WRPS-55815 -FP
Revision 0, Draft

Development and Deployment of the Extended Reach Sluicing System (ERSS) for Retrieval of Hanford Single Shell Tank Waste - 14206 (DRAFT)

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
Office of River Protection under Contract DE-AC27-08RV14800

washingtonriver protectionsolutions
P.O. Box 850
Richland, Washington 99352

Approved for Public Release;
Further Dissemination Unlimited

WRPS-55815 -FP
Revision 0, Draft

Development and Deployment of the Extended Reach Sluicing System (ERSS) for Retrieval of Hanford Single Shell Tank Waste - 14206 (DRAFT)

R. E. Bauer
Washington River Protection Solutions

A. G. Innes
Washington River Protection Solutions

R. R. Figley
Washington River Protection Solutions

Date Published
November 2013

To be Presented at
Waste Management 2014

WM Symposia
Phoenix, AZ

03/02/2014 - 06/14/2014

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
Office of River Protection under Contract DE-AC27-08RV14800

washingtonriver
protectionsolutions
P.O. Box 850
Richland, Washington 99352

Copyright License
By acceptance of this article, the publisher and/or recipient acknowledges the U.S. Government's right to retain a non exclusive, royalty-free license in an to any copyright covering this paper.

APPROVED
By Shauna Adams at 9:05 am, Nov 11, 2013

Release Approval | Date

Approved for Public Release;
Further Dissemination Unlimited

LEGAL DISCLAIMER
This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced from the best available copy.

Printed in the United States of America

Development and Deployment of the Extended Reach Sluicing System (ERSS) for Retrieval of Hanford Single Shell Tank Waste – 14206

Roger Bauer *, Reed Figley *, Alex Innes **
* Washington River Protection Solutions
** AGI Engineering

ABSTRACT:
A history of the evolution and the design development of Extended Reach Sluicer System (ERSS) is presented. Several challenges are described that had to be overcome to create a machine that went beyond the capabilities of prior generation sluicers to mobilize waste in Single Shell Tanks for pumping into Double Shell Tank receiver tanks. Off-the-shelf technology and traditional hydraulic fluid power systems were combined with the custom-engineered components to create the additional functionality of the ERSS, while still enabling it to fit within very tight entry envelope into the SST. Problems and challenges inevitably were encountered and overcome in ways that enhance the state of the art of fluid power applications in such constrained environments. Future enhancements to the ERSS design are explored for retrieval of tanks with different dimensions and internal obstacles.

INTRODUCTION/BACKGROUND

The Hanford Site stores mixed radioactive and chemically hazardous waste in large underground tanks. Hanford has 149 older Single Shell Tanks (SST) and 28 newer Double Shell Tanks (DST) grouped together in farms. All of the SSTs have exceeded their design life, and some have leaked or are assumed to have leaked waste to the environment. A part of the mission of the DOE Office of River Protection is to retrieve the waste in the SSTs into the DSTs for eventual treatment and disposal.

One method that has been successfully deployed for retrieval of the bulk of the waste from SSTs is modified sluicing. Modified sluicing uses the supernatant from the receiver DST to dislodge and mobilize solids in the SST being retrieved. The resultant slurry is pumped to the DST where the retrieved solids settle out and the supernatant is then recycled to continue the process. Modified sluicing is generally effective at removing the majority of the waste from the SST, however there is typically a hard to retrieve heel that remains. Because the regulatory limit to be achieved is a specific volume (360 ft3 for 100 series tanks) deployment of a second technology is usually required to remove the heel to this limit.

Deployment of a separate technology to retrieve the tank heel is expensive and time consuming. Improving the efficiency of the modified sluicing retrieval system by increasing the sluicing effectiveness and by adding a co-deployed heel retrieval technology could improve the overall cost and schedule. The Extended Reach Sluicing System (ERSS) was developed to accomplish this goal.

DESIGN REQUIREMENTS

Prior Evolutions

The ERSS is an evolution of the original Sluicer Tank Cannon design deployed in the 100-series tanks in the C-Tank farm at Hanford between 2002 and 2009. These tanks are 75 feet in diameter and 33 feet deep at the top of the dome. The largest access openings into the tanks are 12 inch diameter pipe 'risers' located on the dome five feet from the wall of the tank. The Sluicer Tank Cannons' purpose was to direct a stream of supernatant pumped from a double-shell receiver tank (in AN tank farm) upon the surface of the waste to wash it toward the center of the tank, where it would be sucked up into a hydraulically-driven multi-stage pump and returned in slurry form to the receiver tank. These original sluicers were deployed in pairs, typically, and operated at pressures of 100 to 200 psi and flows of 68 to 100 gpm. Expelled through a nozzle 5/8" in diameter, the velocity of the supernatant ranged from 71 to 105 ft/sec, with a spray distance of at least 53 feet.

These sluicers had the ability to rotate about their vertical axes by turning the 'mast', the pipe or structural tubing from which the nozzle hung, in order to direct the sluicing stream toward waste adjacent to the riser. A 360 degree arc of coverage was theoretically possible, although administrative controls placed upon operations prevented them from aiming the sluicer stream at the walls due to concerns about tank material integrity. Further aiming of the sluicing stream was possible by actuating a hydraulic motor which varied the nozzle angle in the vertical plane. Tanks C-103, C-104, C-106, C-108, C-109, C-110, and C-111 were retrieved with standard sluicers. Tank C-103 was the only tank retrieved to the regulatory volume limit using only modified sluicing. All other modified sluicing tanks were left with a hard to retrieve heel that required deployment of a second retrieval technology.

Expanded Functionality

To improve and speed up retrieval efforts, the retrieval of these difficult tanks was examined for lessons that could be learned. It was recommended that moving the sluicing stream closer to the waste surface would likely increase the efficiency and efficacy of sluicing. This recommendation resulted in the development of the Modified Sluicing approach using Extended Reach Sluicer Systems, or ERSS. The reach of the ERSS is enhanced by adding an 'elbow' joint just below the riser, and by telescoping the boom section located below the elbow up to 27 feet. In addition to the vertical aiming function at the nozzle, a rotating 'wrist' was added to allow even more precise direction of the sluicing stream. Hydraulic pistons provide the motive force for this extend/retract function, and also restrain the arm so it can be parked at any position in the range of motion. The 'nozzle transverse' (wrist rotation) function is actuated by a second hydraulic motor at the end of the arm. The elbow joint is actuated by hydraulic pistons.

