide a measure of the waste's resistance to cutting with a waterjet. FY 1994 testing will include an examination of the effects of varying various simulant physical properties in an effort to determine the functional dependencies. Once the most important physical properties are identified, simulant development efforts will be focused on obtaining measurements of these properties on waste samples and developing estimates where actual measurements cannot be made in a timely manner.
- Development of interface control drawings and functions and requirements documents will allow for the more efficient communication of the types of services that the waste dislodging and conveyance system will require (e.g., static and dynamic loading, space envelope, maintenance requirements, etc.). These data are needed to support the long reach arm procurement.

3.0 FY 1993 TESTING AND CONCLUSIONS

Brief descriptions of the FY 1993 accomplishments of each of the waste dislodging and conveyance technology development tasks are given in this section. More detailed information can be obtained from the year-end reports prepared by each of the development tasks, which are attached as appendices to this document.

3.1 SOFT WASTE DISLODGING UNIT (WHC)

This section summarizes the Westinghouse Hanford Company's testing program for soft waste dislodging and conveyance technology. This program was initiated to investigate methods of dislodging and conveying soft waste (i.e., tank sludge). The main focus was on using air jets, waterjets, and/or mechanical blades to dislodge the waste and air conveyance to convey the dislodged waste.

A development unit end effector was designed and fabricated for testing. This unit was mated with the modified air conveyance system. The development unit was capable of being configured in several ways. The development unit was also designed to allow key parameters to be varied, such as nozzle size, to determine their affect on waste dislodging.

The development unit was tested in many different configurations. The main configurations examined were the scarifier and the mechanical agitator. The scarifier uses air or waterjets to dislodge the soft waste. The mechanical agitator uses these jets and blades to dislodge the waste. The other parameters that were varied within those configurations were the radial blade/nozzle position, nozzle size, nozzle style, nozzle angle, dislodging media (air or water), dislodging media pressure, tool rotation speed, and tool translation speed.

The engineering data gathered from these tests included tool torque, tool translation loads, waste removal rate, and volumetric effluent dilution ratio. These data were used to evaluate the performance of the development unit. These data will also be used as information for specifying a long reach manipulator.

The development unit and air conveyance system were tested using two clay-based sludge simulants. The clays used were bentonite and kaolin. Tests were performed on flat, homogeneous surfaces, uneven surfaces, and using a heterogeneous waste form (i.e., kaolin sludge simulant containing chunks of hard material to simulate pieces of dislodged salt cake). Tests of the system's response to off-normal conditions were also performed.

The main performance indicators were waste removal rate (target of 30 gallons per minute), and volumetric effluent dilution ratio (waste volume after retrieval:waste removed, target of <5:1). The testing showed that the development unit, under certain configurations, can meet both criteria. The waste removal rate peaked at 100 gallons per minute, and the dilution ratio was as low as 1.06:1.

The testing program produced valuable operational performance data for EM-30. Some of the highlights are as follows:

The testing determined which parameters affect the waste dislodging and conveyance processes. Sludge retrieval rates in excess of 95 gpm were demonstrated. The EM-30 minimum target rate is 30 gpm average. This technology was not expected to be able to retrieve the waste at the target rate. This testing program has shown that the target retrieval rate can be achieved and surpassed.

The testing also demonstrated that minimal water addition is required to dislodge and convey waste. Water addition in the tank is a safety issue. Very small amounts of residual water are left in the tank in some tool configurations.

Robotic deployment of an end effector in sludge simulant was also demonstrated.

This testing program has produced 3 invention disclosures. Two address the development unit configurations and the other addresses the water spray ring for the air conveyance system.

The testing demonstrated that a modified commercially-available, dry materials air conveyance system will handle wet materials and convey waste simulant 60 feet vertically.

Based on the knowledge gained during this testing program, recommendations for future testing are:

Investigation of a slurry retrieval method. This involves using waterjets to slurry the waste prior to conveyance rather than cutting the waste in chunks.

Continued development of water as the dislodging medium rather than air.

Investigation of this technology to develop a universal dislodging tool that would work on all waste types.

