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MVST SCALE-MODEL SLUDGE MOBILIZATION DEVELOPMENT

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MVST-SCALE MODEL SLUDGE MOBILIZATION DEVELOPMENT

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SUMMARY

Development work at Oak Ridge National Laboratory (ORNL) has been undertaken to remove radioactive sludge from underground storage tanks of an unusual construction and geometry. Work at other U. S. Department of Energy (DOE) laboratories has been studied, scale-model development tests have been conducted using Reynolds and Froude numbers for similitude, and recommendations have been made for further study using a single-point sluicing technique and a robot that works with a mobile suction hose. Larger-scale equipment for further development is under construction.

BACKGROUND

Research and operations at ORNL generate low-level and transuranic radioactive wastes that are accumulated in eight underground storage tanks called the Melton Valley Storage Tanks (MVSTs). Because no disposal method is available for these wastes, it has been proposed that they be removed from the tanks for processing and solidification in a Waste Handling & Packaging Plant (WHPP) and eventually sent to the Waste Isolation Pilot Plant (WIPP). Though not originally intended for solids, these waste tanks contain varying amounts of bottom sludge of varying consistencies. The majority of the bottom sludge, which contains an appreciable concentration of transuranics, will be removed to make a solidified waste product that will meet the WIPP acceptance criteria (WAC), and sludge, which contains an appreciable concentration of transuranics, will be removed to make a solidified waste product that will meet the WIPP acceptance criteria (WAC) and also to provide space for future waste liquid. This report reviews progress on developing the best way to remove this sludge.

To understand the problem of sludge removal from MVSTs, refer to Fig. 1, a schematic view of a representative tank. It is a horizontal cylinder (12 ft in diam and 60 ft long). Little is known about either the depth or the distribution of sludge in the tanks. Sludge consistency varies from "concrete-like" in one tank to "very soft and flaky" in another. Sludge depth in the tanks is also believed to vary, ranging from 6 in. to 4 ft.[1] Measurements have been made in only one location, designated "*M*" in the figure. Pump suction is available only at one of two locations, designated F1 or F2. Sludge jets were installed in six locations but were not connected to the pumps. Located considerably to one side of the tank is one manway, marked "C" on the drawing, through which a pump or suction tube might be introduced.

PREVIOUS SLUDGE MOBILIZATION DEVELOPMENT WORK

Radioactive sludge mobilization problems have been addressed in the past by ORNL; the Savannah River Laboratory (SRL); Rockwell Hanford Operations (RHO); Nuclear Fuel Services at West Valley; General Public Utilities (GPU); Batelle Pacific Northwest Laboratory; and commercial nuclear stations. None was quite like the MVST problem.

In a campaign lasting several months, ORNL removed sludge from six underground vertical cylindrical (50-ft (12-m)-diam) tanks (known as the gunite tanks) using a high-pressure 215-psi (1.5×10^6 Pa, 100 gal/min) spray nozzle that was mounted to