Tank C-112 was the first tank to receive an ERSS in June 2011, which was deployed opposite a standard sluicer for comparison purposes. Modified sluicing of this tank was partially successful at breaking through the uppermost crust layer and mobilizing the softer material underneath, but further 'hard heel' cleaning will be necessary. The ERSS sluice nozzle was effective at breaking apart the crust into large chunks, but a method to further size reduce the waste so it can be sluiced is needed. The hard crust layer anticipated in tanks C-101 and C-102 was recognized as a similar challenge such that an additional new feature was added to include high pressure water through special scarifying nozzles that flank the main nozzle. These orbital nozzles discharge 5,000 PSI (34.5 MPa) to assist in breaking up the hard layer, as well as any hard heel remnants. This technology was adapted from hydrodemolition of concrete, a practice that is commonly used to remove concrete from highway bridge decks without damaging the embedded reinforcing steel. Because it may be decided to utilize the high pressure water at later phases of retrieval, including times when the tank bottom is either exposed or just beneath the waste, nozzle selection and operating parameters had to be selected to prevent damage to the mild steel liner material.

Additional design variations

Considerable differences exist in waste levels between tanks, and the tanks needing ERSS are no exception. For example, tank C-102's waste depth is about 124 inches compared to 41 inches (or less) found in most of the other tanks. For this reason, two different sluicer models have been built to date: a 'short-arm' sluicer with a 9.75 ft. retracted boom length for C-102, which differs considerably from the 14 foot length for all other tanks. It is acknowledged that this will probably limit the effectiveness of the retrieval system because of the reduced overall reach of the arm. While there are no current plans to produce other lengths, it is possible to create variation of the design without incurring exorbitant development costs. Other possible variables that could be changed are the distance to the elbow (to accommodate a longer riser pipe), and customized nozzles with specialized spray characteristics.

Adapting the ERSS from the Sluicer Tank Cannon design required increasing the number of hydraulic circuits entering the riser from 2 to 5, plus the addition of a 1/2-inch diameter high pressure wash hose. Probably one of the most daunting design challenges was finding space within the confines of the 12-inch riser's space envelope to safely route these hoses (see figure 6). The final solution was replacement of the original sluicers' relatively large nitrile rubber hoses with ¼" and 3/8" OD wire braid-reinforced thin-wall aircraft fuel line hose. This replacement created additional challenges that would not surface until the retrieval operations for tank C-112 commenced.

SLUICER DESIGN, FABRICATION AND ASSEMBLY

Extended Reach Sluicer Development

The first Sluicer Tank Cannons, designed by AGI Engineering in 2003, had a fixed-length mast and two axes of nozzle movement (Figure 1). This technology has been effective in cleaning a number of single-shell waste tanks to the closure requirements. The sluicers use a coherent stream of sluicing fluid to break up solid waste, enabling it to be pumped out of the tanks. The use of recycled supernatant as a sluicing fluid was

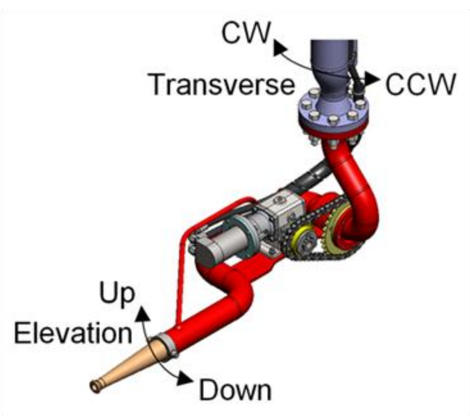

Figure 1. Original Sluicer Tank Cannon Range of Motion

leveraged to reduce the amount of contaminated fresh water created during the process.

Since 2003, there have been 19 sluicers manufactured, with varying upgrades that have improved their reliability and performance. These upgrades included redesign and testing of the sluicing nozzle, as well as the addition of a electro-hydraulic control system. The upgraded sluicing nozzle increased the stream quality and efficiency of the sluicer. The remote/electric control system, which replaced the original hydraulic control system, enabled the sluicer to be operated at an increased distance from the tank, reduced the number of hydraulic extension hoses required for sluicer operation, reduced the probability of failures at the hose interconnects, and improved the control response.

Though the sluicers were seen as a viable option for breaking up the tank waste, including the hard heel (hardest portion of the solidified waste), the fixed installation point of the sluicer under the riser limited the capabilities of the sluicing fluid stream in several ways. Because the locations of the two Sluicers within the tank are fixed, there is approximately 50 feet (15.2 m) horizontally (Figure 2) from the nozzle to the farthest point in the tank. Operating the nozzle at this distance significantly reduces the impinging force of the sluicing fluid stream on the waste. Also, without the ability to place the nozzle closer to the waste, any free liquids that accumulate

