Development and Implementation of a Scaled Saltstone Facility at Savannah River National Laboratory – 13346

Marissa M. Reigel*, Mark D. Fowley,* Erich K. Hansen,* Kevin R. Hera,* Athneal D. Marzolf,* and Alex D. Cozzi,*
* Savannah River National Laboratory, Aiken, SC 29808

ABSTRACT

The Savannah River National Laboratory (SRNL) has supported the Saltstone Production Facility (SPF) since its conception. However, bench scaled tests have not always provided process or performance data related to the mixing, transfer, and other operations utilized in the SPF. A need was identified to better understand the SPF processes and to have the capabilities at SRNL to simulate the SPF unit operations to support an active low-level radioactive waste (LLW) processing facility. At the SPF, the dry premix is weighed, mixed and transferred to the Readco "10-inch" continuous mixer where it is mixed with the LLW salt solution from the Salt Feed Tank (SFT) to produce fresh saltstone slurry. The slurry is discharged from the mixer into a hopper. The hopper feeds the grout pump that transfers the slurry through at least 457.2 meters of piping and discharges it into the Saltstone Disposal Units (SDU) for permanent disposal. In conjunction with testing individual SPF processes over several years, SRNL has designed and fabricated a scaled Saltstone Facility. Scaling of the system is primarily based on the volume capacity of the mixer and maintaining the same shear rate and total shear at the wall of the transfer line. At present, SRNL is utilizing the modular capabilities of the scaled Saltstone Facility to investigate the erosion issues related to the augers and paddles inside the SPF mixer. Full implementation of the scaled Saltstone Facility is still ongoing, but it is proving to be a valuable resource for testing alternate saltstone formulations, cleaning sequences, the effect of pumping saltstone to farther SDU's, optimization of the SPF mixer, and other operational variables before they are implemented in the SPF.

INTRODUCTION

The Saltstone Facility at the Savannah River Site (SRS) is comprised of two facilities, the Saltstone Production Facility (SPF) and the Saltstone Disposal Facility (SDF). The SPF receives low level radioactive waste (LLW) salt solution from Tank 50H for treatment. Although Tank 50H receives transfers from multiple processes at SRS, the primary influent is from the Actinide Removal Process/Modular Caustic Side Solvent Extraction Unit (ARP/MCU). At the SPF, the LLW is mixed with premix (a cementitious mixture of portland cement, blast furnace slag and Class F fly ash) in a "10-inch" Readco continuous mixer to produce fresh (uncured) saltstone that is transferred to the SDF for permanent disposition in a Saltstone Disposal Unit (SDU). Admixtures, if needed, are added inline to the LLW prior to mixing with the premix. The slurry is discharged from the mixer into a nominal working volume 1135.6 liter agitated hopper. The hopper feeds the grout hose pump that transfers the slurry through at least 457.2 meters of piping and discharges it into the SDU for permanent disposal. Fig. 1 shows a simplified process flow diagram for the entire Saltstone Facility.

