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STRATEGY PLAN

STRATEGY TO DEVELOP AND TEST
A MULTI-FUNCTION SCARIFIER
END EFFECTOR WITH AN INTEGRAL
CONVEYANCE SYSTEM FOR WASTE
TANK REMEDIATION

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SUMMARY

This strategy plan describes a coupled analytical/experimental approach to develop a multi-functional scarifier end effector coupled with a pneumatic conveyance system to retrieve wastes from underground storage tanks. The scarifier uses ultra-high-pressure water jets to rubblize and entrain waste forms such as salt cake, sludge, and viscous liquid that can be transported pneumatically.

The three waste types (hard, brittle, salt cake, viscous liquid, and deformable sludge) present increasingly complex challenges for scarification and pneumatic conveyance. Salt cake is anticipated to be the easiest to retrieve because

- 1) a theoretical model of hydraulic rock fracture can be applied to estimate jet performance to fracture salt cake,
- 2) gas-solids transport correlations can be used to predict pneumatic transport.

Deformable sludge is anticipated to be the most difficult to retrieve: no theories, correlations, or data exist to predict this performance. However order-of-magnitude gas-solid correlations indicate particulate wastes of prototypic density can be transported to a height of 20 m within allowable pressure limits provided that the volume fraction of the gaseous phase is kept above 95%.

Viscous liquid is anticipated to be of intermediate complexity to retrieve.

Phenomena that are expected to affect system performance are ranked. Experiments and analyses necessary to evaluate the effects of these phenomena are proposed. Subsequent strategies for experiment test plans, system deployment, and operation and control will need to be developed.

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NOMENCLATURE

A	cross sectional area
c	intrinsic velocity
c_f	skin friction coefficient
CS	cutting surface
C_s	solids spatial concentration by mass
C_D	drag coefficient
d	depth of jet stream
D_p	particle diameter
d_0	nozzle diameter
DOE	U.S. Department of Energy
DSS	double-shell slurry
DST	double-shell tank
D_t	inside diameter of pipe
f_g	gas friction factor
f_s	solids friction factor
g	gravitational acceleration, grain diameter of rock
ΔH	elevation change
h	height of jet from surface, terminal depth of cut
$h_{\max}$	maximum depth of cut
HEPA	high-efficiency particulate air
k	consistency index; permeability of rock
L	acceleration length
l	streamwise separation between fully exposed grains
m_g	mass flow rate of gaseous phase

m_s	mass flow rate of solids phase
n	normal coordinate
ΔP_a	pressure drop due to acceleration
ΔP_f	pressure drop due to friction
ΔP_{fg}	pressure drop due to friction of gas
ΔP_{fs}	pressure drop due to friction of solids
ΔP_g	pressure drop due to gravity
ΔP_t	total pressure drop
p	pore pressure
p_a	atmospheric pressure
p_s	pressure at cutting surface
p_v	vapor pressure of water
P_0	jet total pressure; pore pressure
PNL	Pacific Northwest Laboratory
PUREX	plutonium and uranium extraction
Q	volumetric flow rate
QUEST	Quest Integrated, Inc.
R	radius of curvature
REDOX	reduction oxidation
S	loading, ratio of mass flow of solids phase to the gaseous phase
s	arc length, streamwise coordinate
SST	single-shell tank
TRU	tranuranic
u	water velocity
u_1	water axial velocity component
U_{ch}, U_{salt}, U_x	critical velocity, minimum transport velocity, choking velocity

u_o	droplet axial velocity component
u_g	actual velocity of gaseous phase, gas velocity in axial direction
U_g	superficial gaseous phase velocity
U_0	nozzle exit velocity
u_s	actual velocity of solids phase
U_s	superficial velocity of solids phase
u_T	terminal velocity of a single particle
UST	underground storage tank
v	velocity
v_l	water radial velocity component
v_d	droplet radial velocity component
v_g	gas radial velocity component
WD	interface between wet and dry rock
x	abscissa
y	ordinate

Greek Letters

ϵ	volume fraction of gaseous phase
ϵ_{ch}	volume fraction of gaseous phase at choking
θ	local angle of cut with respect to the horizontal
θ_0	impingement angle
μ_r	rock coefficient of internal friction
μ_w	coefficient of Coulomb friction
ρ	density of water
ρ_g	density of gaseous phase
ρ_{mix}	density of gas-solids mixture
ρ_s	density of solids phase

τ	interfacial shear stress
τ_0	shear strength
τ_y	yield stress

1.0 INTRODUCTION

This report presents a strategy to develop a low-flow-rate, hydraulic end effector coupled with a pneumatic conveyance system to be used to dislodge and retrieve radioactive waste from single-shell tanks (SST) such as those at Hanford. The strategy outlined in this document is the first of a series of strategies that must be developed for the successful deployment of this retrieval concept. Subsequent strategies for experiment test plans, deployment, operation and control, etc. based on the results of the efforts outlined in this document will need to be developed. The end effector uses a high-pressure water jet^(a) operated to dislodge a variety of waste types (hard, brittle solids such as salt cake, deformable sludge, and viscous liquids). The pneumatic conveyance system is configured to remove the dislodged waste and the liquid added by the jet, thereby limiting the accumulation of additional liquid in the tank. The hydraulic end effector is termed a scarifier.

This strategy plan was developed to 1) summarize the knowledge base associated with the design and operation of scarifiers and pneumatic conveyance systems configured for this application, 2) analyze the theory that supports the technology to assess whether the operating regime necessary for successful operation can be sustained, and 3) recommend an approach to guide future investigations. The results of these assessments are summarized in Section 2.0. Components of this hydraulic retrieval system and the physics that describe their operation are analyzed in Section 3.0. Experimental investigations necessary to define end effector and conveyance system performance through separate effects experiments and integrated experiments are prioritized in Section 4.0. The properties of the waste types and proposed simulants are defined in Appendix A. In the remainder of Section

(a) A high-pressure water jet is formed by forcing ultra-high-pressure (P_0) water through a fine diameter orifice (d_0) at a very low flow rate (Q) where

$$\begin{aligned} P_0 &= \sim 1 \times 10^8 \text{ to } 7 \times 10^8 \text{ Pa } (\sim 2 \times 10^4 \text{ to } 10^5 \text{ psi}) \\ d_0 &= \sim 0.008 \text{ to } 0.05 \text{ cm } (\sim 0.003 \text{ to } 0.02 \text{ in.}) \\ Q &= \sim 2 \times 10^{-5} \text{ to } 1 \times 10^{-4} \text{ m}^3/\text{s } (\sim 0.25 \text{ to } 2 \text{ gpm}). \end{aligned}$$

1.0, background information (Section 1.1), objectives (Section 1.2) and scope of the proposed effort (Section 1.3) are presented.

1.1 BACKGROUND

To understand the operating regime for the proposed scarifier/conveyance system, a summary of underground storage tanks (UST) physical characteristics, the currently planned remediation strategy, and retrieval options follows.

1.1.1 Underground Storage Tank Waste Sites

Across the U.S. Department of Energy (DOE) complex, over 200 underground storage tanks have been used to capture, process, and store radioactive waste from weapons materials production processes. To date, very little of this waste has been treated and disposed; therefore, a large inventory currently exists.

At the Hanford site most of the underground storage tanks have a capacity between 1893 and 3785 m³ (5×10^5 and 1×10^6 gal.). The tanks are 22.9 m (75 ft) in diameter and range from 9.1 to 16.8 m (30 to 55 ft) high. Each of the Hanford 22.9-m-dia. (75-ft) tanks contain at least one 1.1-m-dia. (42 in.) dome penetration (riser or manhole) that could be used for waste retrieval.^(a)

The Hanford tanks contain highly radioactive sludges, salt cake, and liquid. The major chemical constituents are nitrate and nitrite salts, hydrated metal oxides, phosphate precipitates, transuranics, and isotopes of strontium, iodine, and cesium. The environment within the tanks is basic and chemically corrosive.

1.1.2 Remediation Strategy

The current Hanford tank waste remediation strategy addresses both safety remediation and permanent disposal. The permanent disposal option involves concentrating the radioactivity into feed stock for a glass plant and incorporating the residuals in a feed stock for a plant to make a low-level

(a) Tank penetration dimensions and locations are summarized in Krieg et al. (1990).

waste form. This low-level waste form is presently designated as grout, although alternatives are being considered. The concentrated feed stream to the glass plant must be compatible with glass acceptance limits.

The only practiced method for retrieving waste from the 3785 m³ (1 x 10⁶ gal.) SSTs is unlimited sluicing. Unlimited sluicing introduces large amounts of water into the SSTs and is no longer acceptable because of the environmental impact of emission of hazardous and radioactive materials from leaking and potentially leaking tanks.

1.1.3 Retrieval Options

Mechanical and hydraulic alternatives have been proposed for waste retrieval. Mechanical systems impose stringent requirements on robotic systems. Because mechanical retrieval systems are difficult to integrate with conveyance systems, robotic systems must deliver retrieved waste in a batch mode to the conveyance system. The robotic arm must be designed to carry a greater payload than required by hydraulic conveyance. In addition, the wear associated with increased movement will reduce time between failures.

Advantages of hydraulic methods are that equipment may be low weight, compact, and require reduced motion and control requirements. The disadvantages of any hydraulic technology are that the addition of water poses the potential for leaking into the environment. It is anticipated that the hydraulic scarifier/conveyer end effector will provide an effective method of controlling the volume of accumulated water by simultaneously dislodging waste with the high-pressure water jet and conveying the waste and water out of the tank. This will minimize added liquid accumulation and therefore minimize the potential for leakage.

1.2 OBJECTIVES

The ultimate objective of this research is to develop the multiple waste form scarifier end effector and pneumatic conveyance technologies into an integrated retrieval system to remediate single-shell tanks. To advance this technology to provide a system that can be used to retrieve waste, a multi-step approach is required to provide a system that can be used to retrieve waste. Each step builds upon the results from the preceding step to develop a

system that can be used in the waste-tank environment. The steps of this approach are summarized.

- Separate Effects Experiments. Separate effects experiments will be conducted to investigate scarifier and pneumatic conveyance parameters to define the range of system operation necessary to retrieve varied waste forms (salt cake, sludge, viscous liquid). The results will be used to develop a scarifier head and pneumatic conveyance test system to be mated in the Integrated Effects Experiments.
- Integrated Effects Experiments. A system test bed will be designed based on the results of the separate effects experiments to test an integrated system consisting of the scarifier head, shroud, and pneumatic conveyance hardware. Experiments will focus on 1) how the waste forms are fragmented into particulate and mobilized by the scarifier, 2) how the scarifier shroud affects the particulate introduction into the pneumatic conveyance system, 3) vertical transport through the pneumatic conveyance system, and 4) effects of introducing inclined and horizontal pipe runs into the pneumatic conveyance system.
- Full-Scale Demonstration. A prototype system will be designed/optimized based on the results of the integrated effects experiments to conduct a full-scale continuous operation test of the system using non-radioactive simulant. The demonstration will include all instrumentation and robotic interfaces necessary to simulate actual waste retrieval. This test will include prototypic separations equipment to remove particulate from the flow stream after its conveyance.
- Hot Demonstration. A full-scale system will be designed to conduct a hot demonstration based on the results of the full-scale cold demonstration. The hot demonstration will retrieve a challenging waste form.
- Single-Shell Tank Waste Retrieval. Full-scale systems will be designed and constructed to retrieve waste from a selected set of waste tanks based on the results from the hot demonstration. These tanks will have waste forms that require the use of this multiple-waste-form end effector.

Strategies to optimize the development and deployment must be developed for each of the program elements listed above. As this concept matures, issues such as system control and operation, deployment, and sensor needs must be addressed. These issues are currently outside the scope of this document.

The objectives of this strategy plan are to

- 1) assess the state-of-the-art of scarification and pneumatic conveyance technologies, available supporting theory, and experimental data base to evaluate whether the technology, as proposed, is suitable to develop into a low-flow rate hydraulic system to be used for single-shell tank retrieval
- 2) evaluate the existing data to determine the gaps in understanding that must be answered through additional investigations
- 3) recommend the parameters to be investigated in the separate effects experiments required as the first step to develop the scarifier/conveyance system.

1.3 SCOPE OF STRATEGY PLAN INVESTIGATION

The scope of the strategy plan investigation is limited to analyzing existing literature and data to

- 1) analyze the physics of key processes (scarifying and pneumatic conveyance) to define relevant parameters and develop the performance criteria for each component and the total system
- 2) evaluate waste characterization data to determine the relevant waste physical and rheological properties to bound the waste form characteristics to be scarified and to bound the anticipated ranges of these properties for development of simulants.

Specific experimental test plans, strategies for control and operation and sensor requirements are not addressed in this document.

The strategy plan and analyses are based on the results of a two-day workshop held at Pacific Northwest Laboratory (PNL) in August 1992. Workshop participants included PNL project staff, William J. Coleman and David O. Monserud from Quest Integrated, Inc. (QUEST) and Dr. Clayton T. Crowe, Professor of Mechanical Engineering at Washington State University. QUEST provided insight about how to develop and test the scarifier for removal of salt cake, sludge, and viscous liquids. Dr. Crowe provided insight to the pneumatic conveyance application.

For the remainder of the research outlined in Section 1.2, PNL and QUEST are proposing a joint effort to optimize the scarifier/conveyance system design for use with tank wastes. Scarifier development and testing will be

performed by QUEST; development and testing of the conveyance system will be performed by PNL. QUEST is the industry leader in water jet technology. They hold the basic patents for abrasive water jet technology and developed the original scarifier.^(a) Dr. Crowe of Washington State University will provide technical guidance and peer review of our program.