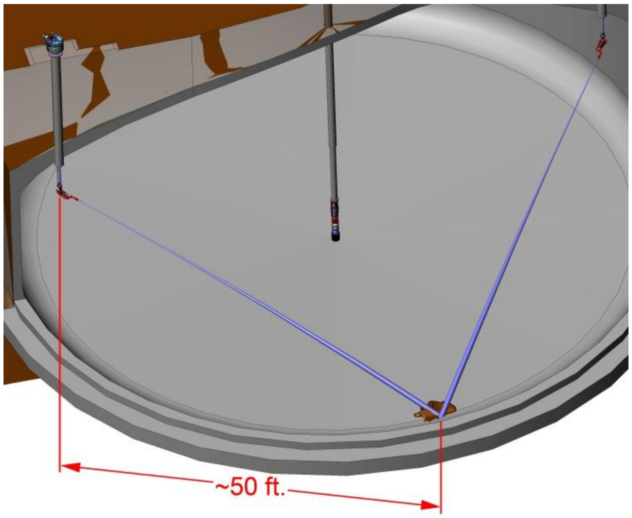

Figure 2. Standard Sluicer Tank Cannon Operation

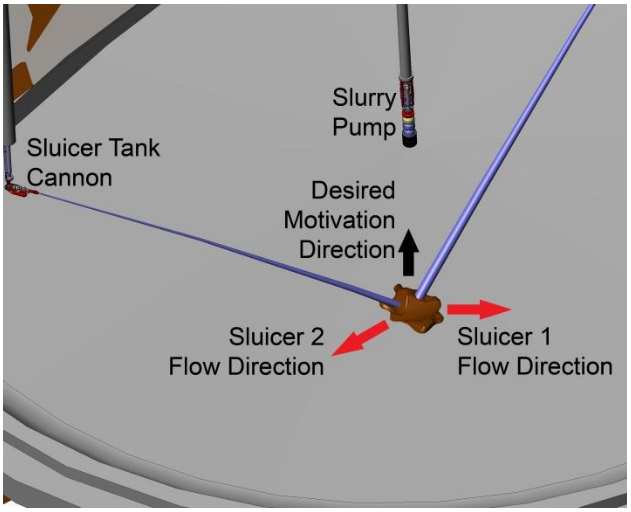

Figure 3. Sluicer Tank Cannon Attitude

above the solid waste in the tank further reduced the force of the sluicing fluid stream. The fixed location of the sluicers and their limited nozzle motion of pan and tilt also made it difficult to orient them in such a way as to motivate all of the waste in the tank directly toward the center mounted pump (Figure 3).

Evolution of the Extended Reach Sluicer Concept

Positioning the nozzle closer to the hard heel was accomplished through the development of a telescoping arm with a pan- and tilt-motion enabled sluicing nozzle on the end (Figure 4). Additionally, the nozzle assembly was designed with the ability to rotate continuously with 360 degrees of movement (as opposed to the original limited motion), in both the elevation and transverse directions, which allowed for more flexibility in targeting the waste and directly motivating the waste to the center mounted pump (Figure 5).

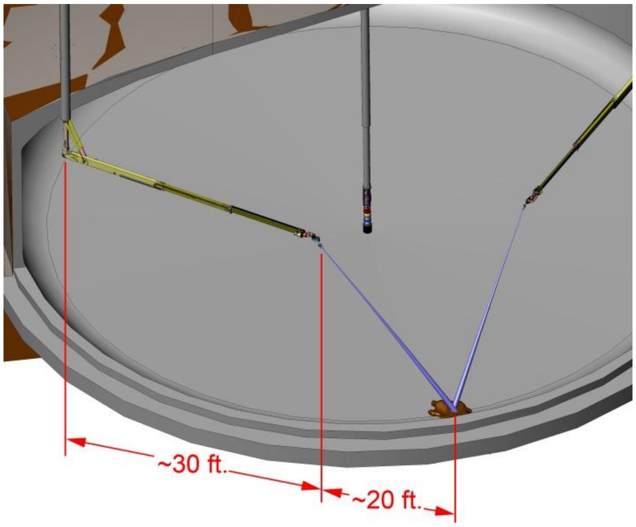

Figure 4. Extended Reach Sluicer Operation

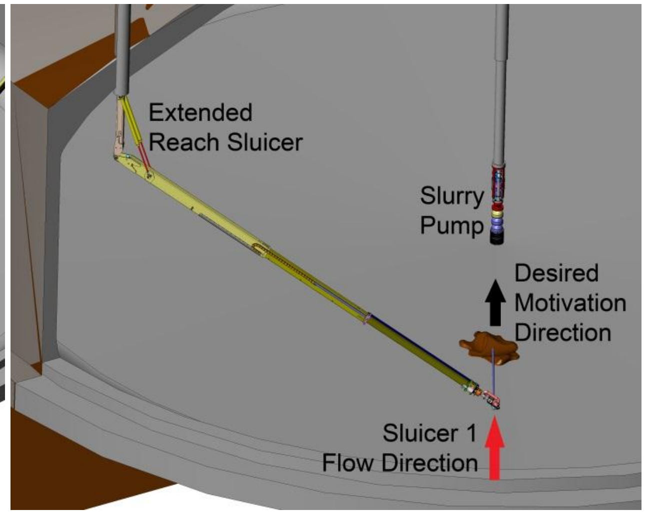

Figure 5. Extended Reach Sluicer Attitude

Designing the sluicer to operate within a highly radioactive environment allows very little recourse to solve problems after the unit is deployed, because once deployed it cannot be serviced, repaired, or upgraded in the tank. To perfect the design, an iterative process was used to identify any potential problems prior field deployment. This process included design, testing, redesign, upgrade and retesting of the unit in a cyclic manner.

Design & Production Challenges & Solutions

Minimizing the distance between the nozzle and the hard heel while preventing the nozzle from hitting the bottom of the tank during installation requires a telescoping boom. Installation of the ERSS in the tank also requires the entire boom to pass through the 12 inch (30.5 cm) diameter tank riser. In order to maintain adequate clearance, the entire in-tank structure must fit through an envelope 11 ¼ inches (28.6 cm) in diameter (Figure 6). The size of this opening limited the number of off-the-shelf components that could be used in the design, because most existing equipment is not compact enough to fit. This necessitates custom-designed components and many of them had to be designed and optimized using Finite Element Analysis, in order to minimize the size, while maximizing the strength and stiffness of the boom (Figure 7).