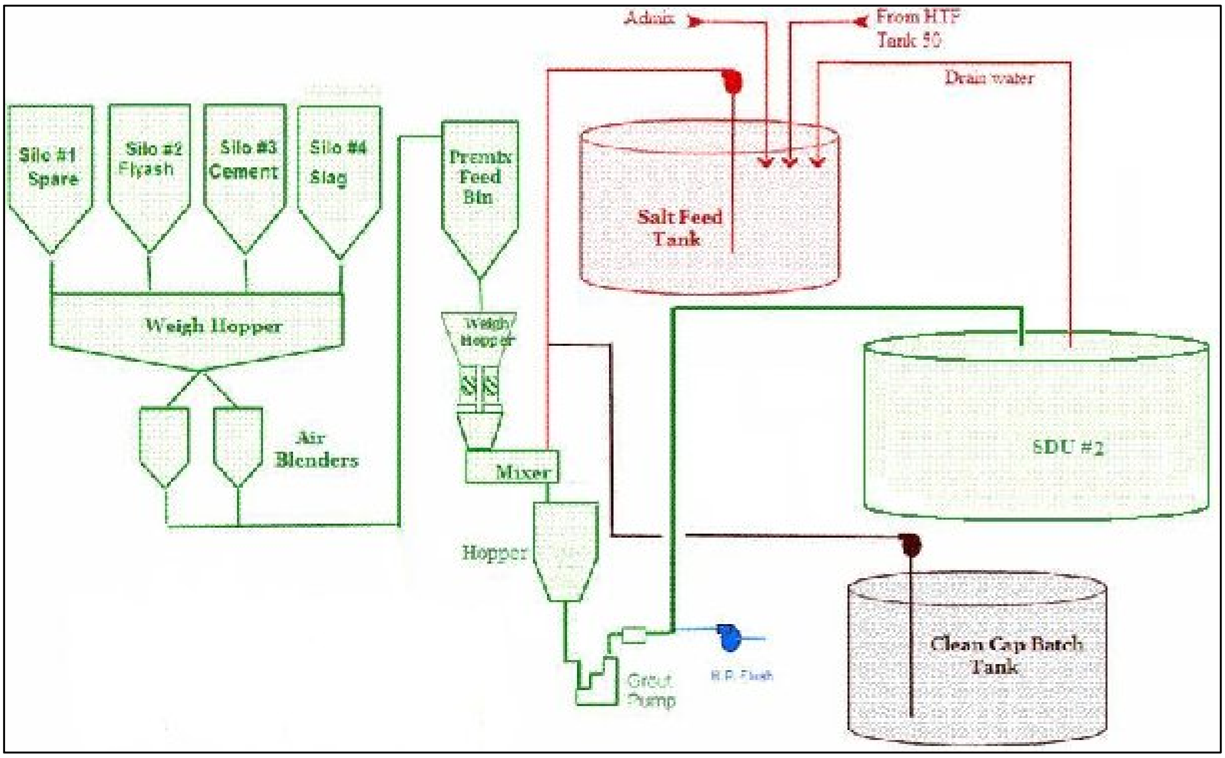


Fig. 1. Simplified Saltstone Facility process flow diagram.

The Savannah River National Laboratory (SRNL) has supported the SPF since its conception. However, bench scaled tests have not always provided process or performance data related to the mixing, transfer, and other operations utilized in the SPF. In 2008, a saltstone product quality assurance team was chartered to develop a path for identifying the key attributes for processability and long term performance for the saltstone produced at the SPF and placed in the SDF [1]. One of the variables identified in the report was the uncertainty in how closely the saltstone formulation process simulates the actual "in-facility" process in the amount of salt solution and flush water, degree of mixing, temperature and other processing attributes [1]. A need was identified to better understand the SPF processes and to have the capabilities at SRNL to simulate the SPF unit operations in order to support the active LLW processing facility. Since 2009, testing related to individual unit operations has contributed to the development and implementation of a scaled Saltstone Facility at SRNL.

DISCUSSION OF SCALED UNIT OPERATIONS

Transfer Line

In 2009, SRNL was requested to develop a bench scale test facility, using a mixer, transfer pump, and transfer line to determine the impact of conveying the saltstone through the transfer lines to the vault on saltstone properties [2]. SRNL developed a bench scale saltstone mixing rig (BSMR), using a conventional mixer and transfer pump to perform initial testing to determine the impact of conveying the saltstone through the transfer lines. Bench scale testing focused on the effect the transfer line has on the rheological properties of the saltstone as it was processed through the transfer line [2]. The Saltstone Facility uses at least 457.2 meters of 7.62 cm American Petroleum Institute (API) 5L pipe as the transfer line from the SPF to the disposal units.