(a) Ultra-high-pressure water jet patents disclosed at Quest, Integrated, Inc. include:

1. "Method and Apparatus for Forming High Velocity Liquid Abrasive Jet," U.S. Patent Number 4,648,215.
2. "Swivel Fitting Arrangement for Use in a Pressurized Fluid Line," U.S. Patent Number 4,669,760.
3. "Nozzle Attachment for Abrasive Fluid-Jet Cutting System," U.S. Patent Pending, European Patent Number 86,108,664.3.
4. "Two Stage Waterjet and Abrasive Fluid-Jet Cutting System," U.S. Patent Number 4,689,939.
5. "Process and Apparatus for Milling with Abrasive-Waterjets," U.S. Patent Pending, Serial Number 270,550.
6. "Abrasive Swivel Assembly and Method," U.S. Patent Number 4,854,091.
7. "Method and Apparatus for Drilling Small Diameter Holes in Fragile Materials with High Velocity Liquid Jets," U.S. Patent Number 4,955,164.
8. "Apparatus for Piercing Brittle Materials with High Velocity Abrasive-Laden Waterjets," U.S. Patent Number 4,934,111.
9. "Abrasive-Waterjet Nozzle Assembly for Small High Drilling and Thin Kerf Cutting," U.S. Patent Number 4,951,429.
10. "Abrasive Swivel," U.S. Patent Number 4,936,059.
11. "High Pressure Dynamic Seal," U.S. Patent Pending, Serial Number 333,342.

2.0 CONCLUSIONS AND RECOMMENDATIONS

A strategy to develop an integrated scarifier end effector and pneumatic conveyance system into a retrieval system to remediate waste forms such as salt cake, sludge, and viscous liquids from single-shell tanks was developed.

- The scarifier/pneumatic conveyance system conceptual design, system operating criteria, and controlling parameters were defined (Sections 3.1 and 3.2).
- Existing theories and empirical correlations that describe scarification and pneumatic conveyance were assessed and gaps in knowledge bases were identified (Sections 3.3 through 3.5).
- Lessons learned from past experiments were compiled and research recommendations summarized (Sections 3.6 and 3.7).

Based on these analyses, recommendations for separate effects experiments to quantify parameter performance for the three waste types and integrated effects experiments to evaluate overall system performance were presented (Section 4.0).

2.1 CONCLUSIONS

The three waste types present in single-shell tanks (hard, brittle, salt cake, viscous liquid, and deformable sludge) present challenges increasing in complexity for scarification and pneumatic conveyance. Salt cake is anticipated to be the easiest to retrieve because

- 1) a theoretical model of hydraulic rock fracture can be applied to estimate jet performance to fracture salt cake,
- 2) gas-solids transport correlations can be used to predict pneumatic transport.

Deformable sludge is anticipated to be the most difficult to retrieve because no theories, correlations, or data exist to predict the ability of jets to erode the sludge, and the cohesive/adhesive nature of the sludge may cause plugging during transport. However order-of-magnitude gas-solid correlations indicate that particulate wastes of prototypic density can be transported to a height of 20 m within allowable pressure limits provided that the volume fraction of the gaseous phase is kept above 95%.

Viscous liquid is anticipated to be of intermediate complexity to retrieve.

The specific phenomena that must be understood during scarifier design and development were identified and ranked in Table 2.1. Separate effects tests will be required to determine the operating parameters that provide adequate control of these parameters.

2.2 RECOMMENDATIONS

The strategy outlined in this document is the first of a series of strategies that must be developed for the successful deployment of this retrieval concept. A combined analytical and experimental approach has been presented to address the immediate research needs identified during the analyses of scarification and pneumatic conveyance. The approach recommends 1) separate effects experiments to optimize scarifier and pneumatic conveyance performance for each waste form followed by 2) integrated experiments to mate the scarifier with the pneumatic conveyance system to investigate steady state and transient operation. Completion of these experiments will resolve questions posed about the limiting phenomena listed in Table 2.1 to permit further advancement of the concept towards an in-tank waste retrieval system.

TABLE 2.1 Phenomena Identification Ranking

Prior-ity	Phenomena	Issue	Resolution	Appli-cation
1	Mobilization (sludges)	Important to achieving uniform waste particle size distribution	Observations from separate effects experiments to provide insights	Scarifier
2	Fracturing (salt cake)	Important to achieving uniform waste particle size distribution	Observations from separate effects experiments to provide insights	Scarifier
2	Droplet formation (liquids)	Important to achieving uniform waste particle size distribution	Observations from separate effects experiments to provide insights	Scarifier
1	Agglomeration	Impacts entrainment of wastes into conveyance system and may cause plugging	Techniques such as using liquid gases may mitigate particle agglomeration	Scarifier and Conveyance System
1	Phase concentration	Impacts entrainment of wastes into conveyance system; excessive concentrations may lead to plugging	Scarifier must be optimized to produce acceptable concentration limits	Scarifier
1	Waste entrainment	Determines efficiency of scarifier system; particle-particle interactions may have negative implications (agglomeration); plugging issues in area change from scarifier to conveyance system	Optimization of scarifier/conveyance system flow field required	Scarifier
1	Liquid entrainment	Impacts working fluid retrieval, moisture content of transported wastes; potential lubricant for sludge transport	Optimization of scarifier/conveyance system flow field required	Scarifier
1	Wall impingement/adhesion	Contact of certain types of sludges with transport system walls may result in waste buildup; freezing or water film may reduce buildup	Separate effects experiments to provide insights into severity of issue	Conveyance system and scarifier
1	Flow field	Correct flow field essential for waste and liquid entrainment and for avoiding plugging. Area changes need to be carefully optimized	Separate and integral tests to aid in design optimization; computational fluid dynamics software for shape optimization may also be used	Conveyance system and scarifier
2	Energy availability	Negative or positive pressure systems have different energy available to overcome pressure drop issues	Design constraints (pressurization) need to be defined to select system design	Conveyance system
2	Phase segregation	Phase distribution should be controlled to enhance scarifier performance and reduce the probability of plugging	Separate effects tests to provide insight into maldistribution	Scarifier and conveyance system
3	Erosion/corrosion	Impacts nozzle wear	Optimization in later development	Scarifier

3.0 SCARIFIER/CONVEYANCE SYSTEM DESIGN AND OPERATION

Scarifiers and pneumatic conveyance systems are successful technologies used commercially^(a) in non-nuclear applications. Integration of these two technologies to effectively retrieve waste from single-shell tanks in a manner that is more reliable, timely, and cost effective than retrieval based solely on mechanical systems is potentially feasible. To evaluate this potential, the concept is described (Section 3.1) and the controlling parameters are summarized (Section 3.2). This is followed by a review of the theories that describe the key phenomena (Section 3.3 - scarifying and Section 3.4 - pneumatic conveyance) and a discussion of how to integrate the two components (Section 3.5). Finally, relevant experiments conducted to determine the feasibility of utilizing pneumatic conveyance and scarification to remediate waste at Hanford and at other radioactive waste sites are reviewed (Section 3.6).

3.1 SYSTEM DEFINITION

The system consists of two components: 1) a compact scarifier to dislodge and mobilize waste and 2) a pneumatic conveyance system to entrain and transport the waste. The scarifier consists of the high pressure jets that dislodge the waste and an aerodynamic shroud that forms the transition between the scarifier and pneumatic conveyance system.

The system (as currently envisioned) would be mounted on a telescoping boom that enters the waste tank through a 1.1-m-dia. (42-in.) riser. An example of how the system might enter the tank, including supporting aspects of the pneumatic conveyance system is shown in Figure 3.1. The pneumatic conveyance inlet would be mated to the scarifier shroud. The scarifier gross position would be controlled by the telescoping boom.

(a) Scarifiers are used to remove concrete from bridge decks without injury to imbedded rebar or deck supports. Pneumatic conveyance systems transport large quantities of ash, coal, stone, lime, grain, and other particulate. In nuclear applications, scarifier models have been developed to decontaminate metal and concrete surfaces (Pezzimenti et al. 1989, Tundo et al. 1988)

FIGURE 3.1 Conceptual Arrangement of Scarifier/Pneumatic Conveyance System

Components of a scarifier system include:

- high-pressure jets, their supply lines and high-pressure intensifier
- shroud and plenum to encase the jets and mate with the pneumatic conveyance system components
- sensors to assess waste type and rate of dislodging.^(a)

It is anticipated that the scarifier high-pressure intensifier would be located in a radiation-free zone for ease of maintenance.

A scarifier head configuration developed for an abrasive-water-jet application is shown in Figure 3.2. A non-abrasive system design would be similar without the additional hardware required to introduce abrasive materials.

Components of a pneumatic conveyance system include:

- vacuum piping
- positive displacement blower
- sensors to assess pressure drop, flow rate, and flow regime
- cyclone separator to remove particulates
- filter to remove any small particles or moisture not removed in the cyclone separator
- high-efficiency particulate air (HEPA) filter system to remove any residual particulate not removed by the filter.

3.2 CONTROLLING PARAMETERS

Under ideal conditions:

- 1) the scarifier system would be operated to produce uniformly sized particulate at a constant production rate
- 2) the shroud would be configured to mobilize the particulate introduced into the scarifier shroud to provide a uniform concentration into the conveyance system and maximum working fluid retrieval

(a) Sensors development is not part of this end-effector development program.

FIGURE 3.2 Scarifier Head Configuration for an Abrasive Water Jet Application

- 3) the conveyance system would be designed to transport all particulate through the conveyance lines with an optimal solid concentration with no particulate settling, agglomeration, or adhesion to conveyance system walls
- 4) the separations equipment would remove all particulate and moisture from the air stream.

The remainder of this strategy plan focuses on how to predict performance for in-tank operations associated with items 1 through 3. Commercial separations equipment exists that can be designed to accomplish item 4. The parameters that control operation of the three components are summarized in Table 3.1.

TABLE 3.1 Parameters that Control System Operation

Scarifier	Shroud	Conveyance Line
jet force - jet pressure (P_0) - orifice diameter (d_0) - height (h) - impingement angle (θ_0)	particle - diameter (D_p) - shape - density (ρ_s) - concentration (C_s) - adhesiveness - cohesiveness - agglomeration	particle - diameter (D_p) - shape - density (ρ_s) - concentration (C_s) - adhesiveness - cohesiveness - agglomeration - fluid (water) content
waste physical properties - shear strength (τ_0) - other undefined properties	aerodynamics - air flow patterns - air velocity - pressure drop in entrance region	multiphase transport - solids loading - particle/fluid interaction - flow regime - spatial concentration - pressure drop per unit length - velocity - moisture

The particle diameter obtained from scarifying depends upon the waste physical properties and the jet characteristics. The mobilization of the particulate depends upon the air flow patterns in the shroud, the particle concentration, and the particle characteristics such as size and density and the physical properties of the particles. Particle size will depend on scarifier operation; therefore, mobilization will be strongly influenced by the design and operation of the high-pressure nozzles. Pressure drop during pneumatic transport of the particulate depends upon the solids loading, the velocity and concentration, the particle/fluid interaction, and particle characteristics. System design will require careful matching of the solids dislodging rate in the scarifier and the maximum conveyance rate in the conveyance system. Adhesion/cohesion between particulate and interaction with the transport line wall as well as particle agglomeration may significantly influence transport.

The specific goals for the integrated scarifier/conveyer technology are to:

- operate efficiently to remove a variety of waste forms including salt cake, sludge, and viscous liquids
- minimize total working fluid accumulation in tanks by maximizing retrieval efficiency to achieve >98% fluid retrieval
- limit water use rate by the use of high-pressure jets
- decrease the footprint of the scarifier unit to 0.30 m x 0.30 m (12 in. x 12 in.)
- decrease scarifier mass to between 45 and 90 kg (100 lbm and 200 lbm)
- achieve a waste retrieval rate of $4.7 \times 10^{-4} \text{ m}^3/\text{s}$ (1 ft³/min) in salt cake^(a)
- reduce entanglement with tank hardware by replacing rotating jets with oscillating or linear jets
- design a conveyance system that does not plug and can transport all waste types
- increase the size of solid aggregates that can be transported by the conveyance system
- decrease the size of solid aggregates that are produced by the scarifier
- increase the vertical lift for the conveyance system to between 12 and 15 m (40 and 50 ft)
- operate and survive in the high-radiation tank environment.

To obtain these objectives it will be necessary to understand the physics of system operation. This understanding can be obtained through theoretical relationships, empirical models, and experimentation. The physics of scarifying and conveyance is described in Sections 3.3 and 3.4, respectively.

3.3 PHYSICS OF SCARIFYING

The high-pressure jet is the major component of the scarifier. The jet impacts the material to be cut and/or mobilized. The interaction of the jet

(a) Based on this retrieval rate an SST containing 4.6 m (15 ft) of salt cake would require 46 day (1104 hrs) of continuous operation to remove the waste.

with the material varies with the physical properties of the material. First the characteristics of a water jet emitting into air are described (Section 3.3.1). To predict scarifier performance it is necessary to understand how the jet interacts with the varied waste forms. Three types of materials will be present in the tank: 1) hard, brittle solids, such as salt cake, 2) deformable sludges, and 3) viscous liquids. The jet is expected to interact differently with each medium. A theory has been developed to describe the erosion rate of hydraulic rock cutting. This theory presents a methodology of how to approach development of mechanisms to predict jet interaction with the various waste forms and may be applicable to cutting solid salt cake type wastes. The theory is summarized in Section 3.3.2. Physical properties of the waste forms that may be important in developing a failure criterion for each waste type are discussed (Section 3.3.3).

