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SY101 IN-SITU VISCOMETER INSTRUMENT SYSTEM DESIGN DESCRIPTION		ECN No.

Name	MSIN	Text With All Attach.	Text Only	Attach./ Appendix Only	EDT/ECN Only
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**SY-101 IN SITU VISCOMETER INSTRUMENT
SYSTEM DESIGN DESCRIPTION**

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SY-101 IN SITU VISCOMETER INSTRUMENT
SYSTEM DESIGN DESCRIPTION

1.0 INTRODUCTION

The Hanford Site contains over 100 underground tanks containing high-level radioactive wastes. Tank 101-SY is a double shell tank containing a caustic mixed-waste slurry. This tank is known to release flammable and toxic gases periodically during events known as rollovers. Waste within this tank historically consisted of two regions, a supernatant liquid layer above a thick sludge layer. These were designated convective (C) and non-convective (NC) regions, respectively, because they had different thermal transport properties, as evidenced by the in-tank instrumentation.

Knowledge of the rheological properties of the material contained in Hanford Site high level radioactive waste tanks is crucial to the understanding of the wastes, and to the success of many of the mitigation and remediation methods. Rheological measurement methods applicable to tank 101-SY were reviewed and evaluated in a report by Pasamehmetoglu et al. (1993). Subsequently, the in situ viscometer (ball rheometer) has been developed through the joint efforts of Pacific Northwest Laboratory (PNL), Los Alamos National Laboratory (LANL), and Westinghouse Hanford Company (WHC) personnel.

This instrument is intended to provide in situ data that allows the determination of yield strength, density, and apparent viscosity of the waste contained in tank 101-SY. This information will be used to improve tank behavior modeling calculations, safety analyses, and structural analyses. Furthermore, such data will provide the means for assessing the effectiveness of mitigation methods, such as the mixer pump installed in tank 101-SY to mix the convective and non-convective layer materials.

2.0 DOCUMENT OVERVIEW

PNL and LANL coordinated the research and development effort for the in situ viscometer system, the waste simulant selections for concept demonstration and validation measurements and supported the hardware design and development. In addition, these labs will lead the data reduction phases of the project.

WHC was the lead organization for the tank 101-SY Viscometer Program, and provided project management and funding support. WHC developed the definitive design and documentation to fabricate, test, operate, and store the system hardware; fabricated/oversaw fabrication of hardware; and interfaced with PNL and LANL to deliver a turnkey system to the SY farm. WHC will install, operate, and

store the system, and will provide acquired viscometer raw data to PNL and LANL to allow data reduction.

This System Design Description (SDD) documents the design of the in situ viscometer consisting of the viscometer instrument, decontamination chamber, and control console. The system was designed and manufactured to achieve the performance objectives dictated by the requirements discussed in K. L. Pearce and T. I. Stokes (1993), C. L. Shepard (1993), and C. L. Shepard et al. (1994). An Operation and Maintenance Manual (for the overall viscometer assembly, WHC-SD-WM-OMM-009) and a collection of more detailed manuals and data sheets from the individual equipment vendors (VI file number 22605) are also available as design documentation. Note that several vendor items were used during viscometer design and fabrication which are not specifically discussed in this document.

The detailed scientific theory of the project has been appended to this document for future reference. Data quality objectives were established in one report. A second report addressed the selection of the in situ ball rheometry and the scientific principle upon which equipment selection was based. A third report attached discussed test strategy and basic data reduction techniques. [The PNL and LANL co-authored reports were fully reviewed prior to being appended to this document.]

The software will be fully documented outside of this report (see WHC-SD-WM-SDR-009), however, some software related aspects are discussed within this report.

Final decontamination and decommissioning of the In Situ Viscometer Instrument is outside the scope of this document.

3.0 FUNCTIONS AND DESIGN REQUIREMENTS

The following requirements guided the ball viscometer instrument development and design:

3.1 BALL RHEOMETER REQUIREMENTS

- The rheometer ball diameter should be no larger than 3.6 inches to ensure that it will pass through the four-inch waste tank riser. This requirement was balanced with the need to maximize the diameter to obtain higher drag force numbers.
- The ball should be fabricated from as dense a material as possible to ensure that it will sink into the very viscous sludge (non-convective) layer under its own weight without the need to apply additional downward force, e.g., using a long rod. Furthermore, the

ball material should be compatible with the tank waste to preclude chemical reaction.

- If the ball cannot sink through any layer of tank waste, recovery actions are to be in place to assure the ball can reach the tank floor.
- The ball should not become lost, stuck, etc., in the tank.

3.2 INSTRUMENTATION AND CONTROL FUNCTIONAL REQUIREMENTS

- The system should be as fully automated as possible with provision for manual operation of ball speed and elevation. Computer controls will be provided to set the direction of ball travel, measurement mode (constant speed or constant load as described below), and control parameter (speed or load) value.
- To the extent practical, the system should be fully controlled from outside the radiation area. The computer will be housed in a control console located just outside the fence in the tank farms. Interconnect cables between the control console and the viscometer instrument on the riser shall connect the computer to the various instrument components (load cell, encoder, motors).
- The system should be weatherproof to allow operation in any expected climate for periods of several days.
- The instrument and control functions shall be designed to meet the applicable NFPA hazard classifications.

3.3 INSTRUMENTATION AND CONTROL PERFORMANCE REQUIREMENTS

- The ball viscometer instrument should achieve the highest accuracy of measurement possible. Also, the system must meet the minimum accuracy requested by all data users (as defined in "Data Users Report," see the Appendices).
- The instrument should be capable of maintaining constant tension on the cable, while allowing the velocity to adjust to near free-fall speed. A computer should monitor force and adjust speed to compensate. This technique would primarily be used for measurements in a well mixed low yield strength region of the tank. (Note that this mode was not completed)
- The maximum momentary cable tension should not exceed 250 pounds (1,112 Newtons) inclusive of the ball and cable weight. Maximum constant load should be under 200 pounds (890 Newtons). Controls

should be implemented to preclude loads in excess of 250 pounds. Resolution should be 0.1 Newton over the entire range of measurements.

- The system must be capable of maintaining constant speed during ball motion and monitoring the force. This technique will be used primarily for measurements in the non-convective layer.
- Speed should vary between dead stop and three feet (91.44 centimeters) per second. Controls should preclude speeds in excess of one meter per second, maximum. Minimum speed required for measurements is 0.05 centimeter per second (cm/sec). Resolution should be 0.1 cm/sec for ball speeds in excess of 10 cm/sec, and 0.01 cm/sec for speeds of 10 cm/sec or less.
- Data output should be stored in ASCII format to allow downloading to data reduction personnel upon completion of operation. In addition, the computer monitor screen will provide real time displays of position, velocity and load data in characters not smaller than 0.5 inch. A real time chart display will be provided on screen.
- The device should be capable of measuring waste density with similar accuracy as described above.

3.4 SAFETY REQUIREMENTS

- The system should be decontaminated to acceptable levels prior to packaging the instrument for storage. This decontamination is to occur prior to removal of the hardware from the tank if possible.
- The components of the viscometer instrument which may be exposed to tank waste shall be constructed of materials which are not severely corroded by tank waste or water. Materials shall be selected which minimize decontamination and decommissioning efforts.
- Shielding shall be incorporated as necessary into the viscometer design to achieve ALARA requirements. The local radiation levels external to the instrument are not to exceed 100 mr/hour. This prevents having to designate the area a "high radiation zone."
- The ball viscometer system should comply with all safety assessment and environmental requirements for attachment to tank SY-101.

3.5 STRUCTURAL REQUIREMENTS

- Loads applied to the tank riser, the dome, and any ancillary support structures must meet all operating and design specifications for

tank SY-101.

4.0 DESIGN DESCRIPTION

This section presents a detailed description of the in situ viscometer system.

4.1 GENERAL DESIGN DESCRIPTION

The in situ viscometer is a "portable" instrument designed to move a sphere shape (ball) up and down (via a cable) in tank waste while recording ball position, velocity, and cable tension. In the field, the viscometer attaches to a decontamination spool piece, which in turn is designed to attach to any 4 inch 150 lb. flange, typical of many available tank risers. The viscometer is controlled by a separate remote electronics console which also collects the pertinent test data.

Drawing No. H-2-818359, SY-101 In Situ Viscometer Assembly, fully describes the in situ viscometer mechanical design. Drawing H-2-818154, SY-101 In Situ Viscometer Electrical, fully describes the in situ viscometer electrical design. A complete drawing list is attached to the "Design Verification" appendix. The major assemblies may be traced back via the installation drawing H-2-818363.

The cable is wrapped in a single layer around the drum reel then looped over a pulley which is in turn attached to a load cell. The drum reel is rotated at controlled speeds by one of two motors coupled to the drum through a speed reduction gear. Only one of the two motors is coupled to the reduction gear at any time for high or low speed ball travel. A clutch connects/disconnects each motor to/from the reduction gear. When zero velocity is desired, no clutch is engaged, and an electro-mechanical brake assures no motion. The instrumentation and control equipment controls the motion of the ball and records ball position, velocity and cable tension data as the ball is raised and lowered through the layers of waste material. A decontamination (water) spray system will be used to clean the ball and cable during withdrawal from the tank.

4.1.1 Test Data

Cable tension is measured by the load cell located in the enclosure directly over the riser. Since the cable to which the ball is attached runs over the pulley wheel riding the load cell, the load cell actually measures twice the tension on the cable plus the weight of the pulley assembly which rides on the load cell (minus any counterbalance force as will be discussed below).

The drag force on the ball is derived from the load cell output by compensating for the known pulley assembly, hanging (unwound) cable, and

ball weights, buoyancy forces, and friction in the main pulley (and counterbalance force when in use).

Ball velocity is based upon the tachometer feedback from the operating motor, known gear ratios, and drum diameter. Note that the cable is wound on the drum in a single layer by a level-wind guide. The ball velocity is equal to the cable velocity. Velocity may indirectly be determined during data reduction phases by integrating the absolute position data. Position data is much more precise than direct tachometer data.

Ball location is determined from the encoder attached to the motor-driven cable drum and the reference location of the ball. The latter is determined by a proximity sensor located in the riser attachment subassembly.

4.2 VISCOMETER SUB-ASSEMBLIES

4.2.1 Ball

Two sintered tungsten balls were ordered. The heavier of the two balls was installed on the viscometer assembly. The two ball diameters were 3.59" as shown on H-2-818359 sheet 6 and weighed 7042.02 grams and 7088.29 grams respectively. The heavier of the two balls was installed on the viscometer prior to shipping from the 306E building. Other weights of interest that were not included in the above weights:

swaged ball fitting (on end of cable) = 0.96 grams
screw insert (that holds cable to ball) = 7.41 grams
cable 1 (84.5' of cable) = 654.79 grams
cable 2 (84' of cable) = 651.70 grams
average mass/foot cable = 7.75 grams/foot

Literature studies and lab testing was performed to assure accelerated corrosion (of the sintered tungsten) was not a concern. (Internal Memo 23460-EBS-94-001) As an additional precaution, the ball was also coated with polyethylene to inhibit what corrosion would be expected.

The theoretical ID of a 4" riser is 4.05". It is estimated that the ball will pass through most 4" risers that are empty. If the riser were not perfectly vertical, there were concerns that the ball may enter the dome space and be unable to re-enter the riser from below. Tests were run in the 306E lab showing that even with a severely tilted 4" pipe (with a blunt straight cut end) the ball will self center and enter the riser. The peak load during these tests was speed dependent and peaked at about 35 lb cable tension.

The cable described below was permanently attached to the ball in a manner which produces minimum deviation from sphericity.

4.2.2 Cable

The national labs estimated that with a 1 psi yield strength material, it would take up to 200 lb force to pull the ball at a slow speed. The cable selected has breaking strength of at least 920 lbs. Swaged fittings on both ends of the cable are used to assure the ball doesn't fall off.

These type connections were tested to verify manufacturer ratings. A swaged ball with shoulder developed full cable strength. A through drilled swaged ball (no shoulder) developed about 500 to 600 lb prior to stripping out. The through drilled ball was selected for field deployment. In the event the ball became entangled around something, it would be desirable to leave the ball behind, rather than the ball and cable. The cable could conceivably get sucked into the pump and cause severe pump damage.

A Stat-Kon ME (conductive polypropylene) from LNP plastics was selected to extrude over the 3/32" 7x19 stainless steel wire cable. The plastic is to prevent waste build up in the cable, and provide less than 1 mega-ohm resistance to ground as discussed in the static control section of this document. The coating thickness is nominally 1/64" thick, resulting in an approximate coated cable OD of 1/8".

The inter-relationship of the OD of the cable, and ID of the orifice plate is critical to the safety analysis (as discussed in Chapter 5 of LA-UR-92-3196 Rev. 10) for possible waste entrainment into the enclosure. See the safety equipment list (appendix of this document) for a more detailed discussion.

Both the extended cable weight and the drag force on the cable must be correctly accounted for in order to determine the drag force on the rheometer ball. The exact weight per foot of the cable used, as averaged over a 84.5' sample, was 7.75 grams per foot.

4.2.3 Drive Train

Two DC servomotors with matching tachometers are used to drive the viscometer cable drum to raise or lower the tungsten ball. A high speed motor is used for linear ball speeds of 3.0 cm per second to 1.0 meter per second (1.18 inch per second to 3.28 feet per second). A low speed motor is used for speeds of 0.5 mm per second to 3.0 cm per second (0.02 to 1.18 inch per second). The speed of each motor is determined by the analog voltage supplied via the control console. The analog voltage corresponds to the desired speed set by the operator as described in the Software Requirements Specification for tank 101-SY Viscometer.

Each of the two motors is provided with a tachometer which supplies an analog signal to the computer representing the velocity of the motor. The motors are coupled to the cable drum through a double-ended speed reducer gearbox

located between them. The appropriate motor is selected and coupled to this gearbox with an electric clutch. There are two clutches, one on either side of the double-ended gearbox (one for each motor). Only one clutch can be activated at any point in time, however, so that only one motor at a time drives the common gearbox which in turn rotates the cable drum to wind or unwind the viscometer cable. The clutches are controlled with relays activated and deactivated by the computer in the control console discussed below. An absolute encoder is attached to the drum drive shaft on the opposite side of the gearbox to provide a digital signal to the computer corresponding to the position of the ball within the waste tank. A second speed reducing gear is located between the low speed motor and its clutch to the double-ended gearbox.

The double ended gearbox (worm gear type) was not self locking as anticipated. The weight of the ball was just enough to unwind the cable drum. Therefore, a new "drive train brake" (electro-mechanical brake) was added to assure the ball does not move unless the computer is causing the motion. The brake consists of a 110 VAC solenoid with a gear tooth attached to the solenoid end. The tooth engages with the optical encoder coupling. Mechanical springs hold the tooth engaged when no power is available, and when a clutch energizes, relays are in place to engage the solenoid, thereby retracting the tooth from the locked position.

The low speed motor is a Motomatic Series E-652 permanent magnet DC motor-generator with tachometer supplied by the Reliance Electric Company, Electro-Craft Servo Products Division. The accompanying Reliance Electric E-652 solid state electronic controller is located in the control console. The motor-generator has two armatures on the same shaft. One drives the motor shaft and the other generates a voltage which is proportional to the shaft speed. The signal from the generator is input to the controller where it is compared to the speed command voltage, i.e., the voltage corresponding to the speed set by the operator. The controller adjusts the voltage supplied to the motor winding in order to increase or decrease the motor speed to maintain the balance between the set speed (command) voltage and the generator voltage. In this manner, the set speed is closely maintained even with changes in load or line voltage, thus providing superior speed range and stability. The servo amplifier supplies 0 to +10 volts for a speed range of 3 to 3000 rpm, adjustable (3.3 volts per 1000 rpm). This shaft speed is reduced by a 50:1 reduction gear flange mounted on to the motor, and is further reduced by the double-ended gearbox discussed previously.

The high speed motor is a 1000DC permanent magnet servo motor Model 1960 with tachometer manufactured by Aerotech, Inc. The accompanying DS160 series servo amplifier supplies high power to the motor at very high efficiency for operation between 0 and 160 volts DC bus levels without component adjustment. As in the case of the low speed motor servo amplifier, the voltage supplied by the DS160 is proportional to the speed set (demand) by the operator. Similarly, the high speed motor tachometer generates a signal proportional to its speed (3

volts per 1000 rpm). The servo amplifier circuit compares the set speed to the actual (tachometer output) and adjusts the voltage supplied to the motor until the two are the same. This motor is capable of maximum speed of 2750 rpm. Unlike the low speed motor, the shaft speed of this motor is not reduced any further than the 15:1 reduction by the double-ended gearbox.

Each motor is coupled to the double-ended gearbox through a Warner Electric Model SF-400 industrial magnetic clutch. The clutches and accompanying conduit boxes are Underwriters Laboratories (UL) and Canadian Standards Association (CSA) rated devices.

With its clutch activated, the corresponding motor is coupled to the cable drum through a double-ended speed reducer gearbox located between the two motors. The device used in the viscometer instrument is a Blue Max worm gear speed reducer supplied by the Alling-Lander Division of Regal-Beloit Corporation. The speed reduction ratio is 15:1.

4.2.4 Instrumentation

4.2.4.1 Load Cell A load cell measures primarily twice the tension on the ball cable. Although the ball itself weighs approximately 16 pounds (71 Newtons), the drag force on the ball can result in much greater cable tension (loads) as stated before. To obtain as accurate data as possible, the system was designed to use several load cells of varying load ranges as shown on the drawings.

As the load increases beyond the rating of the load cell in use, the cell must be replaced with one having a higher load rating. Likewise, if the measured drag force (which is twice the actual drag force) is less than 10 percent of the rating of the load cell, the load cell should be replaced with one of greater sensitivity, i.e., smaller load rating. The load cells, all of which were obtained from Interface Inc., are electrically interchangeable. Changing load cells to accommodate greater loads, or to maintain the required measurement accuracy and precision is done manually following the procedure described in the SY-101 In Situ Viscometer Instrument Operations and Maintenance Manual, K. L. Pearce et al., (1994).

The load cells were constructed of aluminum. The SY-101 liquid waste reacts with aluminum, so a plastic bag has been employed to prevent direct waste contact with the aluminum. If contact occurs, the load cell will become corroded, and the data from that load cell will be questionable.

The load cell specifically measures twice the tension on the cable plus the weight of the pulley assembly which rides on the load cell (minus any counterbalance force as will be discussed below). The cable tension is due to the ball weight, extended (hanging) cable weight, the drag forces on the ball and cable, buoyancy forces, acceleration and friction (cable rubbing orifice/riser,

pulley bearings, etc). Calculations of the drag force on the ball (at constant speeds) can be derived from the load cell output by compensating for the known pulley assembly weight, friction, hanging (unwound) cable weight, cable drag, ball weight and buoyancy force. (and counterbalance force when in use).

There are six load cells available for use in the viscometer instrument. They are rated for maximum loads of 15, 25, 50, 100, 250, and 500 pounds. When a new load cell is installed, the operator must indicate to the system which load cell is in use by setting the Load Cell Type control at the control console as described in the Software Requirements Specification for Tank 101-SY Viscometer (1994). This control allows selection from a discrete list of choices. These choices are displayed as 67, 111, 222, 445, 1,112 and 2,224 Newtons corresponding to the above loads in pounds.

Load cells are bending beam construction wheatstone bridge type strain gauges which generate a voltage proportional to the strain applied on them. The load cells used in the viscometer instrument are Single Point I (SPI) (15, 25, 50, 100 pounds maximum load), and Sealed Super Beam (SSB) (250 and 500 pounds maximum load) units supplied by Interface, Inc. The SPI load cells are designed for controlled environment applications. A moisture resistant coating protects the SPI devices from high humidity up to and including 95 percent and periodic exposure to condensation. These units are not intended for operation in a submerged environment. The SSB Series load cells are precision strain gauges designed for use in all weather, and wash down environments. Both types of cells produce high output of 3 millivolts/volt for easy interfacing to signal conditioning electronics. All load cells are compensated for temperature effects to minimize unwanted zero and output variations.

Excitation voltage for the strain gauge is provided by a Model 465-115 wide bandwidth strain gauge signal conditioner from Calnex Mfg Co. Inc. This unit contains an electronic amplifier and power supply which do have sufficient energy to ignite a flammable gas mixture. Therefore, an Intrinspak Intrinsic Safety (shunt zener diode) Barriers module supplied by Stahl is placed between the load cell and the signal conditioner to preclude the excitation voltage supply and electronic amplifier from creating an ignition hazard. The 465-115 strain gauge input module provides +10 volts excitation to the load cells and produces an output of 0 to +10 volts depending on the load on the strain gauge. The intrinsic safety barriers are qualified for use in Class I, II, III, Division 1 and 2, Group B-G hazardous locations.

The Intrinspak module is located inside a Hoffman industrial enclosure attached to the viscometer instrument support frame. The load cell signal (output of the Calnex signal conditioner) is input to the data acquisition computer in the control console.

The load cells can only withstand a 150% of scale loading and still operate. During change out of a load cell, the load cell may be ruined if the

"changer" accidentally drops the ball and provides a sharp impact load to the load cell.

4.2.4.2 Encoder Position of the viscometer ball is monitored by a multi-turn absolute rotary optical encoder. The device used in the viscometer is a 4096 step x 512 turn absolute encoder Model AAF-100 produced by the Lucas Ledex Encoder Division of Max Stegmann GmbH. The encoder generates a serial output which is converted to parallel data format by a Lucas Ledex serial-to-parallel converter Model SPA-2. This converter is located in the control console. The 21 bits of data are provided as an input to the system computer via a digital input/output board occupying one EISA slot. This is a National Instruments digital input/output board model AT-DIO-32F.

4.2.4.3 Proximity Sensor An inductive 30 mm diameter cylindrical proximity sensor is located between the orifice plate and the isolation valve. The proximity sensor used is a two-wire unit with plug-in receptacle manufactured by Pepperl+Fuchs, Inc. This device is used to sense the presence of the viscometer tungsten ball in the riser attachment. A two-wire sealed cable connects the sensor to a Pepperl & Fuchs single channel transformer isolated type intrinsic safety barrier located inside the Hoffman industrial enclosure containing the load cell Intrinspak intrinsic safety barriers module discussed above. The barrier built-in amplifier isolates and transfers discrete signals from the potentially explosive atmosphere around the tank riser to a safe location at the control console. The conditioned sensor signal is input to the data acquisition computer in the control console.

The proximity sensor and its associated electronic module are intrinsically safe for Class I, Division 1, Group B service. The proximity sensor when used with its electronic module is UL-listed and CSA-certified for use in locations with this classification. The intrinsic safety barriers and the signal conditioning module for the proximity sensor are mounted outside the Class I, Division 1, Group B enclosure on or near the drive train weather housing in a separate enclosure.

The ball has sufficient clearance in the 4 inch riser to swing side to side without the orifice plate installed. Testing revealed that if the swing distance was far enough and the ball low enough, the proximity sensor light will go on and off.

When retracting the ball to home, the proximity sensor light ("BALL HOME") illuminates and the motion is stopped via software control. Since the gear train is not self locking, the ball tends to fall back down slightly until the electro-mechanical brake engages a tooth. Thus, the BALL HOME light may extinguish. This may be confirmed by observing the encoder display.