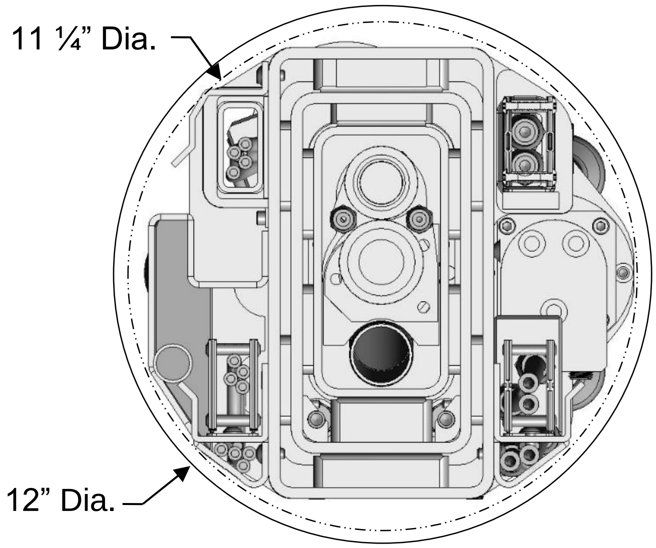

Figure 6. Cross Section of Boom Through a 12 inch Riser

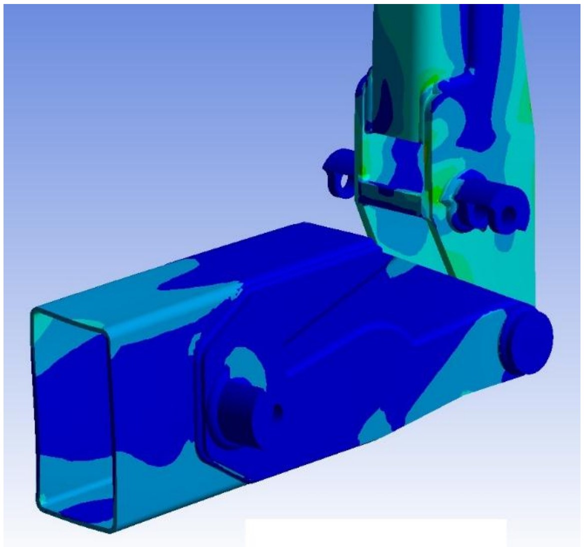

Figure 7. Short Arm Extended Reach Sluicer Elbow Joint Stress Analysis

Because there are no available commercial alternatives, a custom designed rotary union is critical to the elimination of hose management complexities for the nozzle elevation and transverse mechanisms. These are designed, fabricated and tested to be compact enough to fit through the riser opening, while passing the 5,000 PSI (34.5 MPa) high pressure wash supply water to the nozzles. The unions were designed and tested with the objective to minimize the friction within the unit, as the size of the gearbox and motor is also limited.

The nozzle transverse rotary union was designed with two circuits for the hydraulic fluid that run the nozzle elevation motion in addition to the one for the high pressure wash supply water. Radioactive sluicing fluid must not be able to contaminate the hydraulic lines, because the contamination would be transferred throughout the entire system back to the hydraulic power unit, outside of the tank. Due to this constraint, these rotary unions were designed to be completely independent of the process fluid rotary unions, allowing any weapage from the process unions to drain into the tank, in turn preventing radioactive sluicing fluid from having a path to enter the hydraulic system. A weep hole between the high pressure water seals and hydraulic seals also directs any seal weapage from the high pressure water circuit out of the union and back into the tank, ensuring no water enters the hydraulic system.

Sluicing fluid is conveyed to the nozzle assembly using a product hose that is managed by a hose reel as the telescoping boom extends and retracts. Maintaining the appropriate amount of tension on this hose is critically important to avoid damaging it. The hose reel sits just outside of the tank riser, housed within a secondary containment structure with drainage to direct any potential leaks back into the tank.

In order to prevent overshoot and ensure smooth, responsive motion in the controls, an electro-hydraulic control system similar to what was used on the original sluicers was also needed.

Furthermore, unconventional manufacturing techniques had to be developed and utilized to provide the intended functions in a compact boom that is able to fit down a 12 inch (30.5 cm) riser. Carrying the overhung load of the boom while minimizing wear and excess play in the telescoping joints requires the wear pads to be contoured with a CNC mill to match profiles obtained with a best fit method, based on 3D laser scans of the tube profiles.

Additionally, to provide adjustment during fabrication and assembly, as well as to fit many of the components in the available machining centers, machine-before-weld manufacturing procedures are utilized on many of the welded parts.

Extended Reach Sluicer Development

The prototype ERSS was designed, manufactured, and tested over approximately a three and a half month period during the summer of 2010. The prototype was tested by AGI at the factory and shipped to Hanford for further tests. After testing the ERSS at the Hanford Cold Test Facility (Figure 8), the unit was shipped back to the manufacturer for further testing and upgrades.

Based on the Cold Test Facility experience, minor updates were made to the unit in order to ensure proper hose reel operation, improve hose management, and reduce boom deflection and rebound during mast transverse movements. Additionally, any damage resulting from testing, shipping or handling was corrected.

In order to identify future design enhancements and to provide verification of the design, a 200 hour extended duration test was conducted at the manufacturer once all the design improvements had been incorporated into the prototype unit.

Figure 8. Prototype ERSS Testing at the Hanford Cold Test Facility

As a result of observations during the 200 hour test, additional rollers were added to help prevent binding of the process hose, and existing roller profiles were modified to reduce chaffing of the hose. An improved hydraulic motor was also installed on the hose reel and the nozzle rotation hydraulic swivel joint was modified for ease of assembly.

In developing the first field deployable Extended Reach Sluicer, maintaining the proper tension in the product hose while under pressure was a critical design point. The tension is controlled by a pressure reducing/relieving valve that limits the torque applied by the hose reel, based on the known relationship between torque and pressure in the hose reel hydraulic motor. To determine the allowable tension, burst and tensile testing was performed by the hose manufacturer on the pressurized product hose at an elevated temperature. The safety implications associated with the load on the hose, the valve that controls the hose reel tension (hose reel pressure reducing/relieving valve), as well as the valve that controls the telescoping arm extension force (boom extend pressure reducing valve) are discussed in detail in the section on licensing below, but an overview of the safety significant (SS) features of the ERSS mechanism follows.

The manufacturer of the SS hose reel pressure reducing/relieving valve and boom extend pressure reducing valve recommended the hydraulic fluid maintain a level of cleanliness in order to maintain reliable operation. A SS hydraulic filter was added to the Hydraulic Control Manifold to ensure that any debris that may enter the hydraulic system would be removed before it had a chance to foul the SS pressure reducing/relieving valves. The element in this filter is tested by the supplier to ensure that the oil passing through it is discharged meeting the recommended cleanliness requirements.

Later, a second filter in parallel as well as heat tracing would be added to the manifold/filter assembly and hydraulic hoses in order to ensure that increased pressure drops due to colder, more viscous oil would not cause a malfunction of the SS pressure reducing/relieving valves or the hose reel.