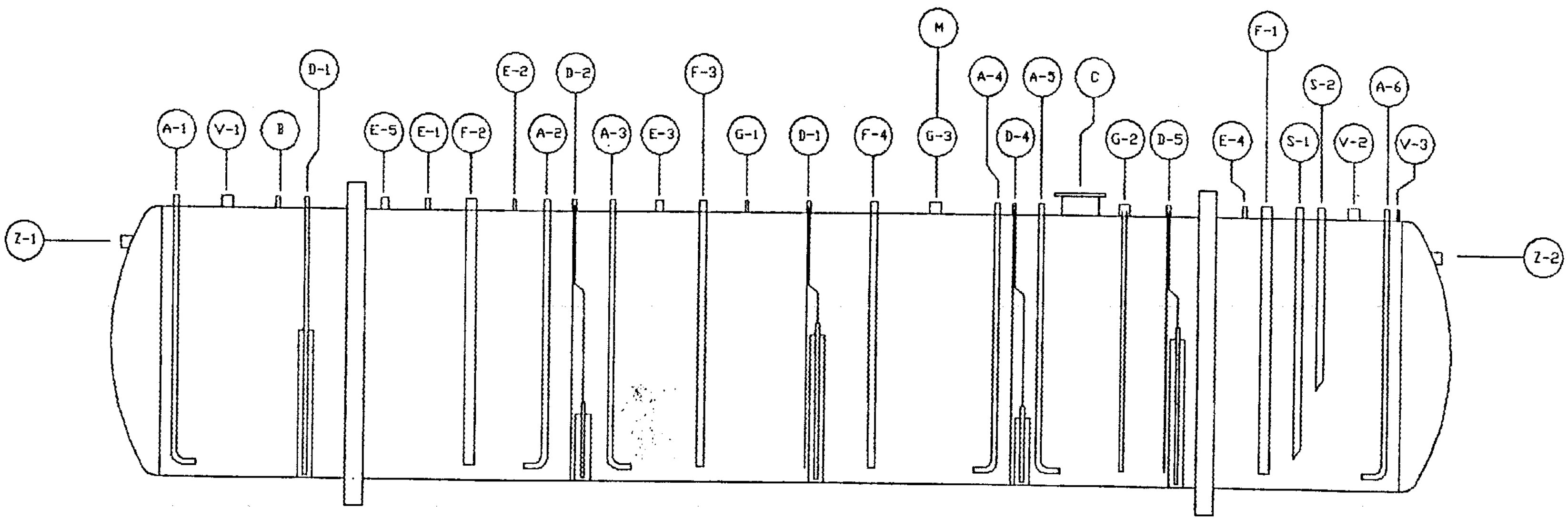

Fig. 1. Cross-section of a Melton Valley Storage Tank.

one side of the tank and rotated around 360°.[2] The mobilized waste solution was pumped from the bottom of the tank using a pit-mounted, progressive-cavity pump, and the slurry was recirculated through the spray nozzle until a certain concentration of solids was reached. Bentonite clay was added as a suspending agent. This technique was successful in removing over 90 wt % of the sludge, although some of the largest crystals remained.[3]

SRL has much larger, approximately 1 million-gal (3.785 x 10^6 L), vertical cylindrical tanks, which contain insoluble hydrous oxide sludge. They successfully used 0.25-in. (0.635-cm) rotating nozzles at 3000 psi (21 MPa) to mobilize sludge, but at the expense of introducing large quantities of water which later had to be evaporated. An alternative technique was developed that introduced a submersible, open-impeller centrifugal slurry pump into the tank. With this method, one pump was used essentially as a mixer: it suctioned slurry and supernatant from the tank bottom vertically and discharged it horizontally at two diametrically opposed points. During this process, the whole pump assembly was rotated slowly about 360°. A second pump of similar design suctioned the mobilized sludge from the tank.[4] Flow rates of 4540 L/min at 180 ft (55 m) of head produced a cleaning radius of approximately 20 ft (6 m) when kaolin clay was used as a sludge simulant. SRL found that the effective cleaning radius (not quantitatively defined) was proportional to the product of the diameter of the nozzle and the velocity of the spray. Once the nozzle diameter and velocity are fixed, the pressure and volumetric flow rate are then set.

RHO removed sludge from 75-ft-diam vertical cylindrical tanks of approximately 1 million-gal capacity, using a technique similar to that used at ORNL but without the admixture of bentonite suspender clay. A 1-in. (2.54-cm)-diam nozzle was attached to a movable boom and operated at 350 gal/min, unsubmerged in the liquid. The device was mounted at one side of the tank, and a skirted slurry pump was placed near the tank center to pump the sludge. The feed to the sluicer nozzle was a supernatant liquid that was propelled by a turbine pump.[5]

Nuclear Fuel Services of West Valley, New York, developed a hybrid of the techniques from RHO and SRL. The West Valley tanks are vertical cylinders, 27 ft high and 70 ft in diam, with a capacity of approximately 500,000 gal and elaborate internal structures.[6] One of their objectives was to homogenize their sludge and supernate in preparation for further processing, as is done in the WHPP. They built a 1/6-scale model and installed two concentric vertical pipes, the inner of which suctioned sludge from the tank while the outer pipe, equipped with 0.25-in. rotating nozzles oriented horizontally, directed a jet to mobilize the sludge. This somewhat complicated mechanism proved inadequate, by itself, to sluice their surrogate sludge. They proposed to solve this problem with the use of two such devices in their actual operations.

GPU, in its damaged Three Mile Island Reactor, Unit 2, has removed sediment wastes generated during the accident.[7] A rotating spray ball jet sluicer, operating at 1000 psi and 25 gal/min, was used unsuccessfully. Eventually, a man was stationed at the manhole of the tank to direct the spray by hand to mobilize the sludge. In the reactor building basement, a modified rover robot fitted with a vacuum hose was used to remove the very fine sediment resulting from river water in-leakage.