For scaling purposes, the decision was to use the same shear rate (or shear stress) as actual field conditions at the wall for scaling, since this is the greatest shear rate in the piping [2]. It was assumed that the condition of flow is either laminar or transitional, given the rheological conditions of testing. Since the wall shear rates were the same, the total applied shear must also be the same in the two scales so as to apply the same quantity of pipe mixing (due to only wall shear). Typical and readily available hose sizes with inside diameters of 0.95, 1.27, 1.59, 1.91, and 2.54 cm ($^3/_8$, ½, $^5/_8$, ¾ and 1inch) were evaluated for use in the BSMR and the results are provided in Table I. In the SPF, the wall shear rate is 250.5 sec^{-1} and the total shear is 57725 sec^{-1} and maintained as the basis for scaling [2]. The analysis indicates that as the inside diameter becomes smaller, the velocity, Hedstrom number, Reynolds numbers, and ratio of Reynolds numbers decrease and the flow is laminar. The laminar flow conditions have the same shear rate profiles given the constant wall shear rate [3]. A saltstone density of 1.7 g/mL, yield stress of 7.4 Pa and plastic viscosity of 0.056 Pa·s were used for scaling. The plant data is provided in Table I. For the 7.62 cm pipe in the SPF, the condition of flow is in the transitional region, but it is more laminar than turbulent. SRNL selected the 1.59 cm ($^5/_8$ in) inner diameter (ID) tubing since the quantity of material is manageable and the flow rate provides adequate time to pull samples during the test time [2]. Hence mixing, or shearing, at the bench scale should be less than that observed in the full scale; therefore, the bench scale tests are considered to be conservative due to the highly laminar condition of flow that exists [2].

Table I. Scaling results for various tubing sizes, maintaining the shear rate and total shear

Parameter	Units	SPF Data	ID of Tubing for BSMR (cm)				
			2.54	**1.91**	**1.59**	**1.27**	**0.95**
Inside Diameter (D)	cm	7.79	2.54	1.91	1.59	1.27	0.95
Volumetric flow rate ($\dot{Q}$)	L/s	9.46	0.34	0.14	0.08	0.04	0.02
Average velocity ($\overline{v}$)	m/sec	1.98	0.66	0.50	0.41	0.33	0.25
Pipe Run (L)	meters	457.2	152.4	114.3	95.1	76.2	57.0
Hedstrom number (N_{HE})	Unitless	24360	2588	1456	1011	647	364
Reynolds number (N_{RE})	Unitless	4694	511	287	200	128	72
Transition Reynolds number (N_{TRE})	Unitless	4281	2537	2366	2291	2226	2173
Ratio of Reynolds number ($\frac{N_{RE}}{N_{TRE}}$)	Unitless	1.10	0.20	0.12	0.09	0.06	0.03
Pressure Drop (ΔP)	kPa	502.6	514.3	514.3	514.3	514.3	514.3
Volume in line (V)	Liters	2180.4	77.2	32.6	18.9	9.5	4.2
Power Per Unit Volume ($\frac{P}{V}$)	W/m^3	2.23	2.28	2.28	2.28	2.28	2.28

The results of scaling down resulted in a shorter transfer line, a lower average velocity, the same transfer time and similar pressure drops [2]. Two BSMR runs were performed. In both cases, wall shearing was shown to reduce the rheological properties of the saltstone as it was processed through the transfer line. Samples taken at the static feed tank showed that gelling impacted the rheological properties of the saltstone before it was fed into the pump and transfer line. A comparison of the rheological properties of samples taken at the feed tank and transfer line discharge indicated that shearing of the saltstone was occurring in the transfer line.

Continuous Mixer

The “10-inch” Readco-Kurimoto, LLC mixer installed in the SPF is a continuous co-rotating twin-screw mixer. Continuous co-rotating twin-screw mixers offer multiple advantages over single screw or batch mixers. The continuous mixer has interchangeable parts, making it adaptable to most processes, it produces material at a similar or faster rate than batch processes, and it reduces mixing time while maintaining tight process control and product quality [4,5]. The co-rotating shafts contain multiple intermeshing lens-shaped mixing paddles and augers that have tight clearances between the paddles and augers and the inside diameter of the barrel which promotes a “self-wiping” or cleaning capability of these mixers (Fig. 2) [4-6]. The machined tolerances between the rotating components and the barrel wall of Readco-Kurimoto, LLC continuous mixers form the high shear rate gaps that cause distributive mixing [4,6] of the premix and salt solution.

Fig. 2. Internal configuration of a Readco-Kurimoto, LLC continuous mixer, note the tight clearances between the intermeshing lens-shaped mixing paddles and the inside barrel diameter.