Damage to the hose and piping in the exposed sections of the ERSS due to freezing winter temperatures was also a concern. Freezing of any residual liquids in this plumbing was prevented by installing insulation and heat trace on the enclosure. Thermocouples were also added to the enclosure so the temperature could be monitored to ensure the piping remained above freezing.

Extended Reach Sluicer Features

The current Extended Reach Sluicer design includes a telescoping boom, which reduces the horizontal distance from the nozzle to the farthest portion of the tank to approximately 20 feet (6 m). The boom also allows the nozzle to reach within approximately 1-5 feet (0.3-1.5 m) of the pump assembly in the center of the tank.

The basic movement of the ERSS includes five degrees of freedom (Figure 9). The mast transverse moves 180 degrees in either direction from center and the boom elevation moves up to 110 degrees from vertical down, to above horizontal. The maximum boom telescoping extension is up to 16 feet (4.9 m), with approximately 30 feet (9.1 m) of overall boom reach

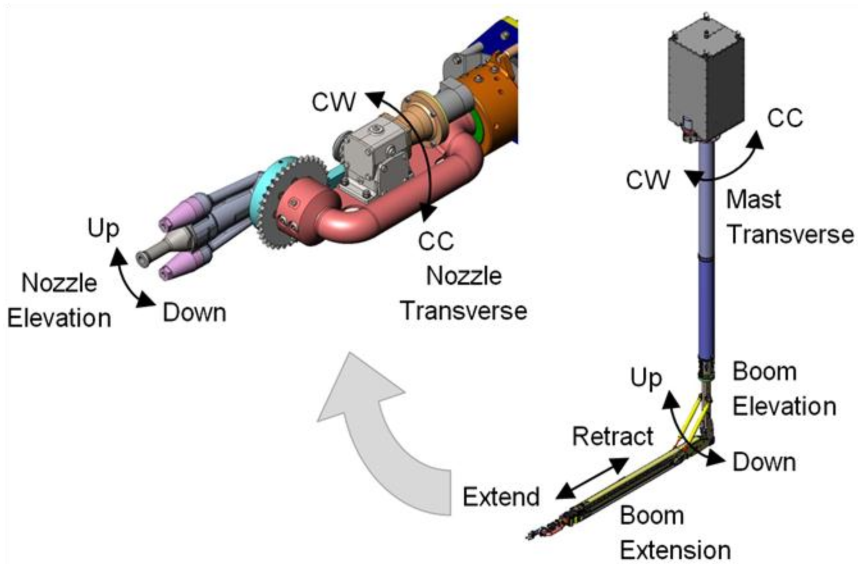

Figure 9. Extended Reach Sluicer Range of Motion

(Figure 10). The nozzle elevation and transverse axes rotate 360 degrees continuously with no stops.

Because the depth of waste prior to sluicing may vary from tank to tank the final length and configuration of the telescoping boom is customizable. This allows the boom length to be maximized, without interacting with the waste in the tank.

The three nozzles on the end of the ERSS boom include a single high flow sluicing nozzle flowing 100 GPM (380 LPM) at approximately 100 PSI (690 kPa). Two orbital wash nozzles are also available for breaking up hard heel at 5 GPM (19 LPM) each and 5,000 PSI (34.5 MPa).

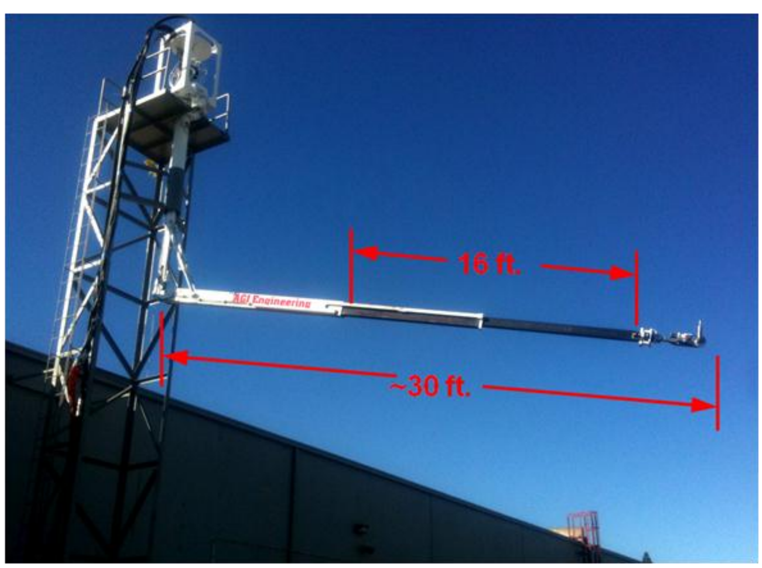

Figure 10. Extended Reach Sluicer Maximum Boom Length

The arm extension of the Extended Reach Sluicer allows the nozzle to be placed much closer to the waste and the added rotational axis of the nozzle assembly allows the sluicing fluid stream to be aimed more directly towards the pump in the center of the tank, for increased effectiveness. The multiple nozzle assembly on the Extended Reach Sluicer also allows the operator to break up hardened waste at an accelerated rate.

The added features and flexibility of the Extended Reach Sluicer improve the efficiency of an already useful technology, while still allowing the unit to be deployed through existing 12 inch (30.5 cm) risers. With the ability to precisely control the sluice stream and focus the sluice energy at close distance, the limitation of the modified sluicing system is now focused on the ability of the pump to capture the stream of heavy particles. The final stage of modified sluicing is usually a bed of heavy granular particles that are not easily entrained by the pump inlet. The next challenge in development of the system will be to improve the efficiency of the pump in capturing these heavy particles.

LICENSING CONSIDERATIONS

Like all nuclear waste sites in the DOE complex, Hanford's tank farms utilizes a licensing framework to authorize operations. This is implemented through, among other things, a Documented Safety Analysis (DSA) of the systems, structures, components and operating procedures. Controls ensure that the equipment, such as the ERSS, function within the framework of the license.