The Batelle Pacific Northwest Laboratories have in progress an interesting development program to characterize in situ the sludge in their underground high-level waste storage tanks. Their hypothesis is that the important variables in designing a sludge mobilization scheme are the yield strength and viscosity of their wastes. The former is important because the cohesion of the sludge must be overcome first, and the latter because once broken up, the sludge must then be dispersed. To this end, they are developing a rotating vane viscometer that can be immersed in their sludge holding tanks.[8]

The Public Service Electrical and Gas Company's Hope Creek Nuclear Power Plant in Salem, New Jersey, has used a robotic device from ARD Corporation, called a Super Scavenger, to vacuum sludge from the bottom of fuel storage pools and spent resin storage tanks. The Super Scavenger functions as a roving suction nozzle on the bottom of the tanks, while a submerged and stationary suction pump removes the sludge. The robot can be equipped with a high-pressure, 1000- to 3000-psi, spray nozzle. It has been used in several nuclear stations since the Hope Creek experience, with favorable reviews.[9]

Other robots are commercially available and are mentioned here for completeness and because of their innovative design. Mitsubishi Heavy Industries of Japan makes a tank-cleaning robot that is designed to remove sludge from the surfaces of tank walls. Unlike the scavenger, it is a propeller-driven submarine, joystick controlled, containing metal ballast tanks and rotating cleaning brushes. SGN, Cogema of France, manufactures spent fuel pool bottom cleaning equipment that is very similar to the scavenger, except for the important fact that an underwater pump is included.

DEVELOPMENT OF SLUDGE MOBILIZATION TECHNOLOGY

Recent experimental work at ORNL has centered around the use of a 1/6-linear-scale model of an MVST constructed of Plexiglass ® and containing linear geometric simulations of all internal structures of the actual tanks.

The question arises of how good the correlation is between the experience extracted from a 1/6-scale model and the problem of sludge mobilization in the actual tanks. Other experience[10] has indicated that with a jet stream exceeding a given value of a dimensionless Reynolds number:

$$N_{Re} = \frac{VD\rho}{\mu}, \tag{1}$$

where

V is velocity, D is nozzle diameter, ρ is slurry density, μ is viscosity;

a typical SRL sludge may be mobilized at a distance in air of approximately 40 ft. Since, as we have indicated, sludge is highly variable in its properties, 40 ft is a maximum value and an approximation. It provides a general indication of the force of impact and the distance a sluicing jet will travel, which are both important parameters.

Once a sludge is mobilized in the MVSTs, transporting it to the pump suction location remains a problem. The worst case must be considered, which is sludge located at the far end of the tank at the maximum distance from the point where it might be pumped. In this event, it appears that the velocity of the open channel flow would be the prime consideration; and a Froude number based on the depth and velocity of this flow would provide a means to scale the data. The Froude number is defined in Eq. (2):

$$N_{Fr2} = \frac{V}{\sqrt{gL}}, \tag{2}$$

where

L is the depth of flow, V is the open channel velocity, g is the gravitational constant.

Sluicing Techniques

Three different surrogate materials, sand, fly ash, and bentonite clay, were tested for this work. Also, three different sluicing techniques were tested: (1) in-tank sludge jets, (2) air sparging, and (3) single-point sluicing. All techniques and materials will be discussed, but most attention will be focused on the single-point technique using fly ash surrogate. A fourth technique, moving-point sluicing or robotic techniques, will be briefly discussed; but it is primarily the subject of later research and development. A distinction should be made here between transporting and mobilizing as they are defined in this article. Mobilizing is defined as the activity of breaking up a block or slug of sludge into more manageable proportions, such as particles less than 500 μm in their principal dimension. Transporting is defined as the action of moving this mobilized sludge from the part of the tank to a point where it might be pumped out; sluicing is the combination of both operations.

The MVSTs are equipped with vertical air sparging pipes, which, though designed to mix the supernate liquid, were proposed for sludge mobilization purposes. A quick experiment was designed. Few parameters were available for variation, except the standard cubic feet per minute of air, sparging flow rate, and the level and type of sludge.

