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HAZARDOUS WASTE RETRIEVAL STRATEGIES USING A HIGH-PRESSURE WATER JET SCARIFIER

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ABSTRACT

The Waste Dislodging and Conveyance Program is sponsored by the U.S. Department of Energy Office of Technology Development to investigate waste dislodging and conveyance processes suitable for the retrieval of high-level radioactive waste. This program, represented by industry, national laboratories, and academia, has proposed a baseline technology of high-pressure water jet dislodging and pneumatic conveyance integrated as a scarifier as a means of retrieval of waste inside Hanford single-shell tanks. A testing program has been initiated to investigate system deployment techniques to determine appropriate mining strategies, level of control, sensor requirements, and address integration issues associated with deploying the scarifier by a long robotic manipulator arm. A test facility denoted the Hydraulics Testbed (HTB) is being constructed to achieve these objectives and to allow longer-duration, multiple-pass tests on large waste fields using a versatile gantry-style manipulator. Mining strategy tests with materials simulating salt cake and sludge waste forms will be conducted to evaluate the effectiveness of mining strategies, forces related to scarifier and conveyance line, and retrieval rate. This paper will describe the testbed facility and testing program and present initial test results to date.

1. INTRODUCTION

The Waste Dislodging and Conveyance Program is sponsored by the U.S. Department of Energy Office of Technology Development to investigate waste dislodging and conveyance processes suitable for the retrieval of high-level radioactive waste. This program, represented by industry, national laboratories, and academia, has proposed a baseline technology of high-pressure water jet dislodging and pneumatic conveyance integrated as a scarifier as a means of retrieval of waste inside Hanford single-shell tanks (Rinker et al. 1994). Waste simulants have been developed to challenge the retrieval process, and this technology has been shown to mobilize and convey the waste simulants at desired retrieval rates while operating within the space envelope and the dynamic loading constraints of the proposed deployment device: a long-reach manipulator (LRM). It has also been demonstrated that the baseline approach has versatility to continuously dislodge and convey a broad range of waste forms, from hard wastes to soft sludge wastes, through the use of rather simple, robust components. Figure 1 provides an overview of the remote retrieval strategy using a scarifier deployed with a long-reach manipulator.

A strategy (Bamberger et al. 1993) was developed to guide an analytical/experimental approach to develop a multi-function scarifier dislodger coupled with a pneumatic conveyance system. Based on the strategy, a testing program has been initiated to characterize aspects of waste dislodging and conveyance processes, evaluate process equipment performance, and address integration issues associated with deploying the scarifier by a long-manipulator arm. The mission of the program is to investigate system deployment strategies to determine appropriate mining strategies, level of control, and sensor requirements. This paper will describe the testbed facility and testing program and present initial test results to date.

2. RETRIEVAL SYSTEM DESCRIPTION

The baseline technology for the waste dislodging is a high-pressure water jet scarifier. High pressure water jet technology has been used by industry for many years for mining, cutting, cleaning, and scarifying materials with a broad range of properties. Proof-of-concept testing have demonstrated that high-pressure water jets can effectively dislodge several diverse waste simulants.

The test scarifier was develop by Quest Integrated, Inc. through collaboration with Pacific Northwest Laboratory (PNL)[1]. This scarifier consists of high-pressure fluid jets mounted on a rotating body and directed at the waste surface. The three rotating jets require approximately 22.7 liters per minute (6 gpm) of water at 344 MPa (50,000 psi). The rotation of the jet carrier is provided by a secondary motion drive, which nominally rotates at 650 rpm. The axis of the secondary motion rotation is normal to the waste surface. The secondary motion drive and jet carrier are contained in an aero-dynamical enclosure mounted concentric to and inside the

[1]PNL is a multiprogram laboratory operated for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830 by Battelle Memorial Institute.

conveyance system inlet shroud. The water jet assembly is encased in a shroud that contains the dislodged waste and water and directs the collected mixture to an air conveyance system.

Figure 2 shows the installation of the scarifier on the gantry mast. To measure dynamic forces due to air suction, inertia, and water jet reaction, the scarifier is attached to a sensor that measures forces and torques along three axes. The sensor is then mounted to a compliant joint, which is attached to the gantry mast and releases in the event of an overload condition. Forces are isolated from the conveyance line by a flexible bellows between the scarifier outlet and the conveyance line. An adjustable spring is used to "zero out" the steady-state moment and forces exerted by the scarifier by providing an alternate load path to the gantry mast.