3.2 MEDIUM-PRESSURE SHROUDED WATERJET EXTRACTOR (UMR)

This section describes the work done by the University of Missouri-Rolla (UMR) team led by Dr. David Summers for the development of a medium-pressure (5,000-15,000 psi) scarifier and a jet pump capable of conveying the dislodged waste material. The medium-pressure scarifier concept is similar to the high pressure scarifier being developed jointly by PNL and Quest. The primary difference lies in the selection of the jet pressure and nozzle diameters. The medium-pressure scarifier uses jet pressures on the order of 10 ksi while the high pressure scarifier uses about 50 ksi. Both systems will likely be operated similarly. In addition to the medium-pressure scarifier, UMR is developing a jet pump capable of conveying the dislodged waste material at the required retrieval rates.

In the confined sluicing concept, a series of high pressure waterjets are used to cut into, and break out, the material in the tank. The cutting head operates within a surrounding shroud, with the shroud connected to the intake line feeding a jet pump. Thus, as the waterjets cut and dislodge material, the excavated material is immediately aspirated into the pump intake, and pumped out of the tank. In this manner there is no net flow of water into the tank, and thus the risk of leakage of material from the tank is minimized.

UMR scarifier development work in FY 1993 focused on demonstrating the applicability of the medium-pressure confined sluicing concept to the dislodging of simulated waste forms. This experimental work has demonstrated that waterjets at about 10 ksi pressure do effectively excavate both saltcake and sludge simulants. The depth to which the waterjets cut into the saltcake simulant was found to be directly proportional, approximately, to the jet pressure, nozzle diameter to the $3/2$ power, and traverse velocity to the $-1/3$ power. Based on these data, it was projected that a cutting head supplied

with 40 gpm of 10 ksi water should be able to meet the target waste dislodging rate of 30 gpm. Such a device would cut a 20-inch wide, 1-inch deep swath through the waste when moved across the waste surface at about 30 ft/min.

A commercially-available jet pump was modified to improve its performance and then used to demonstrate its ability to pump 80 gpm (30 gpm simulated waste, 40 gpm cutting water, and 10 gpm jet pump water) through a vertical lift of 60 feet. This shows that the jet pump is capable of providing the required flow rates and pressures to effectively convey the dislodged waste particles. The use of the jet pump is not dependent on the type of end effector used. The jet pump can be used with any type of waste dislodging unit that is capable of producing pieces of dislodged waste in the size range appropriate for the jet pump. A jet pump conveyance system could be used in place of the air conveyance system. During FY 1993, a demonstration was conducted in which the jet pump was used to convey the simulant dislodged by the medium-pressure scarifier. This combination could extract waste (saltcake and sludge simulants) from a tank without any net water flow into the tank.

Development efforts have been focused on the medium-pressure scarifier, with less effort being applied to the jet pump development. FY 1994 work will include characterization of the jet pump concept including quantification of the reaction forces produced in the conveyance line and the air flow rates the jet pump is capable of sustaining.

The medium-pressure scarifier testing has also revealed that the saltcake simulant will not break easily under the forces generated by the waterjets alone if the distance between adjacent jet cuts is 0.5 inches or more. This is important because it establishes the maximum allowable distance between jet passes. This distance will have a significant influence on the design of a prototypic scarifier, so it must be determined whether this observation is expected to apply to actual saltcake in addition to the simulants. Because this distance between cuts is thought to be a function of primarily the tensile strength of the saltcake simulant, the simulant development task will investigate methods for estimating the tensile strength of SST saltcake and comparing it with that of the saltcake simulants.

The potential of using fan jets instead of round jets in the medium-pressure scarifier was investigated during FY 1993. It was determined that the fan jets do not dislodge the saltcake simulant as efficiently as the round jets. When using a fan jet, the saltcake is fractured into many small (millimeter and smaller) pieces. The round jets can be operated such that centimeter-sized pieces of simulant are generated. Thus, the round jets will give much higher waste dislodging rates for a given jet horsepower.

3.3 HIGH-PRESSURE SCARIFIER AND PNEUMATIC CONVEYANCE (PNL/QUEST)

The objective of the high-pressure scarifier/conveyance project is to develop design specifications for a hydraulic dislodger (scarifier) coupled with a pneumatic conveyance system that minimizes water accumulation during retrieval of salt cake, sludge, and viscous fluids from Hanford single-shell tanks. The development will be accomplished via a multi-year analytical and experimental investigation consisting of six experimental phases. The initial four phases are defined based on simulant properties.