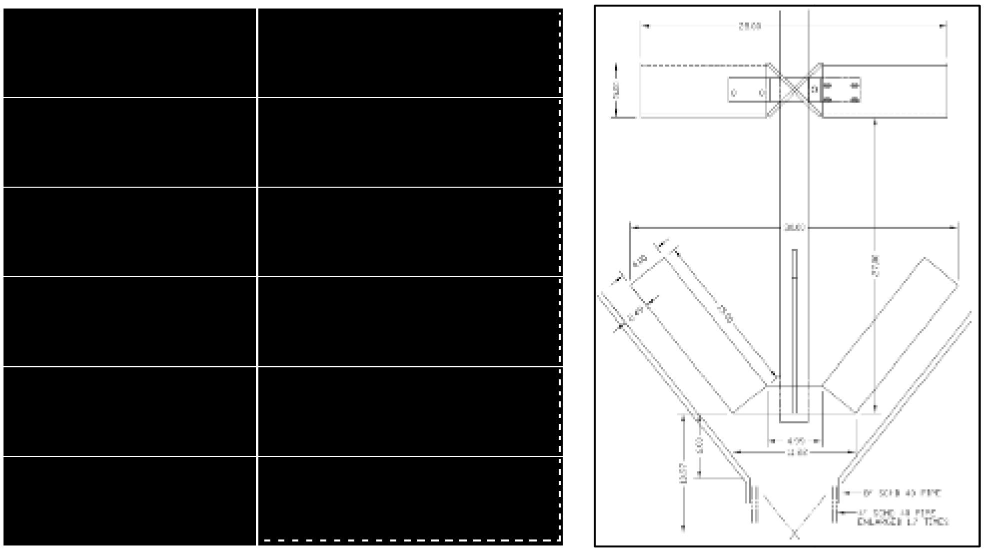
In late 2010 and early 2011, the SPF was experiencing back up of dry feeds in the vertical chute that feeds the “10-inch” Readco-Kurimoto continuous mixer. The dry feeds were setting off both the 0.61 meter and the 2.1 meter indicators in the premix chute to the “10-inch” mixer during multiple days of processing. When the 2.1 meter indicator is tripped, the SPF enters into shutdown [7]. As a result of these and other process upsets, the throughput capacity of the “10-inch” mixer was questioned. SRNL was asked to participate in determining the maximum throughput capacity of the “10-inch” continuous mixer by performing testing with an equivalent “5-inch” continuous mixer. Since Readco-Kurimoto, LLC geometrically (dimension and pitch) scales their mixers, the results from the “5-inch” mixer can be directly scaled to the “10-inch” mixer using a volumetric scaling factor [8]. Using the 1:8 volumetric scaling factor, it was determined the “10-inch” mixer is capable of maintaining a 12.6 kg/s dry feed throughput capacity which is greater than the SPF operational throughput of 8.3 kg/s of dry feed [9].

In conjunction with the BSMR testing in 2009 and the “5-inch” mixer testing in 2011, it was determined that a “2-inch” continuous mixer would be ideal for duplicating the mixing conditions in the SPF on the pilot scale. The same geometric scaling applies for the “2-inch” mixer, resulting in the “2-inch” mixer being 125 times geometrically smaller than the “10-inch” mixer [5]. Therefore, the “2-inch” mixer has a 1:125 volumetric scale ratio with the “10-inch” mixer installed in the SPF [10]. The vendor also uses internal volume of the mixers to calculate the scale-up ratio. The internal volumes of the “2-inch” and “10-inch” mixers are 7.70E-4 m^3 and 0.103 m^3, respectively, resulting in a scale up ratio of 1:133. Since this ratio results in less volume of premix fed to the mixer, the 1:125 ratio was used for scaling to get maximum throughput of material. The “2-inch” mixer has the same number of paddle stages as the “10-inch” mixer; therefore it can be set up with the same paddle configuration.

Grout Hopper

In 2011, the Saltstone Enhanced Low Activity Waste Disposal (ELAWD) project identified the need to replace the existing hopper that connects the Readco-Kurimoto, LLC "10-inch" mixer and the pumping system at the SPF to improve processing of saltstone (Fig. 1). The Saltstone slurry free falls into the grout hopper which feeds the suction line leading to the Watson SPX 100 duplex hose pump. The Watson SPX 100 pumps the saltstone through approximately 457.2 meters of piping prior to being discharged into the SDF disposal units [11]. The nominal working volume of the hopper used in the SPF from 2005 to 2011 was 45.4 liters and did not permit handling an inadvertent addition of excess dry feeds. Saltstone Engineering proposed a new hopper with a nominal working volume of 1136 liters that has an inner diameter of 129.5 cm and is agitated with a mechanical agitator [11]. The larger volume hopper is designed to handle variability in the output of the continuous mixer and process upsets without entering set back during processing [11]. SRNL was requested to mock-up and test a scaled hopper to determine whether this hopper design could be run under vortexing conditions without impacting radar level measurements and be able to incorporate a mass of un-wetted dry feeds into the agitated hopper and be recoverable [11].