3. TEST FACILITIES

To demonstrate the scarifier in an actual mining operation, a test facility denoted the Hydraulic Testbed has been constructed to allow longer-duration, multiple-pass tests on large waste fields using a versatile gantry-style manipulator (see Figure 3). A gantry was selected for implementing the mining operation due to its inherent rigidity, programmability, and large load capacity demanded by a technology development program. The actual gantry manipulator selected, provided by PaR Systems, Inc., includes four degrees of freedom to allow rectangular motion plus mast rotation. The control system of the gantry allows sensor data to be used to update the trajectory in real time. This feature allows candidate proximity sensors to be used in the course of an actual mining operation.

The ancillary equipment of the dislodging system includes a high-pressure hose and two high-pressure pumping units. The balance of the conveyance system includes a conveyance line, a wet/dry separator, a collection hopper, and a blower unit.

4. SYSTEM INTEGRATION

The most complete review of previous single-shell tank waste retrieval studies appears in Gibbons et al. (1993). The pertinent conclusions of this review were that hydraulic sluicing should be used to remove the waste inside the majority of single-shell storage tanks, and that arm-based technologies should be the reference system for tanks where net water addition to the tanks is unacceptable. This development work has therefore been based on the assumption that the scarifier will be deployed inside the tank by a long robotic manipulator having a significant degree of both structural and operational flexibility. A long robotic manipulator will have limited positional accuracy in the vertical plan when subjected to erratic dynamic loading. Also, due to kinematic considerations and joint friction, the ability of a long manipulator to maintain a relatively constant transverse velocity will be limited. Table 1 summarizes these key interface issues, their relative ranking, and potential problem areas.

The current retrieval manipulator design consists of a serial dual-arm arrangement with a long-reach manipulator arm used to deliver a short ($\approx$2.5 m) dexterous manipulator to the work area.

This configuration provides a high degree of redundancy, allowing the manipulator to thread its way around obstacles in the tank.

5. MINING STRATEGY DEVELOPMENT

5.1 Mining Strategy Functions and Requirements

A process deployment strategy will be required to cope with changes in the surface contours of the waste. This shall include addressing the problems of capturing dislodged waste and spent water over uneven terrain, avoiding collisions with the waste surface, and procedures for maintaining an effective stand-off distance over an uneven waste surface. Initially, it is expected that the topography of the waste surface will be irregular. The mining strategy chosen for the retrieval must be such that a high average retrieval rate is maintained. The overall strategy must effectively retrieve waste over the existing topography and tank hardware as well as any topography created by the scarifier itself, including ridges, knobs of harder material, loose chunks, or leftover ribs from previous passes over the surface.

In order to succeed at removing waste from an underground storage tank, a mining strategy is being developed. The function of the mining strategy is to ensure that mining is conducted in accordance with the following criteria.

- The mining strategy must allow waste removal at the design rate of 136 l/m (30 gpm).
- 99% of the waste in the tank must be removed as dictated by agreements in place with state and federal agencies.
- No additional water must remain in the tank once mining is completed.
- The tank, waste removal equipment, personnel, and environment must be protected from damage.
- Water should be recovered at the same rate as it is introduced.
- The strategy must specify the waste removal geometry and path such that the end-effectors' required stand-off distance and velocity are observed.

In order to support these functions, the mining strategy must meet the following requirements:

- The mining strategy must minimize the use of gross degrees of freedom of the long-reach manipulator (mast elevation and rotation) by using the dexterous manipulator to implement the mining strategy. Positioning accuracy will be maximized, energy expenditure minimized, and the use of manipulator bracing will be simplified by this requirement. This strategy will dictate dividing the tank into several regions and using the LRM to move from region to region while using the shorter dexterous manipulator to implement the mining strategy.
- The mining strategy must minimize sharp corners and backtracking in the waste removal path due to the robot's inability to abruptly change direction without slowing down.
- The mining strategy must manage the supernatant liquid in the tank. The mining strategy must minimize the loss of cutting fluid and collect existing supernate in the tank.

- The mining strategy must avoid repeated motions with frequencies in the range 0.1 to 5 Hz. These frequencies are near the fundamental natural frequency of the robot.
- The mining strategy must maintain a constant linear velocity. This is required to maximize the efficiency of the waste removing end effectors and to leave the waste surface as clean and smooth as possible.
- The mining strategy must manage hard and soft waste forms; handle variations in topography and clean the bottom, corner and sides of tank.