The MVSTs were also equipped with sets of vertical pipes, shown in Fig. 1 as A1-A6, which were designed specifically to sluice sludge. These pipes have a "J" shape at their bottom and are capable of delivering large flows of liquid. Between them are found pump suction pipes. As noted, they are not presently available because all piping was not completed; however, the concept was easy to test and possibly useful.

The third sludge mobilization technique, the single-point sluicer, would require a maneuverable discharge pipe to be installed at the manhole location, inside the tank. Fig. 2 shows the general arrangement. The tank would have to have a supernate liquid depth not in excess of 12 in. (and preferably 6 in.) before this technique could be applied to sluicing sludge, since the momentum of the sluicing jet is quickly dampened as the

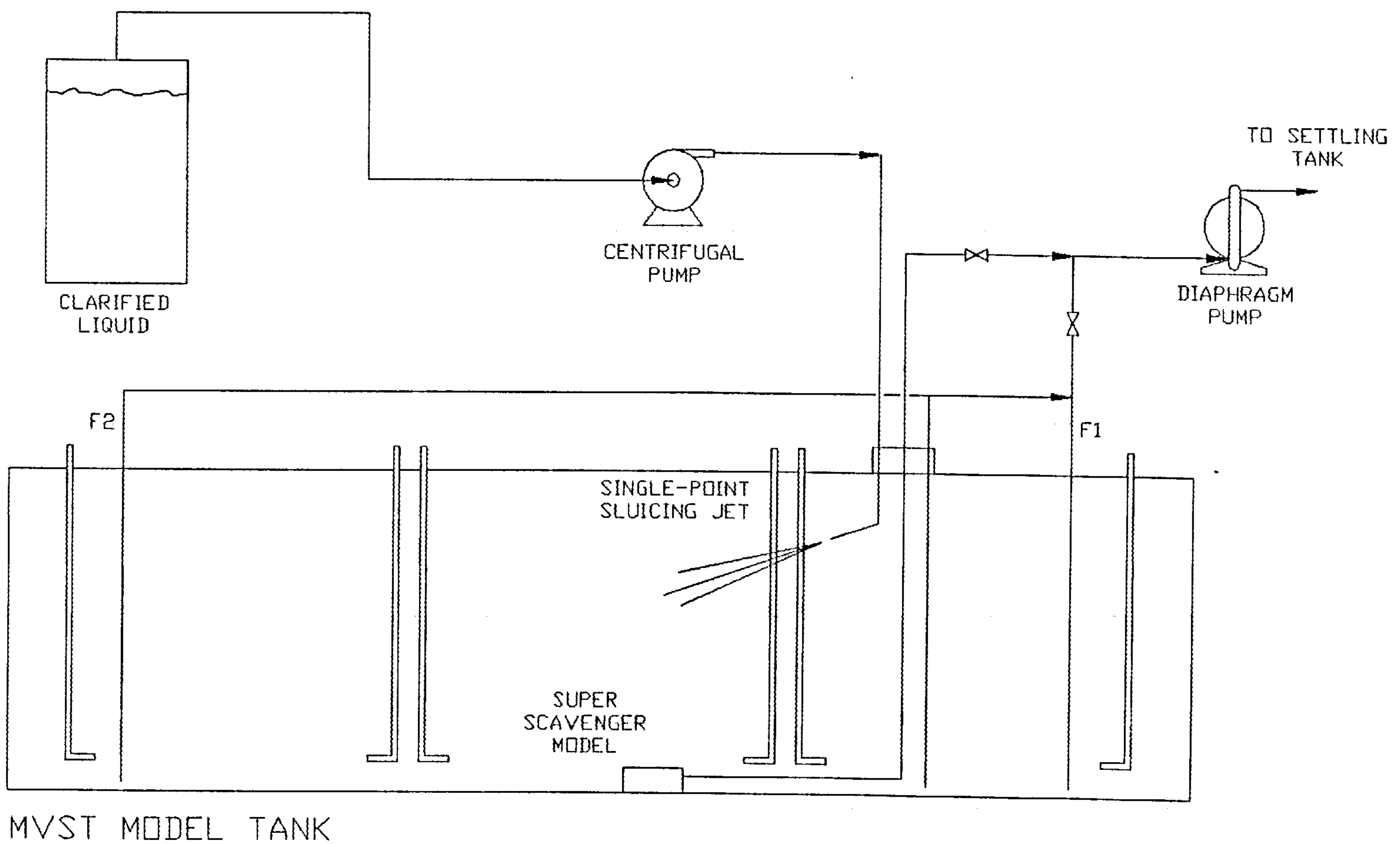

Fig. 2. Single-point sluicing and Super Scavenger techniques applied to MVST model.

liquid layer thickens. The suction could be from one of the existing pump suctions, from a submersible pump at the manhole location, or from a suction pipe at the manhole location.