3.3.1 Jet Properties

A turbulent, free water jet with velocity (U_0), discharged through a circular nozzle with diameter (d_0) into air, can be characterized by three flow fields: 1) the flow of the water core (with axial and radial velocity components u_1 and v_1), 2) the surrounding air flow (with axial and radial velocity components u_g and v_g), and 3) the droplet flow (with axial and radial velocity components u_d and v_d) as shown in Figure 3.3. The flow of each component is governed by a set of continuity and momentum equations, which are coupled together by interaction terms (Eddingfield, Evers, and Setork 1981).

FIGURE 3.3 Flow Fields of a Water Jet Issuing into Air

3.3.2 Hydraulic Rock Cutting

Crow (1973) developed a theory of hydraulic rock cutting. The model consists of a jet with diameter (d_0) at a steady total pressure (P_0); the rock feeds under the jet stream at a constant velocity (v), Figure 3.4.

FIGURE 3.4 Steady High-Velocity Water Jet Model

The cutting interface is steady in coordinates fixed with respect to the jet, and the cut attains some definite terminal depth (h). Crow's model describes the cut depth (h) as a function of P_0 , d_0 , v and pertinent material properties.

Crow's theory of hydraulic rock cutting is developed based on the following phenomena: cavitation, brittle fracture, and permeability. A rectilinear water flow passing at high speed over a granular interface exerts little shear stress because the interface is in a state of almost complete cavitation. However, during jet operation, the jet curves against the cutting surface as shown in Figure 3.4. The curvature induces a high surface pressure, which closes cavity bubbles and exposes the grains to direct impact from the water. The surface pressure would keep the grains in their sockets, were it not for the finite permeability of the rock. Permeability produces a pore pressure beneath the cutting surface, which relieves the normal force on the grains and allows them to be shorn away. The intrinsic speed (c) for rock cutting is based only on properties of the rock and not properties of the jet; c equals $(k \tau_0)/(\mu_r g)$ where k is the permeability of the rock, μ_r is the rock

coefficient of internal friction, and g is a typical grain diameter. The specifics of the theory are summarized in Appendix B. The depth of cut (h)

$$h = 2 \mu_w (d_0 P_0 / \tau_0) \int_0^{\theta} \frac{e^{\mu_w (\theta - \theta_0)} \sin \theta}{1 + (v/c) \sin \theta} d\theta \quad (3.1)$$

shows that the optimum angle of impingement (θ_0) depends on the rock coefficient of Coulomb friction (μ_w) and v/c but must lie between $\pi/2$ and π .

Crow makes some pertinent observations based on the theory applied to single and multiple jet passes.

Single Jet Pass.

- To maximize the depth of cut ($h_{\max}$) with a single pass of a water jet

$$0 < v \leq c/3$$

$$\theta_0 = 150 \text{ deg}$$

$$h_{\max} = 1.01 d_0 P_0 / \tau_0$$

- Under normal impingement when $\theta_0 = 90 \text{ deg}$

$$h = 0.67 d_0 P_0 / \tau_0$$

therefore, a 50% increase in slot depth is obtained by using oblique impingement.

- Shear strength is the only material property regulating $h_{\max}$.

Multiple Pass Jets.

- When multiple passes are feasible, the quantity of most importance is the slot area created per unit time (hv). The feed rate (v) can be raised as long as the produce hv increases because any degradation of h can be made up by multiple passes.
- Conditions that maximize the rate of slot area creation are

$$4 c \leq v \leq (0.42 P_0 / \tau_0 - 1) c$$

$$\theta_0 \rightarrow 180 \text{ deg}$$

$$(hv)_{\max} = (1.47 k d_0 P_0) / (\mu_r g)$$

- Under normal impingement when $\theta = 90$ deg

$$(hv)_{\max} = (0.97 k d_0 P_0)/(\mu_r g)$$

therefore, a 50% increase is obtained by using oblique impingement.

- Shear strength governs the feed-rate window within which efficient cutting takes place but has no effect on the rate at which slot area can be created. The permeability k of the rock imposes an absolute upper limit on the rate of slot area creation.

These observations may be extended to the scarifier application for waste tank remediation. To provide particulate of a desired size it is advantageous to minimize water additions from the jet while maximizing the slot area created per unit time (hv) for multiple pass systems. Oblique impingement with a controlled spacing between passes of the scarifier may be used to produce particulate of a specified size.

3.3.3 Research Needs

The information in Sections 3.3.1 and 3.3.2 showed that 1) a method exists to model a water jet emitting into air and 2) a model has been developed to describe hydraulic rock cutting. The hydraulic rock cutting model may be applicable to predict cutting rate and depth for salt cake; this applicability will need to be verified experimentally. It is not expected that this hydraulic rock cutting model can be applied to cutting deformed sludge or viscous liquids. Additional models or empirical relationships will need to be developed to describe the processes of 1) using a high-pressure water jet to mobilize and entrain sludge and 2) using a high-pressure water jet to disperse and entrain viscous liquid.

3.3.4 Material Properties

For the scarifier system to successfully operate, the ultra-high-pressure scarifier jets will be configured to 1) break-up solid salt cake into a uniformly sized,^(a) finely divided rubble, 2) mobilize sludge into uniformly sized discrete chunks, and 3) disperse viscous liquid into a form

(a) Particle size is not explicitly developed in the hydraulic rock cutting model. It may be controlled by varying the angle of impingement, the spacing between the scarifier passes and other parameters. This relationship can be determined experimentally during the separate effects experiments.

that can be converted into an aerosol and transported. The physical properties of the waste that are anticipated to control its behavior during impaction by the jet are discussed for each waste type.

Single-shell tank waste is being characterized to 1) develop criteria for end effector operation during waste retrieval and 2) develop physical and chemical simulants to evaluate end effector performance. A summary of waste characteristics and physical properties are included in Appendix A.

3.3.4.1 Salt Cake

Salt cake is a hard, brittle, solid expected to fracture on impact. Physical properties that affect its ability to be cut by the high-pressure jet include compressive strength, penetration resistance (steady applied force similar to compressive strength), impact resistance (an impulsive force), shear strength and permeability. The salt cake density, crystalline structure, and particle size distribution that result after the material is cut all affect its ability to be mobilized and conveyed.

3.3.4.2 Sludge

Sludge is a deformable solid; properties of mechanical strength, adhesiveness/cohesiveness, and density are anticipated to affect its ability to be mobilized by the high-pressure jet. After contact with the jet the sludge properties may change from increased water content.

Mechanical Strength. The tank sludge is expected to initially behave as a cohesive solid and not a non-Newtonian liquid. This is a consequence of the interparticle attractions and the structure of particles that form the sludge. The stress required to initiate movement of the sludge is important; this stress disrupts the interlocking structure/chemical attraction of the particulate/liquid system. Several mechanical properties of the sludge quantify the strength of a cohesive solid: shear strength, compressive strength, tensile strength, and penetration resistance.

Adhesiveness/Cohesiveness. The adhesiveness of a material refers to its tendency to stick to other materials. Cohesiveness refers to the strength of the attractions between portions of the same material. Both properties will influence its ability to be mobilized and transported.

Density. Density will affect the gravitational settling of the particulate and therefore, its retrieval and conveyance rate.

3.3.4.3 Viscous Liquid

Liquid rheology, density, and surface tension of the waste are anticipated to affect its ability to be mobilized and transported. Liquid wastes exhibit rheologies varying from yield pseudo-plastic to Newtonian. For Newtonian fluids the Weber number, the ratio of inertial to surface tension forces, is an important parameter in the study of gas/liquid (bubble or droplet) or liquid/liquid interfaces, or where these interfaces are in contact with a boundary. This dimensionless number is defined as the product of the square of the fluid velocity, density, and characteristic length (droplet size) divided by the surface tension. Deformation and breakup of non-Newtonian fluids must be treated by other theories: studies have been made of viscoelastic materials breakup; the effect of surfactants have also been evaluated (Milliken and Leal 1991). A key parameter in predicting the mobilization for a non-Newtonian fluid is the yield stress.

3.4 PNEUMATIC CONVEYANCE

Pneumatic conveyance is the transport of solids by the flow of air or other gases. Pneumatic conveyance is a mature technology for transport of grains, coal, and other dry materials. The application of pneumatic conveyance to the waste retrieval problem is complicated by the fact that the particulates are not dry because of interstitial liquid or fluid added during the cutting process. Cohesive and adhesive effects do not dominate during transport of dry materials. When moisture is present adhesion may influence particulate buildup along the pipe wall, restricting the diameter, thereby increasing velocity and increasing pressure drop. Cohesion may influence particulate agglomeration into larger diameter particulate that is more difficult to transport.

The objective of this study is to establish the parameters and system configuration which will enable transport of the type of particulates generated by the scarifier under steady flow and transient conditions. All

orientations may eventually be included in a pneumatic conveyance system, although vertical and inclined transport are expected to predominate.

Any study of pneumatic transport must be guided by what is known about simpler systems. A review of the multiphase flow concepts applicable to pneumatic conveyance in horizontal, inclined and vertical systems is provided in Appendix C. Analysis and testing will be required to extend this information to gas-solid-liquid mixtures, and to address special problems such as adhesion to walls.

3.4.1 Modeling Gas-Solid Mixtures

The mass flow rate of the solids phase (m_s) in a pipe of cross-sectional area (A) is represented by

$$m_s = \rho_s U_s A = (1-\epsilon) \rho_s u_s A \quad (3.2)$$

where ρ_s is the material density of the solids phase, U_s is the superficial velocity of the solids phase, ϵ is the volume fraction of the gaseous phase and u_s is the phase (actual) velocity of the solid phase. The equivalent expression for the mass flow rate of the gaseous phase (m_g) is

$$m_g = \rho_g U_g A = \epsilon \rho_g u_g A \quad (3.3)$$

where ρ_g is the material density of the gaseous phase, U_g is the superficial velocity of the gaseous phase, and u_g is the phase (actual) velocity of the gaseous phase. The loading (S) is the ratio of the mass flow of the solids phase to the gaseous phase:

$$S = m_s/m_g = (\rho_s U_s)/(\rho_g U_g) \quad (3.4)$$

The concentration (C_s) is the ratio of the mass of the solids phase to the mass of the mixture:

$$C_s = (1 - \epsilon)\rho_s/[\rho_s (1 - \epsilon) + \rho_g \epsilon] \quad (3.5)$$

The denominator of this equation is the density of the mixture (ρ_{mix}).

3.4.2 Upward Flow of a Gas-Solid Mixture in Vertical Pipes

The pneumatic conveyance system proposed for waste retrieval is a negative pressure system with maximum pressure drop of 10^5 Pa (1 atm). The pressure is atmospheric at the entrance to the pneumatic conveyance system and negative at the blower. With this limitation in mind, the general trend of pressure drop in fully-developed systems with superficial gas velocity for a vertical gas-solids flow is explored (Figure 3.5).

FIGURE 3.5 Effects of Solids Rate on Pressure Drop and Choking Velocity

At high velocities, the pressure drop varies essentially with the velocity squared, similar to single-phase flow. This is because the spatial concentration distribution is uniform, and the mixture behaves like a homogeneous fluid. Increasing the loading produces an increased pressure drop caused by the increased momentum loss from particle-wall contact. Decreasing the gas velocity for a given solids flow rate causes the pressure drop to decrease to a minimum and then to increase with further decrease in velocity. As the superficial gas velocity is reduced, the solids velocity is also

reduced and produces a reduced gas volume fraction, which causes the mixture density to increase. The pressure drop associated with gravity is proportional to the mixture density; therefore, the gravitational component of the pressure drop tends to increase. The reduced gas volume fraction at a constant superficial gas velocity also tends to elevate the actual gas velocity which leads to an increased frictional pressure drop. The combined increase in the frictional pressure drop and gravitational pressure drop results in a rapid increase in pressure drop with decreased superficial gas velocity at low superficial gas velocities.

The velocity corresponding to a minimum pressure drop is called the "critical" velocity. Further decrease in the velocity ultimately leads to choking where the transport of the solid phase ceases. The velocity at choking is referred to as the choking velocity (U_{ch}). Most pneumatic conveyance systems operate at velocities higher than the critical velocity.

Systems can be operated at subcritical velocities provided sufficient head is available. These are dense phase flows. These flows can be unsteady as slugs of material move up the duct. With fine powders, slugging may not occur but intense recirculation ensues with solids falling downward near the wall. Leung and Wiles (1976) have identified this flow as dense phase flow without slugging.

3.4.3 Choking Velocity Correlations

Numerous researchers have developed correlations for choking velocities (Yang 1975 and 1983, Rose and Duckworth 1969, Doig and Roper 1963). Klinzing (1981) and Genium (1984) recommend using Yang's correlation for the solids friction factor (f_s) in pipelines at low pressures:

$$f_s = [2 g D_t (\epsilon_{ch}^{-4.7} - 1)]/[u_{ch} - u_T]^2$$

where g is gravitational acceleration, D_t is the inside diameter of the pipe, ϵ_{ch} is the volume fraction of the gaseous phase at choking, and u_T is the terminal velocity of a single particle. Yang (1983) initially assumed that solids friction factor (f_s) is 0.01 but later improved his correlation by taking

$$f_s = 6.8 \times 10^5 (\rho_g/\rho_s)^{2.2} \quad (3.7)$$

3.4.4 Research Needs

Pneumatic conveyance correlations exist for dilute phase transport of dry particulate. These correlations may be used to define conveyance parameters for dry salt cake wastes. Addition of water from jet cutting to the salt cake may compromise the validity of the correlations. Separate correlations need to be developed to predict dilute phase pneumatic transport of sludge and viscous liquids.