4.2.4.4 Pressure Switches Two (redundant) low differential pressure switches are located below the support frame of the viscometer instrument. These units

(Series 107) are manufactured by SOR (Static O Ring) and sense the differential pressure between inside the waste tank and outside the waste tank. When the pressure inside the tank is less than minus one inch of water relative to the ambient pressure around the riser, the pressure switches close a circuit which can then energize all viscometer equipment.

Similarly, when inside tank pressure rises above this threshold (tank dome space is pressurizing), the pressure switches automatically open, creating a disconnect which shuts off electrical power to the viscometer components not qualified to operate in a Division 2 hazardous area.

The Series 107 units are designed for operation in hazardous environments such as might exist around the riser. They contain UL listed and CSA certified snap-action switching elements. The tank dome pressure switches are listed as explosion proof for use in Class I Division 1 Group A, B, C, and D locations. The switches are hermetically sealed and have explosion proof housings. The sense lines for these pressure switches are connected to the spool piece above the isolation valve and below the orifice plate. The reference pressure is atmospheric.

4.2.5 Counterbalance

When the measured drag force is less than several pounds, it becomes impossible to measure total force (approximately the ball weight plus drag force) with any load cell and still maintain the required precision for the drag force. Therefore, for very small drag forces it is necessary to use a low capacity load cell and provide a counterbalance. Without the counterbalance, the low range load cell would already read full scale (i.e. no useable range left). An adjustable extension spring connected to the load cell bracket acts as a counterbalance by pulling upward against the load cell.

The computer software calculations can compensate for the counterbalance force. When a counterbalance is installed, the operator must indicate to the system the amount of counterbalance used by setting the Counterbalance control at the control console as described in the Software Requirement Specification for tank 101-SY Viscometer (1994). The use of the counterbalance in experiments should only be employed in limited cases where quality data are unobtainable otherwise.

4.2.6 Enclosures

The components comprising the viscometer instrument are enclosed in several different enclosures. The motors and associated tachometers, clutches, speed reducing gears, and encoder are located inside a formed and welded stainless steel gasketed weather enclosure, (Enclosure 2) which is not in communication with the tank dome space. This enclosure is ventilated by two fans to prevent heat build up or accumulation of hazardous gasses.

The viscometer components consisting of the cable drum and load cell assembly are located inside of the primary enclosure (Enclosure 3). This is also a stainless steel gasketed enclosure with glass covered observation ports on two sides. Enclosure 3 is designed to preclude release of flammable and toxic gases to the atmosphere from the waste tank.

When tank 241-SY-101 is operating normally, permanent tank ventilation fans maintain a negative pressure of two to five inches of water gauge in the tank dome space. This assures inward flow of air through any leak paths between the atmosphere and the tank dome space. Therefore, during normal tank operation, Enclosure 3 is continuously ventilated by the tank ventilation fans which pull ambient air into the enclosure through a HEPA filter and into the tank dome space via the riser. Readout of the difference between the pressure inside and outside of the enclosure is provided by a Dwyer Instruments, Inc. Series 2000 Magnehelic differential pressure gauge located on a bracket just above the isolation valve hand crank. A second Dwyer Magnehelic pressure gauge (connected to the pitot tube) located on the same bracket, is used as a flow indicator during venting of the enclosure.

As discussed previously, the intrinsic safety barriers used to pass through excitation voltage to the load cell and proximity sensor are enclosed in a NEMA Type 4 junction box designed for use in areas which are frequently hosed down. [The enclosure is a NEMA continuous hinge Type 4 junction box designed for use in areas which may be regularly hosed down, are very wet, or for outdoor use.]

Ventilation system tests revealed several small leaks in the system piping and enclosure systems. These were repaired to pass the acceptance test. Pressure drops occurred at every pipe bend, pipe run, and piping component such as a valve, flapper valve, HEPA, etc. Ten volume changes per hour is a standard to achieve "adequate ventilation" as discussed in the NEC memo. Thorough testing of the ventilation system was performed in the hardware ATP, and is documented in the associated ATR.

4.2.7 Support Frame

The support frame (machine base) consists of welded stainless steel (SS) square tubing with an attached machined SS plate. The frame is used to mount and align the various viscometer components discussed above. The support frame has four eye bolts for lifting purposes. The two jacks provide the means for leveling the viscometer, providing support away from the riser to avoid cantilevering the instrument or loading the riser excessively.

It is possible that the jacks can conceivably be jacked too much, adding undesirable load conditions to the riser. Therefore, a thick rubber gasket is placed between the viscometer and mating component (i.e. decontamination spool piece). The jacks are adjusted until the two bubble gauges indicate the viscometer instrument is level.

4.3 CONTROL CONSOLE

The control console is a weatherproof enclosure which provides a controlled environment for all the power, control, and data collection electronics required for remote operation of the viscometer instrument. It consists of an industrial enclosure modified to provide heating and cooling to accommodate the requirement for sustained operation over several days of various weather conditions. The enclosure houses all the control and data acquisition equipment for the viscometer. The major components are the integrated personal computer system (for operator interface, data acquisition and storage), an Annunciator Panel (with lights indicating electrical power and safety system status), and all the electrical power, power isolation, power conditioning, and motor control circuits.

The control console controls all motions of the probe and acquires, stores, and displays viscometer data on the system computer monitor screen. The control console was also developed to operate the void fraction instrument, shown on drawing H-2-821719. Three manual circuit breakers are located on the front lower panel of the console. The left one controls main console power, and power to qualified equipment on the viscometer. The middle breaker controls power to non-qualified equipment on the viscometer. The right breaker turns the void meter power on.

Data from the viscometer are transmitted to the control console via temporary cabling (Drawing No. H-2-818151, Viscometer Cable Assemblies) for recording and eventual analysis. Interconnecting cables between the instrument and the electronics console will be 250 feet long so that the console can be placed and operated outside the tank perimeter fence, that is, outside the fenced radiation zone of the tank. Since the tank perimeter fence is well outside a 15-foot radius from any of the tank risers, the viscometer control console will not be in a hazardous location (J. H. Bussell et al., 1994) during normal operation or even during loss of ventilation in the tank dome. Consequently, even though the control console and enclosed electrical equipment and devices must be rugged for field use, they need not conform to the same NFPA requirements for service in hazardous locations as do the viscometer instrument components discussed in the previous sections.

The cable interconnections between the viscometer instrument on the tank riser and the control console outside the perimeter fence are shown on the installation drawing (H-2-818363). More specific instrumentation block diagrams showing the particular devices used are presented in the detailed design drawings.

The layout of the control console (Drawing No. H-2-818150, Viscometer Control Console Assembly) shows the locations of the major interface, control, and data acquisition components, and electrical equipment and devices. The Annunciator Panel is located at the top of the console. Just below it is the

computer monitor. The system computer is located in an industrial enclosure below the monitor. The computer keyboard is located on a slide tray below the computer enclosure. Below the keyboard tray is a sliding drawer with a writing surface. Two blank panels below the drawer cover most of the lower half of the control console which contains electrical power, line isolation, and power conditioning electronics.

A circuit breaker panel is located in front and at the very bottom. The control console components will be discussed further in the following subsections.

4.3.1 Data Acquisition and Control

4.3.1.1 System Computer The viscometer instrument is controlled by an integrated personal computer, and operator interface with the system is through point-and-click on the computer monitor screen using the system mouse and the keyboard for alphanumeric input. Each front panel control accessible to the operator is represented by an icon on the computer monitor display. These icons can be accessed and manipulated with the computer mouse. Using the computer monitor screen, mouse, and keyboard, the operator can select the operating mode and input necessary parameter values. The computer then automatically controls the cable drum drive motors, and acquires, displays, and stores ball position, speed, and cable tension data consistent with the selected operating mode.

The data acquisition and control computer is an IBM compatible, AST system. It includes the following features:

- 66 MHz CPU Clock Speed
- 16 MBytes Random Access Memory
- 200 MByte Hard Disk Drive
- 3.5 inch, 1.4 MByte Floppy Disk Drive
- Five EISA Bus Slots
- Two Serial Ports and One Parallel Port
- Microsoft Compatible Mouse
- 101 Key Keyboard
- 13-Inch VGA Monitor

The computer is mounted inside an Advantek rack mountable industrial enclosure with a cooling fan. Access is from the front of the control console and the computer enclosure doors. The keyboard is a Texas Micro Express rack mountable, AT type, spill proof, dust resistant unit.

4.3.1.2 Operator Interface Operator interaction with the viscometer instrument is primarily through a graphical interface. For ease of use the operator interface screen display (front panel) is designed to mimic an instrument with icons of toggle switches representing controls and digital readouts depicting current system information. The operator can set binary controls with the mouse

connected to the system computer. Controls that involve non-binary data such as set points are set with the mouse or the keyboard. The keyboard is also used to enter comments to data files.

The front panel display is used by the operator to interface with the viscometer instrument. This screen provides the means for the operator to specify the appropriate input parameter values for the desired measurements. It also displays current values of ball viscometer operational variables and measurement results. The capability to make the following inputs is provided:

Start/Stop Control - Binary control which starts or stops the movement of the rheometer ball. When the ball is in motion, the "STOP" control is always available to stop it. This control is mouse-operated. The choice is indicated by the toggle switch icon. A backup to the "START"/"STOP" control is implemented in hardware on the Annunciator Panel discussed in Section 3.3.1.4 to shut down all power to the viscometer instrumentation.

Direction Control - Binary control through which the operator chooses "UP" or "DOWN" to set the direction of motion of the rheometer ball. Although this control allows the operator to specify the direction, motion is not initiated until the "START" control is set. Direction cannot be changed when the ball is in motion unless the motion is stopped first. This control is mouse-operated. The choice is indicated by the toggle switch icon.

Record Data Control - Binary control that enables, "ON", or disables, "OFF", recording of data. When recording is enabled, ball position, ball velocity, and cable force data are written to disk file at a rate specified through the Sample Rate control input. When "ON" is selected, a dialogue box is displayed to allow the operator to input descriptive file header information using the keyboard.

Movement and recording take place only for the length of travel indicated by the specified Record Duration.

Sample Rate Input - This input sets the rate at which data will be written to disk file. The sample rate input can be either 15 Hz or 100 Hz. Use of 15 Hz allows approximately 4 times faster machine control response (for software controlled aspects).

Record Duration Input - This input sets the length of distance over which the ball is to travel and data recorded to disk. The minimum permitted distance is 1 centimeter. The operator may set this value with either keyboard or mouse. The currently set value is displayed in the designated window on the screen. The system software is designed to disallow inputs

smaller than the minimum. When the duration input is smaller than the minimum allowable, the value is automatically set at the minimum distance.

Operating Mode Control - A control which selects the operating mode from five options consisting of: calibration, static density, dynamic density, constant velocity test, and constant force test. The selected mode will automatically be displayed on the designated window on the screen. Operating modes are discussed below. Note that the constant force mode is disabled for reasons discussed elsewhere in this document.

Velocity Setpoint Input - This digital input sets the speed at which the rheometer ball is to be moved for constant velocity operation mode. The allowable range is 0.05 to 100 centimeters per second. The operator sets the desired value with either mouse or keyboard, and the input is automatically displayed on the Velocity Setpoint window on the screen. When the input speed is lower than the minimum or higher than the maximum allowable speed, the value is automatically set at the minimum or maximum value, respectively.

Force Setpoint Input - This digital input sets the force (constant) which will be applied to drag the rheometer ball at variable speed to compensate for variations in waste viscosity. The allowable range is 10 Newtons to the maximum rating of the load cell used. The operator sets the desired value with either mouse or keyboard, and the input is automatically displayed on the Force Setpoint window on the screen. When the input force is lower than the minimum or higher than the maximum allowable value, the value is automatically set at the minimum or maximum force, respectively.

Load Cell Control - As noted in Section 3.1.1.3, six different load cells of varying capacity are available to cover anticipated range of drag force. This control selects one of the discrete options of 15, 25, 50, 100, 250 and 500 pound (67, 111, 222, 445, 1112 and 2224 Newton) load cells. The operator sets the desired option to tell the software the size of load cell currently installed. As noted in Section 3.1.1.3, load cells are changed manually following the procedure described in the SY-101 In Situ Viscometer Instrument Operations and Maintenance Manual, K. L. Pearce et al., (1994). The load cell selected (maximum load rating) is automatically displayed in the Load Cell Type window on the screen.

The software automatically checks the ball weight using the load cell parameters it thinks is installed. If the ball weight is not reading free hanging weight in air (about 69 Newtons), the software indicates the wrong load cell is selected. If this warning appears, make sure the ball is freely hanging in air and verify that the correct load cell is installed. [Note that if the operator keeps switching the load cell selection until the warning doesn't appear, that is most likely the load cell currently

installed.]

Counterbalance Control - As indicated in Section 3.1.1.4, a counterbalance may be used with the low capacity load cells to measure small drag forces with the required precision. This control specifies the value of the counterbalance force in Newtons. The operator sets the desired value (predetermined by calibration) of force applied by the extension spring used for counterbalance. A value of zero shall correspond to no counterbalance. The counterbalance force applied is automatically displayed in the Counterbalance window on the screen.

The following outputs are displayed on the front panel screen during routine operation of the viscometer instrument.

Position, Velocity and Force Readouts - Current ball position, ball velocity, and cable tension (load reading divided by two prior to read out, and is compensated for counterbalance if there is one) are displayed digitally in the Position, Velocity, and Load windows on the operator interface screen at all times during operation. The screen update rate is once per second. The ball position is relative to the top of the riser (home position determined by the proximity sensor) in centimeters. The velocity is in centimeters per second, and the force is in Newtons. Direction is positive downwards. Velocity is positive if moving down.

Force vs. Time Strip Chart - A strip chart display of force versus time is provided across the lower half of the operator interface screen. This is the area of the screen with the horizontal grid lines. The strip chart is updated with each new data point obtained once per second as the ball moves. In this display, the force determined from the load cell output (in Newtons) is plotted on the vertical axis, against time (in seconds) plotted along the horizontal axis. 60 seconds of data can be displayed on the screen at any one time. The operator can view previous data (up to 1024 seconds previous) before the data becomes "lost", by using the scroll bar below the strip chart.

Five operating modes are possible and the desired mode is set by the operator via the Operating Mode control on the operator interface screen described above. The following modes are available:

Calibration Mode - This operating mode is used for automatic load cell calibration. Once Calibration is initiated, the viscometer instrument is controlled by the software. The ball is raised 50 centimeters and then lowered 50 centimeters (back to the starting position). Data are recorded starting just before the ball begins to move up and stopping when the ball comes to rest. The sampling rate is 60 data sets per second, each set consisting of the ball position, ball velocity, and cable tension. This mode is not allowed when the ball is initially within one meter from the

home position determined by the proximity sensor.

Static Density Mode - This operating mode is used to determine the density of the waste material in the immediate vicinity of the ball when the waste material is fluidized (convective layer). In this mode, ball position, ball velocity, and cable tension data are automatically recorded while the ball is at rest. Data are recorded for one minute at a rate of ten samples per second. This mode is allowed at any ball position.

Dynamic Density Mode - This operating mode is used to determine the density of waste material in the immediate vicinity of the ball when the waste material is not initially fluidized (non-convective layer). In this mode, ball position, ball velocity, and cable tension data are recorded starting with the ball at rest and while the ball automatically oscillates between two centimeters above and two centimeters below the starting position. Data recording stops when the ball comes to rest at the starting position after five complete cycles are performed. Ball oscillation is intended to fluidize the waste around the ball as discussed by C. L. Shepard, et al. (1994). The frequency of ball oscillation is less than 0.1 hertz. The sampling rate is 60 samples per second. This mode is not allowed when the ball is initially within one meter from the home position determined by the proximity sensor.

Constant Velocity Mode - This operating mode is used to measure drag force on the ball as a function of ball position in the waste while maintaining constant velocity. These data will be subsequently used as input to theoretical or empirical equations (models) to determine waste yield stress and apparent viscosity. In the Constant Velocity Mode the ball moves in the direction set through direction control with cable tension adjusted to maintain the fixed speed set through the Velocity Setpoint input (see operator inputs described previously). If Record Data is clicked "ON", data (ball position, ball velocity, cable tension) are recorded to file at a sampling rate set through the Sample Rate input. Ball motion stops after a length of travel set through the Record Duration input, only when recording data selection is "ON".

Constant Force Mode - This operating mode was intended to measure ball velocity as a function of ball position in the waste while maintaining constant drag force. Design and testing were never successfully completed within the allowed schedule constraints. The software was disabled. If a "constant force" mode is selected, as soon as the screen icon toggle is switched to "ON", a message box will appear stating this mode is unavailable.

While the ball is in motion, system software compares ball position, ball velocity, and cable tension values with preset boundaries. Ball position is monitored 15 times per second at 15 Hz data acquisition rate, or 4 times per

second otherwise. Software automatically stops upward motion when the ball reaches the home position just below the orifice plate and downward motion when the ball approaches the bottom of the tank. Home position is ultimately determined by the proximity sensor and encoder. Ball position relative to home is determined by the absolute encoder. Home position can also be verified by monitoring the force (tension) on the cable. As the ball reaches home and is pulled against the orifice plate, tension on the cable increases. When the ball is within 1 meter from home, its speed is limited to 1.5 centimeter per second automatically. Note that an intermittent tach reading above 1.5 cm/sec will stop the motion.

In the Constant Velocity Mode, software maintains constant velocity and monitors cable tension. The system, however, will not allow the force on the load cell to exceed the load cell rating. Force is maintained below the maximum load rating of the load cell in use even if a higher force is required to maintain the specified velocity setpoint. If the force falls below a predetermined value (7 Newtons) on descent the software stops the ball to prevent the cable from going slack. Testing revealed that no excess cable slack appeared at 10 cm/sec using 15 Hz sampling speed. Higher speeds and/or 100 Hz sampling can easily cause uncontrolled cable unwrapping in the viscometer enclosure, commonly referred to as "bird's nesting".

When Record Data is enabled by selecting "ON" (using the mouse to point-and-click), a data file will be created with the header specified by the operator via the dialogue box. The data file will record ball position, velocity, and drag force data during subsequent operation. The information header includes filename, software version, time and date, viscometer operation mode (calibration, static density, dynamic density, constant velocity, or constant force), setpoint value, load cell used, counterbalance force, and a comment field.

The file is a disk file in a tab-delimited ASCII format. It is stored in a subdirectory that has the current date for a name. The directory at the root level is labeled "data". Finally, the file name is set by the program and not the user. The file name will be the current date with an extension that consists of a single letter representing the viscometer operation mode in which the data were obtained ("c" for calibration, "s" for static density, "d" for dynamic density, "v" for constant velocity, and "f" for constant force) and a sequential two digit number. For example, the absolute file path for a dynamic density file run on January 1, 1994 is:

C:\data\01-01-94\01-01-94.d01

The ASCII feature allows the file to be read by any text editor. The tab-delimited format allows the file to be read by most spreadsheet programs. A tab-delimited format separates each field with an ASCII tab character and each record with a return character, so that each record consists of three numbers. There is a record for each particular position. The ball position is measured

in centimeters from the top of the riser. The ball velocity is recorded in centimeters per second. The force on the ball adjusted for any counterbalance force used is recorded in Newtons.

During operation of the viscometer the "STOP" function of the Start/Stop control on the operator interface screen is always available to stop the motion of the ball. In addition to this control, there hardware Emergency Off button is available on the Annunciator Panel (discussed below) that will stop all motion of the ball.

More detailed software information, such as the source code, etc. can be found in WHC-SD-WM-SDR-009.

4.3.1.3 Hardware Interfaces Hardware interfaces are through National Instrument's data acquisition circuit boards. Use of these boards eliminates the need to write drivers since these boards all work fluently with National Instrument's and LabView software development system used to create the software.

Each input or output is routed through a signal conditioning module or isolation device. The one exception is the digital input from the encoder. The output from the serial-to-parallel converter does not need to be conditioned.

The control loop that maintains constant ball velocity or constant cable tension is implemented in the hardware (not in the software).

4.3.1.4 Software Interfaces The viscometer data acquisition system requires existing software from two sources. The first source is the operating system and windowing environment software from the Microsoft Corporation. Version 5.0 of MS-DOS and version 3.1 of Windows are used. The second source of software is National Instruments, Inc. LabView version 3.0 for the Windows development system was used for the application specific software development, and Version 3.0 of LabView for Windows runtime is used to run the resulting "code".

4.3.2 Annunciator Panel

This panel is the top most panel inside the front door of the control console. Lights on this panel indicate electrical power and safety system status. An emergency shutdown mushroom button and the ON (START) push button switch are also located on this panel. The colored lights are amber, green, or red. The functions of the Annunciator Panel lights and buttons are given below under their grouping as indicated on the panel.

POWER

CONSOLE - Amber indicator light (DS1) which illuminates when the viscometer console power circuit breaker is switched "ON" to indicate that power is applied to the control console and the instrumentation is activated. This switch (CB2) is located on the circuit breaker panel located on the front bottom of the control console.

INSTRUMENT - Amber indicator light (DS2) which illuminates when the viscometer console power circuit breaker is switched "ON" to indicate that power is available to the computer and associated equipment. Note that this lamp is on the secondary of isolation transformer T1, which is protected by internal circuit breaker CB5. The cooling fans in Enclosure 2 (cable drum drive train) are activated when this indicator is illuminated.

VOID FRACTION - Amber indicator light (DS3) which is off when the control console is used to control the viscometer instrument. This same console is also used for control of the void fraction instrument.

24 VDC - Amber indicator light (DS4) which illuminates when the viscometer console power circuit breaker is switched to the "ON" position and internal mode switch S3 is in the viscometer position.

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READY - Green indicator light (DS5) which illuminates when the viscometer motor power circuit breaker is switched to the "ON" position. This switch (CB6) is located on the circuit breaker panel.

ON - Amber indicator light (DS6) which is off until the motor startup switch (SW1) has been pushed to activate the servo motor power supply. This can occur only after both pressure switches are closed as indicated by the Pressure Switch 1 and 2 lights being illuminated and two 17 minute delay timers are terminated, at which time the "HIGH PRESSURE or TIMING" light will extinguish. The delay timers consist of time delay relays which provide a fixed delay time between closing of the pressure switches and enabling of motor power.

On/START (button) - Push button motor startup switch (SW1) is used to activate the servo motor power supply after both pressure switches are closed (as indicated by the Pressure Switch 1 and 2 lights being illuminated) and the delay timers have terminated (as indicated by the HIGH PRESSURE OR TIMING light extinguishing).

Off (button) - Large red mushroom headed push button switch which provides the capability to manually shut down the viscometer. The button is intended to be used in an emergency (if one occurs) when the operator detects the abnormal event.

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Note: All 4 of these lights have a push to test feature.

HIGH PRESSURE OR TIMING - Red indicator light (DS7) is illuminated while either one or both pressure switches are open as indicated by either one or both Pressure Switch 1 and 2 lights being off. This light will only extinguish after both pressure switches are closed (and the corresponding lights are illuminated) and both time delay relays have timed out. This light will illuminate and power to the viscometer non-qualified equipment will be disconnected if either pressure switch opens.