The objectives of the scarifier/conveyance work in FY 1993 were to initiate experiments within the first phase: Phase 1: Conduct ideal system performance evaluation with homogeneous simulants with no surface contour. This was divided into two parts: 1A: Separate effects experiments to optimize scarifier and conveyance system and 1B: Integrated experiments with a combined scarifier/pneumatic conveyance system.

The scarifier aspect of this work focused on conducting scarifier separate effects experiments: 1) to investigate single jet interaction with the salt cake and sludge simulants, 2) to investigate multiple jet interaction, and 3) to investigate multiple jet secondary motion. These experiments were planned by PNL and Quest and conducted at Quest.

The pneumatic conveyance aspect of this work focused on development of the scaling methodology for pneumatic conveyance, the test plan for the pneumatic conveyance separate effects experiments, and test fixture in which to conduct the separate pneumatic conveyance and integrated scarifier/conveyance experiments.

3.3.1. Scarifier Development

The scarifier subcontract with Quest was approved in January 1993. Since then, Quest has developed test fixtures and conducted experimental investigations of the interactions between the saltcake and sludge simulants.

Single Jet Separate Effects Experiments: The objective of the single jet separate effects experiments was to investigate separately parameters that affect jet performance: jet diameter, jet angle from vertical, jet shape, traverse velocity, water pressure, and simulant waste form. Based on these six primary parameters, a factorial experiment was designed. The experiment include a 1/4 replicate of 2^6 factorial design (16 tests). In this experiment the 6 main effects are free of two-way interactions.

The single-jet experimental results show that:

- Removal efficiency increased with hydraulic horsepower, and water efficiency increased with jet pressure. The maximum material removal rate was obtained with the larger jet at the higher pressure for both the round and fan jets.
- Fan jets appear more effective than round jets for dislodging either simulant, at any combination of angle, pressure, and velocity.

Salt-Cake Simulant Tests

The salt-cake simulant reacted differently to the round and fan jets. Round-jet orifices focus individual water particles into coherent high-velocity streams characterized by specific energy densities much higher than with the fan jets.

Round Jet Results

- Round jets cut clean and narrow kerfs into the simulant, to a depth approximately proportional to hydraulic horsepower (the square of the orifice diameter), and inversely proportional to effective traverse speed, a phenomena commonly found in liquid-jet cutting.
- Kerf widths were approximately 4 times the jet diameter.
- Erosion was the primary material removal mechanism, with virtually no secondary fracturing or material dislodging which could be attributed to the jet pass.

- Removed particles were observed to be fines on the order of 0.025 inches in diameter and smaller.
- Volumetric removal efficiency was relatively low for round-jet fracture of salt cake. When the volumetric removal efficiency is divided by the hydraulic horsepower, the results are similar for all test conditions. This is attributed to the dominance of an erosion removal mechanism.
- The maximum water volume efficiency occurs at the highest jet pressure. This is the effect of the hydraulic horsepower per unit area of the waterjet increasing with pressure.

Fan Jet Results

- Two mechanisms dominated fan jet removal: erosion and solid fracture.
- Primary erosion produced dislodged fines of the same size scale as those under the influence of the round jet. The fan jet preferentially erodes the surface in response to local small-scale variations in salt-cake properties. This erosion process produces a non-uniform rough surface. The varying velocity vector components across the fan result in a randomized jet/surface reflection which effectively fractures material off the roughened surface and increases the volumetric efficiency of this jet shape.
- Material removal rate was higher with the fan jets than the corresponding round jets. This was the result of the secondary fracture mechanism, which contributed to total material dislodged.

Sludge Simulant Results

The sludge responded differently under the influence of the round and fan jets.

Round Jet Results

- The round jet sliced cleanly through the sludge simulant which slumped under its own weight behind the jet to close the kerf below approximately 2-inch depth. The larger-diameter round jet pierced to a depth of at least 10 inches in the sludge, but had lost most of its energy at that depth.
- The sludge was not displaced appreciably by either of the round jets; it tended rather to absorb the jet water and liquefy.