If transport of dilute phase salt cake, sludge, and viscous liquids can be sustained in both steady state and transient modes, then investigations into the dense phase transport regime should be considered to extend the region of acceptable transport.

3.5 SCARIFIER/CONVEYANCE SYSTEM INTEGRATION

No theories of transport in the shroud were analyzed to evaluate integration of the scarifier and conveyance system. Particulate characteristics and air flow patterns as outlined in Table 3.1 will significantly affect the particulate mobilization and entrainment into the conveyance system. This phenomenon will be investigated experimentally.

3.6 REVIEW OF PRIOR WORK

Several studies conducted at Hanford in recent years have investigated applying water jets and conveyance technologies to remediate waste tanks.

Water Jet Studies

- In 1990, at the direction of Westinghouse Hanford Company, Quest Integrated, Inc. demonstrated water jet and air jet scarifier technologies for removal of radioactive and hazardous waste (Leist 1990, Quest Integrated, Inc. 1990).

Pneumatic Conveyance Studies

- In 1975, Vitro Engineering conducted an equipment search for standard off-the-shelf pneumatic retrieval equipment. This search was followed by retrieval feasibility testing^(a)
- In 1990, Westinghouse Hanford Company conducted a feature test of an air conveyance system to evaluate the applicability and efficiency of air conveyance as a method for transporting waste dislodged from single-shell tanks (Thompson 1990)
- In 1992, Westinghouse Hanford Company conducted a demonstration to evaluate air conveyance for removal of soft wastes.^(b)

The results from these investigations are summarized in Appendix D.

3.6.1 Conclusions from Past Tests

Several tests have been conducted to determine the applicability of using pneumatic conveyance to transport waste of varying types from the tank. The pneumatic conveyance tests had several points in common

- vendors were asked to supply off-the-shelf equipment for evaluation
- physical simulants of solid salt cake wastes were transported more successfully than physical simulants of moist-sludge-type wastes
- tests were stopped by plugging the conveyance line. No steady-state pressure drop was achieved in the system.
- methods to dislodge the waste and mobilize it prior to its entry into the pneumatic conveyance system need to be improved.

The trend exhibited during these experiments indicates that pneumatic transport may have commenced in the dilute-phase region; however, process variabilities quickly transferred the transport into the dense-phase region. Because of the need to overcome hydrostatic pressure variation, it is difficult and/or impossible to transport with mass loadings that are in the dense-phase region with a negative pressure system. Methods to control the solids feed rate will be required in systems of this type.

(a) Vitro. 1975. Evaluation and Adaptation of Standard Mechanical, Hydraulic and Pneumatic Devices for Salt Cake and Sludge Retrieval at Hanford, VITRO-R-375, Vitro Engineering, Richland, Washington.

(b) J. D. Potter. Single-Shell Tank Soft Waste Dislodging and Conveyance Systems, Development Test Procedure, WHC-SD-TC-026, Rev. A. Westinghouse Hanford Company, Richland, Washington.

Air and water jets have also been investigated experimentally for cutting and dislodging waste. The air and water jet test results highlighted the differences between the waste types: salt cake is manageable to rubblize, using high to ultra-high pressure jets, and convey; sludge and soft wastes, while easily mobilized, are difficult to entrain into a conveyance system. Edge effects of the size of the simulant test pan were found to dominate mobilization of the sludge by the jet; it mobilized the best when the jet penetrated through the waste to the simulant pan. Then forces reflected from the sides and bottom of the simulant pan were utilized to assist mobilization.

3.6.2 Experimental Needs

Review of past experiments shows the need to

- conduct systematic experiments with quantitative rather than qualitative results
- measure parameters that quantify system and device performance
- track performance during both steady state and transient operation
- quantify system performance for each waste type separately prior to combined evaluation
- evaluate the impact of water addition from the jet on waste properties.

3.7 COMPILATION OF RESEARCH NEEDS

During the preceding sections information pertaining to scarifying and pneumatic conveyances have been analyzed to 1) review existing theories that describe the processes, 2) summarize empirical correlations, 3) evaluate prior experimental efforts, and 4) assess the areas where additional research is required. The information will be synthesized in this section to prioritize future analytical and experimental efforts. This information is summarized in Table 3.2.

Of the waste types, moist sludge is anticipated to be the most challenging to scarify and convey because moist waste of this type is anticipated to 1) be difficult to entrain in the shroud, 2) adhere to the sides of the transport line, and 3) agglomerate to form larger masses that cannot be sustained during conveyance.

TABLE 3.2 Summary of State-of-the-Art

Analysis Tool	Salt Cake	Sludge	Viscous Liquid	Comments	Needs
Jet theoretical model	yes	yes	yes	multiphase model of water jet in air	determine interaction terms between jet phases
Jet impingement theory	yes	no	no	theory of hydraulic rock cutting may be applicable to salt cake	theory and/or correlations for sludge and liquids
Jet impingement empirical correlations	yes	no	no	depends on jet shape, correlation for round jet impinging on rock exists	develop for sludge and viscous liquids
Pneumatic transport theory	yes	no	no	theory of dilute phase dry solids transport applicable to dry salt cake	develop theory and/or correlations for sludge and liquids
Pneumatic transport correlations in dilute phase	yes	no	no	dilute phase correlations applicable to dry salt cake	determine applicability of correlations for moist salt cake, sludge and viscous liquids
Pneumatic transport correlations in dense phase	no	no	no	no applicable correlations	develop correlations if transport can occur in this regime

In Section 4.0 a program is presented to provide data for the development of an integrated multi-functional scarifier/conveyance system.

4.0 SEPARATE EFFECTS AND INTEGRATED EXPERIMENTS

An experimental investigation is required to develop the multiple-waste-form scarifier end effector and pneumatic conveyance system into an integrated retrieval system to remediate single-shell tanks. The investigation requires a number of levels of activity, each building upon the results of the preceding investigation to develop a system that can be used in a waste tank environment. The levels were described in Section 1.2: 1) separate effects experiments, 2) integrated effects experiments, 3) full-scale demonstration, 4) hot demonstration, and 5) single-shell tank waste retrieval.

Parameters that affect the scarifier and pneumatic conveyance system performance are discussed in Section 4.1. Recommendations for the separate effects experiments and the integrated experiments are outlined in Sections 4.2 and 4.3, respectively.

4.1 PARAMETERS

The parameter discussion will be segregated to discuss the jet, the scarifier, and the pneumatic conveyance system.

4.1.1 Jet

Items that affect the jet performance are the fluid, the jet shape, the jet process parameters, and geometry.

4.1.1.1 Jet Fluid

High-pressure jets are normally operated using clean, deionized water. This has been effective for conventional applications for cutting materials such as concrete, cardboard, removing surfaces such as paint, etc. Water is the fluid of choice for the majority of waste retrieval activities.

Alternate fluids such as non-Newtonian fluids that gel in the absence of an applied force may be useful for some jet applications where leakage from the system is of major concern.

Compressed gases, such as liquid N_2 or liquid CO_2 , may be used instead of water. These fluids exhibit a phase change upon exit from the jet nozzle, do not add any additional liquid to the tank, and may be able to reduce the

cohesiveness of damp/wet waste through the conveyance system. QUEST has investigated using liquid CO₂ jets for certain applications, with promising results.

4.1.1.2 Jet Shape

The jet shape influences the force per unit area applied to the material. Currently the jets emanate from a circular orifice and impact the material at a point source. Fan jets that spread the impact over a rectangular area may reduce the applied force per unit area. This may be attractive for mobilizing sludge and viscous wastes. QUEST has recently developed high-pressure fan jets.

4.1.1.3 Jet Process Parameters

Jet process parameters include

- pressure - affects the water flow rate and ability to cut material
- traverse speed - affects the depth and quality of cut
- incidence angle - affects the orientation of the cut, the ability to mobilize/fluidize the material, and the particle size of the mobilized material
- deployment velocity of the scarifier head - affects the distance between cuts
- number of jets - affects the water flow rate (total water addition) and ability to mobilize/fluidize the material
- jet configuration - affects the scarifier's ability to work in tanks with debris such as tapes and metal lines. Currently, one or two jets rotate in the scarifier head. The tape debris could wrap around the scarifier head causing the system to malfunction. To eliminate this tendency, oscillatory jet motion or a stationary jet matrix, configured to fire sequentially without rotation may be required.

4.1.1.4 Geometry

Items that need to be considered are

- jet orifice diameter - this in conjunction with the pressure controls the water flow rate
- distance from jet to material to be cut - affects the integrity of the incision

- jet spacing for multiple jet systems - affects the ability of the jet to cover the surface to be scarified and must be evaluated together with the total motion of the end effector.

4.1.2 Scarifier

Items that affect the scarifier design include the shape of the shroud, the utilities associated with scarifier operation, and how the scarifier is deployed.

4.1.2.1 Shroud

The shroud is the link between the scarifier and the pneumatic conveyance system. Its design dictates how well the mobilized waste will be entrained into the pneumatic conveyance system. Items to be considered in this design include the shroud shape (volume and air velocities dictated by the design), whether it includes any secondary jets to assist mobilization, and the type of seal (inlet area) between the scarifier base and the material to be removed. It is anticipated that this inlet area would be variable. Orifices may be required to enhance the air flow into the shroud to maintain the entrainment required for conveyance.

4.1.2.2 Utilities

The scarifier requires an umbilical line to supply the high pressure fluid (water, air, or compressed gas) and must mate with the pneumatic conveyance discharge line. Some configurations may need additional lines supplying water or air to insert into the shroud to enhance mobilization and entrainment. Additional lines for sensors and instrumentation should be anticipated.

4.1.2.3 Deployment

The scarifier requires a positioner to control the gross motion of the system. Currently systems are designed with wheels to roll along the material surface. Units deployed vertically are mounted on rails. In the tank, the unit will be deployed via a telescoping boom.

4.1.3 Pneumatic Conveyance System

Parameters that control performance of the pneumatic conveyance system can be divided into particle characteristics and system characteristics.

4.1.3.1 Particle Characteristics

Particle density, size, shape, wettability, and moisture content affect the ability of the system to entrain and transport particulate.

4.1.3.2 System Characteristics

System parameters that affect system performance include:

- pipe diameter - determines the gas and particle velocities obtained during conveyance
- pipe roughness - affects the pressure drop per unit length. Rough surfaces also enhance the ability of particles to adhere to the walls of the pipe. This decreases the effective pipe diameter, increases the flow velocity, and increases the pressure drop per unit length.
- pipe orientation - the pipe can be oriented horizontally, inclined upward, or vertically, or in a combination. It is most difficult to maintain a homogeneous suspension through horizontally configured pipes. It is preferable to limit orientations to either vertical or inclined. These orientations will reduce the tendency for flow stratification and particles to settle out.
- system capacity - the system capacity is driven by the capacity of the blower.
- flow rate - the air flow rate, particle flow rate, and particle concentration and loading all contribute to the performance of pneumatic transport.

4.2 SEPARATE EFFECTS EXPERIMENTS

Separate effects experiments are proposed to define operating regimes and configurations for the scarifier and the pneumatic conveyance system. Results from these parametric studies will define the configuration(s) to be evaluated during the integrated experiments. This initial investigation will be conducted using a high-pressure water jet. Alternate fluids may be evaluated after the successful development of a water-based system.

4.2.1 Scarifier

A flow diagram describing the scarifier separate effects investigations is shown in Figure 4.1. Initial experiments will be conducted with a single water jet to define the cutting regime for the various waste types.

FIGURE 4.1 Scarifier Separate Effects Experiments

4.2.1.1 Single-Jet Tests

Parameters to vary listed by priority follow:

- simulant type - salt cake, sludge (cohesive and dilatant), viscous liquid
- jet shape - round jet, versus fan jet with priority on the configuration that can dislodge and mobilize all three waste types
- jet incidence angle - optimized for all three waste types, three angles between 0 and 90 will be evaluated
- traverse speed - optimized for all three waste types, three speeds anticipated
- standoff - the sensitivity of the jet to varying distance from the material surface will be evaluated

- pressure - two conditions will be evaluated, 0.28 to 0.38 MPa (40,000 and 55,000 psi)
- flow rate - will be calculated from the pressure near the nozzle

4.2.1.2 Multiple-Jet Tests

After completion of the single-jet test matrix, the test bed will be configured to evaluate the effects of multiple jets. Items to be investigated in order of priority include:

- jet configuration - rotating head or oscillating or a number of linear jets. It is currently envisioned that the linear system may be preferable because it limits the potential for entangling the scarifier head with debris such as tapes.
- number of passes - tests with multiple jets will be conducted to determine whether the number of jets affects the number of passes defined under the single jet tests
- jet incidence angle - determine whether two different incidence angles enhance particle size and mobilization.

4.2.1.3 Performance Evaluation

Performance will be evaluated by observing the particle size distribution and the overall removal rate. Size and uniformity will be determined as follows.

- For hard salt cake, particle size will be measured by sieving and categorizing the particulate by size distribution.
- For sludge, an assessment of particle size distribution will be made through qualitative observations.

Removal patterns will be investigated and a quantitative measure of removal rate will be determined for each waste type.