BALL HOME - Green indicator light (DS8) which is off during normal operation when the viscometer ball is below the proximity sensor position. This light is illuminated when the ball is in the home position inside the riser attachment at the proximity sensor location.

PRESSURE SWITCH 1 - Green indicator light (DS9) connected to the first of the two redundant pressure switches described in Section 4.2.4.4. This switch senses the pressure differential between inside and outside the riser. The isolation valve must be open for the inside riser pressure to equal tank dome pressure given the differential sensing location. The light illuminates when the differential pressure is minus one inch water column or more. If the pressure rises above minus one inch water column, the pressure switch initiates automatic shutdown of the non-qualified viscometer equipment and the indicator light turns off.

PRESSURE SWITCH 2 - Green indicator light (DS10) connected to the second of the two redundant pressure switches described in Section 4.2.4.4. This light performs identically to the one above, and is independent of the above.

The sequence of indicator light illumination during startup, normal operation, and shutdown is described in the SY-101 In Situ Viscometer Instrument Operation and Maintenance Manual, K. L. Pearce et al. (1994).

4.3.3 Air Conditioner and Heater

An 8000 BTU air conditioner provides cooling for the Control Console, while an 800 W electric heater provides heat for cold weather operation. Thermostats for both units are preset. They are interlocked to prevent simultaneous operation.

4.3.4 Electrical Power

All power to the viscometer is routed through the control console. A/C Power distribution for the heater, air conditioner and console instrumentation is via the 240/120 VAC console feed. No direct power connections are made to the viscometer itself.

The control console requires a 4 wire 240/120 VAC 30 A service.

The hot water decontamination pump requires a 4 wire 480 3 phase to run the 7.5 Hp motor.

The water feed pump (sometimes called booster pump) requires 240 VAC to run the 3/4 Hp motor.

A power distribution skid was designed to simplify site power requirements and cable runs, see H-2-821314. The skid takes a 4 wire power feed of 480 VAC 3 phase 35 amperage service disconnect. Thus, only one power cable must be run between the distribution skid and the local power outlet. The skid itself has manual disconnects controlling distribution to the various systems. The hot water pump disconnect may be closed at any time, and the pump has a local switch for operation. The feed pump disconnect should only be closed when the feed pump is required. The feed pump has no local switch. The control console has its own internal circuit breakers, so its disconnect may be closed at any time.

4.3.5 Electrical Safety Circuits

4.3.5.1 Component Description The schematic for the electrical safety circuits is given in the *Viscometer/Void Fraction Elementary Diagram*, H-2-818156. The components for the viscometer enclosure pressure interlocks and ventilation timing are the pressure switches and relays. The relay coils and contacts for the electrical power interlocks are near the bottom. Note that the principal components are redundant, including use of different cables for the connections to the two pressure switches. A description of the various components and how their operation depends on one another follows. A detailed discussion of the operation of the ventilation system is given in Section 4.2.

Pressure switches 2A3S1 and 2A3S2 are mounted on the viscometer and sense the pressure differential between ambient pressure and the pressure within the adapter spool piece above the isolation valve. The switches are normally open and close only when the pressure differential (ambient to spool piece) is -1 inch water gauge or lower.

K2 and K4 are double pole, double throw, delay-on-operate relays, that is, they operate a programmed time period after power is applied. The delay period is programmable from 0.1 second up to 30 minutes. K3 and K5 are standard double pole, double throw relays that operate as soon as power is applied. Contacts for these relays are near the top and bottom of the diagram.

Relays K6 and K7 -- below transformer T2 -- are double pole power types used to connect both 24 VDC and 120 VAC power to the viscometer equipment. The auxiliary contacts on these relays are used to latch the relays once they are energized.

S1 and S2 are the manual push button switches used to control application of power to the viscometer equipment. The remaining components of interest are the annunciator lamps and motor cooling fans, 2A2B3 and 2A2B4. Lamps DS4 through DS6 are power status indicators, and DS7, DS9 and DS10 pressure status indicators.

4.3.5.2 Operation When console power is applied by turning circuit breaker CB2 ON, power is applied to the 24 VDC power supply, PS1, so that DS4 is illuminated. When motor power circuit breaker CB6 is turned ON, the READY lamp, DS5, will light. The other lamps depend on the status of the pressure and ON/OFF switches.

When the spool piece pressure is greater than -1 inch water gauge relative to ambient pressure, both pressure switches will be open. Thus, the associated relays K2 through K5 will be de-energized so that DS7 will be illuminated and power cannot be applied to the viscometer because of open relay contacts.

Operation of the redundant pressure switch and relay circuits is identical, so only one will be discussed. When the isolation valve is opened with the tank under normal positive ventilation, the spool piece pressure will become less than -1 inch water gauge and pressure switch 2A3S1 will close and DS9 will illuminate. Relay K3 will immediately activate, partially enabling power to the motor cooling fans. When the delay time terminates, K2 will activate, partially enabling motor power application, and opening one of the contacts powering DS7.

When both pressure switches have closed, both DS9 and DS10 will be illuminated, and power will be applied to the motor cooling fans through the series K3 and K5 contacts. After both delay relays have timed out, DS7 will go out. When DS7 is out, power can be applied to the viscometer because the K2 and K4 contacts in series with the K6 and K7 relay coils are closed.

Motor power is applied by momentarily pressing the ON/START push button switch, S1. Since the K2 and K4 contacts are closed, relays K6 and K7 will close applying 24 VDC and 120 VDC to the viscometer components.

If either pressure switch opens, or their circuit otherwise becomes discontinuous, all associated relays will drop out and power will be disconnected from all viscometer circuits except the pressure switches. Similarly, when the OFF push button switch is pressed the power and pressure switch associated relays will drop out, resetting the delay time on K2 and K4.

4.4 DECONTAMINATION SYSTEM (DRAWING NO. H-2-821443)

Waste adhering to the cable may be scraped off while passing through the flow orifice or deposited on the cable drum. Waste entrainment calculations by LANL indicate that hazardous amounts of radioactive waste material could be entrained into the viscometer instrument enclosure on top of the riser. Consequently, a decontamination system is required to limit the amount of waste entrained to a level based on ALARA and operating personnel safety requirements.

A decontamination system was developed as shown on drawing H-2-821443. This spool will be in place at all times during the viscometer operation to wash the cable and ball as they are withdrawn from the tank. The decontamination spool uses hot water and the water's impact force to maximize effectiveness of cleaning. The water nozzles are inclined downward to minimize upward splashing effects. During testing it was observed that the decontamination spool piece actually creates a low pressure area in the riser above the nozzles.

Prior experience assures that the SY-101 waste is highly water soluble. The waste will create a film type build up on contacting surfaces during operations.

All components of the decontamination spool are stainless steel to facilitate decontamination and prevent rusting. The feed piping is slanted down to promote self draining as much as possible, in order to minimize maintenance in the winter. The nozzles are placed as near the item to be cleaned as possible for optimal impact force cleaning. They are removable for ease of maintenance when required. The attached filter is intended to prevent field dirt and sand in the water from plugging the spray nozzles.

The nozzles used are a product of Spraying Systems, Series 8001-TC with 0.88 gpm at 3000 psig spraying capacity. The four units are equally spaced at the same elevation. They are mounted on a diameter of approximately four inches. With the viscometer cable at the center of the chamber, full coverage is obtained from all four nozzles. The nozzle housings are inclined 20 degrees down. This is necessary to minimize the upward spread of waste from flying water during the spraying operation, and to ensure that no free standing liquids are left in the decontamination spool at completion of the operation.

A rubber wiper can be incorporated at the top of the spool. This wiper is sized to wipe a water lance, if a water lance must be used. With the water lance wiper installed, the wiper may be expected to apply about 50 pounds drag to the two-inch diameter small water lance in the wiping process.

Water to the decontamination spool is provided from a self heated high pressure water pump connected to a cold water tank truck. The high pressure pump is rated at 3.6 gpm output at 3000 psig, with electronically variable output temperature. A pre-filter has been added prior to the hot water pump to prevent particles from damaging and/or plugging the pump system.

The tank truck is expected to be a standard WHC issue 1500 gallon water truck. Gravity feed is not sufficient to keep the high pressure pump primed, so a feed (booster) pump is also used. The feed pump is a centrifugal type and not easily damaged by particles or other debris. It is not specially filtered.

The Omega water meter used in the decontamination system is also very resistant to damage from small particles. Consequently, it also is not specially filtered.

4.5 STORAGE AND TRANSPORT OF EQUIPMENT

The viscometer will become contaminated during field service. A special transport container has been procured (Type 7A) and is covered by the necessary paperwork (WHC-SD-TP-DAP-005) to allow viscometer transport between the different tank farms on site. The transport container may be used for final disposal/storage as described in the above reference.

Note that the viscometer is reusable plant equipment, and will be used on several different tanks during future retrieval efforts.

4.6 SITE SERVICES REQUIRED

4.6.1 Water

A temporary water supply will be required as discussed above.

4.6.2 Crane and Rigging

The viscometer assembly must be mounted to the riser using a crane for placement. If the assembly is dropped, severe riser damage may result.

4.6.3 Power

Site power is required. One 4 wire 480 VAC, 3 phase 35 amp service receptacle is required.

4.6.4 Other

No air is required. All water lines will be allowed to naturally drain their small quantities of water to the soil. The hot water pump uses diesel fuel for a heat source. The pump will be provided to the site fully fueled.

5.0 VISCOMETER DESIGN CRITERIA COMPLIANCE

5.1 NFPA CLASSIFICATION AND COMPLIANCE

Since the waste tank gas contains flammable constituents, the environment inside the tank, above the convective layer was considered a Class I, Division 1 hazardous location. Furthermore, since the flammable gas of concern is primarily hydrogen, this was designated as a Group B location. Consequently, electrical equipment and devices used in areas of the viscometer instrument which are directly exposed to the tank atmosphere during normal operation as well as any other devices connected or coupled to the same wiring were designed to conform to the National Fire Protection Association (NFPA) requirements (National Electrical Code, NEC) for service in Class I, Division 1, Group B hazardous locations. [Note that this requirement was what the viscometer was designed to.] The NFPA classifications have been in constant debate for the last year, and this SDD document does not intend to set any NFPA classifications.

In essence, the primary viscometer enclosure equipment was made intrinsically safe. Equipment immediately surrounding the primary enclosure that did not meet Class I, Division 2 Group B criteria are automatically de-energized if the tank pressurizes. This automatic de-energization is an active safety system, and was designed with redundancy of the active components.

A detailed discussion of the NFPA classifications as related to the viscometer may be found in WHC-SD-WM-DA-151 "Viscometer Electrical Codes and Compliance". Note that the paper (Rev. 0) was issued prior to release of the electrical drawings, therefore, some of the figures presented in the paper are out of date. However, the arguments are still technically valid.

5.2 STATIC SPARKING CONTROL

The original cable connecting the ball to the cable drum was high density polyethylene coated over a 3/32" stainless steel cable. LANL (Safety analysis preparers) investigated NFPA 77 and warned that nonconductive cable rolling over stainless steel pulleys could create a spark powerful enough to ignite hydrogen. Much time and effort was expended by LANL and WHC to prove there was no static problem, but none of the efforts were successful.

The basic conclusions of this work were:

- 1) Even 100% relative humidity is not assured to control static, an interpretation of the NFPA 77 code.
- 2) 100% R. H. couldn't be assured everywhere in the riser and primary enclosure
- 3) R.H. would have to be monitored if relied upon.
- 4) Mechanical sparks take 1 to 2 joules energy to light hydrogen. This type spark can not be compared to static sparks however.
- 5) Ionizing atmospheres (radiation fields) help control static, but no relation between dose rate and static control suppression was located.
- 6) Resistance through the cable coating of less than one mega-ohm could be considered to control static well enough.

A conductive polypropylene coating was finally located that had less than 1 Mega-ohm resistance, the Stat-Kon ME discussed previously.

5.3 STRUCTURAL COMPLIANCE

The viscometer instrument was analyzed for various design loadings, including seismic effects to the risers, and a design analysis report was issued (see Appendices). The analysis concluded that the viscometer posed no structural threat to the tank, other than from being dropped from an excessive height, which is addressed by the SA.

5.4 MATERIAL COMPLIANCE

All material used in the tank or exposed to the tank environment meets the material requirements as specified in Section 3.0. A materials compatibility report was issued and is referenced in the Appendices.

The components (installed in enclosure 2) located out of the tank on the surface level have been designed for ease of maintenance and will not be exposed to the tank corrosive atmosphere or radiation fields and are therefore suitable for use. In general, all components (exposed to the tank environment) were constructed of 300 series stainless steel, to prevent corrosion from humidity and assist in decontamination.

The only serious compatibility problem arises from using an aluminum load cell in an area where liquid waste may be present (from high speed cable pulls, etc). Therefore, the aluminum can not be exposed to direct liquid contact, and

has been placed inside plastic bags.

5.5 CONTROL REQUIREMENT COMPLIANCE

Successful completion of the software ATP verified the control system met all the necessary requirements.

6.0 OPERATION

6.1 QUALIFICATION TESTING

The viscometer system was fully tested for system operability. Refer to the Acceptance Test Procedures, WHC-SD-WM-ATP-089 Rev. 0 and WHC-SD-WM-ATP-079 Rev. 1, and their associated test reports (ATR's).

6.2 INSTALLATION

An installation procedure has been prepared that fully describes the steps required to install the viscometer instrument on tank 101-SY. Refer to Work Plan, TFPE-YP-0205.

6.3 OPERATION

Operation of the viscometer system will be in accordance with the Test Plan, WHC-SD-WM-TP-219. The viscometer system will not be run outside the procedure or envelope outlined in this test plan.

Caution: The system shall only be operated by specially trained personnel. Personnel not trained must consult with the specially trained personnel to perform installation, removal, and provide general field assistance as required to perform in situ measurements.

6.4 DECONTAMINATION AND REMOVAL

Decontamination and removal of the viscometer instrument shall be in accordance with the procedure steps outlined in TFPE-YP-0205. Permanent disposal is not expected to be necessary in the near future, and has not been procedurally addressed. Note the transport container can be accepted at the Central Waste Complex according to the DAP prepared.

7.0 MAINTENANCE

An Operations and Maintenance Manual (O&MM) has been prepared that fully describes the steps required for maintenance of the viscometer instrument. Refer to O&MM, WHC-SD-WM-OMM-009.

8.0 REFERENCES

- WHC-SD-WM-WP-242, "SY-101 In Situ Viscometer Instrument Engineering Work Plan", K. L. Pearce and T. I. Stokes, October 1993
- LA-UR-93-4300, N-6-93-R152, "The Evaluation of Methods for Rheology Measurements of the Waste Contained in Hanford Tank 241-SY-101," K. O. Pasamehmetoglu, C. Unal, and J. N. Edwards, December 1993
- WHC-SD-WM-CSRS-017, "Software Requirements Specification for Tank 101-SY Viscometer", M. Gimera, March 3, 1994
- WHC-SD-WM-DA-151, REV. 0, "Viscometer Electrical Codes and Compliance", J. H. Bussell et al., May 3, 1994
- WHC-SD-WM-OMM-009, REV. 0, "SY-101 In Situ Viscometer Instrument Operation and Maintenance Manual", K. L. Pearce et al., July 1994
- WHC-SD-WM-ATP-079 REV. 1, "Software Acceptance Test Procedure For Tank 101-SY Viscometer", M. Gimera, July 1994
- WHC-SD-WM-ATP-089 REV. 0, "In Situ Viscometer Instrument Acceptance Test Procedure", K. L. Pearce, July 1994
- WHC-SD-TP-DAP-005 REV. 0, "Documentation and Analysis for Packaging for the Viscometer Box and Spool Piece Drum", M.D. Clements, August 1994
- LA-UR-92-3196 REV. 10, Addendum 1, "Viscometer Safety Analysis for Operation in 241-SY-101", Los Alamos National Labs, July 1994
- WHC-SD-WM-TP-219 REV. 0, "In Situ Viscometer Test Plan, Tank 241-SY-101", T. I. Stokes and K. L. Pearce, July 1994
- TFPE-YP-0205, "Instructions for Installation & Removal Of Viscometer Instrument In Tank 241-SY-101", A. E. Wilder, August 1994

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APPENDIX A

CALIBRATION INFORMATION

APPENDIX: CALIBRATIONS

Figure 1 is a block diagram of the cable tension measuring system. The boxes represent the system components and the arrows represent the signals and their relative direction. It is presented below:

Figure 1

It is composed of the following sub-systems:

- 1- Six discrete load cells ranging from 15 to 500 Lbs. capacity.
- 2- An intrinsic safety barrier.
- 3- A load cell bridgesensor.
- 4- A National Instruments signal conditioning board
- 5- A National Instruments AT-MIO-16 data acquisition board,

Each of the sub systems will be discussed in turn:

Load Cells:

The load cells function as a variable voltage source whose output is directly proportional to the supplied excitation voltage and the weight impressed on them.

The calibration sheets for each of the load cells are contained in the appendix. It can be seen that the sensitivity of each cell is about 3 mv per volt of excitation. This means that when the cell is excited with 1 volt and the cell has its rated weight loading applied, the signal out of the cell's sense lines will be approximately 3 mv.

Although they are not included in the calibration data, the load cells also have a DC offset voltage. What this means is with no load applied, they will still generate a steady voltage. This is referred to as offset, and the manufacturer states that it is no more than 1.00% of rated output voltage. In the previous example this would be .03 mv. Offset is not considered a problem because the computer used to analyze the data can compensate for the steady state error.

Intrinsic Safety Barriers:

There are three sets of intrinsic safety barriers. The first set is for the excitation supply lines. During testing it was determined that this barrier drops a constant 2.7 volts under all conditions of operation. Since the voltage drop is a constant it can be ignored. The other two barriers are for the excitation sense and signal line. There was no measurable voltage drop across these two barriers and thus they have no effect on the signal supplied from the load cell to the Bridgesensor.

Bridgesensor:

The bridgesensor provides the following functions:

- 1- Provides a regulated constant excitation voltage to the load cell regardless of load applied to the cell.
- 2- Filters and amplifies the output of the load cell to the computer system.

The amount of excitation available from the bridgesensor is adjustable from 4 to 15 Volts. The excitation was set to 12.0 volts at the input to the intrinsic safety barrier.

The next adjustment was the offset control. With the input to the bridgesensor shorted, thus zero input, the offset control was adjusted until the output from the bridgesensor was zero volts.

The final adjustment was the gain. The amount of gain provided from the bridgesensor is adjustable from 40 to 1,000. It was set to 250 by applying a known input to the bridgesensor and adjusting the gain until the measured output voltage was 250 times the input voltage.

Signal Conditioning Board:

The signal conditioner board is composed of a filter, over voltage protection for the computer, and a two to one voltage divider. It has no adjustments. Its only effect on the signal is to half its magnitude.

Data Acquisition Board:

The data acquisition board samples the input signal and converts it into a binary number that the computer can process.

Calibration Procedure:

The calibration process was performed in two steps. First, the individual components were calibrated, and then the system as a whole was calibrated. All of the individual components with the exception of the bridgesensor were calibrated at the standards lab. The bridgesensor was calibrated in place and will be discussed in depth in the next section.

Bridgesensor Calibration Procedure:

The bridgesensor was calibrated using the following instrument:

- 1- Fluke Digital Multimeter, (DMM)
Model: 8842
Calibration Expiration: 8-30-94
WHC 002-45-08-039

The first adjustment made to the bridge sensor was made to the excitation voltage of the load cell. With the 15 lb load cell installed, the bridgesensor was energized and allowed to stabilize for a one hour period. After the stabilization period, the excitation voltage going to the sensor side of the intrinsic barrier was monitored. The bridgesensor's B+ excitation control potentiometer was adjusted until the DMM read as close to 12.000 volts as possible. The table below indicates the results of the excitation adjustment when the other cells were substituted for 15 lb cell.

BRIDGESENSOR EXCITATION VOLTAGE VALUES		
LOAD CELL CAPACITY	Excitation V barrier	Excitation V Load cell
15 LB	12.0018	9.2828
25 LB	11.9977	9.2828
50 LB	*	*
100 LB	11.9948	9.2829
250 LB	12.0040	9.2771
500 LB	12.0005	9.2777

The next adjustment was the offset control. With the signal input leads to the bridgesensor replaced with a short circuit, the output was monitored with the DMM. The output offset potentiometer was adjustment for minimum offset. The value was recorded as 0.2 millivolts. This value is independent of the load cells.

The last adjustment was the amplifier gain. For this adjustment, the short circuit on the bridgesensor was replaced with the signal lines coming from the intrinsic safety barrier.

The 15 lbs load cell was then loaded to 10 lbs. The signal generated by the load cell was measured and was recorded as 20.931 Mv. The amplification factor for the bridgesensor was required to be 250. To set this gain, the voltage value recorded in the previous step was multiplied by the required gain of 250, and this yields the desired output voltage of 5.2332 Volts. The DMM was moved from the load cell to the output of the bridgesensor and the bridgesensors gain potentiometer was adjusted until the output signal as read by the DMM matched the calculated signal.

System Calibration:

The system was calibrated by incremental loading and unloading the load cell and recording the resulting voltage at each load step as measured at the computer. One thousand readings were recorded for each loading. The readings were then analyzed and an average, minimum, maximum, and standard deviation were computed. The first reading recorded was with the integral pulley and no other weight on the load cell. This is referred to as a "no load" reading and was used to compute the offset. The next reading was made with a calibrated weight. This process of increasing the weight and recording data was repeated until the weight loading equaled or exceeded 80% of the load cells rating. A minimum of four increasing weight loadings were recorded for each cell. When the final weighted loading was recorded the process was reversed, and the weights were removed and data recorded until the cell was unloaded. Then, the loading and unloading process was repeated one more time, thus there are four voltage readings for each weight loading used.

For each of the weight readings data sets, the four voltage average measurements are again averaged together. This "average of the averages" was used as the input for a least squares routine used to form a linear fit of the data. From the linear fit data, a slope and offset term were developed which were programmed into the virtual instrument. The actual procedure follows:

- 1- A load cell and integral pulley are mounted in the viscometer and all electrical connections are made up. Power is applied to the viscometer and the system is allowed to stabilize for one hour. The cable and ball are not placed on the load cell pulley at this time. At the end of the hour, the load cell voltage being supplied to the computer is recorded in a data file displayed by the lab view program. Each data set represents 1000 samples. For each set of data, four numbers are shown: the average, minimum, maximum, and the standard deviation of the 1000

voltage samples.

2- For the next reading, a calibrated weight was added to the load cell and the same data was recorded as in step one. For the 15 and 25 Lb load cells the ball and cable could not be used due to the leverage effects of the pulley would over range the cells. In this case the weights were applied directly to the load cell.

3- Step 2 is repeated for increasing weights and then decreasing weights. The Loading unloading process is repeated a total of two times. The weight calibration data used to load the cells is presented below: The voltage verses weight loading is included at the end of this appendix.