SRNL selected a scale such that the inside diameter (ID) of cylindrical section of the vessel is 76.2 cm. This selection was based on the operations and placement of the radar level instrument on top of the hopper such that wall effects would not impact its operations. Other vessel scales of 60.9 cm and 91.4 cm ID diameters were considered; however it was determined that 76.2 cm was the most appropriate scale based on volume of material and functionality of the radar instrument. The inside diameter of the proposed hopper from Saltstone Engineering has a dimension of 129.5 cm, therefore the geometric scaling ratio is 76.2/129.5 (the ratio of the test vessel diameter divided by the proposed hopper diameter). For the agitator, geometric similarity is essential to ensure both kinematic (tip speed) and dynamic (Reynolds number, Froude number, etc.) similarities between two different scales [12,13]; although it is difficult to satisfy both conditions. The scaled impeller shaft was designed to allow placement of the bottom impeller at the scaled axial positions of either 15.2 cm or 25.4 cm from the bottom of the tank while maintaining the same distance between the top and bottom impellers, based on the full scale dimensions [11]. Fig. 3 shows the ELWAD grout hopper and agitator design tested by SRNL and installed in the SPF in 2011.



(a) (b)

Fig. 3. ELAWD grout hopper (a) and agitator design (b) installed in the SPF in 2011.

Testing of the 76.2 cm scaled grout hopper showed that the size of the vortex will not impact the operation of the radar level instrument given the nominal range of tank operations is between 1136 liters to 1249 liters in the SPF. Also, the addition of a 128.8 kg mass of un-wetted dry premix to the hopper did not cause operational issues with the proposed hopper, given the test conditions [11]. Review of the saltstone level data indicates that this addition would be difficult to measure during processing, given that in the actual process, the saltstone is being pumped out of the vessel as the dry addition is made. The test data indicated that less than 74 seconds was required to incorporate the solids into the slurry, but in the actual process, this time is expected to be much shorter, since operating with a vortex will help entrain the solids. Baffles are not required for any of the fluids that will be processed through the SPF. Operating with a vortex is adequate for this hopper design, since the intent of this hopper is not to mix the contents, but to keep the slurry in the vessel in constant motion since mixing of the premix and salt solution is occurring in the "10-inch" mixer.

SCALED SALTSTONE FACILITY

Using the scaling from the 2009 BSMR study, the volume capacity of the "2-inch" mixer, and the ELAWD grout hopper study, a scaled saltstone facility concept was developed including a scaled dry feed system, mixer, grout hopper, grout pump and transfer line. A key component of the design was to make the scaled facility modular so that select unit operations could be evaluated separately or the entire facility could be run as a whole. As shown in Fig. 4, after the saltstone is discharged from the mixer, there are at least three options for operating the scaled Saltstone Facility. Since the unit operations are on wheels, the configuration can be altered to fit the scope of the experiment.