4.2.2 Pneumatic Conveyance

A flow diagram describing the pneumatic conveyance separate effects investigations is shown in Figure 4.2. Initial experiments will be conducted with each waste type to bound the region of successful two-phase transport.

FIGURE 4.2 Conveyance System Separate Effects Experiments

4.2.2.1 Parameters

Process parameters will be varied sequentially. Tests will be conducted to develop correlations for normal operation. In these tests salt cake and sludge simulants will be developed from several types of solid materials with varied particle size distributions. The water content of these simulants will

be varied from 0 to 60% to characterize the effect of system performance for very dry to very moist conditions. These tests include evaluation of

- pipe orientation - initial tests will be performed in the vertical orientation, sections or all of the pipe will be clear for visualization
- pipe diameter - may be held constant at a mid-range value of 7.6 to 10 cm (3 to 4 in.)
- solids loading, concentration, and transport velocity will be varied to develop a region of operation
- inclined and horizontal pipe configurations should be investigated after transport in the vertical pipe orientation is completed
- conveyance system assist methods and plugging mitigation methods such as adding water directly to the conveyance system, heating the pipe, and other pipe and waste treatments should be investigated.

4.2.2.2 Performance Evaluation

Performance will be evaluated by measuring system pressure drop and spatial concentration as a function of time. An appropriate steady state value and defined spectrum of fluctuating components of pressure and concentration will indicate stable transport (Keska 1984, 1986, 1989, 1991). A capacitive system has been developed to measure spatial concentration and the fluctuating components of pressure and concentration in real time (Keska 1981, 1985, 1988, 1989). Visual observations of the interior of the pipe will be summarized after each test. In addition to a system mass balance, spatial concentration will be measured.

4.3 INTEGRATED EXPERIMENTS

Based on the results of the separate effects experiments, an integrated design of the scarifier and pneumatic conveyance system will be developed. Integrated experiments will be conducted. The tests will be conducted at full-scale for the scarifier head and shroud; initially the length of the pneumatic conveyance system may be less than full scale. Parameters will be specified based on the results of the separate effects experiments.

Initial experiments will focus on shroud performance to evaluate how well the scarifier and pneumatic conveyance system interface. Entrainment of

the wastes and working fluid into the pneumatic conveyance line depends upon a well designed shroud. After the shroud performance is adequate, the test matrix of simulants will be evaluated to determine the operating range of the entire system. The effects of inclined pipe and bends will be investigated. Steady state as well as transient operations and process upsets will be modeled. As appropriate, mitigations will be investigated.

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APPENDIX A

WASTE PROPERTIES

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WASTE PROPERTIES

Nuclear waste was generated at the Hanford defense complex over its nearly 50 years of operation. The varied chemical operations that have taken place over that period of time have generated a wide variety of chemically heterogeneous wastes. For 35 years, the bulk of the aqueous waste was stored in 149 single-shell tanks (SSTs). For a little over a decade, waste has been stored in 28 double-shell tanks (DSTs), four of which contain double-shell slurry (DSS) that was produced by transferring and concentrating supernatant from SSTs to minimize environmental intrusions caused by leaking SSTs. Estimates of current waste volumes for each of the categories of tank waste are listed in Table A.1

TABLE A.1 Quantities of Hanford Waste

Waste Type	Volume, m ³
neutralized current acid	7,040
complexant concentrate	16,100
plutonium finishing plant	1,460
neutralized cladding removal	3,010
double-shell slurry	83,200
single-shell tank	140,000
Total waste volume	250,810

The wastes in the DSTs and SSTs generally are mixtures of one aqueous phase and a large number of solid phases. The aqueous phase is generally alkaline (pH = ~14) and contains NaNO₃ and varying amounts of complexing agents, fission products, and transuranic (TRU) elements. The solid phases consist of the bulk of the TRUs, fission products, and compounds of process chemicals that precipitated when the waste was made alkaline to keep the storage tanks from corroding. Subsequent evaporation of the aqueous phase of

the SST waste then caused more soluble salts, principally NaNO_3 , to precipitate as salt cake.

A.1 SINGLE-SHELL TANK WASTES

The SSTs contain reprocessing waste of spent fuel from nine plutonium production reactors. From 1949 until 1972, plutonium was extracted by chemical separations plants. During these years, acid waste from several processes [bismuth phosphate, uranium recovery, reduction oxidation (REDOX), and plutonium and uranium extraction (PUREX)] was made basic by adding sodium hydroxide and deposited in the 149 SSTs. The tank capacities ranged from 210 to 3,800 m^3 . Over the years, wastes from different processes have been mixed.^(a) In addition to neutralized process waste, some of the SSTs contain other additions such as

- organic ion exchange resin (Tank 241-BX-101)
- diatomaceous earth (Tanks 241-BX-102, 241-SX-113, 241-TX-116, 241-TX-117, and 241-TX-106)
- natural, depleted, and enriched uranium and plutonium (Tank 241-SX-107)
- solid wastes containing experimental fuel elements, shroud tubes, samarium ceramic balls, uranium, etc. (Tank 241-U-101)

As a consequence, the chemical content of the SSTs is complex and varies from tank to tank. Chemical characterizations for the various tanks are only known within wide ranges of uncertainty. In Table A.2, the contents of these tanks are summarized based on data from July 1989.^(b) The chemistry of these tanks is not well characterized.

(a) Tank solids volumes and brief histories of solids inventories are summarized in Krieg et al. (1990) Appendix A.

(b) Waste Tank Status Report. July 1989. Westinghouse Hanford Company, Richland, Washington.

TABLE A.2 Contents of Single-Shell Tanks

Designation	Number of Tanks	Salt Cake Volume, m ³	Sludge Volume, m ³	Supernatant Volume, m ³	Total Volume, m ³
S	12	18,040	4,430	175	22,645
SX	15	10,770	5,790	360	16,920
T	16	0	7,540	280	7,820
TX	18	25,200	910	20	26,130
TY	6	240	2,160	10	2,410
U	16	10,390	2,415	640	13,445
A	6	3,680	2,130	30	5,840
AX	4	3,350	70	10	3,430
B	16	1,310	6,410	60	7,780
BX	12	580	5,150	390	6,120
BY	12	15,610	2,740	180	18,530
C	16	0	8,200	265	8,465
Total	149	89,170	49,945	2,420	139,535

The composition of the salt cake and liquid together is largely NaNO_3 , NaNO_2 , and NaCO_3 . Some nitrite was added to inhibit corrosion in the tanks and some was generated by radiolysis. The SST sludge contains large quantities of silicon, aluminum, sodium, and iron, and lesser quantities of borates, phosphate, calcium, nonradioactive strontium, magnesium, and zirconium. In addition, although in much smaller concentrations, there are significant quantities of silver, arsenic, cadmium, chromium, mercury, selenium, and fluorides. There should also be substantial quantities of palladium, rhodium, and ruthenium that could be of commercial value. In the past, their recovery was not economical, but advanced chemical separations techniques and an increase in value of rhodium could make their by product recovery attractive.

A.2 WASTE PHYSICAL PROPERTIES

Wastes contained in the underground storage tanks at Hanford have a wide variety of chemical and physical properties. For retrieval operations, such as would be conducted using the scarifier system, the physical properties of the wastes are of primary importance. These properties include: bulk density, hardness, shear strength, viscosity, etc. In general, the wastes can be grouped into three distinct categories based on observations of their physical forms: salt cake wastes, sludge wastes, and viscous liquids. However, physical properties of the wastes can vary widely within any of these groups, and many tanks contain varying amounts of these categories of waste types (i.e. a tank may contain a mixture of sludge, free liquid, and hard salt cake).

Because of the chemical and radioactive hazards associated with using actual waste samples for development testing, and because of the very limited availability of waste samples from the tanks, most testing efforts must be conducted using simulated tank wastes. This is especially true for those activities requiring large quantities of test materials, including such projects as the scarifier system development. To identify a suitable substitute for the waste, those physical properties important to the specific test must be identified and quantified for the actual tank wastes that would be affected. However, to a large extent the characterization of physical properties of actual tank wastes is much less complete than chemical characterization, mostly because suitable methods have not been developed to make those measurements *insitu* (extracting core samples frequently disturbs the sample so that information on its *insitu* physical characteristics is lost). Therefore, simulant preparation must permit relatively simple adjustment of the parameters of the waste simulant, and the achievable properties of the simulants must be conservative compared to available information on actual wastes. Because of the large quantities of test materials frequently needed it is also desirable to have a simulant that is easy and inexpensive to prepare and nonhazardous for ease of using and disposing of the waste.

The following subsections describe: 1) physical properties of the waste that are significant with respect to evaluating the scarifier system, 2)

information on those properties that are available from tank waste characterization, and 3) waste simulants and how well they match or bound the values for the tank wastes. First is a description of salt cake wastes, followed by similar descriptions for sludge-type wastes and viscous fluids.

A.2.1 Salt Cake Wastes

As mentioned earlier, many of the physical properties of wastes that are important to development of retrieval systems have not been well characterized due to a lack of suitable methods for *insitu* measurement of those properties. This is especially true for the salt cake wastes. Therefore, much of the information available for salt cake physical properties comes from measurements made on chemical simulants. The chemical simulants are based on elemental chemical analyses performed on tank waste core samples.^{(a)(b)} Nonradioactive but chemically similar solutions are prepared and evaporated to dryness. Physical properties of these chemical simulants are then measured. Wide ranges of properties have been measured on these chemical simulants. "Nonhazardous" salt cake simulants have then been developed to reproduce measured physical properties of these "hazardous" chemical simulants. Potassium/magnesium sulfate (langbeinite), a commercially available "fertilizer," is being used for this nonhazardous salt cake simulant.

The langbeinite simulants are generally prepared by mixing finely ground dry salt with 10 to 14 wt% water, and allowing the mixture to cure by draining and evaporating. The resultant salt cake is a hard cemented mass of the partially dissolved salt grains. Table A.3 summarizes the properties thought to be important to scarifier testing that have been measured on the chemical simulants and how those values compare with similar measurements on samples using langbeinite, the nonhazardous physical simulant. Other properties may

(a) J. J. Wong. Single Shell Tank Synthetic Saltcake Preparation and Testing, draft internal test report. Westinghouse Hanford Company, Richland, Washington.

(b) M. R. Elmore, N. G. Colton, and E. O. Jones. 1992. Development of Simulated Tank Wastes for the Underground Storage Tank Integrated Demonstration, draft progress report. Pacific Northwest Laboratory, Richland, Washington. September.

be important to the testing as well but information is not yet available and are given as TBD (To Be Determined).

TABLE A.3 Measured Physical Properties for Chemically "Hazardous" and "Nonhazardous" Salt Cake Simulants.

Property	Hazardous Simulants	Nonhazardous Simulants
hardness (penetrometer resistance)	<0.07 to > 345 MPa <10 to >50,000 psi	up to ~160 MPa up to 23,000 psi
compressive strength	~0.7 to 5.5 MPa ~100 to 800 psi	up to 11 MPa up to ~1600 psi
shear strength	~0.07 to 0.3 MPa ~10 to 50 psi	~0.2 MPa ~30 psi
bulk density	<1 to ~2 g/ml	~1.4 to 1.6
impact resistance	TBD	TBD
porosity	30 to 50%	43 to 48%
abrasiveness	TBD	TBD
specific gravity	2.3 to 2.4	2.6 to 2.8

A.2.3 Sludge Wastes

Similar to salt cake sampling, although not as detrimental, retrieving a core sample of sludge waste from a tank disturbs the material with an accompanying loss of some of the physical property information for those samples. Therefore, some, but not all, of the information used to develop nonhazardous sludge simulants comes from the actual waste core samples.^{(a)(b)} Other data come from measurements made with chemically

(a) Internal Rockwell letter for R. L. Weiss to T. R. Pauley on "Additional Analyses on Core Samples from Tanks 241-C-105 and 241-C-106." 65453-87-050. April 14, 1987. Rockwell Hanford Company, Richland, Washington.

(b) T. E. Jones, et al. 1990 to 1992. SST Waste Characterization Project - Core 1, 2, ...10 Data Reports. Reports from PNL to Westinghouse Hanford Company. Pacific Northwest Laboratory, Richland, Washington.

similar sludges.^{(a)(b)} The sludge-type wastes are generally precipitated metal oxides and hydroxides, but may be mixed with numerous nitrate and other salts which can alter physical properties. Hazardous chemical sludge simulants can be prepared that match many of the physical properties (e.g. particle size distributions, slurry viscosity, etc.) if the chemical speciation is correct. Nonhazardous sludge simulants for retrieval testing can then be developed to match the significant physical properties (e.g. shear strength, bulk density, etc.).

For these sludge-type wastes the primary properties important to retrieval are summarized in Table A.4 along with measurements made on nonhazardous sludge simulants. These nonhazardous simulants are generally composed of kaolin or bentonite clay mixtures with other additives as necessary. For example, barium sulfate can be added to clay mixtures to increase bulk density. As with the table of salt cake properties, some properties have not been characterized, and are given as TBD.

TABLE A.4 Measured Physical Properties for Sludge-Type Tank Wastes and Chemically "Hazardous" Simulants Compared to "Nonhazardous" Sludge Simulants.