Sludge Surrogates

The properties of the three surrogate materials are shown in Table 1. The objective of their selection was to provide materials which bracket the range of behavior which might be anticipated based on the laboratory data of an actual MVST sludge sample.[11] Further refinements in this selection will be possible with additional data. The fly ash was chosen because its settling velocity as a function of concentration is uniformly greater than those of the W26 sample available data. It was not clear whether the actual sludge was flocculated; but bentonite clay was picked as a flocculating surrogate to evaluate its properties, principally from the point of view of mobilization. Pumping bentonite sludge, once mobilized, should be relatively simple. Sand was chosen to provide a surrogate that would be more difficult to mobilize and transport than the fly ash. Water was the interstitial liquid, sodium nitrate was rejected because of its health hazards, and its higher density would make surrogates less prone to settle.

RESULTS

AIR SPARGING TESTS

Finding suitable experimental parameters for the 1/6-scale model tank was difficult in the air sparging experiments. A 20-scfm airflow can be brought to bear in the actual tank, and experiments were performed in the model tank at 18 scfm. With sand as

Table 1. Surrogate materials

Sand	
Average particle size	500 μm
Settling velocity	15 wt % - 8.52 mm/s 30 wt % - 5.76 mm/s 47 wt % - 4.29 mm/s
Particle density	2.31 g/cm^3
Bentonite clay	
Average particle size	90% between 3 and 31 μm
Settling velocity	~0
Solution density	2.5 wt % - 1.02 g/cm^3 5.0 wt % - 1.03 g/cm^3 7.5 wt % - 1.05 g/cm^3
Fly ash	
Average particle size	4 μm
Settling velocity	4.85 wt % - 3.22 cm/min 6.5 wt % - 2.59 cm/min 9.6 wt % - 2.04 cm/min 18.5 wt % - 0.185 cm/min
Density	4.85 wt % - 1.03 g/cm^3 6.5 wt % - 1.04 g/cm^3 9.6 wt % - 1.06 g/cm^3 10.5 wt % - 1.12 g/cm^3

a surrogate, no transportation or mobilization was observed at this flow rate. The air flowed effectively through the interstices without so much as budging a particle. The experiment was repeated with fly ash, which, as can be seen from Table 1, should be easier to mobilize; similar results were obtained.

SLUDGE JET EXPERIMENTS

There are several different possible arrangements by which the sludge jets could, in principle, be operated. Pump suction could be taken between two opposing jets in operating simultaneously, which is probably the most promising arrangement. All jets could be operated simultaneously, and pump suction could be taken from one end, or one jet might be operated and pump suction taken from a distant point. The jets are all on the center line of the tank and fixed.

Since at first this technique was believed to be the most promising, sand was used as the surrogate sludge to create a situation of the greatest sluicing difficulty. The arrangement in which the pipe suction was located between the jets was chosen for initial testing. The jets were operated to produce Froude numbers, less than 0.02 (subcritical, $N_{Fr} < 1$). The Froude number is a dimensionless number characteristic of open channel flow, measuring the flow ratio of gravitational to inertial forces. The channel depth and velocity are variables. Less than 1% of the solids were removed during a 3-min experiment at a sluicer N_{Re} of 70,000. The quantity of solids collected could be enhanced by proper positioning of the suction pipe because a small amount of sand was entrained directly from the pump suction. (An interesting result was found here because more entrainment occurred when the suction nozzle was about 1 in. from the surface than when it was immediately adjacent to it owing to the formation of vortices.) Because the Froude numbers and Reynolds numbers chosen already represented optimistic projections to the actual tanks (i.e., the actual tanks could not be operated at flows this large), this technique appeared less promising after one experiment.

The above experiment was repeated using fly ash, which is a more sluicable surrogate; it produced similar results. The test was not repeated with the bentonite clay.

A second arrangement for sludge jet sluicing of sand was chosen in which all jets were operated simultaneously and the suction was taken at one end of the tank near the manhold location. Very little solids were actually pumped from the tank, but the action of the sludge jets produced piles of sludge somewhere near the midpoint between adjacent sludge jets. This is shown in Fig. 3, which depicts the shortcomings of the technique. The results with fly ash again were very similar, which made the whole technique of doubtful utility.