CALIBRATED WEIGHTS LISTING		
DESCRIPTION	CALIBRATION	POUNDS
BALL & INSERT	*	15.645
SHACKLE	*	3.5352
SLING	*	.4553
CABLE, 12 FEET	*	.2099
2 LB WEIGHT	#52, WHC 002-86-01-062	2.0004
5 LB WEIGHT	#54, WHC 002-86-01-062	5.0010
10 LB WEIGHT	#D61, WHC 002-86-01-062	10.0020
10 LB WEIGHT	#D67, WHC 002-86-01-062	10.0015
50 LB WEIGHT	#B54, WHC 002-86-01-074	50.0085
50 LB WEIGHT	#24, WHC 002-86-01-050	50.0095
50 LB WEIGHT	#47, WHC 002-86-01-050	50.0093
50 LB WEIGHT	#49, WHC 002-86-01-050	50.0103

* Indicates that the items were individually weighted using the following calibrated equipment:

Sartorius balance
Model: 1507
WHC 677-06-01-24, Expires 9-22-94

4- From this voltage verses weight data, a least squares

routine was used to develop a linear fit to the raw data. This new "smoothed data" was the basis of the equations used in the virtual instrument to convert the voltage readings into force. There are two factors of interest in a linear equation, the slope and the offset terms. Each of these factors will be discussed below.

The no load offset voltages represent the combined effect of DC offset from the load cell and the weight of the integral pulley/load cell combination. The offset is not desirable since it leads to inaccuracies in the weight readings. The pulley weight is a constant and is not important in the analysis of the data. The offset term is read directly as the average of the four averages of no load weight voltage reading multiplied by the conversion constant.

The factor to convert the measured voltage to a weight is given as a conversion constant. It is the slope of the weight verses voltage curve and is defined by the equation below:

$$K_c = \frac{\text{Cableload}}{(V_{\text{mea}} - V_{\text{off}})}$$

Where:

V_{mea} The voltage from the linear fit data when the maximum weight was used as the load.

V_{off} The no load offset voltage from the linear fit data.

K_c Conversion constant.

Cable load The actual cable tension during the calibration process. For the dead weights it equals 1/2 the weight used, for the ball weight it is equal to the weight used.

5- In the final step each of the load cell tension factors instruments was programmed. The offset voltage as derived in the previous step were subtracted from the measured voltage. The difference was then multiplied by the derived conversion constant. This process can be represented by the following equation:

$$Cableload = (V_{mea} - V_{off}) * K_c$$

The conversion equations constants for the six load cells are tabulated in the following table. Unless indicated elsewhere, $k_c * V_{off}$ is measured in newtons and K_c has the units of newtons per volt:

CONVERSION EQUATION CONSTANTS		
LOAD CELL CAPACITY	$k_c * V_{off}$	K_c
15 LB	-1.43055	9.06573
25 LB	-5.98296	14.9392
50 LB	-1.29471	30.0098
100 LB	-13.0513	59.1952
250 LB	1.24898	149.568
500 LB	10.4567	291.484

This calibration process ignores the individual devices and is a system type calibration. As long as the individual parts do not change, such as the bridge sensor or signal conditioning module the results are valid.

Velocity Measurement System:

The velocity measuring system is composed of the following components:

- 1- An integral mounted DC tachometer coupled to each of the motor drives,
- 2- The signal conditioning board
- 3- The data acquisition board

The tachometer is a generator whose output voltage is directly proportional to its shaft speed. For any given RPM, it will generate a unique voltage. The signal conditioning and data

acquisition board are used to read that voltage and the lab view software is used to scale and display it.

The system was calibrated as follows. A calibrated digital tachometer was coupled to the shaft of the tachometer under test. A command signal to activate the drive was initiated. The reading from the digital tachometer was noted along with the corresponding output voltage from the tachometer. The process was repeated for both directions of drive rotation and various speeds. Based on the geometry of the cable drum, cable diameter and the various gear boxes, an equation can be set up which directly relates tachometer RPM to cable speed. It is shown below for both the high and low speed drives:

$$V_{cable} = \frac{RPM}{GearRatio} * radius * 2 * \pi * 1 \frac{min}{60sec}$$

Where:

V_{cable} Cable velocity, mm/sec

RPM Tachometer RPM

Radius Cable drum radius plus one half of cable diameter, 8.3554 cm.

Gear ratio high speed drive - 15 : 1

low speed drive - 750 : 1

Once the cable speed and the tachometer output voltage are known, a simple scaling factor is used to change the measured tachometer voltage to cable speed in the virtual instrument for that tachometer. This process is repeated for the other tachometer system.

Ball Speed Control:

The ball speed control system was calibrated after the ball velocity system was calibrated. A command signal to move the ball at the top of its speed range was initiated. The ball velocity was recorded as shown on the now calibrated front panel. The calibrated ball velocity was then compared to the command signal for the ball velocity. If they were not the same, the ratio of the two signal was used in the motor command virtual instrument. The process was repeated for the other direction and then repeated for the other drive. A graphical presentation of

tachometer RPM, computer command voltage and tachometer output voltage is presented at the end of this report for both drive systems. Positive voltage and RPM indicate that the ball is moving down.

Position Measurement System:

This position measuring system is based on the following instrument:

- 1- A 512 turn, 4,906 positions per turn absolute position encoder, model AAF100.

It is an optical type encoder that is coupled to the shaft of the cable drum. As the description implies, one revolution has been divided into 4,906 equal unique increments and this has been continued for 512 complete revolutions. That is an angular resolution of .07338 of a degree. Based on the geometry of the cable and drum this corresponds to a ball position resolution of .012819 cm per encoder count.

To calibrate the system, the ball is raised into the ball home position. When this occurs, a data file is created with the unique encoder position corresponding to the home position. On subsequent start ups the position virtual instrument compares the home position reading to the current position, takes the difference and scales it to represent centimeters from home on the virtual instrument.

Cable stretch was not accounted for.

Load Cell Used: 15 lb

Notes: weights directly applied - no doubling.

Weight Used	Weight	Minimum	Maximum	Mean	Standard Deviation
0 lb	0.0000 N	0.1425	0.1755	0.1588	0.0056
2 lb	8.8982 N	0.6345	0.6662	0.6497	0.0055
5 lb	22.2456 N	1.3693	1.4038	1.3861	0.0057
7 lb	31.1438 N	1.8591	1.8951	1.8748	0.0057
10 lb	44.4911 N	2.5903	2.6230	2.6072	0.0055
12 lb	53.3893 N	3.0716	3.1058	3.0885	0.0057
15 lb	66.7367 N	3.8449	3.8803	3.8612	0.0059
15 lb	66.7367 N	3.8425	3.8754	3.8581	0.0057
12 lb	53.3893 N	3.0814	3.1146	3.0967	0.0058
10 lb	44.4911 N	2.5916	2.6230	2.6074	0.0056
7 lb	31.1438 N	1.8643	1.8961	1.8796	0.0057
5 lb	22.2456 N	1.3678	1.4005	1.3843	0.0056
2 lb	8.8982 N	0.6339	0.6665	0.6488	0.0058
0 lb	0.0000 N	0.1428	0.1770	0.1594	0.0055
0 lb	0.0000 N	0.1440	0.1791	0.1596	0.0056
2 lb	8.8982 N	0.6351	0.6674	0.6498	0.0055
5 lb	22.2456 N	1.3678	1.4017	1.3834	0.0055
7 lb	31.1438 N	1.8591	1.8945	1.8757	0.0054
10 lb	44.4911 N	2.5879	2.6236	2.6046	0.0058
12 lb	53.3893 N	3.0801	3.1143	3.0961	0.0060
15 lb	66.7367 N	3.8147	3.8553	3.8350	0.0058
15 lb	66.7367 N	3.8187	3.8504	3.8334	0.0057
12 lb	53.3893 N	3.0841	3.1155	3.0984	0.0056
10 lb	44.4911 N	2.5912	2.6236	2.6071	0.0057
7 lb	31.1438 N	1.8616	1.8936	1.8771	0.0056
5 lb	22.2456 N	1.3712	1.4041	1.3853	0.0055
2 lb	8.8982 N	0.6360	0.6677	0.6504	0.0055
0 lb	0.0000 N	0.1447	0.1773	0.1595	0.0055

In[1]:=

```
data = ReadList["15 Lb Data", Number, RecordLists -> True ]
```

Out[1]=

```
{{0.1588, 0}, {0.6497, 4.44911}, {1.3861, 11.1228}, {1.8748, 15.5719},  
 {2.6072, 22.2456}, {3.0885, 26.6947}, {3.8612, 33.3683},  
 {3.8581, 33.3683}, {3.0967, 26.6947}, {2.6074, 22.2456},  
 {1.8796, 15.5719}, {1.3843, 11.1228}, {0.6488, 4.44911}, {0.1594, 0},  
 {0.1596, 0}, {0.6498, 4.44911}, {1.3834, 11.1228}, {1.8757, 15.5719},  
 {2.6046, 22.2456}, {3.0961, 26.6947}, {3.835, 33.3683},  
 {3.8334, 33.3683}, {3.0984, 26.6947}, {2.6071, 22.2456},  
 {1.8771, 15.5719}, {1.3853, 11.1228}, {0.6504, 4.44911}, {0.1595, 0}}
```

In[2]:=

```
factors = Fit[ data, {1, x}, x ]
```

Out[2]=

```
-1.43055 + 9.06573 x
```

In[3]:=

```
factorPlot = Plot[ factors, {x, 0, 5}, PlotStyle -> {Thickness[0.0005]}]
```

```
In[4]:=
```

```
pointsPlot = ListPlot[ data ] ;
```

In[5]:=

```
Show[ factorPlot, pointsPlot, AxesLabel->{"Volts", "Newtons"} ]
```

Out[5]=

-Graphics-

Load Cell Used: 25 lb

Notes: weights directly applied - no doubling.

Weight Used	Weight	Minimum	Maximum	Mean	Standard Deviation
0 lb	0.0000 N	0.3839	0.4160	0.3985	0.0057
5 lb	22.2456 N	1.1285	1.1606	1.1440	0.0056
10 lb	44.4911 N	1.8719	1.9022	1.8866	0.0055
15 lb	66.7367 N	2.6328	2.6703	2.6478	0.0062
20 lb	88.9800 N	3.3542	3.3884	3.3700	0.0059
20 lb	88.9800 N	3.3557	3.3884	3.3708	0.0057
15 lb	66.7367 N	2.6315	2.6709	2.6516	0.0059
10 lb	44.4911 N	1.8750	1.9070	1.8872	0.0055
5 lb	22.2456 N	1.1285	1.1618	1.1442	0.0058
0 lb	0.0000 N	0.3842	0.4169	0.3991	0.0056
0 lb	0.0000 N	0.3836	0.4150	0.3987	0.0057
5 lb	22.2456 N	1.1295	1.1642	1.1458	0.0057
10 lb	44.4911 N	1.8698	1.9034	1.8844	0.0057
15 lb	66.7367 N	2.6221	2.6547	2.6375	0.0057
20 lb	88.9800 N	3.3496	3.3899	3.3661	0.0060
20 lb	88.9800 N	3.3508	3.3850	3.3670	0.0054
15 lb	66.7367 N	2.6407	2.6843	2.6615	0.0072
10 lb	44.4911 N	1.8738	1.9058	1.8882	0.0055
5 lb	22.2456 N	1.1282	1.1584	1.1430	0.0055
0 lb	0.0000 N	0.3851	0.4141	0.3990	0.0055

In[6]:=

```
data = ReadList["25 Lb Data", Number, RecordLists -> True ]
```

Out[6]=

```
{{0.3985, 0}, {1.144, 11.1228}, {1.8866, 22.2456}, {2.6478, 33.3683},  
 {3.37, 44.49}, {3.3708, 44.49}, {2.6516, 33.3683}, {1.8872, 22.2456},  
 {1.1442, 11.1228}, {0.3991, 0}, {0.3987, 0}, {1.1458, 11.1228},  
 {1.8844, 22.2456}, {2.6375, 33.3683}, {3.3661, 44.49}, {3.367, 44.49},  
 {2.6615, 33.3683}, {1.8882, 22.2456}, {1.143, 11.1228}, {0.399, 0}}
```

In[7]:=

```
factors = Fit[ data, {1, x}, x ]
```

Out[7]=

```
-5.98296 + 14.9392 x
```

In[8]:=

```
factorPlot = Plot[ factors, {x, 0, 5}, PlotStyle -> {Thickness[0.0005]}]
```

```
In[9]:=
```

```
pointsPlot = ListPlot[ data ] ;
```

In[10]:=

```
Show[ factorPlot, pointsPlot, AxesLabel->{"Volts", "Newtons"} ]
```

Out[10]=

-Graphics-

Load Cell Used: 50 lb

Notes: some weights directly applied - no doubling.

Weight Used	Weight	Minimum	Maximum	Mean	Standard Deviation
0 lb	0.0000 N	0.0195	0.0577	0.0405	0.0058
5 lb	22.2456 N	0.3909	0.4291	0.4113	0.0058
10 lb	44.4911 N	0.7666	0.8060	0.7885	0.0063
15 lb	66.7367 N	1.1383	1.1780	1.1607	0.0059
ball only	141.0522 N	2.3703	2.4078	2.3912	0.0059
ball + 5 lb	185.5433 N	3.1158	3.1531	3.1364	0.0059
ball + 5 lb	185.5433 N	3.1168	3.1525	3.1364	0.0060
ball only	141.0522 N	2.3715	2.4084	2.3917	0.0057
15 lb	66.7367 N	1.1426	1.1807	1.1618	0.0060
10 lb	44.4911 N	0.7654	0.8029	0.7861	0.0056
5 lb	22.2456 N	0.3934	0.4288	0.4138	0.0056
0 lb	0.0000 N	0.0226	0.0589	0.0418	0.0058
0 lb	0.0000 N	0.0180	0.0583	0.0415	0.0057
5 lb	22.2456 N	0.3961	0.4315	0.4155	0.0057
10 lb	44.4911 N	0.7635	0.8038	0.7841	0.0057
15 lb	66.7367 N	1.1285	1.1700	1.1509	0.0063
ball only	141.0522 N	2.3672	2.4100	2.3907	0.0061
ball + 5 lb	185.5433 N	3.1165	3.1531	3.1348	0.0057
ball + 5 lb	185.5433 N	3.1131	3.1516	3.1341	0.0062
ball only	141.0522 N	2.3706	2.4072	2.3901	0.0058
15 lb	66.7367 N	1.1255	1.1667	1.1477	0.0059
10 lb	44.4911 N	0.7724	0.8090	0.7916	0.0057
5 lb	22.2456 N	0.3946	0.4312	0.4148	0.0057
0 lb	0.0000 N	0.0189	0.0601	0.0407	0.0058

In[1]:=

```
data = ReadList["50 Lb Data", Number, RecordLists -> True ]
```

Out[1]=

```
{{0.0405, 0}, {0.4113, 11.1228}, {0.7885, 22.2456}, {1.1607, 33.3683},  
 {2.3912, 70.5261}, {3.1364, 92.7717}, {3.1364, 92.7717}, {2.3917, 70.5  
 {1.1618, 33.3683}, {0.7861, 22.2456}, {0.4138, 11.1228}, {0.0418, 0},  
 {0.0415, 0}, {0.4155, 11.1228}, {0.7841, 22.2456}, {1.1509, 33.3683},  
 {2.3907, 70.5261}, {3.1348, 92.7717}, {3.1341, 92.7717}, {2.3901, 70.5  
 {1.1477, 33.3683}, {0.7916, 22.2456}, {0.4148, 11.1228}, {0.0407, 0}}
```

In[2]:=

```
factors = Fit[ data, {1, x}, x ]
```

Out[2]=

```
-1.29471 + 30.0098 x
```

In[3]:=

```
factorPlot = Plot[ factors, {x, 0, 5}, PlotStyle -> {Thickness[0.0005]}
```

In[1]:=

```
data = ReadList["50 Lb Data", Number, RecordLists -> True ]
```

Out[1]=

```
{ {0.0405, 0}, {0.4113, 11.1228}, {0.7885, 22.2456}, {1.1607, 33.3683},  
  {2.3912, 70.5261}, {3.1364, 92.7717}, {3.1364, 92.7717}, {2.3917, 70.5  
  {1.1618, 33.3683}, {0.7861, 22.2456}, {0.4138, 11.1228}, {0.0418, 0},  
  {0.0415, 0}, {0.4155, 11.1228}, {0.7841, 22.2456}, {1.1509, 33.3683},  
  {2.3907, 70.5261}, {3.1348, 92.7717}, {3.1341, 92.7717}, {2.3901, 70.5  
  {1.1477, 33.3683}, {0.7916, 22.2456}, {0.4148, 11.1228}, {0.0407, 0} }
```

In[2]:=

```
factors = Fit[ data, {1, x}, x ]
```

Out[2]=

```
-1.29471 + 30.0098 x
```

In[3]:=

```
factorPlot = Plot[ factors, {x, 0, 5}, PlotStyle -> {Thickness[0.0005]}]
```

```
In[4]:=
```

```
pointsPlot = ListPlot[ data ] ;
```

In[5]:=

```
Show[ factorPlot, pointsPlot, AxesLabel->{"Volts", "Newtons"} ]
```

Out[5]=

-Graphics-

Load Cell Used: 100 lb

Notes:

	Weight Used	Weight	Minimum	Maximum	Mean	Standard Deviation
0		0.0000	0.2106	0.2438	0.2259	0.0056
ball only		70.5261	1.3879	1.4264	1.4080	0.0060
ball + 10 lb		115.0172	2.1378	2.1759	2.1597	0.0059
ball + 20 lb		159.5061	2.8906	2.9288	2.9118	0.0058
ball + 50 lb		310.7256	5.4681	5.5087	5.4910	0.0063
ball + 50 lb		310.7256	5.4681	5.5078	5.4910	0.0063
ball + 20 lb		159.5061	2.8952	2.9367	2.9160	0.0061
ball + 10 lb		115.0172	2.1436	2.1811	2.1652	0.0058
ball only		70.5261	1.3913	1.4304	1.4127	0.0061
0		0.0000	0.1978	0.2359	0.2195	0.0061
0		0.0000	0.1968	0.2368	0.2196	0.0054
ball only		70.5261	1.3885	1.4285	1.4107	0.0057
ball + 10 lb		115.0172	2.1432	2.1838	2.1642	0.0060
ball + 20 lb		159.5061	2.8952	2.9361	2.9179	0.0061
ball + 50 lb		310.7256	5.4642	5.5060	5.4883	0.0062
ball + 50 lb		310.7256	5.4642	5.5063	5.4863	0.0063
ball + 20 lb		159.5061	2.8949	2.9340	2.9164	0.0064
ball + 10 lb		115.0172	2.1439	2.1844	2.1651	0.0059
ball only		70.5261	1.3889	1.4285	1.4115	0.0059
0		0.0000	0.1968	0.2368	0.2195	0.0058

In[11]:=

```
data = ReadList["100 Lb Data", Number, RecordLists -> True ]
```

Out[11]=

```
{{0.2259, 0}, {1.408, 70.5261}, {2.1597, 115.017}, {2.9118, 159.506},  
 {2.916, 159.506}, {2.1652, 115.017}, {1.4127, 70.5261}, {0.2195, 0},  
 {0.2196, 0}, {1.4107, 70.5261}, {2.1642, 115.017}, {2.9179, 159.506},  
 {2.9164, 159.506}, {2.1651, 115.017}, {1.4115, 70.5261}, {0.2195, 0}}
```

In[12]:=

```
factors = Fit[ data, {1, x}, x ]
```

Out[12]=

```
-13.0513 + 59.1952 x
```

In[13]:=

```
factorPlot = Plot[ factors, {x, 0, 5}, PlotStyle -> {Thickness[0.0005]}]
```

```
In[14]:=
```

```
pointsPlot = ListPlot[ data ] ;
```

```
In[15]:=
```

```
Show[ factorPlot, pointsPlot, AxesLabel->{"Volts", "Newtons"} ]
```

```
Out[15]=
```

```
-Graphics-
```

Load Cell Used: 250 lb

Notes:

Weight Used	Weight	Minimum	Maximum	Mean	Standard Deviation
0	0.0000	-0.0299	0.0101	-0.0077	0.0061
ball only	70.5261	0.4428	0.4791	0.4621	0.0060
ball + 20 lb	159.5061	1.0358	1.0727	1.0567	0.0059
ball + 50 lb	310.7256	2.0490	2.0862	2.0693	0.0058
ball + 100 lb	533.1790	3.5345	3.5828	3.5582	0.0066
ball + 100 lb	533.1790	3.5327	3.5730	3.5552	0.0059
ball + 50 lb	310.7256	2.0425	2.0825	2.0656	0.0061
ball + 20 lb	159.5061	1.0333	1.0733	1.0572	0.0061
ball only	70.5261	0.4431	0.4803	0.4641	0.0057
0	0.0000	-0.0281	0.0134	-0.0066	0.0058
0	0.0000	-0.0278	0.0095	-0.0069	0.0062
ball only	70.5261	0.4416	0.4825	0.4626	0.0057
ball + 20 lb	159.5061	1.0333	1.0748	1.0550	0.0057
ball + 50 lb	310.7256	2.0490	2.0871	2.0700	0.0060
ball + 100 lb	533.1790	3.5370	3.5726	3.5587	0.0063
ball + 100 lb	533.1790	3.5358	3.5742	3.5573	0.0060
ball + 50 lb	310.7256	2.0459	2.0862	2.0687	0.0057
ball + 20 lb	159.5061	1.0367	1.0760	1.0572	0.0061
ball only	70.5261	0.4431	0.4803	0.4640	0.0060
0	0.0000	-0.0278	0.0110	-0.0066	0.0059

In[9]:=

```
data = ReadList["250 Lb Data", Number, RecordLists -> True ]
```

Out[9]=

```
{{-0.0077, 0}, {0.4621, 70.5261}, {1.0567, 159.506}, {2.0693, 310.726},  
 {3.5582, 533.179}, {3.5552, 533.179}, {2.0656, 310.726},  
 {1.0572, 159.506}, {0.4641, 70.5261}, {-0.0066, 0}, {-0.0069, 0},  
 {0.4626, 70.5261}, {1.055, 159.506}, {2.07, 310.726}, {3.5587, 533.179},  
 {3.5573, 533.179}, {2.0687, 310.726}, {1.0572, 159.506},  
 {0.464, 70.5261}, {-0.0066, 0}}
```

In[10]:=

```
factors = Fit[ data, {1, x}, x ]
```

Out[10]=

```
1.24898 + 149.568 x
```

In[11]:=

```
factorPlot = Plot[ factors, {x, 0, 5}, PlotStyle -> {Thickness[0.0005]}
```

```
In[12]:=
```

```
pointsPlot = ListPlot[ data ] ;
```

```
In[13]:=
```

```
Show[ factorPlot, pointsPlot, AxesLabel->{"Volts", "Newtons"} ]
```

```
Out[13]=
```

```
-Graphics-
```

500 Lb Cell

WHC-SD-WM-SDD-043
Rev. 0

Load Cell Used: 500 lb

Notes:

Weight Used	Weight	Minimum	Maximum	Mean	Standard Deviation
0	0.0000	-0.0595	-0.0186	-0.0375	0.0061
ball only	70.5261	0.1840	0.2225	0.2052	0.0059
ball + 50 lb	310.7256	1.0123	1.0495	1.0337	0.0059
ball + 100 lb	533.1790	1.7804	1.8210	1.8016	0.0060
ball + 200 lb	978.0883	3.2925	3.3383	3.3168	0.0065
ball + 200 lb	978.0883	3.2922	3.3313	3.3142	0.0062
ball + 100 lb	533.1790	1.7719	1.8091	1.7923	0.0058
ball + 50 lb	310.7256	1.0065	1.0446	1.0272	0.0057
ball only	70.5261	0.1834	0.2219	0.2044	0.0061
0	0.0000	-0.0537	-0.0156	-0.0375	0.0060
0	0.0000	-0.0592	-0.0211	-0.0373	0.0058
ball only	70.5261	0.1834	0.2216	0.2044	0.0059
ball + 50 lb	310.7256	1.0117	1.0495	1.0324	0.0059
ball + 100 lb	533.1790	1.7767	1.8137	1.7966	0.0059
ball + 200 lb	978.0883	3.2986	3.3420	3.3207	0.0063
ball + 200 lb	978.0883	3.2919	3.3383	3.3156	0.0064
ball + 100 lb	533.1790	1.7807	1.8192	1.8009	0.0061
ball + 50 lb	310.7256	1.0126	1.0495	1.0332	0.0057
ball only	70.5261	0.1828	0.2219	0.2036	0.0060
0	0.0000	-0.0577	-0.0211	-0.0372	0.0060

In[14]:=

```
data = ReadList["500 Lb Data", Number, RecordLists -> True ]
```

Out[14]=

```
{{-0.0375, 0.}, {0.2052, 70.5261}, {1.0337, 310.726}, {1.8016, 533.179},  
 {3.3168, 978.088}, {3.3142, 978.088}, {1.7923, 533.179},  
 {1.0272, 310.726}, {0.2044, 70.5261}, {-0.0375, 0.}, {-0.0373, 0.},  
 {0.2044, 70.5261}, {1.0324, 310.726}, {1.7966, 533.179},  
 {3.3207, 978.088}, {3.3156, 978.088}, {1.8009, 533.179},  
 {1.0332, 310.726}, {0.2036, 70.5261}, {-0.0372, 0.}}
```

In[15]:=

```
factors = Fit[ data, {1, x}, x ]
```

Out[15]=

```
10.4567 + 291.484 x
```

In[16]:=

```
factorPlot = Plot[ factors, {x, 0, 5}, PlotStyle -> {Thickness[0.0005]}]
```

```
In[17]:=
```

```
pointsPlot = ListPlot[ data ] ;
```

```
In[18]:=
```

```
Show[ factorPlot, pointsPlot, AxesLabel->{"Volts", "Newtons"} ]
```

```
Out[18]=
```

```
-Graphics-
```

Roy Bender

WESTINGHOUSE STANDARDS LABORATORY PHYSICAL AND ELECTRICAL REPORT

CUSTODIAN/ADDRESS HOPKINS BL L6-38 TRUMENT		STANDARDS CODE NUMBER 679-29-05-004		NEW ☒ REFERENCE NUMBER 378872																																									
LOAD CELL INTERFACE SPI-15-141 15 LBS		SERIAL NUMBER C39478	PROPERTY NUMBER N/A	RECALL STATUS 1 ACTIVE 2 NONRECALL 3 SUSPENDED 4 DELETED	ORGANIZATION CODE W22330 WORK ORDER JKB04																																								
SENDER BLAINE 6-5013	ROOM N/A	BUILDING 306E	SERVICE DEPARTMENT 8	RECALL CYCLE 360	TOLERANCE HISTORY 1 IN 2 OUT 3 NA 4 FAILED																																								
INSTRUMENT SPECIFICATIONS		COMMENTS $\pm 1.03\% FS$ $\pm 1.03\% OFFS$		DATE RECEIVED 940208	SHIPPING DAY WE																																								
STANDARD(S) USED IN CALIBRATION TRACEABLE TO NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY OR NATIONALLY RECOGNIZED STANDARDS 4:1 RATIO ☒ Y ☐ N ☐				TRAINING HOURS																																									
JF883 EXPIRATION DATE 2-27-94 WEIGHT 0.062 EXPIRATION DATE 2-24-95				CALIBRATION HOURS 3.0																																									
0.02-56-01-018 1-28-95 PWR SUP				REPAIR HOURS																																									
0.02-45-08-039 8-30-94 JI-8842				OTHER HOURS 2.0																																									
REMARKS EXCITATION 10.000 VDC				MATERIALS																																									
PROCEDURE NUMBER 146... Interface-Load-Cell Rev.0				TOTAL CHARGE = (5.120 x SUM OF HOURS) + MATERIAL																																									
				DATE CALIBRATED 04-11-94 DATE DUE 04-11-95																																									
				AMBIENT TEMPERATURE = 23°C																																									
<table border="1"> <thead> <tr> <th>Test Load</th> <th>Compression</th> <th>FINAL</th> <th>TOL</th> </tr> </thead> <tbody> <tr> <td>Applied (lbs)</td> <td>kN/mm²</td> <td></td> <td></td> </tr> <tr> <td>0</td> <td>0.000</td> <td>SAME</td> <td>SEE ABOVE</td> </tr> <tr> <td>3.0</td> <td>6.329</td> <td></td> <td></td> </tr> <tr> <td>6.0</td> <td>12.646</td> <td></td> <td></td> </tr> <tr> <td>9.0</td> <td>18.970</td> <td></td> <td></td> </tr> <tr> <td>12.0</td> <td>25.294</td> <td></td> <td></td> </tr> <tr> <td>15.0</td> <td>31.613</td> <td></td> <td></td> </tr> <tr> <td>6.0</td> <td>12.646</td> <td></td> <td></td> </tr> <tr> <td>0.0</td> <td>0.000</td> <td></td> <td></td> </tr> </tbody> </table>						Test Load	Compression	FINAL	TOL	Applied (lbs)	kN/mm ²			0	0.000	SAME	SEE ABOVE	3.0	6.329			6.0	12.646			9.0	18.970			12.0	25.294			15.0	31.613			6.0	12.646			0.0	0.000		
Test Load	Compression	FINAL	TOL																																										
Applied (lbs)	kN/mm ²																																												
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MOVED BY 4-13-94 CALIBRATED BY [Signature] Sanford Operations and Engineering Contractor for the United States Department of Energy Westinghouse Sanford Company Subsidiary of Westinghouse Electric Corporation Box 1970, Richland, WA 99352																																													

WESTINGHOUSE STANDARDS LABORATORY PHYSICAL AND ELECTRICAL REPORT

Rev. 0

CUSTODIAN/ADDRESS TRAN TT L7-04		STANDARDS CODE NUMBER 602-29-05-001		NEW MODIFY		REFERENCE NUMBER 383549	
INSTRUMENT LOAD CELL INTERFACE SPI-50-141 50 LBS		SERIAL NUMBER C41941		PROPERTY NUMBER N/A		ORGANIZATION CODE W23850	
SENDER TT TRAN 2-3981		ROOM N/A		BUILDING 306E		WORK ORDER N2BG1	
INSTRUMENT SPECIFICATIONS $\pm 0.03\%$ F.S.		COMMENTS		RECALL STATUS 1 ACTIVE 2 NONRECALL 3 SUSPENDED 4 DELETED 5 PM 6 NONDATA M&T		TOLERANCE HISTORY 1 IN 2 OUT 3 NA 4 FAILED	
STANDARD(S) USED IN CALIBRATION TRACEABLE TO NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY OR NATIONALLY RECOGNIZED STANDARDS		4:1 RATIO Y ☒ N ☐		RECALL CYCLE 360		DATE RECEIVED 940815	
EXPIRATION DATE 002-45-08-039 8-9-95-8842		EXPIRATION DATE 002-45-04-003 10-27-94-887		DATE RECEIVED 940815		TOLERANCE AS RECEIVED 1 IN 2 OUT 3 NA 4 FAILED	
REMARKS MONITOR 10VDC PWR SUPPLY FOR EXCITATION VOLTAGE		REPAIR HOURS		OTHER HOURS		MATERIALS	
* OFF SET VOLTAGE ZEROED OUT. 3.10 mV		TOTAL CHARGE = (\$120 x SUM OF HOURS) + MATERIAL		DATE CALIBRATED		DATE DUE	
PROCEDURE NUMBER WHC-8-INTERFACE-LOAD-CELL REV.0		AMBIENT TEMPERATURE -23°C		08-16-94		08-16-95	

TEST LOAD	COMPRESSION	TOL
IN LBS	AS FOUND	FINAL
0.0	RUN 1 * 0.000	RUN 2 0.000 SAME
5	3.242 mV	3.244 mV
10	6.479 "	6.482 "
20	12.966 "	12.965 "
25	16.208 "	16.208 "
30	19.448 "	19.448 "
40	25.928 "	29.930 "
45	29.172 "	29.171 "
50	32.409 "	32.411 "

PIN	COLOR
A +10.00 VDC	RED
B +SIG	GREEN
C -SIG	WHITE
D -10.00 VDC	BLACK

APPROVED BY D. J. Nelson	8-16-94	CALIBRATED BY B	WHC STOLAS 26	Hanford Operations and Engineering Center for the United States Department of Energy	Westinghouse Standard Company Westinghouse Electric Corporation 1500, Richmond, VA 23133	PAGE 1 OF 1
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RUSH

APPROVED BY <i>J. N. [Signature]</i> 4-13-94	CALIBRATED BY <i>[Signature]</i> [Stamp]	Hanford Operations and Engineering Contractor for the United States Department of Energy	Westinghouse Hanford Company Subsidiary of Westinghouse Electric Corporation Box 1970, Richland, WA 99352	PAGE 1 OF 1
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WESTINGHOUSE STANDARDS LABORATORY PHYSICAL AND ELECTRICAL REPORT

CUSTODIAN/ADDRESS HOPKINS BL T-6-38 INSTRUMENT		STANDARDS CODE NUMBER 679-29-05-001		NEW ☒ MODIFY ☒		REFERENCE NUMBER 378870	
LOAD CELL INTERFACE SSB-250 250 LBS		SERIAL NUMBER C30818	PROPERTY NUMBER N/A	RECALL STATUS 1 ACTIVE 2 NONRECALL 3 SUSPENDED 4 DELETED		ORGANIZATION CODE W22330	WORK ORDER JKB04
SENDER BLAINE 6-5013		ROOM N/A	BUILDING 306E	SERVICE DEPARTMENT 8	DATE RECEIVED 360	TOLERANCE HISTORY 1 IN 2 OUT 3 NA 4 FAILED	
INSTRUMENT SPECIFICATIONS ± .12% FS		COMMENTS I.12% FS			SHIPPING DAY WE		
STANDARD(S) USED IN CALIBRATION TRACEABLE TO NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY OR NATIONALLY RECOGNIZED STANDARDS 4:1 RATIO Y ☐ N ☒				TRAINING HOURS			
EXPIRATION DATE 015-45-04-001 7-27-94 001-29-01-001 8-11-95				CALIBRATION HOURS 3.0			
REMARKS EXCITATION, 10VDC				REPAIR HOURS			
PROCEDURE NUMBER WHC-8-Interface-Load-Cell Rev.0				OTHER HOURS 2.0			
				MATERIALS			
				TOTAL CHARGE = (\$120 x SUM OF HOURS) + MATERIAL			
				DATE CALIBRATED 04-12-94 DATE DUE 04-12-95			
				AMBIENT TEMPERATURE = 23°C			

Test Load Applied (lbs)	Compression mV/°F	FINAL	TOL
0.0	0.000	SAME	SEE ABOVE
50.0	6.450		
100.0	12.820		
150.0	19.260		
200.0	25.535		
250.0	31.955		
100.0	12.810		
0.0	0.000		
A +10V Red			
B +8V Green			
C -8V White			
D 10V RETURN Black			

APPROVED BY 4-13-94 W.D. Nelson	CALIBRATED BY E	Hanford Operations and Engineering Contractors Residing at Westinghouse for the United States Electric Corporation Department of Energy Box 1970, Richland, WA 99352	PAGE 1 OF 1
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WESTINGHOUSE STANDARDS LABORATORY PHYSICAL AND ELECTRICAL REPORT Rev. 0

CUSTODIAN/ADDRESS HOPKINS BL L6-38		STANDARDS CODE NUMBER 679-29-05-002		NEW ☒ MODIFY ☒ REFERENCE NUMBER 378869	
INSTRUMENT LOAD CELL INTERFACE SSB-500 500 LBS		SERIAL NUMBER C23114	PROPERTY NUMBER N/A	RECALL STATUS 1 ACTIVE 2 NONRECALL 3 SUSPENDED 4 DELETED	ORGANIZATION CODE W22330 WORK ORDER JKB04
SENDER BLAINE 6-5013		ROOM N/A	BUILDING 306E	SERVICE DEPARTMENT 8	RECALL CYCLE 360 DATE RECEIVED 940208
INSTRUMENT SPECIFICATIONS I.08% FS		COMMENTS I.08% FS			TOLERANCE HISTORY 1 IN 2 OUT 3 NA 4 FAILED
STANDARD(S) USED IN CALIBRATION TRACEABLE TO NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY OR NATIONALLY RECOGNIZED STANDARDS		TRAINING HOURS			
0.15 4.5 04-001 7-22-94 001-29-01-001 8-16-95		CALIBRATION HOURS 3 0			
002-56-01-018 1-28-95		REPAIR HOURS			
002-45-08-039 8-30-94		OTHER HOURS 2 0			
REMARKS EXCITATION, 10VDC		MATERIALS			
PROCEDURE NUMBER WHL-4-Interf-Load Cell 500.0		TOTAL CHARGE = (5120 x SUM OF HOURS) + MATERIAL			
		DATE CALIBRATED 04-12-94 DATE DUE 04-12-95			
		AMBIENT TEMPERATURE = 23°C			

Test Load	Compression	AS FOUND	FINAL	Tolerance
0	0.000	0.000	SAME	I.08%
100	6.609			
200	13.183			
300	19.784			
400	26.334			
500	32.924			
600	39.514			
700	46.104			
800	52.694			
900	59.284			
0	0.000			

A +10V	Red
B +5V	Green
C -5V	White
D 10V RETURN	Black

APPROVED BY 4-13-94 D. J. Nelson	CALIBRATED BY R	Sanford Operations and Engineering Contractor for the United States Department of Energy	Westinghouse Sanford Company Subsidiary of Westinghouse Electric Corporation Box 1970, Richland, WA 99352	PAGE 4 of 1
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WESTINGHOUSE STANDARDS LABORATORY PHYSICAL AND ELECTRICAL REPORT

CUSTODIAN/ADDRESS CHUBB KL L6-86		STANDARDS CODE NUMBER 002-86-01-062			NEW MODIFY		REFERENCE NUMBER 377719		
VOLUME		SERIAL NUMBER			PROPERTY NUMBER		ORGANIZATION CODE W22800		
WEIGHT AVOIRDUPOIS 10 LB. WEIGHT SET		N/A		N/A		RECALL STATUS 1 ACTIVE 2 NONRECALL 3 SUSPENDED 4 DELETED		WORK ORDER MDOON	
REMARKS		ROOM		BUILDING		SERVICE DEPARTMENT		RECALL CYCLE 360	
940224		N/A		3717B		7		TOLERANCE HISTORY IIII	
		COMMENTS				DATE RECEIVED 940201		TOLERANCE AS RECEIVED	
						SHIPPING DAY		1 IN 2 OUT 3 NA 4 FAILED	
						NA			

INSTRUMENT SPECIFICATIONS

*CAL STATEMENT REQUIRED - APPARENT MASS VS 8.045
EST. UNCERTAINTY OF REPORTED VALUE = 25PPM
 STANDARD(S) USED IN CALIBRATION TRACEABLE TO NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
 OR NATIONALLY RECOGNIZED STANDARDS: _____
 A:1 RATIO Y ☐ ☒

EXPIRATION DATE	EXPIRATION DATE
001-86-02-005 7/27/95	Post account 10/1/95
002-06-03-002 7/25/94	
002-06-03-004 7/25/94	

דאס איז דאס צווייטע געזעץ פון דער שולע.

PROCEDURE NUMBER

*SUBSTITUTION AS PER NBS #77

WEIGHT		AS FOUND
#51	1 LBS	453.5435 grams
52	2	907.1686
53	2	907.1830
54	5	2267.966
55	5	2267.950
56	5	2267.932
57	5	2267.981
58	5	2267.895
59	5	2267.964
60	5	2267.942
61	10	4535.928
62	10	4535.892
67	10 ✓	4535.694

APPROVED BY

CALIBRATED BY

WAC
STDLA
53

Sanford Operations and
Engineering Contractor
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Department of Energy

Westinghouse Hanford Company Subsidiary of Westinghouse Electric Corporation Box 1970, Richland, WA 99352	PAGE
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WESTINGHOUSE STANDARDS LABORATORY PHYSICAL AND ELECTRICAL REPORT

CUSTOMER/ADDRESS CHUBB KL 8-10 INSTRUMENT		STANDARDS CODE NUMBER 002-86-01-050		NEW MODIFY	REFERENCE NUMBER 360934
WEIGHT AVOIRDUPOIS 50 LB. SET		SERIAL NUMBER MARKED 50	PROPERTY NUMBER	RECALL STATUS 1 ACTIVE 2 NONRECALL 3 SUSPENDED 4 DELETED	ORGANIZATION CODE W55540 WORK ORDER MDOON
SENDER 920327	COMMENTS	ROOM BUILDING 3717B	SERVICE DEPARTMENT 7	RECALL CYCLE 720	TOLERANCE HISTORY IIII
INSTRUMENT SPECIFICATIONS AMSI E-1617 Group 5 ($\pm 1.1g$)		DATE RECEIVED 920301		TOLERANCE AS RECEIVED 1 IN 2 OUT 3 NA 4 FAILED	
STANDARD(S) USED IN CALIBRATION TRACEABLE TO NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY OR NATIONALLY RECOGNIZED STANDARDS		EXPIRATION DATE		TRAINING HOURS	
002-06-01-013 7/14/92 002-86-02-001 5/19/92		002-86-01-075 5/26/92		CALIBRATION HOURS 8.0	
001-86-02-005 12/23/92				REPAIR HOURS	
REMARKS				OTHER HOURS	
				MATERIALS	
				TOTAL CHARGE = (\$120 x SUM OF HOURS) + MATERIAL	
				DATE CALIBRATED DATE DUE	
PROCEDURE NUMBER SUBSTITUTION AS PER NBS #77				5-27-92 5-27-94	
				AMBIENT TEMPERATURE =	
WEIGHT	AS FOUND				
50 LBS 1	grams				
2					
3					
4					
5	22, 679.66				
6					
7					
8					
9					
10					
11	22, 680.11				
12	22, 679.43				
13	22, 679.14				
14	22, 679.31				
15	22, 680.22				
16	22, 679.41				
17	22, 679.17				
18	22, 680.29				
19	22, 679.91				
20					
21	22, 679.44				
22	22, 679.58				
APPROVED BY W. H. H. 06 02 92	CALIBRATED BY BA	MAC 53	Hanford Operations and Engineering Contractor for the United States Department of Energy	Westinghouse Hanford Company Subsidiary of Westinghouse Electric Corporation Box 1970, Richland, WA 99352	PAGE 1 of 2

Hanford Operations and
Engineering Contractor
for the US
Department of Energy

Westinghouse Hanford Co.
Subsidiary of Westinghouse
Electric Corporation
BOX 1970 Richland, WA 99352

PHYSICAL AND ELECTRICAL
STANDARDS LAB REPORT

CODE NO. 002-86-01-050
DATE 5-27-92

WEIGHT	AS Found
50 LBS 23	22,679.51 grams
24	22,679.33
25	NA
26	22,679.66
27	22,679.41
28	NA
29	22,678.93
30	NA
31	NA
32	22,679.41
33	22,679.11
34	22,679.67
35	NA
36	22,679.44
37	22,679.71
38	22,679.24
39	NA
40	22,679.40
41	22,679.66
42	22,679.91
43	22,679.77
44	22,679.29
45	22,679.64
46	NA
47	22,679.22
48	22,679.43
49	22,679.67
50	NA

Page A-45

APPROVED BY

W. H. H. 060292

CALIBRATED BY

BK

WHC
STD LAB
53

PROCEDURE NO.