Property	Tank Waste or Hazardous Simulant	Nonhazardous Simulants
shear strength	<100 to >50,000 dynes/cm ²	up to ~80,000 dynes/cm ²
bulk density	up to 1.8 g/ml	up to ~1.8 g/ml
specific gravity	TBD	TBD

(a) C. M. Keller. 1991. Preparation of SST Sludge and Liquor Simulants. Internal Westinghouse Hanford Company memo to J. J. Wong. Westinghouse Hanford Company, Richland, Washington. October 4, 1991.

(b) M. R. Elmore, N. G. Colton, and E. O. Jones. 1992. Development of Simulated Tank Wastes for the Underground Storage Tank Integrated Demonstration, draft progress report. Pacific Northwest Laboratory, Richland, Washington. September.

A.2.4 Viscous Liquids

This category of waste type has generally not been characterized, except for information available on supernate or interstitial liquids contained in the other waste types. Some liquid waste simulant development has been conducted.^{(a)(b)} If these viscous liquids will contain suspended solids from the sludges or salt cakes being retrieved from the tanks, the presence of the solids will significantly alter their physical properties (e.g. density, viscosity, surface tension, etc.). These are probably the primary properties of interest for retrieving liquid wastes with the scarifier system, and can usually be duplicated with much less difficulty than either the salt cake or sludge wastes. Viscous liquid waste simulants have not been specifically identified and developed, however it is anticipated that some of the systems that have been investigated, including sucrose or salt solutions and suspensions with common solids, would satisfy the simulant needs for this phase of testing.

(a) C. M. Keller. 1991. Preparation of SST Sludge and Liquor Simulants. Internal Westinghouse Hanford Company memo to J. J. Wong. Westinghouse Hanford Company, Richland, Washington. October 4, 1991.

(b) M. R. Elmore, N. G. Colton, and E. O. Jones. 1992. Development of Simulated Tank Wastes for the Underground Storage Tank Integrated Demonstration, draft progress report. Pacific Northwest Laboratory, Richland, Washington. September.

APPENDIX B

THEORY OF HYDRAULIC ROCK CUTTING

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THEORY OF HYDRAULIC ROCK CUTTING

Crow (1973) developed a theory of hydraulic rock cutting. The model consists of a jet with diameter (d_0) at a steady total pressure (P_0); the rock feeds under the jet stream at a constant velocity (v). The cutting interface is steady in coordinates fixed with respect to the jet, and the cut attains some definite terminal depth (h). Crow's model describes the cut depth (h) as a function of P_0 , d_0 , v and pertinent material properties. The geometrical properties of the cutting surface are shown in Figure B.1. The surface follows the curve $y(x)$, where the ordinate (y) increases downward into the stone, and the abscissa (x) increases backward along the cut. The origin of the coordinate system is the point where the jet first impacts the stone. The arc-length (s) specifies location along the cutting surface; θ is the local angle of the cut with respect to the horizontal. The jet can enter at an impingement angle θ_0 ; theory indicates that impingement angles greater than 90 deg will produce deeper cuts. To simplify the fluid dynamics, Crow makes the assumption that the depth (d) of the jet stream is everywhere small compared with the radius of curvature (R)

$$d \ll R \text{ or } d_0 \ll h \quad (B.1)$$

The equations of motion are written in the form of integrals through the depth of the curved jet (Figure B.1). The variable of integration is the normal coordinate (n), perpendicular to the streamwise coordinate (s). The density of the water (ρ) is constant throughout the flow. The water has velocity (u) and the pressure (p) at the location (s, n). Along the interface (s, d) between air and water, p must equal the atmospheric pressure (p_a). Streamline curvature raises p to some higher pressure (p_s) at the cutting surface ($s, 0$). The water speed u is uniform across the jet at $s = 0$ and has a value u_0 related to the stagnation pressure (P_0) in the pressure intensifier by the Bernoulli equation

$$P_0 - p_a = 1/2 \rho u_0^2 \quad (B.2)$$

FIGURE B.1 Cutting Surface Geometry and Coordinates

The jet width is constant by assumption; therefore, volume conservation takes the form

$$\int_0^d u \, dn = u_0 d_0 \quad (\text{B.3})$$

Conservation of motion normal to the streamlines results in a pressure balance

$$p_s - p_a = 1/R \int_0^d \rho u^2 \, dn \quad (\text{B.4})$$

Conservation of momentum parallel to the streamlines relates the decay of streamwise momentum flux (ρu^2) to the shear stress (τ) on the cutting surface

$$d/ds \int_0^d \rho u^2 \, dn = -\tau \quad (\text{B.5})$$

The interfacial shear stress (τ) is caused by the drag of water upon grains protruding from the cutting surface. To construct a model of τ the general nature of flow around a grain is examined. The grain is treated as a

rough sphere, having diameter (g) small compared with the stream depth (d) so that the grain participates in the hydrodynamic environment of the cutting surface. The phenomenon governing the shear stress is cavitation; the cavitation number $[(p_s - p_v)/(1/2 \rho u^2)]$ (where p_v is the vapor pressure of water) is small which means that cavity bubbles trail behind the grains (Figure B.2).

FIGURE B.2 Cavitation Model

As the radius of curvature increases, the level of cavitation increases, and the water loses contact with the grains. As the radius of curvature decreases, the surface pressure (p_s) increases and collapses the cavity bubbles, thereby exposing more grains to direct impact of the water. The fully exposed grains have streamwise separation (l). The interfacial shear stress can be written as

$$\tau = 1/2 \rho u^2 c_f (p_s - p_v)/(1/2 \rho u^2) \quad (\text{B.6})$$

where the skin friction coefficient (c_f) is some increasing function of the cavitation number. This is further simplified into the friction law

$$\tau = \mu_w (p_s - p_v) \quad (\text{B.7})$$

where the water exerts Coulomb friction upon the rock, a friction proportional to normal pressure but independent of flow velocity; μ_w is the coefficient of Coulomb friction.

To pace the jet, the cutting surface must be in a continuous state of incipient failure. A failure criterion to complement the friction law [Equation (B.7)] is developed based on the coefficient of internal friction for the rock (μ_r) and the finite permeability of the rock. The high surface pressure (p_s) forces water through the pores of the cutting surface, creating a precursor of saturated rock (Figure B.3).

FIGURE B.3 Permeability Model

The pore pressure (p) within the saturated region ranges from p_s at the cutting surface (CS) down to p_a at the interface between wet and dry rock (WD). The pore pressure relieves the internal friction and results in a failure criterion

$$\tau = \tau_0 + \mu_r (p_s - p) \quad (\text{B.8})$$

The pressure difference ($p_s - p$) just beneath the cutting surface can be found by applying Darcy's law for the flow of fluid through a porous medium. The criterion for failure of the cutting surface is based on a hypothesis fundamental to this theory: the rock is in a continuous state of incipient fracture one grain diameter (g) beneath the cutting surface. Shear stress on the rock side of the cutting surface is

$$\tau = \tau_0 + \mu_r g v/k \sin \theta \quad (\text{B.9})$$

where k is the permeability of the rock. Implicit in Equation (B.9) is an intrinsic speed (c) for rock cutting

$$c = (k \tau_0) / (\mu_r g) \quad (B.10)$$

APPENDIX C

THEORY OF PNEUMATIC CONVEYANCE

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THEORY OF PNEUMATIC CONVEYANCE

A review of the multiphase flow concepts applicable to pneumatic conveyance in vertical, horizontal, and inclined systems is presented. All orientations may eventually be included in a pneumatic conveyance system; although vertical and inclined transport are expected to predominate. The information is based on data established for gas-solid mixtures.

C.1 VERTICAL TRANSPORT CORRELATIONS

The total pressure drop (ΔP_t) for the upward flow in a dilute system is expressed as

$$\Delta P_t = \Delta P_a + \Delta P_g + \Delta P_f \quad (C.1)$$

The terms on the right side are respectively the pressure drop caused by acceleration (ΔP_a), gravity (ΔP_g), and friction (ΔP_f). The pressure drop caused by acceleration occurs because the solids enter the pipe at a low velocity and must be accelerated to their equilibrium velocity. After the equilibrium velocity has been achieved, the pressure drop due to acceleration is zero. The gravitational pressure drop is simply caused by the weight of the solids and the frictional pressure drop is caused by the wall friction and the momentum loss from particle-wall collisions.

C.1.1 Pressure Drop Caused by Acceleration

The pressure drop caused by acceleration occurs primarily at the pipe entrance. Acceleration length (L) is equivalent to entrance length in a single phase system and is the length needed to achieve stable transport conditions. Acceleration lengths for gas solids flows can be considerably longer than the entrance length for single phase flows (about 30 diameters). Many correlations have been proposed for acceleration lengths. For horizontal, inclined and vertical pipes, Rose and Duckworth (1969) propose the following correlation to predict acceleration length.

$$L/D_t = 6 [(m_s / (\rho_g g^{0.5} D_t^{2.5})) (D_t/D_p)^{0.5} (\rho_s/\rho_g)]^{1/3} \quad (C.2)$$

where D_t is the inside diameter of the pipe, m_s is the mass flow rate of solids, ρ_g and ρ_s are the densities of the gaseous and solids phases, g is gravitational acceleration, and D_p is the particle diameter. There are, however, no well verified, generally accepted predictive techniques. In most practical systems, both the acceleration length and the pressure drop associated with it are small and neglect of the acceleration length and the associated pressure drop does not significantly affect the total pressure drop.

Another source of pressure drop is the acceleration of the gas caused by a change in volume fraction of the gaseous phase (ϵ). The volume fraction of the gaseous phase generally exceeds 95% in dilute systems. A further effect may be the change in gas velocity due to a change in density because of pressure and temperature changes. Generally these effects are not considered.

C.1.2 Gravitational Pressure Drop

The pressure drop per unit length due to gravity is simply the product of the mixture density and acceleration due to gravity.

$$\Delta P_g / \Delta H = g [(1 - \epsilon) \rho_s + \epsilon \rho_g] \quad (C.3)$$

where ΔH is the change in elevation.

C.1.3 Frictional Pressure Loss

The pressure loss caused by friction is subdivided into the pressure loss from the gaseous phase (ΔP_{fg}) and that from the solids phase (ΔP_{fs}).

$$\Delta P_f = \Delta P_{fg} + \Delta P_{fs} \quad (C.4)$$

The conventional Darcy-Weisbach correlation is used for both phases; that is,

$$\Delta P_{fg} = f_g (\Delta L/D_t) (\rho_g u_g^2/2) \quad (C.5)$$

$$\Delta P_{fs} = f_s (\Delta L/D_t) [(1 - \epsilon) \rho_s u_s^2/2] \quad (C.6)$$

where u_g and u_s are the actual velocities of the gaseous and solids phases. Many correlations have been published for the solids friction factor (f_s), such as those by Yang (1978), Jones et al. (1967), Rose and Duckworth (1969) and Ozbelge (1983 and 1984). Ozbelge obtained a correlation and developed a model for the solids friction factor in vertical upward pneumatic conveying lines.

$$f_s = 0.0054(S \rho_g/\rho_s)^{-0.115} [u_g D_t/((u_g - u_s) D_t)]^{0.339} \quad (C.7)$$

where S is the solids loading and D_p is the particle diameter. The correlation is valid for the following ranges of variables when air is used as the carrier:

- ϵ volume of the gaseous phase, 0.980 to 0.999
- D_p particle diameter, 213 to 503 μm
- ρ_s particle density, 2600 to 2707 kg/m^3
- D_t pipe diameter, 6.76 to 13.54 mm
- u_g superficial gas velocity, 6.0 to 12.5 m/s.

The correlation is good to $\pm 20\%$ if experimental data of Hariu and Molstad (1949) are used. The frictional pressure drop is given by

$$\Delta P_f = f_g (\Delta L/D_t) (\rho_g U_g^2/2) \quad (C.8)$$

The gas friction factor (f_g) is calculated assuming standard single phase flow techniques. The equation is limited to loadings less than 12.

C.1.4 Volume Fraction of Gaseous Phase in Dilute Phase Systems

Reasonable estimates of the volume fraction of the gaseous phase (ϵ) can be made by defining that the slip velocity between phases is equal to the terminal velocity (u_T) of an isolated particle. Thus

$$u_T = u_g - u_s = U_g/\epsilon - U_s/(1 - \epsilon)$$

C.1.5 Application of Correlations for Dilute Phase Transport to Conveyance Operation

It is useful to examine the correlations provided to determine the probable characteristics of a pneumatic conveyance system. Actual system design requires performing iteration to solve all equations describing pneumatic transport. However, it is possible to determine the upper bound of operation and estimates of important features such as the maximum volume fraction and mass fraction of solids during operation by performing the first steps in the iteration. Examining the relationship between mass fraction of solids and volume fraction of solids will also reveal the importance of controlling the particle size and erosion rate during scarifier operation.

In order to determine the limits of operation, it is first necessary to describe the features of the scarifier and pneumatic conveyance system that are relevant to operation of the conveyance system. The relevant features are

- The scarifier is located near the bottom of the tank.
- Air enters the scarifier shroud at atmospheric pressure.
- The air compressor or blower for the system is located outside the tank, exhausts to the atmosphere, and can increase the pressure head by at most one-half atmosphere (50 kPa).
- The pneumatic conveyance system must lift the solid-liquid-gas mixture approximately 20 m.
- Scarifier operation governs the particle size and consequently, the terminal velocity of the particle in air.
- The solids density will be approximately 2000 kg/m³.

The critical parameters for this system are:

- The total pressure drop across the conveyance system must be less than $\Delta P_{\max} = 50 \text{ kPa}$.
- The elevation change for the solid-liquid-gas mixture is $h = 20 \text{ m}$.
- The terminal velocity (u_T) of the particulate in the conveyance line that was eroded by the scarifier is set at some value.