5.2 Baseline Strategies

The two baseline strategies illustrated in Figures 4 and 5 are being evaluated: serpentine mining and pit mining. In the serpentine mining strategy illustrated in Figure 4, the end-effector is swept over the waste surface in a regular pattern, removing waste to form horizontal planes. This mining strategy would be the easiest for an operator to implement. In addition, it is the most efficient in terms of cutting rate, since the end effect is cutting waste at all times.

In the pit mining strategy depicted in Figure 5, waste is removed gradually in a pattern that forms a pit. The intent of this approach is to use the pit to manage any excess water that escapes the end-effector. Using this approach, waste is first removed from the inner section of the region to be excavated. Because the scarifier removes only 2.54 cm (1 in.) of waste during each pass, several passes will be required to form the initial pit. As retrieval continues, outer rings of material are removed. It may be required to turn off the water jets as the scarifier is moved from one ring to the other to minimize water losses; this limitation will be brought out during testing. This water management strategy can be augmented by using multiple passes for each ring (to improve efficiency) and by angling the scarifier toward the inside of the pit to facilitate drainage. If multiple passes are not taken at each level, this will lead to a very shallow pit that may have less impact on the flow of water than the existing topography of the waste. Pit mining such as this has been proposed by the University of Missouri as the optimal pattern for waste removal, given the constraints listed above.

6. TESTING FOCUS AREAS

Table 2 provides an overview of the testing program matrix. The first testing segment will verify the ability of the proximity sensors to maintain a constant stand-off distance between the scarifier and the waste surface over various challenging topography. Next, the reaction forces at the scarifier interface plate will be measured separately due to suction, inertia, and jet reactions. This will greatly simplify the force data reduction from subsequent testing. Next, mining strategy tests with salt cake and sludge simulants will be conducted to evaluate the effectiveness of mining strategies, forces related to scarifier and conveyance line, and retrieval rate. Performance of the system during off-normal events and the ability of the system to deal with waste topography will also be evaluated. In addition, tests will also be conducted to quantify dislodging efficiency as a function of waste stream properties (amount of material, depth of cut, and surface quality).

6.1 Waste Simulant Development

Waste dislodging and conveyance processes will require system qualification tests using actual radioactive waste materials or simulated waste. Testing with radioactive waste has disadvantages involving the volume of material available, significant hazards to personnel, and high cost to run tests. The use of simulated waste is promoted to overcome these strategies. However, the application of simulants is not without its difficulties. Characterization of waste inside Hanford underground storage tanks is very limited and may not span relevant waste properties. Until such time that physical characterization data becomes available for the actual tank wastes, the simulant properties must be carefully designed to expose the limitations of the process and span the range of properties expected to be critical to the processes studied.

Simulants have been designed to capture the essential characteristics of hard salt cake type-wastes and sludges. Salt cake recipes typically contain a water/dynamate or water/dynamate/ silica mixture, while sludge recipes contain a water/kaolin or water/bentonite mixture. It is expected that these recipes will bound the critical properties of the actual sludge in the tank.

6.2 Deployment Instrumentation Development

This section of testing will evaluate instrumentation to maintain a constant stand-off distance in an underground storage tank environment. Software will be developed to modify the path of the gantry end effector based on sensor input using the RPM capabilities of the gantry. The instrumentation will be used to modify the gantry position in real time to maintain a constant stand-off distance on hard and soft simulants and various topography.

Lasers and ultrasonic sensors, among others, have been ranked and evaluated in terms of their ability to measure proximity in the hostile tank environment. At this time, ultrasonic sensors appear to be the most promising technology. Two sensors will be installed on the shroud at the leading and trailing edge, and about one 5 cm beyond the shroud. This will allow the system to prepare for abrupt changes in topography without collisions.

Testing will verify the controllability and accuracy of the proximity sensors and control software to maintain a constant stand-off distance. Maintaining a relatively constant stand-off distance is of importance because of constraints imposed by the air conveyance system. Parametric testing has shown that the stand-off distance should be 5.08 cm (2 in.) nominally with an allowable deviation of $\pm$3.8 cm (1.5 in.). If the scarifier is too close to the surface, the vacuum may suck the shroud into contact with the waste surface (known as the smooch effect). Conversely, if the scarifier is too far away, the shroud will not be able to effectively contain the dislodged particles. To maintain the correct stand-off distance with the gantry robot control system, it is only necessary to vary the position of the vertical mast. For the initial testing, the gantry cannot be used to align the scarifier with an angled surface because the robot lacks a wrist necessary to accommodate additional degrees of freedom.