PAGE

2 of 2

WESTINGHOUSE STANDARDS LABORATORY PHYSICAL AND ELECTRICAL REPORT

CUSTOMER/ADDRESS CHUBB KL		STANDARDS CODE NUMBER 002-86-01-074		NEW ☐	REFERENCE NUMBER 359742
78-10 STRUMENT				MODIFY ☐	WORK ORDER MDOON
WEIGHT AVOIR HOWE & S/N D42-D66		SERIAL NUMBER B53-B72	PROPERTY NUMBER	ORGANIZATION CODE W55540	TOLERANCE HISTORY
SENDER 920510		ROOM 3717B	SERVICE DEPARTMENT 7	RECALL CYCLE 720	DATE RECEIVED 920501
INSTRUMENT SPECIFICATIONS A WSI E-617 Group 5 (+1.1g)		COMMENTS 50LB / 45EA		RECALL STATUS 1 ACTIVE 2 NONRECALL 3 SUSPENDED 4 DELETED	TOLERANCE AS RECEIVED 1 IN 2 OUT 3 NA 4 FAILED
STANDARD(S) USED IN CALIBRATION TRACEABLE TO NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY OR NATIONALLY RECOGNIZED STANDARDS				TRAINING HOURS	
EXPIRATION DATE				CALIBRATION HOURS 12.0	
REPAIR HOURS				OTHER HOURS	
MATERIALS				TOTAL CHARGE = (\$120 x SUM OF HOURS) + MATERIAL	
REMARKS				DATE CALIBRATED DATE DUE	
PROCEDURE NUMBER Substitution as per NBS #77				5-26-92 5-26-94	
WEIGHT		AS Found			
B. 53 50 LBS		22, 678.71 grams			
54		22, 678.86			
55		NA			
56		NA			
57		22, 679.28			
58		22, 678.90			
59		22, 679.66			
60		NA			
61		22, 679.09			
62		22, 678.94			
63		22, 679.21			
64		22, 678.41			
65		NA			
66		NA			
67		22, 678.74			
68		22, 679.30			
69		22, 678.91			
70		NA 22, 678.04			
71					
B 72		22, 678.96			
Countdown					

APPROVED BY

H. H. H. 060292

CALIBRATED BY

B

Hanford Operations and
Engineering Contractor
for the United States
Department of Energy

Westinghouse Hanford Company
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Electric Corporation
Box 1970, Richland, WA 99352

PAGE

1 OF 2

**PHYSICAL AND ELECTRICAL
STANDARDS LAB REPORT**

CONFIDENTIAL

BOOK NO. 002-86-01-074
DATE

DATE _____

5-26-92

WHC-SD-WH-SDD-043
Rev. 0

WEIGHT	AS Found
D 402 50 LBS	NA
43	22, 678.71 grams
44	22, 679.04
45	22, 679.38
46	NA
47	NA
48	22, 679.39
49	22, 679.34
50	NA
51	22, 679.61
52	22, 679.07
53	NA
54	22, 679.79
55	NA
56	NA
57	22, 678.88
58	NA
59	22, 679.77
60	22, 679.20
61	22, 679.44
62	22, 679.49
63	NA
64	NA
65	NA
66	NA
$50 \text{ LBS} = 22, 679.618 \text{ grams}$	

APPROVED BY
 H. J. 06 02 92

CALIBRATED BY
 [Signature]

PROCEDURE NO.
 53

PAGE
 2 OF 2

WESTINGHOUSE STANDARDS LABORATORY PHYSICAL AND ELECTRICAL REPORT

CUSTODIAN/ADDRESS TRAN TT L7-04		STANDARDS CODE NUMBER 602-67-11-001		NEW ☒	REFERENCE NUMBER 379644
INSTRUMENT DATA ACQUSN SYSTEM AST PREMMIA 4-66D		SERIAL NUMBER 501129-07	PROPERTY NUMBER WC43907	MODIFY ☒	ORGANIZATION CODE W23850
SENDER TT TRAN 6-8475		ROOM N/A	BUILDING 306E	RECALL STATUS 1 ACTIVE 2 NONRECALL 3 SUSPENDED 4 DELETED	RECALL CYCLE 360
INSTRUMENT SPECIFICATIONS See Data Sheet		COMMENTS W/NEC MULTISYNC 3D SN# 94M16168M		DATE RECEIVED 940328	TOLERANCE HISTORY 1 IN 2 OUT 3 NA 4 FAILED
STANDARD(S) USED IN CALIBRATION TRACEABLE TO NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY OR NATIONALLY RECOGNIZED STANDARDS		4:1 RATIO ☒ Y ☐ N ☐		TRAINING HOURS	
EXPIRATION DATE 002-14-01-032 6-22-94		EXPIRATION DATE		CALIBRATION HOURS 6.0	
002-45-08-023 4-1-94				REPAIR HOURS	
				OTHER HOURS 3.0	
REMARKS				MATERIALS	
PROCEDURE NUMBER WHC-4-AST-PREMMIA-4-66D REV. 0				TOTAL CHARGE = (\$120 x SUM OF HOURS) + MATERIAL	
VM				DATE CALIBRATED 4-1-94 DATE DUE 4-1-95	
				AMBIENT TEMPERATURE - 23°C	

COPY

APPROVED BY DPR 04-1-94	CALIBRATED BY WHC STDLAB 39	Hanford Operations and Engineering Contractor for the United States Department of Energy	Westinghouse Hanford Company Subsidiary of Westinghouse Electric Corporation Box 16299 Richland, WA 99352	PAGE 1 OF 4
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RUSH

PROCEDURE NAME - 17	STANDARDS CODE NUMBER	REFERENCE NUMBER
1115 4-AST-PREMMIA-466D	602-67-11-001	379644

VM

REV.0

DATA SHEET

WHC-SD-WM-SDD-04~

Rev. 0

		Standard INDICATION			MANUFACTURER SPECIFICATION
			AS FOUND	FINAL	
5B41		10V	4.9935		±.01462V
#1		8V	3.9954		
		6V	2.9959		
		4V	1.9979		
		2V	.9954		
		0V	-.0021		
		-2V	-1.0037		
		-4V	-2.0004		
		-6V	-3.0014		
		+8V	-4.00002		
		-10V	-4.99908		
5B41		-10V	-5.00418		
#2		-8V	-4.00482		
		-6V	-3.00415		
		-4V	-2.00408		
		-2V	-1.00463		
		0V	-.00335		
		2V	.99700		
		4V	1.99523		
		6V	2.99469		
		8V	3.99444		
		10V	4.99389		✓

APPROVED BY JEB 04/194	CALIBRATED BY JEB	WHC STD LAB 39	Page 2 of 4
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PROCEDURE NAME - 17	STANDARDS CODE NUMBER	REFERENCE NUMBER
WHC-4-AST-PREMMIA-4-66D	602-67-11-001	379644

VM

REV. 0

DATA SHEET

WHC-SD-WM-SDD-043
Rev. 0

FUNCTION	Channel #0 INDICATION	Standard Indication		MANUFACTURER SPECIFICATION
		AS FOUND	FINAL	
Analog OUT	- 5.00000	-4.999986	Same	Not Known
	- 4.00000	-4.000119		
	- 3.00000	-2.999986		
	- 2.00000	-1.999913		
	- 1.00000	.999859		
	0.	.000102		
	1.00000	.999707		
	2.00000	1.999917		
	3.00000	2.999960		
	4.00000	4.000049		
	5.00000	5.000238		
	Channel #1			
	5.00000	5.000447		
	4.00000	4.000474		
	3.00000	3.000352		
	2.00000	2.000304		
	1.00000	1.000212		
	0.00000	.000328		
	- 1.00000	.999483		
	- 2.00000	-1.999797		
	- 3.00000	-2.999905		
	- 4.00000	-4.000057		
	- 5.00000	-5.000336		

APPROVED BY JL Ball 4-1-94	CALIBRATED BY WHC STDLAS 39	Page 3 of 4
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LOW SPEED MOTOR CALIBRATION

Procedure for Direct Calibration of Load Cells

1. For each load cell use a minimum of 4 weights (5 would be better) which span at least 80 % of the load cell range. The first weight should be the zero weight (load cell and pulley, just as before). Uniform spacing between the weights is not necessary, but there should be significant differences between the weights. For example, for the 15 lb load cell a reasonable set of weights might be 0, 2, 5, 10, and 12 lbs. If the weights are suspended from the cable, use as short a cable as is reasonably possible and maintain approximately the same cable length for all experiments in which the cable is used.
 2. Perform measurements with increasing weights and then decreasing weights and then repeat again, so that there are 4 sets of measurements with each weight. For example, for the 15 lb load cell suggested above the sequence would go 0, 2, 5, 10, 12, 12, 10, 5, 2, 0, 0, 2, 5, 10, 12, 12, 10, 5, 2, 0.
 3. 1000 points per measurement are sufficient. For each measurement calculate the mean and standard deviation. SAVE THE RAW DATA! It's a pretty good bet that some statistical person will want to look at them from some other angle and we should not have to repeat these experiments.
 4. For each data point, plot the average of the 4 average values. Do a least squares linear fit to the data to determine the slope. Perform another least squares fit assuming a quadratic function and see if things change. If the coefficient to the quadratic term is very small (very likely) then a linear fit to the data is sufficient.
 5. Provide us with the raw data and the averages and standard deviations obtained in Step 3.
- [76] From: Chester L Shepard at ~PNL33 8/4/94 1:01PM (3631 bytes: 17 ln, 1 fl)

To: Michael (Mike) Gimera at ~WHC177
cc: James B Colson at ~PNL14, Troy I Stokes at ~WHC207
Subject: Load cell calibration

----- Message Contents

Text item 1:

Mike -

After reading your writeup and after some discussions among ourselves, we think that the experiments you performed should be repeated. Sorry, but that's the way it is. Attached is a wp file outlining what we feel is an acceptable way to perform the tests. We would also like to obtain the data and perform some statistical analysis ourselves.

I hope that this does not cause a major impact on the schedule. If the tests are performed as outlined, we'll

WHC-SD-WM-SDD-043
Rev. 0

have a very defensible position on the calibration of the
load cells.

Chet

APPENDIX B

DATA QUALITY OBJECTIVES

Battelle

Pacific Northwest Laboratories
Battelle Boulevard
P.O. Box 999
Richland, Washington 99352
Telephone (509) 372-4678

November 15, 1993

MIT93:1548

bcc: CL Shephard
~~CL Shephard~~
File/LB

Jack Lentsch
Senior Project Manager
Mitigation Project
Westinghouse Hanford Company
Mail Stop R2-78
Richland, WA 99352

Dear Mr. Lentsch:

Please find attached a letter report by C. L. Shephard titled *Report on Data Requirements and Hardware Selection for In-situ Ball Viscometer*. This completes the deliverable for user data requirements and hardware.

If you have any questions, please call me on 372-4678.

Very truly yours,

A handwritten signature in black ink, appearing to read "C. W. Stewart", with a long horizontal line extending from the end of the signature.

C. W. Stewart, Manager
Flammable Gas Project

CWS/lcs

Attachment

WHC-SD-WM-SDD-043
Rev. 0

REPORT on DATA REQUIREMENTS and HARDWARE SELECTION
for IN-SITU BALL VISCOMETER

CL Shepard
Pacific Northwest Laboratories

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Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

**Report on Data Requirements and Hardware Selection
for In-situ Ball Viscometer**

CL Shepard, PNL

Nov. 8, 1993

1. Introduction

The in-situ ball rheometer is designed to provide data concerning the rheological properties of the waste contained in tank 101-SY. It is imperative that the data collected and the results obtained are useful to the community presently concerned with the mitigation of the waste contained within this tank. To ensure that this objective is met, discussions were held with representatives of different groups in order to determine their data needs. This report is a synopsis of these discussions. Four separate groups were identified as potential users of the data. Persons contacted included Don Trent (PNL), who is involved with Tempest modelling of the tank, Randy Marlow and John Strehlow (WHC), involved with structural analysis of the tank, Kemal Pasamehmetoglu and Cetin Unal (LANL) who are concerned with the safety analysis of activities performed within the tank, and Judith Bamberger, Paul Scott, and Gita Golcar (PNL) who are involved with the eventual retrieval of waste from the tank. Very specific questions were asked of these groups, including:

1. From where in the tank are data needed?
2. When should data be collected?
3. In what manner are the data useful?
4. What is the required accuracy of the data?

Responses from each group are given below.

2. Data requirements for groups involved with Tank 101-SY

Modelers of the behavior of the waste in tank 101-SY have the most global data requirements. Rheological data (density, yield stress and apparent viscosity at low shear rates - less than 10/sec) are needed in order to more accurately predict the behavior of the waste in this and other tanks through use of the TEMPEST code. The occurrence of tank rollover events is controlled in part by these parameters. Gas retention in the waste depends on the yield stress and the low shear rate viscosity. The tank region of interest is the nonconvective layer. They feel that the convective layer is presently well characterized and additional measurements will only tell them what is already known. Since rollovers may involve all or part of the nonconvective layer and modeling of the tank requires information on the entire tank, modelers would like to know the rheological properties everywhere in the nonconvective layer. In addition they would like to know it at all times between gas release events. In addressing their needs, it is apparent that sampling should be performed over a suitable volume of the tank so that some realistic average value for the tank rheology can be obtained or some distribution of the rheological properties can be identified. In addition sampling frequency should be high enough so that changes in rheological properties over time are observable. In the past, tank rollovers occurred at about six month intervals, so sampling on at least a one month interval probably would have been appropriate if rollovers were the sole concern. Essentially data are required on the time scale for changes within the tank. With the mixer pump now in place and operational, this time scale may now be less than one month.

However, a firm number will have to wait until more experience is obtained with the pump. Accuracy requirements are not very stringent, but firm and defendable numbers for accuracy requirements have not been forthcoming from this group. When pressed, it appears that 20 % to 40 % errors in the yield stress and zero shear rate viscosity values are certainly acceptable. Knowledge of the accuracy is important, so that allowances can be made in predicted results. Inaccuracies in rheological parameters affect results more or less linearly, so that a small error in yield strength will not result in a large error in predicted gas retention, for instance. The prospect of just the availability of any reasonably reliable data is cause for excitement within this community, and such data would represent a radical improvement over the present situation. Don Trent is not particularly concerned with accuracy at present, and has pointed out that many questions concerning the ultimate accuracy of derived rheological properties cannot be addressed at this time. Only after some model development has been accomplished and simulant testing has been performed will we have a reasonable idea of how well the ball rheometer may perform, and the final answer may have to wait until actual tank data are obtained and analyzed. In the end, we will be limited in how well we can model the waste fluid, regardless of how well we measure velocity and drag force. This limit will depend somewhat on the rheological character of the waste itself. Since we cannot in advance determine the accuracy at which we derive rheological properties and we can answer such questions only after the ball rheometer has been built and deployed (at which time it's too late to address desired accuracy), it becomes rather pointless to worry excessively about accuracy. The accuracy will be whatever it is and we will simply live with it. All we can do is perform the force and velocity measurements as precisely as possible, recognize the limited range of usefulness of the instrument and use it within that range. He remains confident that the derived rheological parameters will be of sufficient accuracy to be of great use to modelers and other data users. Considering the estimated error of around 1000 % for present rheological values, his confidence is probably justified.

Safety assessment of tank activities also requires knowledge of rheological properties (density, yield strength, and apparent viscosity at strain rates less than about 10/s). Safety assessment relies in part on the TEMPEST code for predictions, and so the rheological parameter range of interest is about the same as that of the modelers, as is the measurement frequency and locations of measurements. Rollover occurrences are the driver for the need for this data. Safety considerations were a factor in the responses from most groups questioned. The LANL safety assessment considers several possibilities. Drop accidents were one such possibility, where knowledge of the yield strength and viscosity at low shear rates would allow better estimates of the effect of instrumentation falling through the nonconvective region. Better estimates of these effects would allow less conservative imposed operational controls during installation/removal of tank equipment. LANL has expressed no interest in measurements in the convective layer, since it is already understood sufficiently well. Another consideration is the effect of the mixer pump on various instrumentation presently residing or planned to be resident in the tank, such as the sonic probe or the VDTT's (Velocity Density Temperature Trees) or the MIT's (Multi-functional Instrument Trees). As the mixer pump is operated fluid flow past these instruments and the mixer pump itself can result in force loads and bending moments and vibrations which may result in critical damage to the instrumentation. In lieu of firm in situ data, levels of conservativeness have been employed which make the design and operation of any in tank equipment difficult to accomplish. The density and the rheological properties (particularly the viscosity) of the fluid are necessary ingredients in the estimation of fluid flow effects past instrumentation. Momentum transfer to the instrumentation will depend on the density, viscosity, and the fluid strain rate, which is related to the fluid velocity. It may be that we will require the viscosity at strain rates greater than what is ultimately obtainable from our modeling and our measurements. However, since viscosity is believed to decrease with increasing strain rate, we will probably be able to determine an upper bound for the viscosity at higher strain rates which is much more reliable than presently used values.

Safety analysis personnel are also very interested in the mixer pump and its effects on the tank waste. Future pump testing, test plan development, and safety analysis coverage of these tanks require more knowledge of the effectiveness of this mitigation technique. Data are needed in regions of the tank where the mixer pump is pointed during its operation, and in regions where little mixing is expected. The safety group would like to know rheological properties such as the yield strength and the zero shear rate viscosity in the affected region immediately before the pump is operated and as soon as practical after its operation is completed. Some means of quantifying the extent of mixing is needed. The disturbed volume may be quite different in rheological terms from the same volume before pump operation. If significant mixing occurs the waste may behave in a Newtonian fashion and have no yield strength. Then fluid density, solids fraction, and viscosity may be desired. It may not be possible to determine the viscosity to good precision if it is too low, but an upper bound can be established. Presently safety analysis is interested in determining the extent of mixing, and as such the boundaries dividing mixed and unmixed material before and after pump operation are important. Detailed rheological information is not necessary to map the boundaries, and accuracy requirements for this particular task are therefore extremely relaxed. We need only be able to tell the difference between fluid of very low viscosity and no yield strength and fluid with very high viscosity and substantial yield strength.

Accuracy is important to the safety group, but it is more important to know the uncertainties in the derived rheological properties, which include the yield strength and the viscosity at low strain rates. This uncertainty will be included in safety assessment calculations, and more accurate knowledge will result in less constrained operations. Initial estimates of the probable accuracy of this device are around 30 % to 50 % for both the viscosity and the yield strength and this figure seems acceptable for safety analysis. However, there is no strong driver to stipulate any firm number which must be met in order to be useful. Since they now use viscosities and yield strengths which are believed to be much too high and essentially have no accuracy there is little question that these measurements will dramatically improve the situation. The message from the safety analysis group is the better the accuracy the less constrained operations become, and virtually any realized accuracy in the measurements will be a welcome improvement.

The WHC structural group needs rheological data so that they can understand the effect that may result on instrumentation as the nonconvective layer, or portions of it, flows past such instrumentation during a rollover event. The density of the material also clearly matters. Their concerns are then largely based on safety and equipment well being. Better estimates of the viscosity, even at low shear rates, will allow more confidence in loading calculations. These estimates need not be precise, since they are operating in a region of high Reynolds number (about 25), and factors of, say two, errors will not change the loading estimate significantly. The mixer pump is their present focus of attention, but other instrumentation, such as the sonic probe and the instrument trees, are also considered or will be considered. They would like to determine the loads and torques applied to the mixer pump in the event that a large mass of the nonconvective layer flows past it during a release. They have no interest in the convective layer, since it is already well characterized.

Another problem which is of concern to this group is the analysis of potential seismic events and their possible effect on the tank and instrumentation suspended within it. The behavior of the nonconvective layer when subjected to seismic oscillations will depend on the yield strength of the material and the magnitude of the acceleration. If the nonconvective layer yields and then flows the consequences for in tank instrumentation are different (worse) than if this layer does not yield. Therefore estimates of the yield strength are important to this group, as well as the viscosity after yielding.

This group requires rheological data which is representative of the tank on average, and so measurements from somewhere near the middle of the tank would be appropriate. If the time variation of the rheological parameters is significant then data are required at a frequency consistent

with the time scale of changes. Accuracy requirements are not stringent, but as with the safety group, knowledge of uncertainties is important.

Sometime in the future the waste will be pumped from this tank to somewhere else. Optimization of the mixing and retrieval process also requires knowledge of the rheological properties of the waste. Data needs as presently envisioned are outlined in a WHC report (Retrieval Technologies Characterization Data Needs by P.K. Bhatia, WHC-SD-WM-RD-039, September, 1993). Their data needs are quite extensive, and only a small portion of them can be addressed with the ball rheometer. This report points out a need for yield stress, shear stress, and viscosity measurements over an unspecified range of shear rate. The data are required for equipment design and for transport predictions. Data are needed for both the nonconvective layer and the mixed slurry. Stated accuracy requirements are fairly stringent (density to within 5 % and stress measurements to as low as 10 %), and the ball rheometer may have difficulty in making sufficiently precise measurements. Their accuracy requirements are not entirely clear at present (for instance, no accuracy requirement for viscosity was mentioned), and annual updates of this report are planned which will allow better definition of their requirements in the future.

Before the waste is pumped it will be mobilized and mixed. Knowledge of the yield strength, viscosity and density distribution is important for both mixing and pumping to an external vessel, as the loads on the pumps and therefore the pump sizes and also the effectiveness of a mixing pump will depend on such information. No mention is made in the above report concerning a range of strain rate over which rheological data are needed. After mixing it is doubtful that we will be able to speak of a convective and a nonconvective layer. The waste should be somewhat homogenous. It will probably not possess a significant yield strength, but will have some viscosity. The ball rheometer method may not be applicable unless the viscosity is quite high, and it is not believed that this will be the case. Estimates for a fully mixed waste (based on experiments with a chemical simulant) indicate a viscosity of around 500 cP for low strain rates, well below the useful range for the ball viscometer if the fluid is Newtonian. The fluid density or more importantly the density of solids suspended in the fluid may be of primary interest to this group along with the solids settling rate, and these data can be obtained with reasonable precision with the ball rheometer. In addition the ball rheometer would be useful in determining the extent of mixing, simply by probing to observe if any very high viscosity material is still present during a test. Data would be required from somewhere near the middle of the tank. The required accuracy and the range of some parameters has not yet been fully determined. It may be that future versions of the Characterization Data Needs Report will provide more definitive information. This group should be revisited as the time for retrieval draws nearer.

3. Expected Instrument Performance

It is important for all to realize what the ball rheometer is capable of and understand its limits. Primarily the ball rheometer will be useful in wastes where the viscosity is very high, say greater than 10,000 cP. This is because we have a good theoretical understanding of flow around a sphere only at very low Reynolds numbers (less than 0.1) where the flow can be described as creeping flow, and this implies low ball velocities. The drag force on the ball scales as the viscosity in a Newtonian fluid and as a complicated function of yield stress and viscosity in a yield-pseudoplastic fluid. High viscosity or a significant yield strength are needed in order to obtain a measurable drag force. As such the ball rheometer is ideally suited for probing the nonconvective layer. In this region, modeling of the fluid character and the subsequent development of relationships among measured velocities and drag forces and the derived rheological parameters are the major challenges. The ball rheometer is a poor choice for performing accurate measurements in the convective layer. It may work in a mixed layer where the fluid is nearly Newtonian (with low viscosity) but contains suspended particles. In attempting to probe such a mixed region, very little drag force will be experienced by the ball, either dropping or falling, and accurate estimates of the viscosity will be difficult. Density of such a mixed fluid can be obtained from static measurements

with reasonable accuracy (initial estimates indicate less than 2 % error). It is likely that suspended solids fraction can be determined from such measurements. While the ball rheometer may possibly have difficulty giving precise information about the rheology of the mixed region, it can determine the depths to which effective mixing has occurred. The drag on the ball (if being raised) or the effective weight of the ball (if being lowered) will change dramatically at the boundary between the two regions.

For in situ measurement of rheological properties the ball rheometer is the method of choice. In a report which will soon be released (Comments on Rheology Measurements for the Waste Contained in Hanford Tank 101-SY by K.O. Pasamehmetoglu, C. Unal, and J.N. Edwards of LANL) difficulties with measurements performed using standard rheological techniques are discussed. Rheological data obtained with cone and plate viscometers provide data with a large uncertainty and a lack of repeatability, possibly due to the large crystals contained within the waste. The crystal sizes in many cases exceed the cone and plate clearance distance resulting in grinding of the crystals as the device is operated. Measurements using cylindrical spindles show better results in laboratory tests with a chemical simulant, however implementing such a device in the tank would represent major difficulties. In addition, even in laboratory testing there is an unresolved issue concerning particle migration during tests with a rotating spindle. This report supports both in situ and laboratory testing using ball viscometry. This method shows the most promise for reliable accurate rheological measurements both on actual tank samples and for in situ applications.

Summarizing, the ball rheometer is best suited for quantitative measurements in the nonconvective layer. In the convective layer it is limited in its quantitative capability for viscosity measurement, and its best use may be to allow a determination of the boundary between the convective and nonconvective layer. In addition, reasonably accurate density measurements will be possible with this device in the convective or mixed region. It should be noted that there is presently little interest in obtaining quantitative data about the convective layer, and so the ball rheometer, however limited, may be perfectly acceptable. The same may not be true about regions where strong mixing has occurred. Viscosity information may or may not be obtainable from such a region, depending on the fluid rheology. Detailed accurate information about this region, such as solids content and distribution, solids settling rate, and viscosity may require an altogether different probe operating under different scientific principles.