It is possible to estimate the lower bound for the gas volume fraction ($\epsilon_{\min}$) that must be achieved during conveyance in this simple system by

ignoring the pressure loss due to friction and assuming pressure drop arises only as a result of hydrostatic pressure variations. Rearranging Equation (C.3) and neglecting the contribution of the gas density relative to the total mixture density results in

$$\begin{aligned}\epsilon_{\min} &= 1 - \Delta P_{\max}/(\rho_s g h) \\ &= 1 - 50 \text{ kPa}/(2000 \text{ kg/m}^3 \cdot 9.8 \text{ m/s}^2 \cdot 20 \text{ m}) \\ &= 0.87\end{aligned}\tag{C.10}$$

Using the critical parameters for this system this results in a minimum gas volume fraction of $\epsilon_{\min} = 0.87$, or a solids volume fraction of 0.13. At this spatial concentration, there would be pressure head developed by the blower sufficient to overcome the hydrostatic pressure drop. However, there would not be sufficient excess head to cause the system to flow. In fact, the system must operate at a higher gas volume fraction, and it might be anticipated that a gas volume fraction of 95% might be required during operation.

More important parameters are the volume fraction of the gaseous phase (ϵ) also called the void fraction and the ratio of the mass flow rate of particulate (m_s) to the mass flow rate of gas (m_g). These are:

$$m_s/m_g = [\rho_s (1 - \epsilon) u_s]/(\rho_g \epsilon u_g)\tag{C.11}$$

It is desirable to optimize the ratio (m_s/m_g) during conveyance. Examination of the relation reveals several features:

- For a given gas volume ratio, the ratio of the particle mass flow rate to the gas mass flow rate (m_s/m_g), increases with decreasing ratio of the particle terminal velocity to the gas velocity (u_t/u_g) for constant volume of the gaseous phase. Consequently, higher mass solids throughput can be achieved at the same gas volume ratio by decreasing the particle size achieved by the scarifier.
- For a given gas volume ratio, the maximum value of

$$m_s/m_g = \rho_s/\rho_g (\epsilon^{-1} - 1)$$

and occurs in the limit when the terminal velocity of the particles fed into the system is very small compared to the gas velocity.

For a typical scarifier/conveyer system, the ratio of the densities would be expected to be on the order of $\rho_s/\rho_g \sim 2000$, and the design gaseous volume fraction might be selected to be 95%. In this case the maximum possible solids mass flow ratio would be $m_s/m_g \sim 105$ kg solid/kg gas. This will occur when the solids are broken into very small fragments by the scarifier, or when the gas velocities are permitted to be very large.

- For a given gas volume ratio, the minimum value of $m_s/m_g = 0$. This occurs when $u_T/u_g = 0$. This situation is one in which gas is moving just fast enough to keep particles in suspension, but no material is removed from the scarifier and conveyed out of the tank.

This situation will tend to occur when the particles are very large, or if the maximum gas velocity achieved in the system is very low. Because high gas velocities are associated with large frictional losses, the total pressure drop will be lower when particles are conveyed than when large particles are conveyed at the same volume fraction.

Up to this point, the volume fraction has been discussed as though it were an independent parameter subject to control. However, during operation volume concentration is controlled indirectly by controlling the mass flow ratio. It may be predicted by rearranging Equation (C.11). In order to ensure the gas volume fraction remains above the minimum value the mass flow rate of the two phases, the gas velocity and the particle settling velocity must be controlled such that

$$[(\rho_s/\rho_g) (m_g/m_s) (1 - u_T/u_g) + 1]^{-1} > \epsilon_{\min} \quad (C.12)$$

If this criterion is not met, then the pressure drop across the system will not be sufficient to convey solids, and the system will choke, most likely to be followed by plugging. Choking can occur if the particle size eroded by the scarifier is too large resulting in a larger u_T than can be conveyed, or if the dislodging rate is too high for the conveyance system. In the scarifier and pneumatic conveyance system, the solids settling velocity and the particle mass flow rate that must be conveyed will be determined by scarifier operation, while the gas velocity and the mass flow rate will be more strongly influenced by the design of the blower or compressor used to move the air.

It is clear that operation of the two systems must be tightly linked. The scarifier must provide a feed at low enough mass flow rate and of a small enough size to prevent the gaseous volume fraction from exceeding its upper bound. At the same time, the mass flow rate should be kept high enough to ensure adequate throughput. The conveyance system must be sized to provide the appropriate gas velocity and gas mass flow rate to convey the feed provided by the scarifier. If the two systems are not properly sized, the conveyance system will plug or alternatively may operate at lower solids loadings than necessary. For this reason, accurate correlations to predict the operation of both components will be crucial to design of the complete system.

C.2 GAS-SOLIDS FLOW IN HORIZONTAL LINES

During gas-solids flow in horizontal lines, the particles conveyed at high velocities will remain suspended in the flow and the system will behave as a single phase flow with a modified friction factor. In this situation the pressure drop will decrease with decreased velocity. As the flow velocity is reduced, particles will tend to settle out on the bottom of the pipe. The result will be a reduced cross-sectional flow area for the gaseous phase and an increase in the phase velocity of the gaseous phase. As the accumulation of the particles continues, the increase in gaseous phase velocity causes an increase in pressure drop. The velocity corresponding to the minimum pressure drop is called the "saltation" velocity. Systems operating at velocities exceeding the saltation velocity are dilute while those with velocities below the saltation velocity are dense.

C.2.1 Flow Patterns

The major flow patterns that have been observed in horizontal gas-solids flow are shown in Figure C.1. Transition between the various flow patterns is gradual and there are intermediate flow patterns. The flow patterns are numbered in the order of increasing solids concentration.

FIGURE C.1 Flow Patterns During Gas-Solid Horizontal Pipe Flow

The **symmetric-disperse** pattern occurs at high solids velocity. In this regime, particles are uniformly distributed in the gas stream. As the solids velocity decreases, effects of gravity cause the concentration of particles in the bottom layers to increase. This is the **asymmetric-disperse** pattern. With a further decrease in the gas velocity (i.e. increase in solids concentration), saltation velocity is reached and the particles begin to deposit at the bottom of the pipe. Small clusters of particles are formed that slide along the bottom of the pipe. This pattern is called **immature dune** by Wen and Galli (1971) and moving bed by Govier and Aziz (1972).

With further decrease in gas velocity, deposition of particles increases and the clusters grow into dunes to form the dune flow pattern. The motion of the particles along the wall ceases or is very slow. Gas accelerates as it approaches the dune (caused by flow area restriction) and then decelerates (caused by expansion) after passing the peak of the dune. Particles are blown off one dune and deposit on the next dune downstream.

Further decrease in solids-to-gas ratio and/or gas velocity can result in the flow of gas and solids in alternate slugs. With further decrease in gas velocity, solids fill most of the pipe cross-section, and solids loadings

up to 900 kg/kg of gas have been achieved with this flow pattern (Wen and Galli 1971). With further decrease in air velocity and/or solids concentration, the pipe gets blocked, and flow ceases.

C.2.2 Prediction of Saltation Velocity

Several researchers (Rose and Duckworth 1969, Doig and Roper 1963) state that saltation velocity is numerically equal to the choking velocity in upward flow. The correlation of Rose and Duckworth (1969), may be applied for both

$$U_x = 3.24 u_T [m_s/m_g]^{0.2} [D_t/D_p]^{0.6} [\rho_g/\rho_s]^{0.7} [U_x^2/(g D_t)]^{0.25} \quad (C.13)$$

for this application, $U_x = U_{salt} = U_{ch}$ depending on the type of flow.

Ochi (1991) conducted an experimental investigation to determine the saltation point of coarse particles. Experimental conditions included pipe diameters of 40, 50, and 60 mm and three types of particles having diameters ranging from 2.0 to 4.1 mm. Ochi (1991) also developed an expression to predict saltation velocity.

$$U_{salt} = 1.05 f_s (g D_t)^{0.5} [u_T/(g D_s)]^{0.82} (m_s/m_g)^{0.25} \quad (C.14)$$

C.2.3 Pressure Drop in Dilute Phase Pipe Flow

Pressure drop in horizontal flow may be expressed as

$$\Delta P_t = \Delta P_a + \Delta P_f \quad (C.15)$$

Acceleration pressure drop and frictional pressure drop have been demonstrated to be the same as for dilute phase vertical flow. These correlations will be valid as long as velocity is well above the saltation velocity. Acceleration length may be calculated by the Rose and Duckworth correlation, Equation (C.2).

C.4.3 PRESSURE DROP IN INCLINED PIPES

Genium (1984) presents a method to estimate pressure drop from up flow in inclined pipes when the gas velocity is well above the saltation or choking

velocity. Calculate frictional pressure drop and acceleration pressure drop as for dilute phase vertical flow. To estimate the gravitational pressure drop, calculate Δp_g for vertical up flow and then multiply by $\sin \theta$, where θ is the angle of inclination with horizontal.

C.4.4 PRESSURE DROP IN BENDS

Pneumatic conveying lines involve many 90 deg bends. Krauss (1980) states that there are no reliable correlations for pressure drop in bends and recommends considering the bend to be a straight pipe of length 1.6 times its actual length measured along its axis. Leung and Wiles (1976) recommend that pressure drop in bends be estimated according to the E.E.U.A. Handbook (1963)

$$\Delta p_{\text{bend}} = 0.5 \text{ to } 1.5 [u_g^2 \rho_{\text{mix}} / (2 g)] \quad (\text{C.16})$$

where ρ_{mix} is the density of gas-solid mixture given by

$$\rho_{\text{mix}} = (1 - \epsilon) \rho_s + \epsilon \rho_g \quad (\text{C.17})$$

The design should be based on the more conservative result.

APPENDIX D

REVIEW OF PRIOR EXPERIMENTS

APPENDIX D

REVIEW OF PRIOR EXPERIMENTS

Several studies conducted at Hanford in recent years have investigated applying water jets and pneumatic conveyance technologies to remediate waste tanks. The results from these investigations are summarized.

D.1 PNEUMATIC CONVEYANCE

To support the Hanford Federal Facility Agreement and Consent Order^(a) milestone M-06-01: "Identify Waste Retrieval Technologies to be Tested in Scale-Model Tank, October 1990", Westinghouse Hanford Company conducted a review of single-shell tank waste retrieval options (Krieg, Jenkins, Leist, Squires, and Thompson 1990).

D.1.1 AIR CONVEYANCE TESTS IN 1975

An experimental investigation conducted by Vitro^(b) in 1975 was analyzed by Krieg et al. (1990) who state:

"Pneumatic recovery methods investigated focused on a subatmospheric, high-volume airflow system that would lift sludge and granular salt cake up to 18.3 m (60 ft) to a proposed above-tank retrieval station. There, 18.9-m³-capacity (5000 gal.) portable tanks would be loaded for truck transport. The suction nozzle would be attached to a flexible pipe, which would be moved in the tank by an undefined, remote-controlled arm. Tests were conducted with a commercially available, truck-mounted pneumatic system to lift sludges and salt cake from test drum 4.9 to 18.3 m (16 to 60 ft). These tests were successful in retrieving soupy, granular, synthetic wastes but were less successful with solid materials. High-pressure water jets were added to the system to investigate their ability to breakup 'frozen salt cake and reacted clay-caustic products.' It was determined that a 6.9×10^7 Pa

(a) Ecology, EPA, DOE. 1989. Hanford Federal Facility Agreement and Consent Order. Washington State Department of Ecology, U.S. Environmental Protection Agency, and the U.S. Department of Energy, Olympia, Washington.

(b) Vitro. 1975. Evaluation and Adaptation of Standard Mechanical, Hydraulic, & Pneumatic Devices for Salt Cake and Sludge Retrieval at Hanford, Appendix C Pneumatic Retrieval System, VITRO-R-375, Vitro Engineering, Richland, Washington.

(10,000 psia) water jet at 2.5×10^{-4} and 3.2×10^{-4} m³/s (4 to 5 gal./min) broke up and highly emulsified these products; the resulting emulsified product was pneumatically retrievable. The 6.9×10^6 and 1.4×10^7 Pa (1,000 psia and 2,000 psia) water jets, at the same flow rate, did not break up the products."

The retrieval tests were conducted with VIP Corporation's Model 700 Vactor Vacuum Truck. The system had a nominal 1.3 m³/s (2700 ft³/min) triple-stage suction fan, providing a suction of 54 kPa (16 in. Hg). The 0.2-m-dia. (8-in.) hose was made of flexible stainless steel. Data from this test are summarized in Table D.1. The tests were conducted using chemical simulants. Recipes and property data are summarized in Table D.2.