The test series will include abrupt drop-off and rises (Figure 6), inclined surfaces (Figure 7), and rough surfaces. In addition, tests will be conducted to verify controllability of the system over various waste types (salt cake, sludges, water) and in the presence of water jet spray, high velocity air, and noise. Because this is a development program, this approach will help isolate weaknesses in the system and identify needed improvements.

6.3 Test Results To Date

Preliminary testing at Quest has shown that the scarifier can retrieve both hard salt cake and sludges at or above the target retrieval rate of 136 liters/min (30 gpm) for short durations. Construction activities are nearing completion for the HTB to allow mining strategy testing to begin in 1995. Initial testing will determine if the retrieval rate of 136 liters/min rate can be sustained for long periods of time over varying waste types and topography.

The development of the software and instrumentation to maintain a constant stand-off distance is well underway. Two ultrasonic proximity sensors have been installed on the scarifier and tested using data acquisition and control software that receives the sensor position data and updates the trajectory of the gantry. Early results are promising, although testing of the system will continue to verify the operation of the sensors under a variety of simulant surface conditions, scarifier velocities, and in the presence of water jet spray, high velocity air, and noise.

7. CONCLUSIONS

The data generated from these tests are essential to allow the completion of definitive system design of actual in-tank components. Testing of full-scale prototype end effectors, cold testing, operations research, and operator training will be considered as long-range uses for the Hydraulic Test Bed.

8. ACKNOWLEDGEMENTS

The Waste Dislodging and Conveyance Program is sponsored by the U.S. Department of Energy Office of Technology Development.

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10. NOMENCLATURE

HTB	Hydraulic Testbed
LRM	Long Reach Manipulator
WD&C	Waste Dislodging and Conveyance

Table 1. Interface Issues between Scarifier and Long Reach Manipulator

Rank	Key Interface	Problem areas/risk
1	Dynamics	Bound loads due to scarifier and conveyance line
2	Mining Strategy	Develop patterns and sequences that scarifier will move through to extract all the waste. Include considerations for non-uniformity of surface, geometry of cut, and debris
3	Accuracy/Repeatability	Determine accuracy, repeatability, and maneuverability requirements to implement mining strategy and achieve desired retrieval rates.
4	Physical Interface	Define physical interface between LRM and scarifier
5	Sensor Requirements	Define the requirements for instrumentation to maintain a constant stand-off distance over various topography while maintaining the desired retrieval rates and near 100% water recovery.
6	Controls Requirements	Determine the level of control sophistication required to achieve desired retrieval rates. Evaluate the use of tele-operation versus robotic control to implement the desired mining strategy.

Table 2. Overview of the Testing Program Matrix

Test Focus	Test Parameters	Key Data Expected
1. Verity instrumentation to maintain a constant stand-off distance	• Surface Roughness • Traverse Velocity • Angle of Incline • Waste Type	Stand-off distance over various waste types and topography in the presence of water jet spray, high velocity air, and noise.
2. Reaction forces due to separate effects	• Stand-off Distance • Air flow • Position of Gantry • Traverse Velocity • UHP Water Flow	• Reaction forces due to suction, inertia, jet reaction • Pressure drop in conveyance line
3. Initial system checkout & performance verification. • 2 tests	• Simulant type (saltcake and sludge)	• Retrieval rate • Reaction forces • Pressure drop in conveyance line • Air flow rate required to sustain flow
4. Hardpan Testing • 9 tests	• Two salt cake recipes • Two sludge recipes • Mining strategy - serpentine and pit	• Retrieval rate • Reaction forces • Cutting efficiency • Pressure drop in conveyance line • Conveyance line lubrication required
6. Topography/Mixed Waste •5 tests	• Hard and Mixed Waste • Various topography	• Retrieval rates • Reaction forces • Cutting efficiency • Pressure drop in conveyance line • Conveyance line lubrication required