3. Summary

In reviewing the comments received from the representatives of the groups requiring rheological data some conclusions can be reached. No group has any need for data involving the convective layer, only the nonconvective layer. Data requirements for a mixed region have not been completely formulated to date and this process is ongoing. It is likely that detailed information about a mixed region will become valuable as attention is turned towards the questions concerning the effectiveness of the mixer pumps and other mitigation devices, such as the sonic probe. It is believed that the ball rheometer can provide very useful and fairly accurate rheological data (yield strength and low strain rate viscosity) for the nonconvective layer but will have limited capability for measurement of viscosity in a convective region and maybe a mixed region. The ball rheometer can measure density with good accuracy in a mixed region but it is not clear if this implies that it can provide sufficiently accurate information about suspended solids distribution or settling times. Concerning investigation of mixing pump effectiveness, it is clear that data should be obtained in the regions affected by the mixing pump, and that such data should be acquired sometime before its operation and sometime after its operation.

Data should also be acquired at other locations within the tank and at intervals consistent with the time scale for changes within the waste. Access locations are limited and it appears that, aside from mixer pump considerations given above, locations near the center of the tank are most useful to all. Practical considerations will limit the spatial extent of viscometer data collection. We may

have more flexibility as to the times during which we gather data, so that in addition to regular scheduled (e.g., weekly) sampling, we may be able to sample at special times, like right before or after an expected rollover or operation of the mixer pump.

The advent of the mixer pump has changed our understanding of the cyclic events which used to occur in the tank. It may be that another rollover event such as we have become accustomed to observing never occurs again so long as the pump, or perhaps the sonic probe, is resident in the tank. It is clearly important that we use our measurement methods to analyze the effect of the pump on the nonconvective layer.

There appears to be no requirement for extremely precise rheological data, except for perhaps retrieval purposes. If we can measure yield strength and low strain rate (less than about 10/s) viscosity to within 20 % to 40 % it appears that most parties will be satisfied. It is important to understand and clearly state the uncertainties in our measurements and derived quantities. These uncertainties can then be used to bound calculations.

Of all methods for performing in-situ measurements of rheological properties, the ball rheometer appears to be the best suited for our applications. Installation difficulties within the tank are minimal, and the associated hardware are relatively simple. Only the ball and cable are deployed within the tank (no additional sensors or electrical devices or hydraulic systems), thereby minimizing safety concerns. In addition to its simplicity, the ball rheometer is believed to be the best choice for obtaining reliable accurate rheological data for the nonconvective layer.

APPENDIX C

THEORY OF OPERATIONS

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January 26, 1994

MIT94-1690

Jack Lentsch
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Dear Mr. Lentsch:

Please find attached a letter report, #PNLMIT-012694, by C. L. Shephard titled *Theory of Operation for the Ball Rheometer*. This completes the deliverable for activity 0038 on your master schedule.

If you have any questions, please call me on 372-4678.

Very truly yours,

C. W. Stewart, Manager
Hydrogen Mitigation Project

CWS/kah

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Theory of Operation for the Ball Rheometer

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Theory of Operation for the Ball Rheometer

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Abstract

Knowledge of the rheological properties of the material contained in Hanford Site high-level radioactive waste tanks is crucial to the success of many of the mitigation and remediation methods and to the understanding of the behavior of the wastes. The ball rheometer is being developed to provide in-situ measurements of the rheological properties of the waste contained in Tank 101-SY. The need for these data arise from several sources, including modelers of tank behavior, tank safety analysts, and structural analysts. In addition, there is a need to assess the effectiveness of mitigation methods, such as the mixer pump.

Past rheological data obtained from core samples of the waste in 101-SY is suspect insofar as its reliability is concerned, owing mostly to the inability of cone-and-plate viscometers to analyze samples containing particles of sizes larger than or comparable to the gap distance between the cone and plate. It is believed that the ball rheometer can avoid many of the difficulties associated with past measurement procedures because it operates in situ. The ball rheometer measures no fluid properties directly, but rather measures drag force on the ball and the velocity of the ball. These measurements must be related to fluid properties such as the yield stress and viscosity through non-Newtonian fluid theory. A suitable fluid model for the waste is necessary in order to reduce the ball rheometer data to obtain rheological parameters.

In this report we present the ball rheometer concept and discuss the theory behind its application. Several fluid models are described, and the relationships between the drag force and velocity of the ball to rheological parameters are given for each model. These models are all steady-state models where the flow about the ball is fully developed. We also present an operational procedure for the performance of tests in the tank and give details of the components making up the ball rheometer system. Descriptions of testing in the convective or mixed layers and in the nonconvective layer are described. In addition, an error analysis is presented showing which measurements are most important in determining the accuracy of derived rheological parameters. This analysis was based on the assumption that a Bingham fluid model is representative of the waste. The error analysis shows that the performance of the ball rheometer depends on the actual values for the yield stress and viscosity in addition to measurement errors. Relatively low

viscosities (less than 10,000 cP will be difficult to measure with accuracy, especially if the fluid has a high yield stress (greater than 3500 Pa). A high yield stress will also require that the ball be manually assisted to the tank bottom, rather than proceeding there under gravity.

The ball viscometer is expected to have different capabilities in different layers of the fluid. In the convective or mixed layer, which is characterized by a near zero yield stress and a relatively low viscosity, the ball rheometer is expected to be able to determine fluid density quite accurately. Only an upper bound to the viscosity is expected. It should also be able to distinguish the locations where fluid boundaries exist, such as between the convective layer and the nonconvective layer. In the nonconvective layer where the yield stress and viscosity are expected to be high enough, the ball rheometer should be able to measure both yield stress and viscosity to within about 50% of true values, but may have difficulty in accurate measurements of density. We feel that the largest obstacles in development of a successful ball rheometer are in the determination of a reasonably accurate fluid model for the waste and the nature of the waste, including waste inhomogeneities.

The ball rheometer is expected to provide the following information:

1. fluid density to 5% of true value in the convective or mixed region,
2. yield stress and viscosity to 50% of true value in the nonconvective layer,
3. location of fluid interfaces where fluid properties change abruptly, and
4. data which allow a determination of the effectiveness of mitigation methods, such as the mixer pump.

The ball rheometer is expected to provide interpretable data when the measurement parameters are within the following ranges:

1. fluid density is greater than 1 gm/cm^3 and the fluid has no significant yield stress
2. viscosity is greater than 10,000 cP, and
3. yield stress is less than $70,000 \text{ dynes/cm}^2$ (1 psi).

The degree to which these measurement objectives are accomplished will form the basis for measuring the success of the ball rheometer.

1.0 Introduction

The Hanford Site contains over 100 high-volume tanks containing high-level radioactive wastes. The tank which has received the most attention is Tank 101-SY, which is a double shell tank containing a caustic mixed-waste slurry. The ball rheometer developed

in this work is intended at least initially for application in this tank. Tank 101-SY is known to periodically release flammable and toxic gases during events known as rollovers. The tank waste is largely made up of two layers, a supernatant liquid layer underneath which is a thick sludge layer. The two layers are called the convective (C) and the nonconvective (NC) regions, so called because of the thermal transport properties ascribed to each. Although they have significant uncertainty, the current rheology data suggest the existence of a yield stress in the highly viscous nonconvective layer. Gas generated in the waste can be held in the NC layer if the material yield strength or its viscosity is high enough. Gas cannot be held in the C layer to any appreciable extent unless it is in solution. As gas continues to be generated by chemical or other processes, the number of gas bubbles and/or their sizes increases in the NC layer. A rollover occurs when the amount of gas trapped in the nonconvective region becomes great enough to overcome forces holding it in place. These forces are believed to be dependent on the rheology of the nonconvective region and perhaps the bubble surface tension. The buoyancy forces on the bubbles exceed the restraining forces arising from the yield stress and the viscosity of the NC layer. Rheology is then seen to be quite important in determining the nature of gas release events in this tank. A review and evaluation of rheological measurement methods applicable to Tank 101-SY is given in a report by Pasamehmetoglu et al. (1993). Part of the reason for development of the ball rheometer is to determine the yield strength and apparent viscosity of the NC layer so that modeling of tank behavior through codes such as TEMPEST can become more reliable. However, characterization of the rheological properties of this layer is not desired solely for modeling purposes. Other groups involved with the tank safety and structural analysis are also interested in the rheological parameters of the NC layer.

In addition, there is keen interest in determining the mitigation effectiveness of mixer pumps installed in Tank 101-SY. The mixer pump mixes the NC layer with the C layer by directing high-speed liquid streams into the NC layer, thereby diluting and displacing the sludge material. The working fluid is liquid from the C layer. Presumably a mixed layer is created which has a very low yield stress and the volume of the NC layer is diminished. The gas retention capability of the waste is therefore reduced. In this instance, attention will be given primarily to the density, rheology, and spatial extent of the region where waste from the nonconvective layer has been mixed with the waste of the convective region. Details on the requirements of users of the rheological data which will be gathered by the ball rheometer are given in a report by Shepard (1993).

Some of the conditions within the tank are known from in-situ instrument arrays and from past tank sampling. Most of the rheological information obtained to date comes from hot cell testing of core samples drawn from Tank 101-SY (Allemann 1992; Tingey 1992). We will discuss these data shortly. Roughly, there is a liquid layer of about 15 ft. in depth and beneath that is the nonconvective layer, also of about 15 ft. depth. The unmixed liquid layer is very nearly Newtonian in behavior with a fairly low viscosity (about 25 cP). This layer is of minor interest in the unmixed form. The NC layer has a high particle concentration and possesses a yield strength as well as a high viscosity after

yielding. The temperature of the waste is around 45°C and exhibits a time and spatially dependent variation in the NC layer. Mixing by convection is believed to be why the liquid layer shows little spatial thermal variation. The densities of the NC and C layers are not too different, with specific gravities of about 1.7 and 1.5, respectively. The surface level of the tank varies between cyclic gas release events, and this is due to generation and buildup of gas within the NC layer. Variations of the order of 1 ft. have been observed in the level of the surface.

Past measurements of the rheological properties of the waste in Tank 101-SY have shown some anomalous behavior and there is some question as to the reliability of these data. Rheology measurements have been made on samples obtained from the tanks and placed in a hot cell. For example, core samples from Tank 101-SY were taken during windows C and E; those samples were used for rheology measurements (Tingey 1992).

These measurements show that there is considerable difference in the convective layer viscosity for samples from windows C and E. While window C samples show that the convective layer is nearly Newtonian, with a viscosity on the order of 10 cP, the window E samples show a highly non-Newtonian behavior, with very high viscosities (on the order of 10^6 cP) at low shear rates, even for the convective layer. The core samples were obtained during a window (within 2 to 3 weeks) following a GRE while the waste was in its settling stage. Thus, one speculation is that the sample obtained during window E actually corresponded to a chunk of a nonconvective (NC) layer while this chunk was settling down through the convective layer. There are other possible explanations for these anomalous observations, most of which have to do with the procedures used for sample capture and sample handling.

Interpretation of rheology measurements for waste from the NC layer also present some challenges. Typically, the rheograms show that the shear stress is a decreasing function of the strain rate at low strain rates. This behavior is not observed as a quasi-steady and stable rheogram for any other material (and/or slurries) investigated in the literature. Besides measurement errors, this behavior can only be explained by the "disordered to ordered" transition in highly concentrated suspensions (Merrington and Woodcock 1991). However, such transition is highly transient and metastable in nature and should not be used as a quasi-steady rheogram. Later attempts were made to quantify the thixotropic behavior of the NC layer samples by running experiments at constant shear rate for several minutes and recording the shear stress. From the behavior of the curve, we concluded that several minutes was the time constant of the material, and the waste sample had reached equilibrium in those tests (Hall and Phillips 1992). However, when plotted on a stress-strain rate curve, the results were similar to the transient rheograms because there was a region where the stress was a decreasing function of a strain rate. It is worth mentioning that, according to Merrington and Woodcock (1991), the transition from a disordered to ordered arrangement in highly concentrated suspensions can be a very slow process and may take "many hours, possibly days." If one uses the transient rheogram in quantifying the quasi-steady behavior of a system, unrealistic results and

conclusions follow. For example, if we were to use the current rheograms to design a waste retrieval system consisting of a retrieval pump and piping system, in a certain range of parameters, we would conclude that increasing the pump head would result in a reduction in flow.

The temperature dependence of the NC layer viscosity also requires further investigation. The data indicate that over a certain range of temperatures and strain rates, viscosity increases with increasing temperature, in marked contrast from most fluids. Currently, we overlook this empirical behavior and model the viscosity as being a decreasing function of temperature similar to pure liquids (Allemann 1992). However, the observed behavior has been reported in the literature for suspensions and may be real (see, for instance, Fig. 6.15 in Ferguson and Kemblowski 1991). This observation has important consequences if one were to use heating as a mitigation or remediation scheme.

Finally, the experimental methods used to establish the rheology of the NC waste layer also has a number of drawbacks. The disturbance caused during removal and storage of the samples is likely to influence the rheological properties. Likewise, the viscometers (cone and plate) used in those measurements require small sample sizes. The placement of these small amounts of material into the viscometer is likely to create additional changes in the rheological properties. Also, the particles in the waste slurry are believed to be 1 to 100 μm in size. For a cone-and-plate viscometer used in the hot-cell measurements, this particle size is likely to interfere with the gap, resulting in erroneous viscosity or yield stress measurements. At Los Alamos National Laboratory this effect was investigated using a simulated waste containing salt crystals with similar sizes to the salt crystals in the real waste (Piccola et al. 1993). The results indicate that while repeatable data with small scatter could be obtained using spindles, the cone-and-plate data are unrepeatable and exhibit erratic scatter. The postulated mechanism for this behavior was that the narrow gap in the cone-and-plate viscometer (13 μm) resulted in grinding up the salt crystals and was not capable of quantifying the viscoplastic behavior of the mixture. In most cases, the viscosity measured using the cone-and-plate viscometer was an order of magnitude greater than the viscosity indicated by the spindles. We summarize the above mentioned study and its findings briefly in the next section.

There are direct and indirect methods for laboratory measurements of yield stress (see Dzuy and Boger 1983). Indirect methods are based on the interpretation of fundamental shear-stress shear-rate data. The yield stress is obtained by extrapolating the shear-stress shear-rate curve as the shear rate goes to zero. In practice, this straightforward method is not usually possible with the use of commercially available viscometers because the low shear rate data are not available. Even when low shear rate data are available, the instrumentation uncertainty and other errors due to slip flow make this method questionable (Goodrich et al. 1989). In addition, this method requires that the rheogram be identified correctly. The use of a different fluid model also results in different yield stress quantities. The direct methods involve the vane method (Dzuy and Boger 1985, Keentok et al. 1985), stress relaxation method, and measuring the shear stress at which

flow first begins under constant shear stress, or shear rate conditions. There are other special methods, such as a cylindrical specimen between two parallel plates under constant load (Navickis and Bagley 1983); penetration of solid objects, such as cone and plate, needle, or sphere into an initially horizontal test specimen; application of constant torsional moment to one end of a rod or hollow cylinder made of the test material; or measuring the drag force acting on a stationary plate submerged in a moving test material (see Dzuy and Boger 1985). Some of these methods are not applicable to fluid materials and the success of these techniques depends on the capability of the test material to exhibit well-defined yielding under selected experimental conditions. However, there are still questions that the quantity obtained by these tests can be identified as true yield stress. Usually, the yield stress is measured by several methods for comparison purposes.

The yield stress of 101-SY waste samples was measured by the vane method, which is the method of measuring the shear stress at which flow first begins under constant shear-stress or shear-rate conditions (see Tingey 1992). There are significant differences (about 100%) between quantities obtained from the vane method and from the method of measuring the shear stress at the onset of flow under constant shear rate. It is worth noting that when the quantities obtained from the two methods mentioned above are compared with the quantity obtained from the indirect method (extrapolation of shear stress to zero shear rate), the yield stresses differ by orders of magnitude.

Currently, we do not have any data to correlate the effect of dilution on the waste rheology. Person (1992) measured the viscosity of a mixture of the C and NC layers, using the proportions that are believed to exist in the tank. Roughly, the mixture consists of 100% dilution of the NC layer with the C layer. The mixture exhibited a shear thinning behavior with viscosities ranging from ≈ 400 (low shear rate) to 50 cP (high shear rate) over the range of 5 to 1000 s^{-1} shear rates. The measurements were done at room temperature using a cylindrical bob spinning inside a fixed outer cylinder (spindle). These spindle measurements provide one data point for the dilution effects. However, we believe further analysis of the data is required to confirm that the mixture remains homogeneous during the spinning action and that migration of the solids as a result of centrifugal forces does not affect the measurements.

The above discussion points out the need for additional rheology data on the waste in Tank 101-SY. Some measurements have simply not been made while others are suspect primarily because of the difficulty of obtaining measurements with the waste using standard laboratory measurements. As evidenced in a report outlining the needs of the data users community (Shepard 1993), it is important to have knowledge of the waste's rheological properties to sufficient precision so that the behavior of the waste can be understood from numerical modeling and so that safety and structural concerns can be adequately addressed. In addition, the effectiveness of mitigation strategies, such as the mixer pump, can be measured with rheology data.

The ball rheometer, which is the subject of this paper, is proposed as at least a partial solution to these data needs. The intent of ball rheometry is to provide further rheological information (shear stress at low shear rates, apparent viscosity at low shear rates, and density) from in-situ measurements of 101-SY waste. It is believed that it will be most successful at measurements of the yield stress and zero shear rate viscosity of the NC layer and the density of the C layer or a mixed layer. It should also be very effective at determination of the boundaries between the NC layer and the C or mixed layer. None of the quantities mentioned above are directly measured with the ball rheometer. Rather, these quantities must be inferred through theoretical relationships connecting measured quantities to rheological properties. A reasonably accurate model for the fluid is necessary, particularly for the NC layer and the mixed layer. Laboratory studies using chemical simulants of the waste will be relied upon to help develop the model, as will the actual data collected in Tank 101-SY. Fortunately, there is no identified requirement for very precise determination of rheological parameters. It is sufficient to determine viscosity and yield stress to within about 50% of true value in the NC layer, while density information is most important in the C layer or mixed layer where errors of several percent are acceptable.

There are circumstances which can result in partial failure of the ball rheometer, most notably in the NC layer. Our inability to guarantee success here results mostly from an incomplete knowledge of this layer. If the layer is highly stratified or if the layer is inhomogeneous to a sufficient extent, we will have difficulty obtaining the rheological parameters to sufficient precision. We will be able to determine that it is stratified or inhomogeneous, however. The requirement for homogeneity at least over some limited depth of the waste is due to theoretical limitations wherein rheological properties are related to measured quantities only under the conditions of steady-state fluid flow. The theoretical description of transient phenomena has not been suitably addressed to date.

The measures by which ball rheometry will be considered successful are listed below.

1. If a reasonably accurate fluid model describing the NC layer can be developed and if yield stress and zero shear rate viscosity can be determined to within 50% of true value from this model and the actual measurements, ball rheometry has served one of its purposes.
2. If the density of the C layer or mixed layer can be determined to within 5%, the ball rheometer has provided meaningful results. It is assumed here that the mixed layer will have no significant yield stress.
3. If the interface between different liquids where rheological properties abruptly change, such as between the C or mixed layer and the NC layer, can be determined to within 1 ft, the ball rheometer is successful. It should be remembered that this boundary may be somewhat diffuse if the C layer is replaced with a mixed layer.

4. If the ball rheometer can provide information as to the effectiveness of various mitigation strategies, such as the mixer pump or perhaps the sonic probe, then it is successful. Viewed in this sense, the ball rheometer would need to possess the ability to measure changes in the fluid properties.

It is presently believed that the ball rheometer will be capable of meeting the above success criteria.

The remainder of this report is organized as follows. In Section 2 we present the results of past testing with simulated waste. In Section 3 we show present plans for performing testing in the tank, including a description of the ball rheometer system. A discussion of various fluid models which may be applicable to this problem is given in Section 4. A discussion of errors and their propagation is presented in Section 5. The need for further laboratory experiments and a description of these tests make up Section 6, and Section 7 is a summary.

This report is not the final word on the topics covered here. A subsequent report will follow which outlines the final test procedure to be followed in experiments performed in Tank 101-SY. This report will also contain an analysis of errors based on the best available fluid model and finalized hardware specifications. The results of the experimental tests described in Section 6 will also be presented.

2.0 Past Measurements with Simulated Waste

In order to understand the reasons why ball rheometry is being used as the method of choice for in-situ measurement of rheological properties, we should begin by reviewing experimental results obtained using chemical simulants. As suggested in the previous section, standard rheological measurements have not provided consistent results.

Los Alamos initiated work (Piccola et al. 1993) to evaluate the adequacy of the cone-and-plate viscometry, including difficulties associated with this measurement method and repeatability of tests for the waste materials. There was a lack of repeatability in tests reported by Tingey (1992). Also, Hall and Phillips (1992) mentioned that they did not obtain reasonably similar data when a test was repeated.

To compare the cone-and-plate measurements with other methods, we selected the following additional techniques:

- cylindrical spindle,
- cylindrical spindle with a small sample adapter, and
- falling-ball viscometer (performed subsequent to the experiments of Piccola et al. 1993).

First, the spindles and the cone-and-plate techniques are based on the measurement of torque in a shear flow field. The cone-and-plate viscometer involves two plates separated (one being inclined 5°) with a small clearance ($13\ \mu\text{m}$). The bottom plate is rotated with a constant speed, and the torque is measured. The measured torque is converted to the shear stress at a given shear rate. Each measurement gives a steady-state point on the rheogram. We could also record the shear stress as a function of time as it reaches the steady-state conditions. The cylindrical spindle is a simple rotating cylinder in a larger cylindrical sample container. The small sample adapter technique also uses cylindrical spindles with the sample in a smaller container. The falling-ball method is based on the measurement of the terminal velocity of a ball falling through a stagnant sample. We have only preliminary data taken with this method. For a given fluid sample, we obtain the shear-stress-shear-rate (or viscosity-shear rate) relationship for each method. Below, we briefly summarize our findings, i.e., the comparison of rheology results we obtained from each technique.

The cone and plate and spindles were calibrated with the Newtonian calibration fluids at different temperatures. Each method gave the same results, with excellent repeatability.

When we used a non-Newtonian fluid with no particles [potassium polyacrylate-water mixture (Arigel)], the cylindrical spindle and cone and plate gave reasonably similar results, and the repeatability of tests was reasonably good, as shown in Figure 1. The tests with the small sample adapter indicated some disagreement with values obtained from the cylindrical spindle at lower shear rates. It is worth remembering that the sample was mixed before each experiment was started and that the shear rate was increased stepwise (see Piccola et al. 1993 for details). The data at each shear rate were taken at several different intervals, involving a minimum of five revolutions. Uncertainty bars including instrumental uncertainty are shown in Figure 1 and elsewhere to indicate the range of variations of separate measurements at any given shear rate. If no uncertainty bars are presented for a data point, the size of the data point represents the instrumental uncertainty. The variation in viscosity at a given shear rate can be thought of as the measure of the change in the fluid state with time. It is evident that variation in the measured viscosity at the lowest shear rate is significant in tests with the small sample adapter. These tests give relatively lower viscosities at lower shear rates. Above a shear rate of $0.88\ \text{1/s}$, the agreement between these three methods is reasonable.