Fan Jet Results

- Fan jets were effective in dislodging sludge.
- Sludge responded to the fan jets more in terms of bulk displacement than erosion. The distributed jet pressure appeared to push, or

shape, a trench through the sludge with a size proportional to the swept area within the fan.

- The larger fan jet cleared sludge to a distance of approximately 5 inches in front of the nozzle.
- The sludge displaced by the fan jets tended to be lifted or rolled above the surface--creating ribbons of sludge, or be pushed in front of the jet thus forcing a mound of otherwise undisturbed neighboring sludge to rise from the surface.
- Removal efficiency was higher at the lower traverse speeds. Lower traverse speeds give the jet a longer effective jet dwell, and the opportunity to remove a greater material mass. Also the effective stand-off distance increases as material is removed. If removal efficiency increases as a function of stand-off distance, the overall efficiency can increase with decreasing traverse speed.

Multiple-Jet Experiments:

The objective of the multiple jet experiments is to explore the interactions between jets. Interaction effects between multiple jets are anticipated to result in removal efficiencies greater than the simple sum of the individual jets. The parameters that were investigated included nozzle stand-off distance, axial and radial angle of the jet relative to the work piece, nozzle type, and spacing between the nozzles.

The multiple-jet experiments are in progress. Two outcomes are desired: 1) to produce the required particle size distribution and 2) to direct dislodged waste upward and into the transport system entrance.

Sludge Simulant Results

- Fan/fan-jet combination was judged to be superior for sludge dislodging.

Salt Cake Simulant

- For multiple passes, the average volume of material removed per pass was larger with multiple passes than with a single pass over a new surface. Second layer removal, at a lower z-axis position in the simulant, is likely to produce greater volumetric removal rates than those obtained in the first layer removed.
- In the round/fan-jet combination, kerf depth progressively deepened with each successive pass. The kerf stabilized at a limiting value.
- The round jet cuts a narrow deep kerf, while the fan jet cuts a relatively wide and shallow kerf. When the round/fan-jet

combination is used and multiple passes are incorporated, the round-jet separates thin webs of material from the simulant and the fan jet follows, pulverizing the thin web.

- The round/fan-jet combination shows promise with a dislodger configuration that incorporates secondary motion.
- The round/round-jet combination appears to remove large amounts of material due to the greater power intensity. The jets cut an hourglass shaped kerf.
- The round/round-jet kerf shape lends itself to a secondary motion device.
- The fan/fan-jet combination cuts a relatively wide and shallow kerf.
- The fan/fan-jet combination may prove acceptable in a system that does not have a secondary motion and may also perform relatively well in the presence of mixed waste.

Multiple-jet experimental data is still being analyzed to determine which combinations should be investigated with secondary motion. Several types of secondary motion can be implemented into a scarifier: rotary motion, oscillatory motion, or multiple stationary jets that fire linearly. The secondary motion that creates the most efficient motion may not turn out to be rotary motion. A reciprocating linear motion has an advantage in the fact that none of the operating time is spent waiting for the jet to return to the location of the new material. The effect of traverse velocity will also be investigated during the secondary motion experiments.

3.3.2 Pneumatic Conveyance Development

The initial design for the scarifier/conveyance system was to retrieve waste at a rate of 7 to 15 gpm. There is also benefit to increase this retrieval rate to 30 or 60 gpm.

Scaling Methodology: To allow the effect of varying transport line diameter to be investigated a scaling methodology has been developed. A dimensional analysis was conducted to quantify the effects of increasing retrieval rate and pipe diameter. The dimensional analysis showed that the ratio of mass flow rate of particulate to the mass flow rate of gas is a function of seven parameters.

The effect of pipe diameter appears in the Reynolds number and the Stokes number. Scaling to larger pipe diameters would affect these two variables. One would not expect that a slightly higher Reynolds number would have a significant effect. A larger Stokes number would lead to a longer acceleration length which would be significant if the acceleration distance is comparable to the pipe length.

Test Plan: The pneumatic transport test plan focuses on providing mechanistic performance data to develop performance correlations for retrieval. Pneumatic transport usually concerns the transport of dry solids in air. The transport associated with single-shell tank retrieval will involve transport of wet material. The waste is wet and cutting liquid from the scarifier will further lubricate the waste^a. A test plan was developed to investigate transport of dry and wet wastes to investigate the effects of particle diameter, solids loading, air flow rate, and liquid addition for the two simulant types.