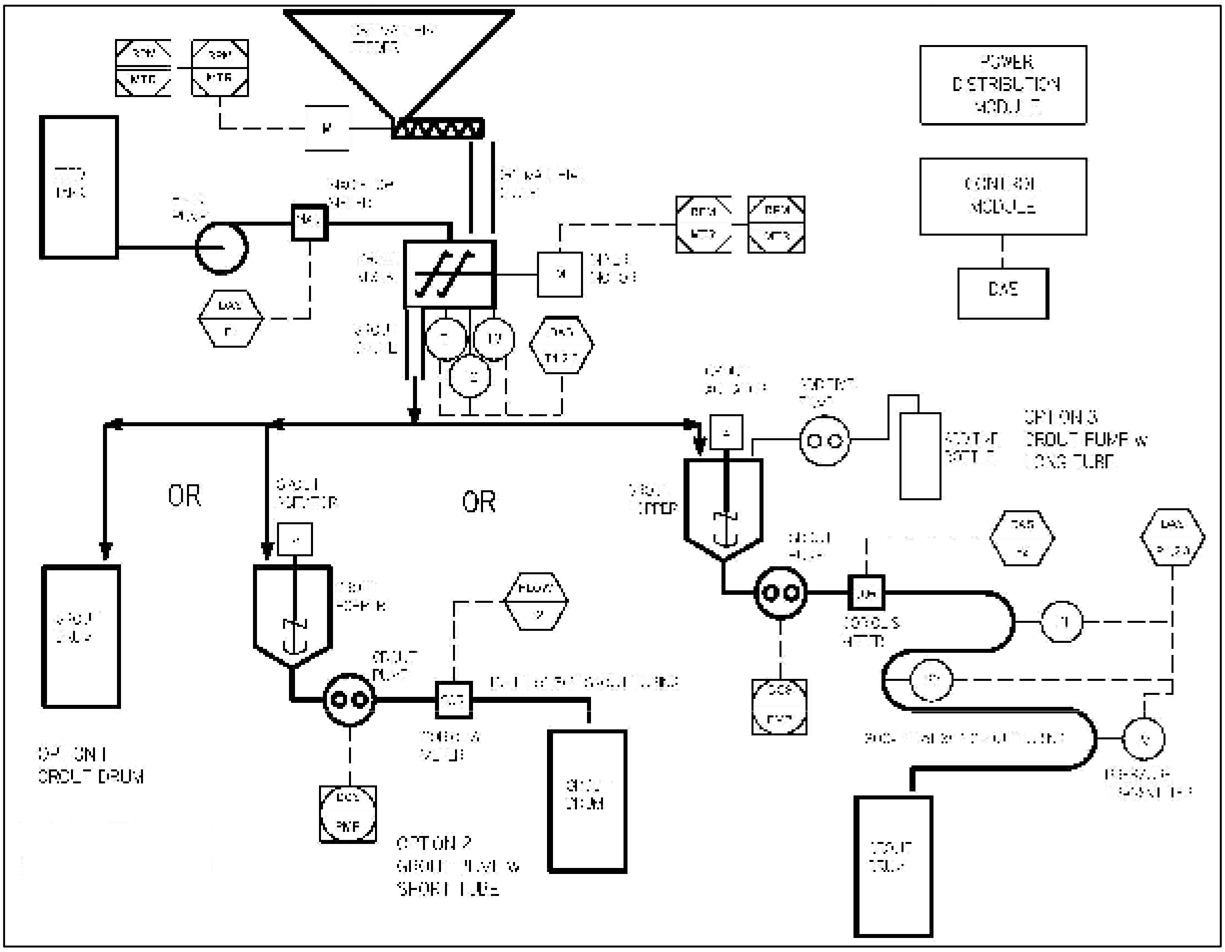


Fig. 4. Process and instrumentation diagram showing three options for operating the scaled Saltstone Facility.

Fig. 5 shows the scaled Saltstone Facility set up for running “option 3” of Fig. 4. The scaled system consists of a Mechatron “MC” dry feeder coupled to a Readco-Kurimoto “2-inch” twin-screw continuous processor (mixer) which mixes the dry feeds with liquid. The Readco mixer discharges the slurry into a hopper. A Watson-Marlow Bredel SPX20 hose pump transfers the slurry from the hopper through 91.4 m of 1.59 cm ($^{5}/_{8}$ in) ID tubing to a 208 liter drum.