SINGLE-POINT SLUICING EXPERIMENTS

Development of this technique was inspired by the success of Weeren et al. in a campaign at ORNL, which dated from the early 1940s, to remove deep sludge from tanks. These tanks are right vertical cylinders and consequently very different geometrically from the MVSTs. This general technique was tested with all three surrogates with mixed results in the scale tank.

Experimentation began with fly ash. A 3 wt % fly ash/water solution was placed in the tank and deposited uniformly as a 1-mm-thick layer of ash along the tank bottom. The sluicing nozzle was a simple tube without flow spacers or any tapering. It produced a crude nonoptimized solid jet stream. These tests, by their nature, were qualitative.

Test 1

The first test was performed at a pump suction flow rate much greater than the sluicing flow rate, a simulation of an actual operation which would empty the tank. The nozzle was directed to the far end of the tank, and the sluiced material was suctioned from the manhole location. The Froude number was consequentially not constant;

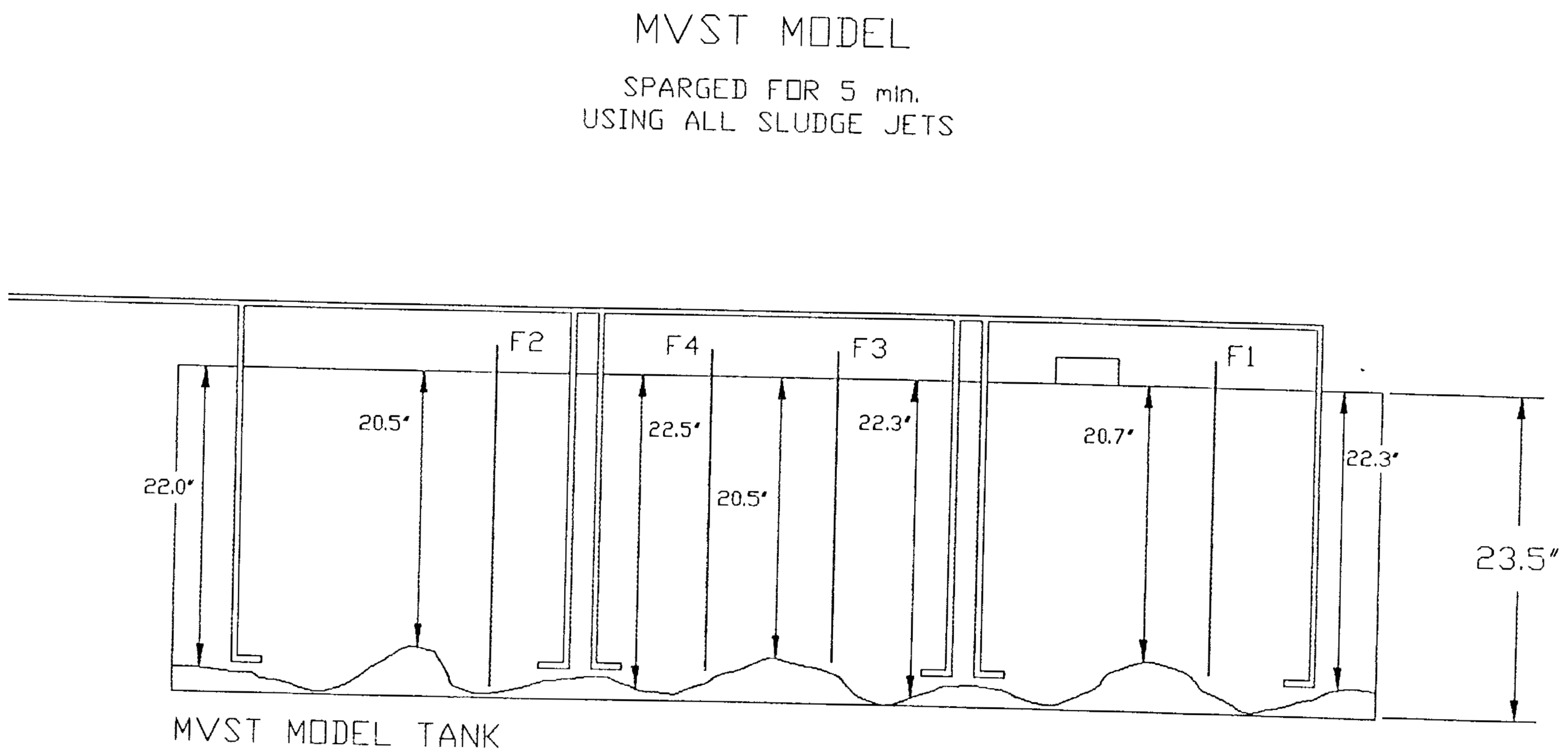

Fig. 3. Typical sludge profile after sludge jet operation.