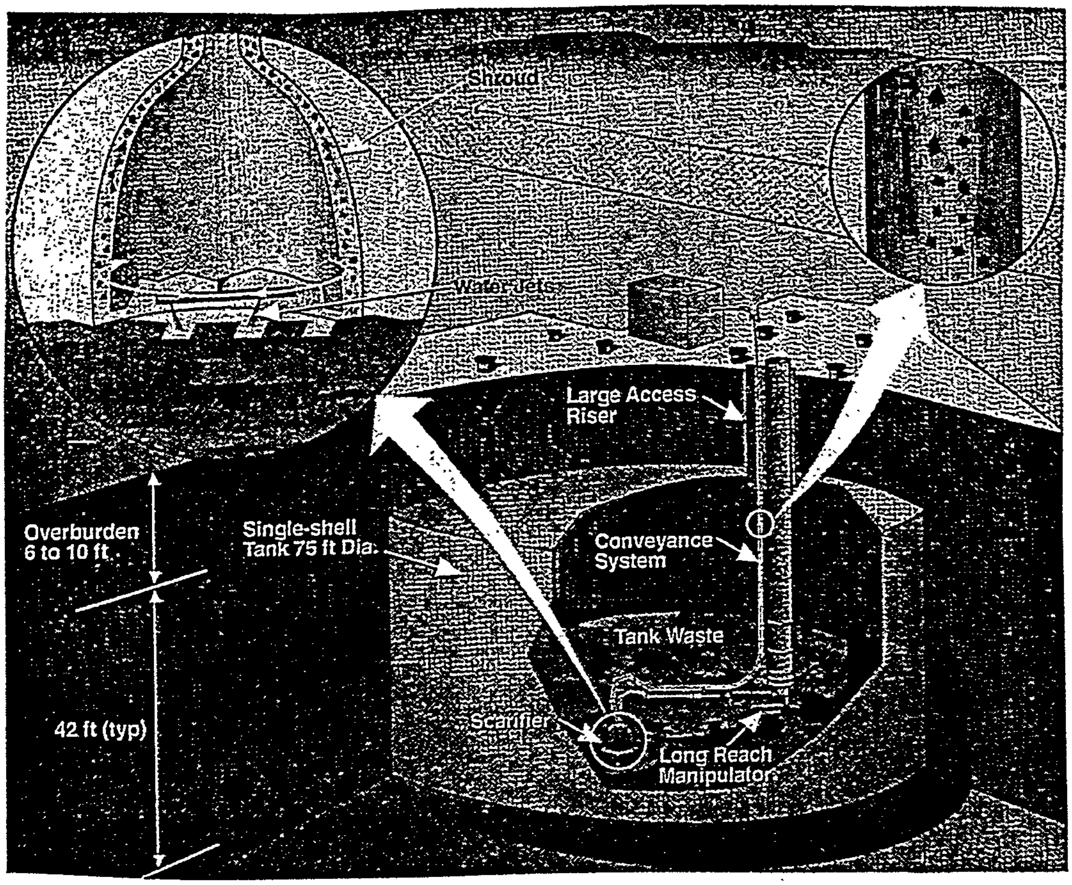

Figure 1 **Retrieving Radioactive Waste from an Underground Storage Tank using a High Pressure Scarifier**