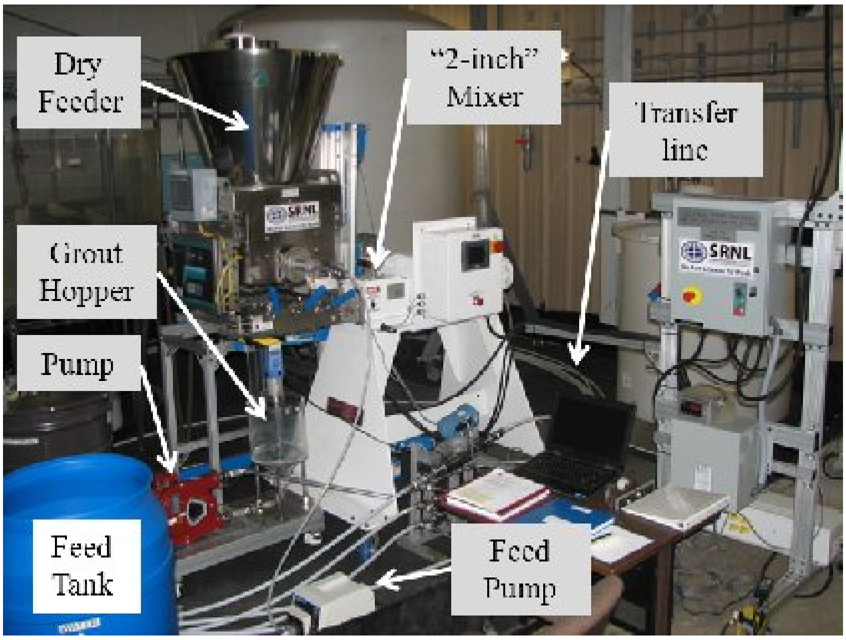


Fig. 5. Scaled saltstone set up of the dry feeder, "2-inch" mixer, and collection vessel used in the mixer wear testing.

The pilot scale dry feeder is a Schenck AccuRate volumetric Mechatron "MC" Screw Feeder capable of feed rates from 3.93E-02 m^3/s to 2.60E-3 m^3/s (0.05 – 330 ft^3/hr) with volumetric accuracies of approximately 2% of the feed rate. The feed hopper has about a 0.40 m^3 (14 ft^3) storage capacity and the feed screws can be re-configured to the desired application.

The slurry hopper was designed by SRNL based on the 1135.6 liter working volume ELAWD hopper. The same scaling parameters used in the ELAWD hopper testing were applied to the scaled Saltstone Facility grout hopper. The scaled hopper has a maximum volume of 16.6 liters. The inner diameter is 26.4 cm and the overall height of 54.6 cm. The hopper is designed to be operated with an agitator to keep the inventory of the hopper in motion. The agitator speed is controlled by a Caframo Ultra Torque Model BDC1850 overhead stirrer with a speed range of 1.26 rad/s to 189 rad/s (12 – 1800 rpm). The maximum torque is 565 N-cm for the low speed range and 113 N-cm for the high speed range. The agitator design can be changed since the stirrer accepts up to 0.95 cm (3/8 in) shafts.

The grout pump is a Watson-Marlow Bredel SPX20 hose pump capable of achieving a flow rate of 0.265 L/s (4.2 gpm) at a maximum discharge pressure of 758 kPa (110 psi). The pump displaces 0.15 L/rev and has an operating speed up to 7.85 rad/s (75 rpm) continuous or 11.0 rad/s (105 rpm) intermittent. It is capable of handling materials with high viscosities and densities and fluids with temperatures up to 79 °C. The pump transfers the saltstone through 91.4 m of 1.59 cm ($^5/_8$ in) ID tubing. An Emerson T-series straight tube full-bore coriolis flow and density meter is installed in the hose after the pump. Sampling stations are positioned every 30.48 m along the hose. Solenoid valves, controlled via CPU, activate the pinch valves to allow samples to be taken.

In December 2011, water was successfully run through the entire scaled saltstone facility, excluding the dry feeder. In February 2012, saltstone was made utilizing the premix feeder, SFT, and “2-inch” mixer. The results of this testing showed that the scaled Saltstone Facility is capable of producing saltstone at equivalent rates and rheological properties as the SPF.

During 2012, SRNL utilized the modular capabilities of the scaled Saltstone Facility to investigate the erosion issues related to the auger and paddles inside the SPF mixer. The recently disposed SPF mixer showed an area between the auger and paddle that eroded and the saltstone in this area cured due to the lack of shearing. This created a natural orifice that reduced the capacity of the augur, causing the dry premix entering the mixer to back up, leading to facility shutdowns. The scaled Saltstone Facility was used to test alternate paddle configurations and mixer settings that can increase the operating life of the SPF mixer so that maintenance and replacement and rework of the actual SPF mixer are minimized.

Full implementation of the scaled Saltstone Facility is still ongoing, but it is proving to be a valuable resource for testing alternate saltstone formulations, cleaning sequences, the effect of pumping saltstone to farther SDU’s etc. before they are implemented in the active Saltstone Production Facility. In addition, it can be utilized to investigate the source of process upsets and test proposed changes to the operating strategy.