Pneumatic Conveyance Test Fixture: A pneumatic conveyance test fixture was designed and is under construction in the PNL 336 Building at Hanford. The test fixture is instrumented to develop mechanistic pressure drop and transport data for waste transport during both pneumatic conveyance separate effects experiments and when the system is integrated with the scarifier. The test fixture will permit tests at two pipe diameters: 3 inch and 4 inch. Initial tests will be conducted over a conveyance length of 20 feet. In its current location, the system can be lengthened to prototypic length of 60 feet by addition of pipe segments into an existing pit in the building. These experiments will be conducted in FY 1994.

3.4 WASTE SIMULANT DEVELOPMENT

Efforts in FY 1993 were concentrated on the development of simulated saltcake for use by the dislodging and conveyance technology development tasks. Earlier development of a sludge simulant and subsequent use by one of

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- (a) Westinghouse Hanford Company Soft Waste Dislodging Investigations showed that transport is enhanced when a small amount of water sprayed into the conveyance inlet is used to lubricate the conveyance line.

the tasks beginning in FY 1992 had established the kaolin clay/water mixture as the reference sludge simulant.

At the beginning of FY 1993 the principal investigators for the technology development tasks were contacted and asked to provide input regarding the role of simulated wastes during the course of their FY 1993 testing efforts. Specifically, they were requested to outline the types of tests to be conducted, and to describe what they felt were the critical parameters of the waste simulants that would challenge the performance of their particular waste dislodging and/or conveyance technology. A summary of these discussions was prepared and submitted as a milestone report in November 1992.

From discussions with these other tasks, it was generally agreed that the critical properties of the saltcake affecting retrieval would likely be compressive strength and shear strength. For sludges the principal properties were thought to be shear strength and cohesiveness. Density of both materials would affect performance of the waste conveyance system, but did not seem to be a significant concern since the simulants would likely be in an appropriate range compared with actual waste.

Realistic, yet conservative, target values for saltcake simulant strength properties have been developed by characterizing chemically-similar saltcake simulants. Although chemically similar, these simulants are difficult to prepare and chemically hazardous, so they are not suitable as simulants for the waste dislodging and conveyance testing tasks. The target compressive strength and shear strength were measured on these hazardous saltcake samples. The target compressive strength for saltcake was established at -4000 psi, and the target shear strength was set at -800 psi.

A saltcake simulant composed of "fine" particle size langbeinite fertilizer (one trade name is "sulfur-k-mag") mixed with 14 wt% water, compacted well into molds, covered, and cured at ambient conditions for at least one week should have -3000-4000 psi compressive strength and -700-800 psi shear strength.

Data are available for shear strength of tank sludge samples. It is recognized that extracting and homogenizing the core sample may disturb the

structure of the solids and give a lower shear strength reading than would be measured in situ on undisturbed material. However, lacking in situ measurements in actual waste to use as a basis for sludge properties, a target shear strength for the sludge waste type of 50,000 dynes/cm² has been selected. The sludge cohesiveness was simulated by incorporating qualitative information from core sample analyses (e.g., the sludge was "sticky" with a consistency of "peanut butter").

Kaolin clay mixed with water (2/3 kaolin:1/3 water by weight) gives a shear strength measured at up to ~49,000 dynes/cm². The kaolin clay mixtures do not require any cure time, unlike the saltcake, before testing.

Subsequent discussions with waste dislodging and conveyance task principal investigators indicates that other properties of the simulants not previously recognized may be important to the performance of their respective technologies (e.g. the low-intermediate pressure waterjet cutting being evaluated at UMR may be affected by the tensile strength of the saltcake, and possibly other physical properties, in addition to the compressive and shear strengths). Only those properties of the sludge and saltcake simulants mentioned in this discussion have been considered to date. Future simulant development efforts will need to adjust simulant compositions and/or preparation procedures to incorporate other physical properties of the wastes as they are identified as being critical to the performance of the dislodging and conveyance technologies.