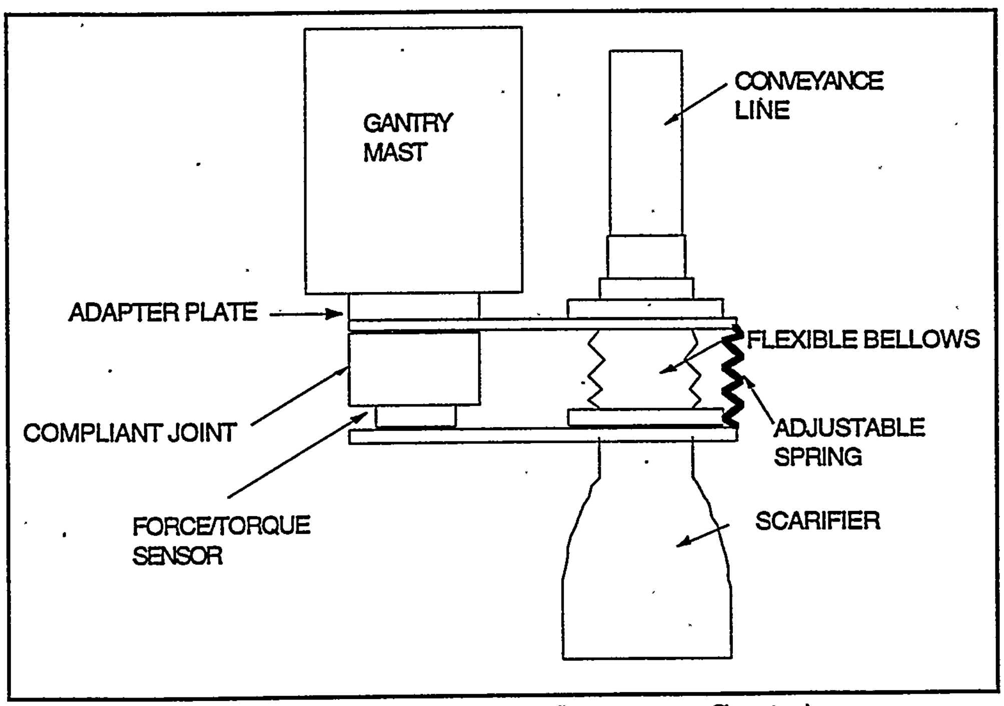

Figure 2 **Scarifier Attachment to Gantry**

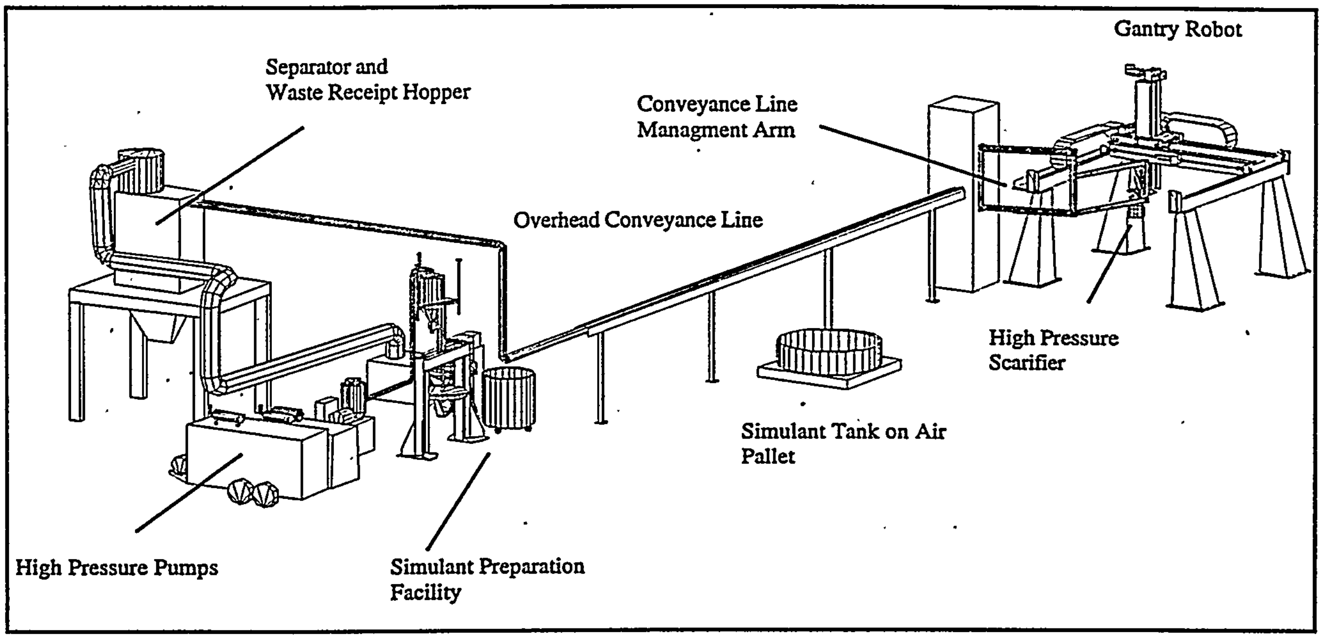

Figure 3 **Waste Dislodging and Conveyance Hydraulic Testbed**

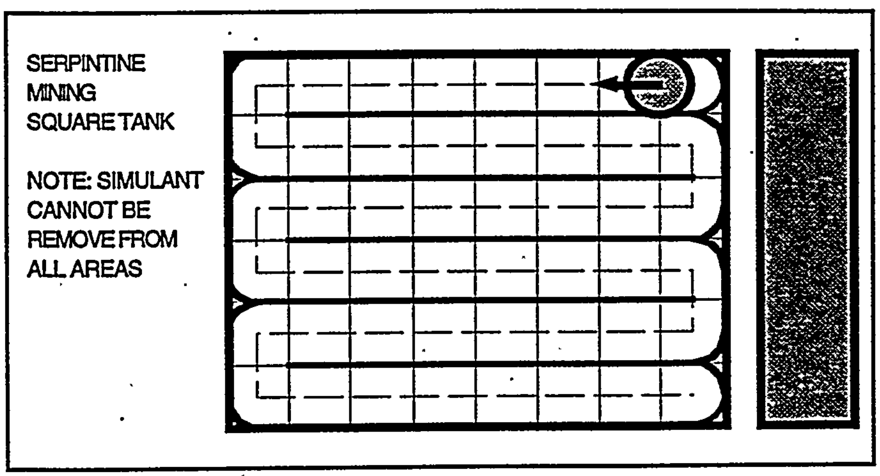

Figure 4 **Serpentine Mining Strategy**