CONCLUSIONS

SRNL has supported the SPF since its conception. However, bench scaled tests have not always provided process or performance data related to the mixing, transfer, and other operations utilized in the SPF. A need was identified to better understand the SPF processes and to have the capabilities at SRNL to simulate the SPF unit operations to support an active LLW processing facility. At the SPF, the dry premix is weighed, mixed and transferred to the Readco “10-inch” continuous mixer where it is mixed with the LLW salt solution from the Salt Feed Tank (SFT) to make fresh saltstone slurry. The slurry is discharged from the mixer into a hopper. The hopper feeds the grout pump that transfers the slurry through at least 457.2 meters of piping and discharges it into the Saltstone Disposal Units (SDU) for permanent disposal. In conjunction with testing individual SPF processes over several years, SRNL has developed a scaled Saltstone Facility. Scaling of the system is primarily based on the volume capacity of the mixer and maintaining the same shear rate and total shear at the wall of the transfer line. To date, SRNL has utilized the modular capabilities of the scaled Saltstone Facility to investigate the erosion issues related to the auger and paddles inside the SPF mixer. Full implementation of the scaled Saltstone Facility is still ongoing, but it is proving to be a valuable resource for testing alternate saltstone formulations, cleaning sequences, the effect of pumping saltstone to farther SDU’s, optimizing the SPF mixer, and other operational variables before they are implemented in the SPF.

REFERENCES

1. Spires, R.H., "Strategy for Saltstone Product Quality Assurance," Washington Savannah River Company, LWO-SPT-2008-00031, Revision 0, March 20, 2008.

2. Cozzi, A.D., Hansen, E.K., Jones, T.M., and Safford, Y.R., "Bench Scale Saltstone Process Development Mixing Study," Savannah River National Laboratory, SRNL-STI-2011-00346, June 2011.

3. Bird, R.B., Stewart, W.E., and Lightfoot, E.N., *Transport Phenomena,* Second ed. John Wiley & Sons, Inc., 2002.

4. Kalyon, D.M., *Polymer Rheology and Processing, Chapter 28: Mixing in Continuous Processors*.

5. "Readco Kurimoto, LLC, Continuous Processors", 2010.

6. Lawal, A. and Kalyon, D.M., "Mechanisms of Mixing in Single and Co-Rotating Twin Screw Extruders," *Polym. Eng. Sci.,* **35**, [17] 1325 - 38 (1995).

7. Reigel, M.M., Fowley, M.D., and Pickenheim, B.R., "Evaluation of Saltstone Mixer Paddle Configuration for Improved Wear Resistance," Savannah River National Laboratory, SRNL-STI-2012-00549, Revision 0, September 2012.

8. Meijer, H.E.H. and Elemans, P.H.M., "The Modeling of Continuous Mixers, Part I: The Corotating Twin-screw Extruder," *Polym. Eng. Sci.,* **28**, [5] 275 - 90 (1988).

9. Carter, A.R., Leita, J.N., Tihey, J.R., and Occhipinti, J.E., "Engineering Position for Saltstone Mixer Testing at Vendor Facility," Savannah River Remediation, SRR-WSE-2011-00083, March 30, 2011.

10. Myers, S.R.K., Inc), to M. M. Reigel, E. K. Hansen, and A. B. Barnes, *Personal Communication*

11. Hansen, E.K., Pickenheim, B.R., Leishear, R.A., Marzolf, A.D., et al., "ELAWD Grout Hopper Mock-Up Testing," Savannah River National Laboratory, SRNL-STI-2011-00465, Revision 0, October 2011.

12. Oldshue, J.Y., *Fluid Mixing Technology,* First ed. Chemical Engineering McGraw-Hill Publication Company, 1983.

13. Dickey, D.S., "Dimensional Analysis, Similarity and Scale-Up," *Process Mixing – Chemical and Biochemical Applications: Part II, AIChE Symposium Series*, Vol. 89, p. 143 - 50.

14. "Schenck AccuRate" Accessed on: September 4, 2012. Available at <http://www.accuratefeeders.com/mechatronfeeders.html>