In view of this iterative process of developing physical simulants, other analytical techniques are being considered to better characterize the simulants. A texture analyzer^b is one tool to be evaluated that may provide a more comprehensive set of physical properties of the waste simulants. A texture analyzer system has been located, and is being set up for this evaluation.

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- (b) A Texture Technologies Corp. Model TA.XT2 texture analyzer has been acquired for testing. This device measures the force required to push any of several differently-shaped probes into a paste-like material at a selected rate. The force required to extract the probe is also measured. In many respects, the texture analyzer is similar to a penetrometer.

3.5 WATER CANNON DEVELOPMENT (LLNL)

In FY 1992, the hydraulic impact end effector (water cannon or rubblizer) was successfully demonstrated as a tool capable of fracturing hard salt cake. However, the 1992 device tended to drill holes in the salt cake simulant rather than produce small fragments. The objective of the FY 1993 performance testing program was to enhance the tool's removal rate.

The ability of the water cannon to fracture the salt cake simulants was significantly enhanced by increasing the pressure from 40 to 50 ksi. The increase in pressure increases the shock energy of the hydraulic impact. The energy per unit volume of the tool is increased at higher pressures. The primary effort was to increase the quantity and decrease the size of the resulting fragments. The geometry of the tool outlet was evaluated to direct the energy more efficiently for spalling action. Various outlet configurations were tested for their effect on controlling the fracture patterns. Shock energy can be raised by increasing the internal volume of the end effector. This approach may be effective if combined with containment of the fluid flow. The containment serves to resist fluid outflow and thus increases the pressure within the hole. Addition of a seal between the tool outlet and the waste surface will be evaluated and tested.

LLNL completed the final approval of the Safety Note and the Operational Safety Procedure. Restrained, one cubic foot simulant samples were then cast and tested. These restrained samples were cast to evaluate the edge effects and simulate firing at large monoliths. Last year's testing and this year's testing at Quest evaluated samples with free surfaces. The pattern testing has been evaluated to determine the effect, if any, on material removal rates. It was determined that the overall pattern was not as critical as the pattern of successive shots. The fragment size was less than two inches when the spacing between shots was two inches. Impaction of the steel casing in line with the sample edge resulted in no fracturing or change to the waste simulant surface. This test implies that there is little danger of fracturing the surrounding concrete tank lining.

Quest has completed required upgrades and maintenance on their 55 ksi tool. The preparation of 24 one cubic foot, two 2000 pound and one 8000 pound

samples has been completed. Quest has completed testing using the standard nozzle design at both 40 and 55 ksi. Three nozzle designs have been fabricated and tested. These three designs were a divergent, a convergent, and a three-hole nozzle. Testing has shown that the converging nozzle appears to show promise in the area of spalled off materials. This nozzle produced several fragments and larger spalled areas than the other nozzles. The three hole nozzle appears to perform well for fragmenting the salt cake. This nozzle split two of the test samples completely in half. Additional work included the design and manufacture of the nozzle seal. Testing of this seal is underway.

3.6 IN-TANK HARDWARE REMOVAL END EFFECTOR DEVELOPMENT (SNL/SPEEDWAY HYDRAULICS/QUEST)

Robotics technology is being developed to provide internal tank hardware (ITH) removal to facilitate removing high-level radioactive waste located in the single-shell storage tanks. Several different commercial cutting technologies were investigated, such as scissors shears, plunge shears, hacksaws, circular saws, circular pipe cutters, band saws, abrasive waterjets, lasers, and plasma cutters. Two cutting methods were selected based on environmental operating conditions and robotic deployment requirements. They are the plunge shear cutter and the abrasive waterjet. Sandia teamed with industry (Speedway Hydraulics and Quest) to investigate the potential for robotic deployment of these two cutting technologies for in-tank hardware removal.

Speedway Hydraulics designed a commercial plunge shear cutter for rescue applications involving automobile accidents. This manually-controlled hydraulic cutter can cut 2-inch schedule-40 steel pipe in a single blade pass. It cuts by concentrating the hydraulic pressure at the tip of a tool steel blade that plunges through the pipe. After the blade pierces through the object, the cutting area remains nearly constant as the blade finishes the cut. This cutting method results in a lightweight tool. This cutter only weighs 28 pounds. Sandia teamed with Speedway Hydraulics to modify this current 2-inch cutter and design a larger 4-inch cutter for robotic deployment. SNL integrated the necessary operating sensors and docking

sensors for autonomous docking and cutting under Robotic control. The deployed weight of the 2-inch cutter is 45 pounds and the 4-inch cutter is 95 pounds. The devices successfully demonstrated autonomous docking and cutting under robotic control using a Titan II robot.