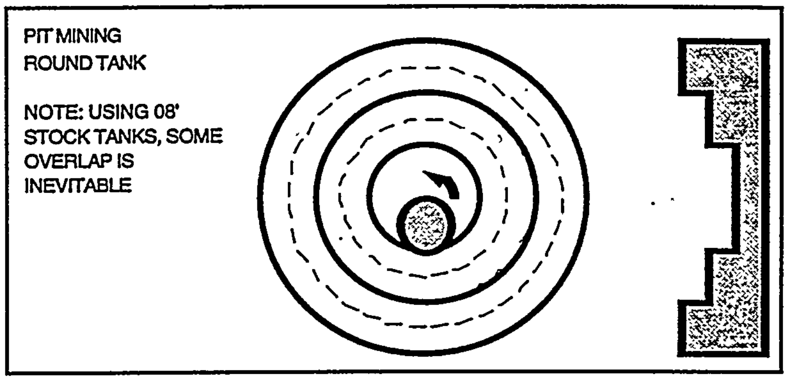

Figure 5 **Pit Mining using a Round Tank**

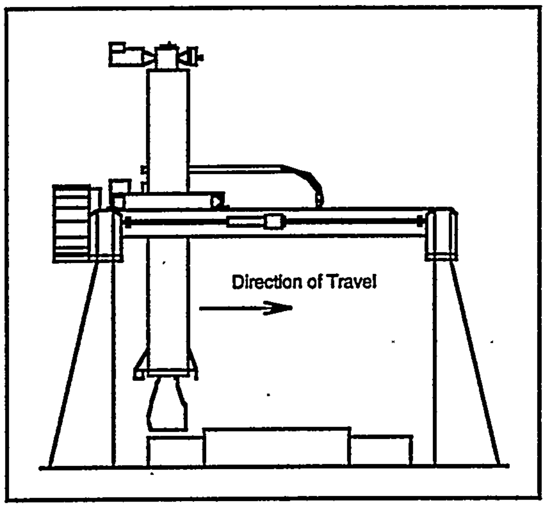

Figure 6 **Abrupt Drop-off Test**

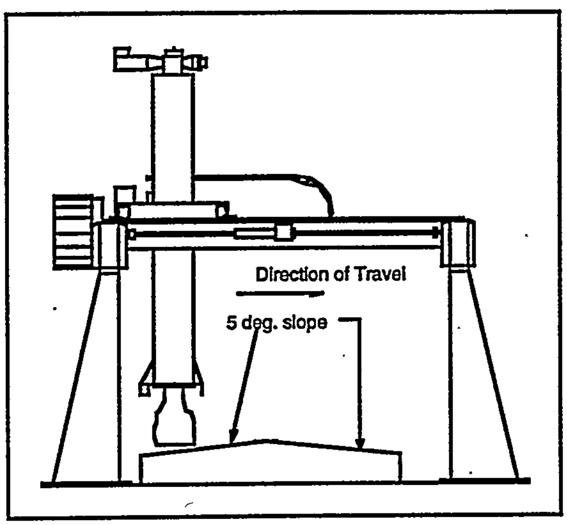

Figure 7 **Inclined Surface Test, 5°**