TABLE D.1 Results from Pneumatic Retrieval Tests
with VIP CP Model 700 Vactor Vacuum Truck

Test	Vertical Lift, ft	Hose Length, ft	Waste Type	Retrieval Rate, barrels/hr	Water Rate, gpm	Rate Pressure, psi	Remarks
6	60	112	jelly	5	0		Two men required to manipulate nozzle
7	60	112	caustic liquid	40	0		Excessive air leaks, liquid leg formed at 1.5 min, 1.2 barrel
8	60	112	water	60	0		
9	16	36	water	240	0		Two 55-gal. barrels H ₂ O
10	16	36	jelly	slow	0		Breakup device required, Barrel No. 16, 1 ft of sand and 8 in. salt cake
1,2,5	16	36	frozen salt cake	0	0	0	
				0	5	2,000	Five nozzles directed straight
				0	4	10,000	Cut hole 18 in. deep, 2 in. dia.
3	16	36	clay	~0	5	2,000	
4	16	36	clay	~6	4	10,000	One nozzle manually directed
11	16	36	jelly	10>	5	1,200?	Barrel No. 17, real sticky, salt cake needs bigger container
12	16	36	jelly	10>	5	1,200	five nozzles impinging 6 in. below air inlet

TABLE D.2 Simulant for 1975 Conveyance Test

Caustic Liquid		
Material	Moles	Wt%
NaAlO ₂	1.8	10
NaNO ₂	2.1	10
NaNO ₃	3.4	20
NaOH	3.6	10
H ₂ O	40.0	50
Density		1.4 to 1.5 g/cc

Salt Cake	
Pure NaNO ₃ crystals interlaced with 5 to 50 Wt% caustic mother liquor (from recipe for caustic liquid). Salt cake is considered saturated when it contains 30 Wt% mother liquor.	
Typical sieve range for NaNO ₃ crystal aggregates is 0.707 mm to 1.41 mm. When observed under a microscope the crystals range from 0.177 mm to 0.595 mm.	
bulk density	1.41 ± 0.19 g/cm ³
particle density	2.31 ± 0.21 g/cm ³

Damp Salt Cake	
Damp salt cake with particle sieve size of 0.707 mm exhibits the properties of a jelly.	

Sludge		
Thick, sticky, dark	brown	paste
Density, g/cm ³	Synthetic	103A
wet	1.4	1.5
particle, air dried	1.9	2.1
topped, air dried	1.5	---
Composition	Synthetic	Sludge
Component	Wt%	
H ₂ O	31	
NaNO ₃	6	
NaNO ₂	8	
NaAlO ₂	10	
Fe(OH) ₃	11	
Na ₂ SO ₄	17	
Sr(OH) ₂	6	
Na ₂ CO ₃	14	

D.1.2 AIR CONVEYANCE TESTS IN 1990

An off-the-shelf air conveyance system was evaluated as a method of waste retrieval. The test objective was to evaluate conveyance of a sludge simulant up to a 18 m (60 ft) elevation difference. The system tested was a Hi-Vac Corporation^(a) Model 240, LP Hi-Vac. The system could sustain a vacuum pressure on 61 kPa (18 in. Hg). The vacuum line was made of flexible coiled hose about 0.1-m- dia. (4-in.). The simulant recipe, test conditions and observations are summarized in Tables D.3 and D.4.

TABLE D.3 Simulant for 1990 Pneumatic Conveyance Test

Simulant Recipe	
13.5 Wt% bentonite clay (200 mesh)	
32.4 Wt% barium sulfate (400 mesh)	
54.1 Wt% water	
Physical Properties	
bulk density	1.6 g/ml
viscosity	1.7×10^6 cP
color	beige
rheology:	cohesive
	yield pseudoplastic paste

The method chosen was to test conveyance using a commercially available system without modification. The results showed that using that system with modest water addition

- vertical and horizontal runs could not successfully be combined (Test 2)
- steady state vertical conveyance was not demonstrated (Test 2)
- waste could be conveyed horizontally without system plugging and steady state pressure was approached (Test 3A and 3B)

A plot of pressure increase versus percent of material conveyed for these tests is presented in Figure D.1 (Thompson 1990).

(a) Hi-Vac Corporation, Marietta, Ohio.

TABLE D.4 Results from the 1990 Pneumatic Conveyance Tests

Test 1: Vertical Configuration	
Hose run: 13 m (42.5) ft vertical	
Observations:	
1.	Hose coated with 6 mm (0.25 in.) layer after transport of $\sim 0.03 \text{ m}^3$ ($\sim 7 \text{ gal.}$)
2.	Water conveyed intermittently to reduce material build up on hose walls
3.	Hose plugged after transport of $\sim 0.08 \text{ m}^3$ ($\sim 20 \text{ gal.}$)
4.	Water injection added to inlet of feed nozzle
5.	Final 0.04 m^3 (10 gal.) conveyed without problems
6.	Maximum vacuum pressure 61 kPa (18 in. Hg)
Test 2: Vertical/Horizontal Configuration	
Hose run: 18 m (60 ft) vertical, 12 m (40 ft) horizontal with 180 deg bend	
Water injection system	
Observations:	
1.	0.06 m^3 (15 gal.) conveyed in 20 min. period with water injection
2.	During this period the vacuum climbed steadily, indicating line plugging
3.	Transport terminated at a pressure of 58 kPa (17 in. Hg), just prior to plugging
4.	Inspection of the line showed that most material deposited in the hose at the transition from vertical to horizontal run
5.	Inspection of the hopper showed that 0.008 m^3 (2 gal.) reached the hopper, the remaining 0.05 m^3 (13 gal.) was deposited in the line
6.	Maximum vacuum pressure 58 kPa (17 in. Hg)
Test 3A: Horizontal Configuration	
Hose run: 15.2 m (50 ft) with 3-360-deg loops and 3-90-deg bends	
Larger water injection system	
Observations:	
1.	0.06 m^3 (15 gal.) conveyed at vacuum pressure of 41 kPa (12 in. Hg)
2.	Test stopped for system inspection. No material was observed on hose walls.
3.	Test not restarted.
Test 3B: Horizontal Configuration	
Hose run: 30 m (100 ft) with 3-360-deg loops and 3-90-deg bends	
Larger water injection system	
Observations:	
1.	$\sim 0.17 \text{ m}^3$ ($\sim 45 \text{ gal.}$) of simulant conveyed
2.	No buildup observed on walls
3.	Maximum vacuum pressure of 49 kPa (14.5 in. Hg)

D.1.3 AIR CONVEYANCE TESTS IN 1992

Conveyance experiments are ongoing in FY-92 as a part of experiments to investigate the performance of soft waste dislodging end effectors.^(a) Two end effector configurations are being tested: 1) mechanical agitator

(a) J. D. Potter. Single-Shell Tank Soft Waste Dislodging and Conveyance Systems, Development Test Procedure, WHC-SD-TC-026, Rev. A. (In preparation). Westinghouse Hanford Company, Richland, Washington.

FIGURE D.1 Pressure Increase during Conveyance Tests

configuration and 2) a scarifier configuration.^(a) The scarifier configuration uses the same body as the mechanical agitator, but the blade assembly replaced by a nozzle assembly with the addition of an inlet extension assembly. The air conveyance system to be tested is a commercial unit from Hi-VAC Corporation, consisting of an AC Power Head Model #475 (75 hp) with a bottom dump hopper (30 ft³) and a 0.15-m-dia. (6-in.) hose.

Three types of simulants are specified to model the soft waste:

- kaolin clay and water having "thin and soupy" consistency
- kaolin clay and water having "peanut butter" consistency

(a) The WHC test scarifier configuration differs significantly from the one described in this strategy plan. The WHC system has a maximum jet water pressure of 10.3 MPa (1500 psi) in comparison with from 206 to 379 MPa (30,000 to 55,000 psi) for the other design.

- bentonite clay and barium sulphate having "thick modeling clay" consistency.

In addition to the simulants, debris and obstacles, such as measuring tapes and 16 gauge copper wire may be incorporated into the samples.

D.2 SCARIFIER

Scarifiers are used to erode solid materials using high pressure water jets; the eroded material is conveyed pneumatically away from the surface.

D.2.1 Scarifier Tests in 1990

Quest Integrated, Inc., under subcontract to Westinghouse Hanford Company, conducted experiments at their facility to appraise air and water jet scarifiers as potential dislodging tool candidates for single-shell tank waste retrieval activities. Tests performed employed air and water jets to cut soft and hard salt cake, as well as sludge. Water jet pressures as high as 379 MPa (55,000 psi) have been tested, while air jet pressures were regulated to a maximum of 10 MPa (1500 psi). The diameter of the nozzle orifice was altered during the tests, while the water pressure was regulated to keep the water use rate constant at $9 \times 10^{-5} \text{ m}^3/\text{s}$ (1.5 gpm). Recipes for the simulants are summarized in Table D.5. Test results are summarized in Table D.6.

The test results suggest that scarifiers would be successful when used to erode salt cake or soft sludge. However, difficulties were encountered when eroded soft sludges were conveyed pneumatically. No attempts were made to optimize the scarifier or the conveyance system during this proof-of-principle test.

D.2.2 Scarifier Applications at West Valley

A variety of water jet systems, abrasive and non-abrasive, were used during decontamination of the West Valley Nuclear Services facility (Tundo, Gessner, and Lawrence 1988). The non-abrasive water jet was used to

- remove concrete buildup from cement mixers without damaging the internal parts of the mixer. (The cement mixers were used to mix concentrated low-level liquid waste with cement to encapsulate the waste in concrete.)

TABLE D.5 Simulant for 1990 Air/Water Jet Scarifier Feature Tests

Sludge	
Component	Wt%
bentonite clay, 200 mesh	13.3
barium sulphate, 400 mesh	32.4
water	54.1
bulk density, g/ml	1.6
viscosity, cP	1.7×10^6
rheology	yield pseudoplastic paste
Hard Salt Cake	
Component	Wt%
sulfur K-mag	80
water	20
bulk density, g/ml	2.0
compressive strength, MPa	1.4
psi	200
Sulfur K-mag is a potassium sulphate and magnesium sulfate crystalline commercial fertilizer. When cured it yields a very hard, brittle cake of salt.	
Soft Salt Cake	
Component	Wt%
urea	80.0
sugar	11.4
water	8.6
bulk density, g/ml	1.1
Urea or carbamide is a granular commercial fertilizer. When mixed with water and sugar, it possesses a firm, but strengthless, snow cone-line consistency that is somewhat sticky.	

- the water jet was used to remove smearable and fixed contamination from cell ceilings, walls and floors and was very effective for removing contaminated paint.

The surface scarifier used for this work contained 8-high-pressure jets. As the unit traversed along its path, the high-pressure jets rotated, removing a 0.356 m (14 in.) wide surface area. A shroud mounted over the spray head, is used to contain all the spray debris, which was collected via a vacuum system. The scarifier operated between 172 MPa (25,000 psi) and 241 MPa (35,000 psi). The traverse speed was varied to control the depth of surface

removed. The operating pressure and traverse speed depended primarily on the integrity of the paint or concrete surface to be removed.

TABLE D.6 Test Results for 1990 Air/Water Jet Scarifier Feature Tests

Hard Salt Cake - Water Jet
The water jet cut the hard salt cake with an incision slightly larger than the orifice diameter. Three orifice diameters were chosen to obtain pressures of 69, 186, and 345 MPa (10,000, 27,000 and 50,000 psi), each with a flow rate of $9 \times 10^{-5} \text{ m}^3/\text{s}$ (1.5 gpm). At low traversing speeds cutting efficiency was improved by increasing the cutting pressure to 345 MPa (50,000 psi). At high traversing speeds the improvement was not visible. At both speeds the 69 MPa (10,000 psi) jet is visibly less effective.
Soft Salt Cake - Water Jet
During these tests the water jet blasted through the 0.08 m (3-in.) depth of simulant and reflected off the bottom of the pan.
Hard Salt Cake - Air Jet
An air jet could not cut the hard salt cake. Traversing the sample left no impression.
Soft Salt Cake - Air Jet
The 10 MPa (1500 psi) air jet blew out a kerf as deep as the pan and 0.05 to 0.1 m (2 to 4 in.) wide. Reflection of the air jet off the bottom of the pan was credited for the effect. With pressure reduced to 200 psi the air jet cut a trough 0.03 m (~1-in.) wide and ~0.038 to 0.044 m (~1.5 to 1.75-in.) deep. The trough did not penetrate to the pan bottom.
Sludge - Air Jet
With a 10 MPa (1,500 psi) air jet emanating from a 3-mm-dia. (0.125-in.) orifice, one pass over the sludge at 2.0 m/s (400 ft/min) uplifted the sludge and threw much of it around. This was caused by reflection. With reduced pressures of 0.69 to 1.4 MPa (100 and 200 psig) the jet cut cavities in the sample.
Hard Salt Cake - Parallel Cuts - Water Jet, Air Jet
Parallel cuts separated by 1.3, 2.5, and 3.8 cm (0.5, 1.0 and 1.5 in.) were made at a jet pressure of 379 MPa (55,000 psi). The salt cake between cuts fractured for separations of 1.3 and 2.5 cm (0.5 and 1.0 in.) but not for 3.8 cm (1.5 in.). All sections fractured at a depth of 3.8 cm (1.5 in.) although the cut depth was 5.1 to 6.4 cm (2 to 2.5 in.). When the water jet cuts were followed by air jets, the same results were obtained.
With the water jet at a 45-deg angle salt cake fractured and broke out at a depth of 3.8 cm (1.5 in.) at separation distances of 1.3 and 1.9 cm (0.5 and 0.75 in.) but not at 2.5 cm (1.0 in.). Another test using an air jet followed by a water jet produced similar results.
Cuts 3.8 to 6.4 cm (1.5 to 2.5 in.) deep were also obtained with a jet at a 20-deg angle to the salt cake. For water jets and air and water jets the maximum separation distance to produce sample breakout was 2.5 cm (1 in.).
To evaluate consistency of sample breakout for separate tests were performed with a 45-deg angle jet. Water only, and air and water tests were compared. Tests with separations of 1.3 cm (0.5 in.) were successful in breaking out all cut pieces. In tests with separations of 2.5 cm (1 in.) only the air and water jet combination was able to break out all cut samples.

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