however, it would vary from 0.007 to ultimately a large super-critical value (> 1), probably near the end of the sluicing experiment. The sluicing-nozzle Reynolds number was 13,000, and the pump suction pipe Reynolds number was 40,000. (Assuming 1-in. and 6-in. pipes, these numbers would correspond to 5- and 100-gal/min values, respectively, in the full-scale tanks.) At the end of this test, after 7 min, less than 0.2 wt % of sludge was found in the sluiced product, which meant only 7% efficiency had been achieved. Although quite low, this was still much better than in earlier tests. The 5-gal/min figure could easily be raised in the full-scale tanks and represents a very conservative value.

Test 2

The second test was more interesting. The operation took place at steady state, with the flow rates of the sluicing nozzle and the suction pump nearly equal. The nozzle was again at the manhole. The average Froude number remained constant at approximately 0.006. The term average Froude number here means that large local variations in the velocity and depth of the flow were possible and could not be determined. A significant improvement in the sluicing performance was achieved by manipulating the jet back and forth along the entire length of the tank. Nearly all (98% and 82% in the two experiments) of the fly ash (as a 3 wt % solution) was removed in the course of this experiment. The Reynolds number of the jet was about 13,000, and the suction pipe Reynolds number was very close to this value. This experiment, which took 7 min, was the first real breakthrough, suggesting that the major problem is transportation, rather than mobilization of fly ash sludge surrogate, and that the Froude number, or variations of it, is relevant. Maneuvering the sluicing jet probably altered the Froude number most dramatically.

Test 3

The third variation of the single-point sluicing technique was to introduce the jet sluicer at the manhole location as before, with the pump uptake at the existing, as installed, tank suction line (location F1 or F2, Fig. 2). Although this pump suction location is not the same in all eight tanks, one advantage is that it is nearer the place where the most distant, and, hence, most difficult to transport, sludge lies. At a sluicing jet Reynolds number of 10,000 and a Froude number of 0.003, 99.8% of the sludge was removed in 17 min using 90 L of sluicing water, a very good result.

OTHER GEOMETRICAL VARIATIONS

Other variations on this technique were attempted, again with fly ash. The previous test was repeated with the exception that the sluicing liquid had approximately the same concentration of fly ash as the liquid in the tank. It seems fairly clear that less ash could be removed from the tank in this manner, but it may simulate more accurately conditions of actual sluicing operations. The results were equivocal, since the solids concentration measurement technique (bulk density) was not sensitive enough to detect that the slurry contained additional solids after sluicing. This line of experimentation is worth pursuing because there is undoubtedly some upper limit, beyond which the sluicer begins to add solids to the tank rather than to remove them. Further experimentation along the lines of Weeren's work is planned.

The existing pump discharge nozzle of the MVSTs (location E-5, Fig. 1) was used as the single-point sluicing jet in another variation of the technique. The suction was then taken from an existing pump suction in the tank. This arrangement has the advantage in theory that it does not introduce any new equipment into the tank; however, it failed in mobilizing much sludge. The pump discharge nozzle spews liquid essentially vertically, and no net transport of sludge occurs in the horizontal direction. The maneuverability of the sluicing nozzle is, therefore, vital.

SINGLE-POINT SLUICING WITH OTHER SURROGATES

The single-point sluicing technique was tried with sand at essentially the conditions of the successful fly ash experiments, and little or no sluicing was achieved. The impact of the sluicing jet on the far end of the tank was adequate to stir the sand well and, per our definition, "mobilize" it. The problem was that it then settled between the tank end and the suction location. The flow rates were adjusted to their maximum values, Froude number = 0.2 (owing to the shallow depth), corresponding to the maximum pumping rates currently available in the MVST tanks, and a slight improvement was noted. Sand could be mobilized from the near end of the tank to the manhole location (note in Fig. 1 that the manhole is near one end of the tank) at a sluicing rate described by a Reynolds number of 30,000. This represented transport through a distance of less than 25% of the length of the tank. Sand could be transported using this technique, but the fact that the single-point jet was fixed at the manhole location (practically a necessity because of the design of the actual tanks) precluded its being transported from the far end of the tank. In other words, a slug of sand was moved through a distance of 225 cm at a sluicing flow of Reynolds number of 10,000 and Froude number of 0.008. This technique only works providing that sludge is being moved away from the sluicing nozzle.