Whereas the original sluicers used rigid stainless steel pipe to convey the sluicing fluid to the end of the arm, and rotary unions to allow pivoting motion, extending and bending the sluicer arm requires a more flexible conduit. Hose-in-hose transfer lines (HIHTL) were developed and licensed to provide a flexible and relatively low cost method of establishing the waste transfer routes needed for single shell tank retrieval. The inner hose of an HIHTL is the pressure boundary and, as such, is qualified and licensed by the DSA, similar to rigid primary piping material. It is available to be procured from an NQA-1 supplier, and was thus recommended for the ERSS application.

The Control Development Process at WRPS is used to determine the controls and critical features of the ERSS for licensing by the DSA. Several failure modes were considered, but the final controls focus upon those that affect the containment of the waste at the pressure boundary. Because the hose had been previously qualified for static applications, failure modes were postulated that might arise as a result of the motion of the hose as it would be configured in the ERSS. Telescoping the arm of the sluicer demands that the hose be paid out from a hose reel residing in the shielded enclosure above the tank dome as the arm extends. Some level of tension force must be maintained on the hose to prevent it from drooping or jamming inside the mast. And, in order to avoid kinking the hose when retracting it, the hose reel must also collect the hose in an orderly fashion. Managing the forces upon the hose in the cycles of extension and retraction was identified as a source of potential failure modes.

The failure mode identified was tearing the hose apart due to imposed tension forces exceeding the strength of the hose, which could ultimately result in the release of contamination into the secondary containment box for the sluicer components above the tank. This became the focus of new engineering controls that challenged the designers and resulted in some novel applications of hydraulic pressure control components.

Testing by the manufacturer determined the maximum allowable tensile force that, when combined with internal pressure commensurate with the supernatant pumping system, would fail the hose. With this specified, the manufacturer knew that they needed to regulate the take-up tension of the hose reel working against the extension forces produced by the hydraulic cylinders and gravity. Their engineers designed their system to do this by choosing a swash-plate hydraulic motor and appropriate gearing. The swash plate motor runs continuously with the hydraulic fluid circulating at constant flow and pressure conditions, and the tension force produced is a function of the line pressure hydraulic fluid. Yet the reel can be held stationary or even rotated in the reverse direction without damaging the motor. For the first ERSS, the pressure control provided by the Hydraulic Power Unit's (HPU) built-in pressure relief valve (PRV) was licensed to protect the hose. Its margin of safety was 1.1. This PRV was procured as General Service (GS) and upgraded by WRPS through Commercial Grade Dedication (CGD). However, it was decided for later iterations of the ERSS design that a higher safety factor was desirable and this could no longer be provided by the PRV due to other design constraints.

The line pressure for the hose reel motor (and the corresponding hose tension) are further controlled through a pressure reducing device built into the hydraulic distribution manifold situated in the tank farm between the hydraulic power pack and the sluicer. Further analysis of the system determined that this component could be a more direct way of protecting the hose which could be done with a higher margin of safety, but only if it could be ensured that the device was continuously operable. Fouling of the very closely toleranced fluid passages that could prevent the delicate armatures from moving as needed to create and maintain the desired pressure limitations downstream was identified as a failure mode that needed to be addressed. Filtration of the hydraulic fluid is standard practice to maintain cleanliness in any hydraulic power system, yet, because of the vulnerability of fouling, an additional filter was added to the hydraulic fluid distribution manifold expressly for the hose reel and extension cylinder circuits.

Designating this pressure reducing valve and filter media as Safety Significant and thereby imposing additional inspections and tests of the components prior to use protects the assumption that it is not possible to compromise the integrity of the hose due to the tension force produced by pulling on the hose with the hydraulic cylinders and the hose reel motor simultaneously.

CONSTRUCTION AND TANK INTERFACE

The shielded enclosure for the above-tank portion of the ERSS is a 7 ft. tall box of 2-inch plate, welded together, which is mounted above the riser and provides an interface with the riser pipe flange, as well as the entry point for the supernatant HIHTL. (See Figure 11) This leak tight shielding structure allows for the detection of leaked fluid that might gather in the bottom and direct it safely into the tank.

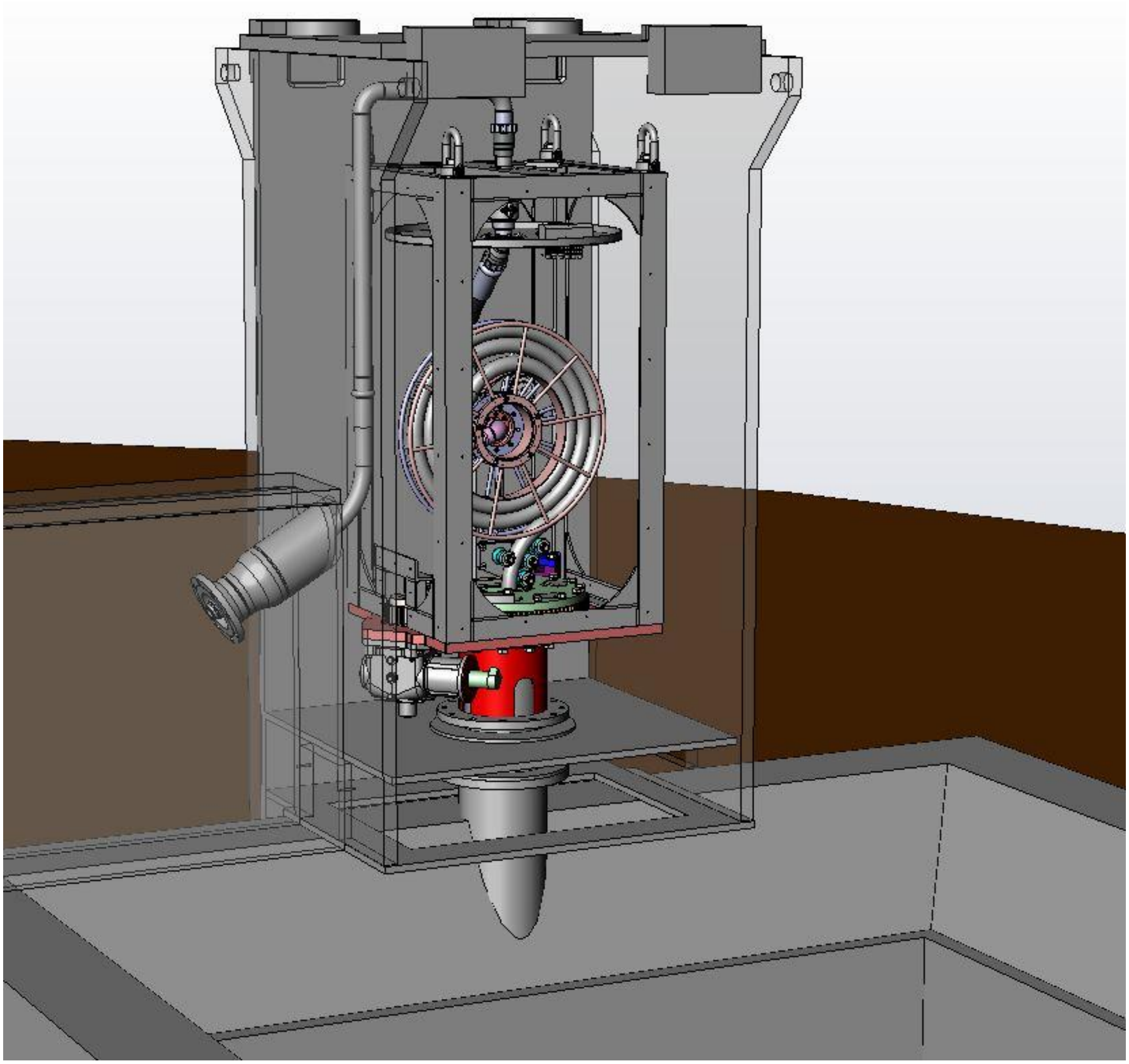
Figure 11. ERSS inside shielded enclosure as installed in tank C-101 riser 2.