Sandia and Speedway Hydraulics conducted experimental tests using a large breadboard cutter to investigate the feasibility of designing a larger plunge shear cutter to cut pipe up to 12-inches in diameter. This study examined various design parameters to optimize the cutting force and reaction loads on the arm and tank. A curved cutting foot provided the best results. The results from this study and the small plunge cutter demonstrations indicate cutting pipe up to 4-inches is very feasible; cutting pipe up to 8-inches is feasible; and cutting pipe between 8 and 12 inches is more difficult due to weight constraints. A large 12-inch pipe cutter could weigh between 400 and 600 pounds.

Sandia conducted a survey of waterjet technology to determine current commercial capabilities of robotically deploying an abrasive waterjet. The study indicated that several companies can provide an abrasive waterjet system consisting of a power supply, tubing or hoses, and a nozzle to be interfaced with a manipulator. Only Quest provided a high pressure seal technology for use in their Intelligent Nozzle System. This technology provides a precision quick-change of abrasive waterjet nozzle cartridges within the tank environment when they wear out. This is a very desirable feature for robotic deployment.

Along with Quest, Sandia investigated the feasibility of deploying an abrasive waterjet system under robotic control. Quest fabricated a mass mockup of an abrasive waterjet. Sandia integrated this mass mockup with a Titan II robot to examine the amount of jitter that resulted as the robot moved the jet along a typical cutting path. The design team also developed a concept for adapting the abrasive waterjet services to a robotic arm. The amount of jitter measured in this system was 0.062-inch total displacement shaking at 3 hz frequency. Using these data, Quest conducted an experiment to evaluate the cutting efficiency of an abrasive waterjet when subjected to this type of jitter. Based on initial testing, abrasive waterjet cutting of in-tank hardware is feasible within the expected limits of robotic control,

although the efficiency is reduced which results in longer cutting times. If the robot cannot provide sufficient motion within the jitter requirements, then the abrasive waterjet cutter will require an independent motion supply while the robot arm is held stationary.

Several unresolved issues require further investigation. The method of handling the cut piece during a cutting operation depends upon the philosophy of the arm operation. Can the in-tank hardware end effector let the piece fall or does it have to hold on to it after cutting? Holding the cut piece will result in a heavier, more complex end effector. How to determine when an abrasive waterjet cutter has cut through the object is another problem. This information must be supplied to the control software in order to provide any efficiency at all to the abrasive waterjet cutting operation. Also the abrasive waterjet cutter should be deployed under robotic control to verify system performance as predicted from the component jitter testing.

APPENDIX A

SINGLE-SHELL TANK SOFT WASTE DISLODGING AND
CONVEYANCE SYSTEM DEVELOPMENT TEST FINAL REPORT
(WHC-SD-WM-TRP-171, Rev. 0)

J. F. Thompson
G. D. Thompson
A. F. Wellner

Westinghouse Hanford Company

APPENDIX B

DEVELOPMENT OF A MULTI-FUNCTIONAL SCARIFIER DISLODGER
WITH AN INTEGRAL PNEUMATIC CONVEYANCE RETRIEVAL SYSTEM
FOR SINGLE-SHELL TANK REMEDIATION (PNL-8901)

PNL

J. A. Bamberger
M. A. McKinnon

Quest Integrated, Inc.

D. A. Alberts
D. E. Steele

Washington State University

C. T. Crowe

APPENDIX C

HYDRAULIC IMPACT END EFFECTOR
FINAL TEST REPORT L-16930-1
(UCRL-ID-116220)

S. Couture
E. Grasz

Lawrence Livermore National Laboratory

APPENDIX D

TECHNOLOGY DEVELOPMENT OF
INTERNAL TANK HARDWARE END EFFECTORS
(SAND 94-1579)

F. J. Oppel

Sandia National Laboratories

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