The single-point sluicing technique worked very well with a 17 wt % suspension of bentonite clay and water in the scale tank covering a depth of 1.5 in. in the tank, a volume of 23 L, or about 2 vol % of the tank. This mixture produced a gel-like suspension of 1000 cP viscosity at low shear rates. Interestingly, this gel was no problem whatever to mobilize and transport. It broke into small particles at the impact of the jet, and they were easily swept to the pump suction at a Reynolds number of 10,000. The operation required 12 min and 20 gal of liquid. The Froude number was unobtainable because of the large volume of the gel-like sludge and the lack of open channel flow. A summary of the most successful sluicing experiment is shown in Table 2.

SUPER SCAVENGER AND OTHER ROBOTIC TECHNIQUES

The Super Scavenger is basically a mobile suction hose that is designed to remove sludge without the action of a sluicing jet (although such an attachment is

Table 2. Most useful sluicing experiments

Experiment	Surrogate	N_{Fr}	N_{Re} (Nozzle)	Sluicing efficiency
Stationary single-point nozzle suction	Fly ash 3 wt %	0.007	1-3 E+04	7
Manipulated single-point manhole suction	Fly ash 3 wt %	0.006	1-3 E+04	82-98
Manipulated single-point remote suction	Fly ash 3 wt %	0.003	1 E+04	99
Manipulated single-point remote suction	Sand	0.2	3 E+04	Negligible
Manipulated single-point remote suction	Bentonite clay	N/A	1 E+04	Complete

available). A 1/6-scale model of the scavenger was constructed. The most significant scaling characteristic of the scavenger is the linear velocity at the bottom suction port. (At a flow rate of 11.4 L/min, a 16 wt % fly ash-water slurry was removed in 17 min.) The ability of the scavenger to remove sludge near the tank obstructions (e.g., the spargers and the pump suction lines) was limited. Navigation around these obstructions in the real tank is considered to be one of the main difficulties of this technique. The flexibility of the suction hose attached to the scavenger model is an important variable in determining whether it can maneuver underneath horizontal obstructions. The diameter of the suction holes, hence, the entrainment velocity, can be adjusted.

DISCUSSION

The relevance or application of this data to the actual full-scale MVSTs is a question that should be further addressed in subsequent work. For the single-jet sluicing nozzle: there exist actual nozzle data[12] indicating that at proper flow rates and pressures, a jet can reach sludge at a distance of 40 ft, the approximate distance that would be required in the MVST operation. A significant concern still is whether the sludge suction entrainment can be represented using the Reynolds and Froude numbers for dynamic similitude. Particle entrainment in the suction pipe is most effective in turbulent flow that the suction pipe Reynolds number can predict. Particle transport appears to be related to the open-channel flow characteristics and the Froude number. The lowest suction Reynolds number chosen in this work, 10,000, would correspond to a very feasible 100-gal/min flow in the actual 6-in-suction line at a slurry viscosity of 5 cP; the maximum Froude number of 0.007 would require a flow of 80 gal/min with a 1-ft deep slurry in the actual tanks. These numbers are offered to fix some value that has been shown to work; they are by no means optimized, and we have not determined their range or minimum values. This work has indicated that (1) the single-point sluicing technique requires a maneuverable nozzle, (2) a pump suction point as near as possible to the sludge is desirable, and (3) the thinner the layer of supernate liquid the better sludge may be mobilized.

Future work should involve the testing of the single-point technique at a larger scale, further evaluation of the scavenger technique, and, though only briefly tested herein, evaluation of a no-sluicing technique (i.e., how much sludge can be removed by operating the existing Moyno pumps in a recirculating mode). Sludge is so thin in some tanks that substantial amounts may thereby be removed.

This work has shown qualitatively that the sludge jets, partially installed, and the air spargers, fully installed in the MVSTs, are probably not worth pursuing.

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