Installation of the first ERSS into the riser at tank C-112 followed the site's work control processes, and the work package was executed with minimum difficulty. A crane was used to lower the sluicer mast through the riser so that the upper portion fit neatly in the shielded enclosure. Hydraulic lines to operate the various positioning functions, as well as the 'spider', a set of 3 hydraulically actuated wedges which center and restrain the sluicer mast inside the riser pipe, were routed and connected. Construction Acceptance Testing and Operational Acceptance Testing followed to ensure the system was leak free and operating as intended.

The ERSS modified with high-pressure water nozzles were installed in tanks C-101 and C-102 in Summer of 2012, using similar processes as the C-112 ERSS.

OPERATION EXPERIENCE

Early Successes and Challenges

Experience operating the ERSS began with approximately 30 hours of operator training on use of the C-112 system without actually transferring any waste to or from the tank. The ERSS operated very well in that time period, with all of the hydraulic functions working well. Once readiness for the retrieval was declared, sluicing began. Compared with its counterpart original sluicer, the ERSS was a resounding success. Whereas the sluicing stream from the original sluicers merely 'bounced off' of the waste surface, the ERSS' ability to train the stream of supernatant upon small cracks and fissures in the irregular waste surface at close range dramatically improved the ability to get underneath the crust. Such undermining of the crust weakened it so that it could be broken away in smaller pieces, exposing the softer waste underneath, which was mobilized toward the pump with relative ease. The promised retrieval productivity improvements were attained and, until the tougher 'hard heel' material at the bottom was exposed, the ERSS almost made it possible to meet the ambitious goals set for the tank C-112 retrieval project.

Soon after the start of operation, the routine surveillance of the hydraulic oil level in the HPU reservoir indicated an anomalous low reading. No evidence of a hydraulic oil leak was found above ground, so a camera deployed inside the tank was trained upon the sluicer arm and oil was observed dripping from the end of the arm. Both nozzle positioning functions on the end of the arm were still operable, and dripping could be observed that increased when they were actuated in the control room. Determination of the exact leak location was hampered by the low resolution of the video inspection system, but the general location suggested that handling the arm during installation could have caused physical damage to the hoses. It was determined that if the hydraulic motors could be used to position the nozzle appropriately, the hydraulic hoses supplying them could then be disconnected and sluicing could continue with only the gross positioning of the remaining (boom extend/retract, boom elevation and mast rotation) functions. While retrieval efficiency was reduced, the ERSS continued operating until it was determined that the hard heel remaining was impervious to further sluicing.

Tank C-101

For tank C-101, both of the next generation ERSSs were also upgraded with design improvements to prevent handling damage suspected on the prior unit. Furthermore, custom metal shipping crates and special handling procedures were added as precautions. Predictably, retrieval of this tank progressed slowly at first, as the crust was known to be very hard. However, with time, the ERSS eventually broke through the crust and retrieval progressed at a steady pace comparable with earlier tanks. Having both ERSS sluicers available simultaneously (although they did not run at the same time) gave the operations crews many opportunities to refine their techniques for moving the waste to the pump. Notably, feedback from the Process Engineer for the retrieval indicated that vigorous movement of the sluicing stream around the tank using the additional ERSS aiming functions compared favorably, from a retrieval volume measurement standpoint, to the practice of leaving the stream in one place and moving it intermittently. As described below, the high pressure water spray functionality commenced once sluicing effectiveness trailed off on the harder remnant material in the tank.

Periodically throughout the retrieval, hydraulic leaks were discovered and dealt with. Eventually both sluicers, like the ERSS in tank C-112, completed their missions with their nozzle fine positioning functions disabled. Cameras were used to pinpoint the sources of the leaks: they all originate from discrete places on the ¼" hydraulic hoses. Theories of the causes of the leaks no longer focused upon physical damage from handling, concentrating instead on environmental factors such as the chemicals and radiation inside the tank, as well as an obscure phenomena, damage by electrostatic discharge.

Due to the reduction in nozzle positioning and the resulting loss of efficiency, and concerns for adding organic hydraulic oil to the tank, a campaign of focused engineering effort was started to learn the cause(s) of the leaks and how to prevent them from happening in the future. Two outside consultants, in cooperation with the WRPS and AGI engineering teams, were engaged to help with the investigation. Radiation was an early leader in the search for a culprit because the hoses are constructed from a PTFE (Teflon) liner tube tightly wrapped with a stainless steel braided sheath for strength and protection. PTFE is known to have properties, ductility for example, that diminish with exposure to radiation fields, and is therefore not generally recommended for such use.

To better understand the leaks, deprived of the ability to examine the contaminated in-tank equipment, the prototype ERSS sluicer was returned to AGI's facility and upon examination was found to also have 'pinhole' leaks originating from the same hydraulic hoses. This sluicer had never been exposed to the tank radiation environment, which was a very important clue in the search for the cause.

Examination of the prototype hoses under a microscope showed that the damage was occurring from the inside of the hose. Dark-colored deposits were found in elongated pits running parallel to the longitudinal axis of the hose. In consultation with the hose's manufacturer, the cause was linked to electrostatic discharge across the thickness of the inner PTFE tube to the outer braid. The fast moving low-electrical-conductivity hydraulic fluid tends to build an electrical charge upon the inner surfaces of the tubing which eventually surpasses the dielectric breakdown strength of the hose liner material. An arc passes through the tube wall to the grounded braid and the charge dissipates. This may have been happening many times before a certain location experienced enough arcs to create a pinhole leak.

Another important clue that implicates static discharge is the absence of pinhole leaks in the larger tubes of the same construction which supply the boom extend/retract and boom elevation actuators. It is reasoned that, with similar flow rates, the larger cross sectional area of these hoses drops the velocity of the fluid to a level that does not cause the static charge to build up in the first place. It is likely that the damage was done to the hoses even before the ERSSs were installed in the tank. To ensure that all the bugs are worked out of the sluicers, each unit is run-in tested for 96 hours prior to delivery for installation. It is believed that this operation time was sufficient to cause the damage.

Consultant Recommendation

Several recommendations were made by the outside consultants engaged to help solve the problem. Notably, the first recommendation was usually to switch the hoses to conventional nitrile rubber construction, which is both conductive and known to work well in radiation environments. Due to the previously described configuration of the riser, space limitations were what drove the use of the smaller diameter tubing. Increasing the hose size would institute a severe re-design of the arm and would most likely result in a system that would require a riser larger than those available.

One recommendation that has been seriously considered is removing the high-speed settings for nozzle aiming controls, which was a feature added to improve efficiency. In the end, over-reliance upon this setting may have accelerated the creation of the pinhole leaks in the hose membrane. Any opportunity to slow the flow of the oil in the hoses, even at the expense of retrieval productivity, was seen as a positive change to prolong the life of the leak-prone function.

Dealing with the electrostatic charge emerged as the leading area for improvement. A conductive hose is available in the currently-used configuration which has carbon black impregnated in the PTFE lining. This creates a continuous ground path on the inner surface of the inner tube which wicks away static charge to a suitable ground point. In fact, four subsequent ERSS were built with conductive PTFE hoses (for both ¼" and $^{3}/_{8}$" sizes) in place of the non-conductive ones that developed leaks in prior sluicers.

Avoidance of further vulnerabilities associated with PTFE material are being addressed by investigating the possibility of replacing the hoses with a formulation of conductive ETFE (Tefzel) in place of the PTFE. ETFE is recognized to have superior ductility in the presence of prolonged radiation exposure. To date, however, 'cold' cyclic pressure transient testing of one such formulation failed to attain a suitable number of pressure cycles for the ERSS application.

High Pressure Water Functionality

The first opportunity to use and demonstrate the effectiveness of the high pressure water nozzles came during the retrieval of tank C-101, but not until most of the tank waste was removed. This was too late in the retrieval to test the original notion that using 5000 psi pressure water for breaking through the hard crust layer would dramatically speed up retrieval. As previously mentioned, the ability to focus the main supernatant stream on the waste slowly, but surely, worked away at the fractured the crust and allowed normal retrieval to progress. Later in the retrieval, however, the rate of transferring solids to the receiver tank slowed considerably because the sluicing could not reduce the waste to the size needed to pump it out as a slurry. These cobble-sized chunks were merely being moved around on the bottom of the tank by the sluicing stream. By this time, the high pressure water system was available, so it was connected and used to blast the remaining waste. This was effective at size reducing these chunks, but ultimately the resultant heavy particles could not be entrained in the pump slurry and not enough was removed from C-101 to meet the goal set for the acceptable volume of solids that can remain in the tank.

High pressure water will be used in the next attempt to retrieve the hard heel in tank C-112 and on tank C-111 hard heel waste. Tank C-102 will be the first opportunity to test the efficacy of high pressure water on top-layer crust material.

CONCLUSIONS

Lessons Learned

Several opportunities have been available to learn from and improve upon past and current generation sluicer development and deployment. Some of the lessons learned from the ERSS team's experiences are listed below:

- Improved retrieval effectiveness can be achieved by bringing the sluicing nozzle closer to the waste surface. The ERSS has proven itself in Tank C-112 by outperforming the previous-generation Sluicer Tank Cannon mounted in the same tank.
- Some waste surfaces are almost impervious to traditional sluicing methods, so innovations like the high pressure water spray nozzles that can dramatically speed up recovery of waste should be implemented, providing that doing so doesn't create undue impacts on the cost and schedule of the projects
- The difficulties with the leaks that occurred in the hydraulic system were incorrectly diagnosed in part due to the lack of high resolution cameras in the tanks. A second misdiagnosis might have blamed the difficulties upon material incompatibility for radioactive environments. Timely examination of the prototype produced the correct diagnosis and allowed the ERSS program to continue.
- Modern machine design techniques greatly accelerate the development of highly specialized machinery. Iterative optimization techniques allow restricted space constraints to be met while maintaining adequate safety factors for strength and serviceability.

Future Evolutions and Challenges

For taller tanks, longer sluicer arms with further extension capabilities will be needed. The basic ERSS design can be adapted to accommodate this evolution. Other capabilities that should be explored in future adaptations are the ability to maneuver around internal obstacles such as air-lift circulators and thermowells that are permanently installed in later SST designs in the Hanford tank farms.

As the technology of the sluicer system improves, the limiting factor for retrieval efficiency will shift to the pumping capability. Development of the pumping system that will efficiently remove the heavy particle "sand" left after removal of all the easily mobilized "fines" is the next hurdle to be cleared.