Because waste includes crystalline particles, we also tested the first three methods with a bentonite-water mixture that included some fine particles. The bentonite-water mixture, with a volume ratio of 1 to 10, respectively, was prepared and kept in a container for 1 day. The three methods gave reasonably repeatable and similar results for the rheology measurements, as shown in Figure 2.

Figure 1. Apparent viscosities measured by three different methods for a non-Newtonian potassium polyacrylate-water mixture.

Finally, we used a simulated waste that included the same chemical species as the waste in Tank 101-SY. The comparison of results obtained from the cylindrical spindle, cylindrical spindle with a small sample adapter, and cone-and-plate viscometers is given in Figure 3.

The sample size necessary for the cylindrical spindle tests is relatively large (500 cm^3). The simulated waste was mixed in the container before experiments. Small volumes taken from different locations of the container were then taken by syringe as samples of those used in the cone-and-plate device. The square symbols in Figure 3 show the apparent viscosity measured by the cylindrical spindle at the beginning of the tests. The apparent viscosity showed an exponentially decreasing trend with the increasing shear rate for the cylindrical spindle tests. The variation in viscosity during a measurement at a given shear rate was negligible. However, when the sample was mixed and the cylindrical spindle tests were repeated 1 hour later, some variations, especially at lower

Figure 2. Apparent viscosities measured by three different methods for a non-Newtonian bentonite-water mixture involving suspended fine particles.

shear rates (at the beginning of the test) were evident. The apparent viscosity tended to increase slightly in the second series of tests conducted with the cylindrical spindle. This difference shows the significance of the aging effect of the waste. Thus, the cone-and-plate measurements were conducted at the same time as the cylindrical spindle measurements to eliminate the effect of aging of the sample.

The results obtained from the cylindrical spindle with a small sample adapter are also included in Figure 3. The only difference between the cylindrical spindle and the cylindrical spindle with a small sample adapter is the gap between the container and spindle, which is relatively small with the small sample adapter. It is clear that the use of a small sample adapter results in an increase in the apparent viscosity at a given shear rate. However, the viscosity again decreases smoothly and exponentially with reasonable repeatability. Note that tests with a small sample adapter were obtained on a different date so that simulant aging may be important. This may be one of the reasons for the

Figure 3. Apparent viscosities measured by three different methods for a non-Newtonian waste simulant involving suspended crystalline particles.

shift we see in the viscosity. Another possible reason for the differences could be that particle migration may be limited in a small gap. The primary information in Figure 3 is the repeatability of a test at a given time and variation of the viscosity with the shear rate. In this sense, the use of a small sample adapter also results in reasonably repeatable results, and the measured viscosity exponentially decreases with shear rate.

The apparent viscosity at a given shear rate varied significantly during cone-and-plate tests, as shown in Figure 3. The cone-and-plate tests were performed with two different cone-and-plate sizes, which require different sample sizes (the data are represented by circles and inverse triangles). Both sizes showed significantly varying apparent viscosity during a test at a given shear rate. The repeatability of the data using the cone-and-plate device was observed to be unacceptably high. The apparent viscosity measured by the cone-and-plate device at a given shear rate is also almost an order of magnitude higher than that obtained with the cylindrical spindle viscometer.

Figure 4. Apparent viscosities measured by three different methods for a non-Newtonian, 1-day-old waste simulant involving suspended crystalline particles.

Although we repeated the cone-and-plate tests several times on different days with different samples, we observed the lack of repeatability and measured the different viscosity each time. An example of these repeat tests is shown in Figure 4, which shows the results obtained from the 1-day-old simulant. Figure 4 indicates the same results we presented in Figure 3; the cylindrical spindle shows a reasonable variation at a given shear rate, whereas the cone-and-plate device results in relatively large variations. Also, the measured values by the cone-and-plate device are high relative to values obtained by the cylindrical spindle.

Results shown in Figures 3 and 4 indicate that the cone-and-plate device may not yield correct measurements of the waste viscosity, and the current Tank 241-SY-101 waste rheology data could have significant uncertainty. The current waste rheology data should therefore be used with caution in any analyses.

We believe that the most important reason for the lack of repeatability is the crystalline size. The waste simulant we used included particle sizes up to 40 μm . Comparison of this size with the clearance of the cone-and-plate viscometer, 13 μm , suggests the possibility of grinding. The selection of the same particle characteristics for each cone-and-plate experiment is almost impossible when a very small sample is needed. We concluded from this study that the cone-and-plate technique is not adequate for the rheology measurements in the waste.

The data taken with cylindrical spindles show good repeatability. However, we could not conclude whether this method gives the correct measurements because there is a concern with particle migration in a shear flow. If the particles migrate, the assumption of homogenous concentration is not valid, and measurements are misleading.

To validate the spindle measurements, we performed some preliminary falling-ball experiments at Los Alamos. The terminal velocity is determined by measuring the flight time over a given distance using x-ray radiography (Mondy et al. 1986). Two different falling balls were used: a stainless-steel ball with a diameter of 3/8 in. and a tungsten-carbide ball with a diameter of 1/8 in. The falling-ball viscometer gave reasonably similar viscosity results with the cylindrical spindles, as shown in Figure 5. This does not necessarily mean that both techniques give the same results because the flow fields are different and the Reynolds number may not be the correct scaling parameter. Nevertheless, it gives an idea for the first-order comparison.

The falling ball measurements showed that the fluid thinned each time a ball was dropped through it. For Newtonian fluids, viscosity is a fluid property and should not be a function of the ball size and material in this technique. This is valid when the particles are suspended homogeneously in a continuous liquid phase. Figure 5 indicates that this is not the case for this solution (tungsten-carbide and stainless-steel balls gave different results). In addition to non-Newtonian effects (where viscosity is a function of the flow field), there appears to be local disordering in the fluid structure. These are preliminary results; however, they indicate that for this particular waste simulant, the interpretation of falling ball results is also not straightforward. However, we believe that among the methods investigated, the falling ball technique is still a promising technique because the data collection occurs from undisturbed fluid as the ball falls through it. Also, it may be possible to determine an apparent viscosity to describe the waste's fluid dynamics if sufficient data are obtained using the falling ball experiments.

3.0 In-situ Ball Rheometer Measurements in Tank 101-SY

Accurate in-situ rheology measurements would be the best approach for determination of the character of the waste. A simple methodology for obtaining in-situ measurements is presented in this paper. However, it is important to emphasize that the ball rheometer

Figure 5. Comparison of viscosity of simulated waste using a cylindrical spindle and falling ball.

methodology has possible shortcomings due to the range and variability of the waste material. For instance, it may provide more reliable yield stress and viscosity information in the NC layer than in the C layer, and density measurements will probably be more accurate in the C layer than in the NC layer. If possible, the ball rheometer measurements should be supplemented with results obtained from hot cell testing.

The objective is to design a method that can provide in-situ measurements of the waste rheological properties. Our goal is to keep the design and operation of the equipment as simple as possible without jeopardizing the accuracy of the measurements. Naturally, there is a tradeoff between simplicity and accuracy. We believe the proposed method meets the simplicity requirements and provides a reasonable degree of accuracy (about 50%) of rheological properties for very low shear rates. In addition, the ball rheometer minimizes the difficulties associated with deploying instrumentation within a waste tank. No electrical components or sensors will be introduced into the waste, only a ball and

some cable. Therefore safety concerns, while still apparent, are considerably reduced and manageable.

One could engineer other types of in-situ measurement methods. An example recently proposed by WHC was to insert a rotational device (such as a spindle in a jacket) into the waste. This method has certain disadvantages as compared to a simpler falling-ball viscometer:

- It is more difficult to design, build, and operate.
- It disturbs the waste during insertion, whereas the disturbance and measurement can be simultaneous with a falling or raising ball.
- A falling ball makes use of the infinite waste environment, whereas trapping the local waste inside the jacket is a problem.
- It has the same problem with particle migration, as mentioned for the laboratory measurements.
- Based on the problems treated in the literature, it is easier to obtain shear strength information from falling-ball data than from spindle data.

The areas where the in-situ falling-ball viscometry has its shortcomings are common to spindle measurements. The only obvious advantage of the spindle is that one can control the shear rates. For a falling ball, the shear rates ranging from 0 to $1.5 V/d$ (where V and d equal ball velocity and diameter, respectively) are integrated over the entire sheared surface, and it is necessary to use an appropriate model to reduce the data into terms of a rheogram.

In addition, the deployment of a simple device such as a falling ball may be used to evaluate the effectiveness of various mitigation schemes that are being tested in Tank 101-SY. For instance, we can use the ball before and after pump operation in a given direction to evaluate how jet mixing changes the rheology. Also, we can use it in parts of the tank furthest away from the jet orientation to obtain data on effects such as piling of solids and local growth of the NC layer.

3.1 Measurement Procedure

A diagram of the device which will be used for in-situ ball rheometry measurements is shown in Figure 6. The instrumentation consists primarily of a spool wound with a single layer of cable, and two pulleys around which the cable runs, and a load cell which measures twice the tension in the cable plus the weight of the pulley assembly which rides on the load cell. The cable spool is driven by an electric motor and the ball velocity is determined from an encoder attached to the spool. The encoder measures the

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Figure 6. Diagram of in-tank apparatus

rotational velocity of the spool from which cable velocity is determined from a knowledge of the spool diameter. The ball velocity equals the cable velocity. In almost all cases of interest, the ball will be either lowered or raised at a constant velocity while the force measured with the load cell is recorded. The acceleration of the ball from some initial velocity to some final constant velocity is somewhat adjustable. Measurements of the cable tension while the ball is at constant velocity form the most important data collected during these experiments. Ball location is easily determined from a knowledge of the ball velocity as a function of time and the reference location of the ball. Both falling ball and raising ball experiments can be performed with this arrangement. In addition, static measurements can be performed where the ball is at rest and the apparent weight of the ball is measured with the load cell. These measurements are for determination of the waste density.

The entire assembly shown in the diagram will be housed within an enclosure and is designed to interface to a 4-in. riser pipe through which the tank waste is accessible. A decontamination system will be employed for washing the cable and ball as they are withdrawn from the tank. All motors and electronics associated with ball velocity control and measurement and load cell measurements will be housed in a weatherproof enclosure. The data will be transmitted via temporary cabling to a remote station for recording and eventual analysis.

The actual measurement procedure which will be followed has not yet been finalized. It is expected that measurements will be obtained somewhat along the following lines.

3.1.1 Case I. Unmixed Liquid Layer Over Undisturbed NC Layer

First the ball weight is measured in the tank head space and the value is recorded. The ball reference position should also be established. Testing for pulley friction and load cell calibration should also be performed at this time. Values for the load cell calibration and the ball weight and pulley friction should be compared to reference values established earlier, so that changes in the performance of the instrumentation can be determined. After system checkout and calibration tests, we are ready for testing in the convective layer. After being lowered into the liquid layer, the effective weight of the ball is again measured to determine the liquid density. The ball will be lowered at slow velocity (10 cm/s) through the entire layer until the sludge interface is reached. It is important to first determine the depth to the NC layer. At intervals of about 1 ft. density measurements are obtained throughout the layer. The sludge layer will be evidenced by a reduction in the cable tension to values which may approach zero as the ball is lowered at a constant velocity of 10 cm/s. When the tension is observed to drop in some dramatic fashion, the ball velocity should be reduced to 1 cm/s and the cable tension should be recorded as the ball is dropped at this velocity. If the cable tension approaches zero (adjusted for cable and pulley weight), the ball velocity should be reduced to 0.1 cm/s. If the cable tension remains at near zero, then the velocity should be dropped to the minimum possible value, about 0.02 cm/s. If the cable tension does

not increase, the ball is being supported by the NC layer and will not sink. If a non-zero reading was obtained at any of the above velocities, then the ball will sink. The above steps are necessary in order to determine a suitable cable tension for the initial drop into the NC layer. We now retrieve the ball until the tension approximates the last value measured under static conditions in the C layer. The position of the ball where this occurs defines the liquid-sludge interface. The position is recorded, and at this time the density profile of the liquid layer is also known. The ball is retrieved about 20 cm and then the ball is retrieved at high velocity (1 m/s) and a measurement of the drag force is obtained to determine the viscosity of the fluid. The same measurement is repeated under falling conditions with the ball descent rate at 1 m/s. The ball is stopped before it reaches the sludge layer. Both the raising ball and the falling ball tests should then be repeated, so that the ball is returned to near the top of the C layer. Due to the fact that the maximum ball velocity is limited to about 1.5 m/s, it is not possible or advisable to perform actual free fall tests in the C layer where some actual terminal ball velocity is approached. Measurements with the C layer are now complete.

Assume for the moment that the ball will sink under its own weight. The ball is then lowered to the NC layer and a force is chosen which will be maintained as the ball is lowered at variable velocity. This force is the first non-zero value measured during our initial tests in the NC layer where restraining force was measured at different velocities. Let the ball sink as far as it can, even to the bottom, and record the velocity as a function of position. The variation in the velocity with a constant restraining force will provide very useful information about the inhomogeneities of the waste.

The technique described immediately above may have some difficulties for waste which has significant inhomogeneities, particularly if the yield strength varies considerably as a function of depth. If the NC layer has even a modest yield stress, most of the drag force on the ball is due to the yielding of the material. To maintain a constant restraining force in changing yield conditions, the ball velocity must undergo large changes. It may not be possible to maintain the constant force condition. If this is observed to be the case, then on repeat runs which are performed later, we should hold the velocity constant at a low value (0.1 cm/s) and record the variation in the restraining force.

If the ball will not sink under its own weight, then we must be prepared to physically sink the ball using a long rod which is manually pushed from the surface. No data should be collected during this operation, except the amount of cable released from the spool has to be accounted for.

With the ball near the bottom of the tank, either by sinking under its own weight or by manual assistance, we can then begin experiments using retrieval of the ball. We should attempt to collect data at a minimum of five different velocities which span as large a velocity range as possible. Current designs allow the ball to be controllable from a maximum of 1.3 m/s down to 0.02 cm/s. Our first velocity should be 0.05 cm/s. It is presently not clear how long or how far we should pull the ball in order to obtain steady-

state flow conditions about the ball. Further laboratory testing with similar diameter balls in heated simulants may clarify this issue. For the moment we will adopt results already found in the laboratory with simulants. Tests performed in the laboratory show that we will typically reach steady-state flow conditions after about 10 cm. Therefore tests at each velocity should be performed for time intervals such that 15 cm of distance is traveled. The second velocity should be 0.1 cm/s, followed by 0.5 cm/s and then 1.0 cm/s and finally 2.0 cm/s. Thus, a single complete test will require a distance of about 75 cm (or 2.5 ft.) for performance. Operator judgement will be required in determination of when a steady-state condition has been reached and in setting the pull distance on any particular set of tests. If additional modeling shows that velocities in excess of 2 cm/s can provide useful information, then testing may also be performed at higher velocities.

At the end of each drag test, we will perform measurements to determine the local density of the NC layer. Thus, density measurements occur after each 15 cm pull at some given velocity. The ball should be oscillated in order to fluidize the waste around the ball and then a static measurement should be performed. Additional laboratory testing is necessary to determine the parameters of the oscillation. However, the general procedure is fairly clear and we have approximate ideas concerning frequency and amplitude. First the ball should be lowered about 3 cm into the region through which the ball has already passed. Then the ball should be oscillated at an amplitude of about 2 cm (peak-to-peak) at a frequency of about 0.1 Hz. While we can control the pulling of the ball, the settling relies on gravity. The ball should be pulled up 2 cm in about 4 seconds, then allowed to settle for 6 seconds (same deceleration and same amount of line played out) and then the process is repeated. After five cycles the ball should be retrieved 1 cm and then a static measurement should be obtained. Force and velocity data should be obtained during the whole process. The prospect of fluidizing the NC layer in this manner has been attempted with some success in the laboratory, but it is not clear that the method will work in the tank. An examination of the data taken during this exercise will shed light on the utility and reliability of the data. Even if fluidization occurs, there is some question as to whether the measurement will provide a true measure of the local waste density. If this method fails, some other technique may have to be developed in order to make this most difficult measurement.

Testing should then be continued throughout the rest of the NC layer proceeding upwards. For the second series of tests, the order of the velocities should be reversed, going from 2 cm/s to 0.2 cm/s. Another static measurement should be obtained at the end of the second run. On the third run we should start at the high velocity again and work towards the low velocity, while on the fourth run we should start at low velocity and work towards high velocity. The process should continue until the top of the NC layer is reached, with the order of the velocities following the first four runs. If the NC layer is 15 ft., we should expect about six complete runs. The ball should be immediately returned to the bottom of the tank if it will sink on its own, and then left there until

another set of data are required. Repeat experiments should be performed at intervals no closer together than one day in order to examine the reproducibility of results.

Interfaces to and within the NC layer deserve some attention. In traversing the waste, the ball disturbs a volume much greater than the actual ball volume. The effected volume is not yet well known and may depend on rheology as well as ball size. However, as a rule of thumb, the ball will affect material to a distance such that the affected area is about ten times the ball cross-sectional area. Thus material within a radius of about 15 cm centered on the ball will be influenced by the ball and we can assume that material within 15 cm above and below ball center will also be influenced. Therefore test results obtained with the ball closer than 15 cm to the tank bottom, tank wall, or NC-C layer interface should not be considered in data reduction. The influence of layers or interfaces adjacent to one in which the ball is located points out a possible limitation to the usefulness of the ball rheometer. As mentioned above, we will require about 75 cm to perform a test over a suite of velocities. It is implicitly assumed that the waste is homogeneous over the entire 75 cm. If the waste is not uniform then the derived rheological results will suffer in accuracy. The nature of the inhomogeneity is important. If the inhomogeneity is random with small deviations about some average values, then we should still expect good average results with increased uncertainties. If the NC layer is actually made up of many layers where the rheology changes in the same direction from top to bottom, then we will have considerable difficulty in reducing the data unless somehow these changes are accounted for. Thus, it is very important to understand the nature of the waste as soon as possible, and this is why the first test described above where the ball traverses the waste either at constant velocity or under constant force is planned. While the presence of inhomogeneities is lamentable from a data reduction point of view, it should be remembered that on some higher plane what we are really after is an accurate characterization of the waste. If the ball rheometer can show that the waste is inhomogeneous, then we have collected valuable information about it, regardless of our ability to reduce the data to accurate rheological parameters.

3.1.2 Case II. Mixed Layer Above Unmixed Sludge Layer

This case represents a very important use for the ball rheometer, perhaps the most important. The data obtained under these conditions not only help determine waste rheological properties but also will be used to determine the effectiveness of the mixer pump. Looking longer term, it is possible that the ball rheometer may also become a primary diagnostic for judging the effectiveness of the sonic probe or other mitigation techniques.

If the C layer becomes fairly thoroughly mixed with the NC layer, it can be expected that it will have a very low yield strength in addition to a low viscosity. We will attempt measurement of these properties, but they may be difficult owing to an expected low drag force, especially at low ball velocities. Probably the most important measurement which we can perform in the mixed region is that of effective fluid density, which we

should be able to measure to good precision. From this single measurement we can obtain an idea of the solids distribution within the mixture and, if measurements are performed over time, the solids settling rate.

The procedure begins as in Case I above. We measure the weight of the assembly in the tank dome space first and then immerse the ball within the liquid and perform density measurements throughout the mixed layer at about 1 ft. intervals. If there is a nonconvective layer, we will find it as before and we will then position the ball at the top of the NC layer and begin tests in the C layer with the ball in retrieval mode. At this point the procedure may change from that followed in Case I. The rheological properties may not be consistent throughout the entire layer. First we should pull the ball at 1 m/s until we reach the top of the layer. Then we should drop it at 0.6 m/s until we reach the NC layer. Then we should retrieve it at 0.3 m/s until we reach the top again. We should then return the ball to the top of the NC layer at 0.5 m/s to begin tests in this region. Data should be collected in all of these rising and falling ball tests.

Testing in the NC layer will be conducted as described in Case I. This layer may or may not be very thick, and so it may not be possible to run an extended series of tests where measurements over the same velocity range can be repeated several times. If the ball will sink on its own weight, we will follow the steps described above in Case I. If the ball will not sink (more likely in this case), we should again manually push it to the bottom. However, when measurements are concluded in the NC layer, the ball should not be returned to the tank bottom but left in the mixed region. The difficulty associated with sinking the ball combined with the fact that measurements are most useful in the mixed region suggest that this approach is the most favorable.

If testing shows that the NC layer is not very thick, say less than 2 ft., there is no point in performing measurements in the NC layer because it will be too difficult to obtain reliable data (due to interface effects). In addition, this volume becomes relatively unimportant in the tank dynamics.

3.2 System Description

3.2.1 Ball

The ball to be used in this system should be of diameter 3.6 inches (9.1 cm) and be made from tungsten or a tungsten alloy. The ball diameter is chosen so that it will fit down a nominal 4-in. diameter riser pipe and the material is chosen so that the ball density be as high as practical. Both ball diameter and density are driven to be as high as practical in order that the ball has the greatest likelihood of sinking, under its own weight, into the nonconvective layer, which may possess a yield strength of order 1 psi. The ball should be coated with a polyethylene coating of thickness around 0.003 inches in order to reduce crystalline accumulation on the ball. A cable (described below) should be permanently attached to the ball in such a manner that minimal deviation

from sphericity is obtained. Other (smaller) ball diameters and densities may be identified as useful from experimentation or modeling results.

3.2.2 Cable

The cable must be strong enough to support a weight of 500 lbs. Multi-strand stainless steel cable with a diameter of 1/8 in. is appropriate. The diameter of the cable is not critical, and thicker cables are acceptable. However, efforts should be made to keep the cable diameter and weight as small as possible while satisfying the loading requirement, which is critical. Both the extended cable weight and the drag force on the cable must be accounted for in determination of the drag force on the ball. Minimization of these forces is the best approach, and this is accomplished by minimizing the cable diameter and weight. The cable should be supplied with a polyethylene coating in order to prevent crystal build up and facilitate decontamination procedures.

3.2.3 Load Cells

The load cells measure about twice the tension in the cable plus the weight of mechanical components, such as the main pulley. The tension is due to the ball weight, extended cable weight, the drag force due to the ball and cable, buoyancy forces, and friction in the main pulley. Due to the design of the instrument, some of these loads are measured at twice their true value. The pulley friction and the weight of the mechanical components are measured at their true values while the weight of the ball and cable, the drag force, and the buoyancy force are measured at twice the true value. Some confusion will result if we are not careful in our discussions to distinguish between actual load and measured weight or load. Unless specifically stated otherwise, we will consider measured loads in the text below. The load carried by the cable will in most cases be much larger than the pulley and supporting structure weight, and we will not concern ourselves with loads other than those carried by the cable in the discussion below. In any calculation of ball drag force the weight due to mechanical components and to the main pulley friction must be accounted for.

The load cells should have a total error (from all sources) of less than 0.1% of full-scale reading. The desired accuracy of the drag force measurements is 1%. Therefore, if the measured drag force (which is twice the actual drag force) is less than 10% of the rating for the load cell, the load cell should be replaced with one of greater sensitivity (i.e., smaller load rating). The ball will weigh about 16 lb (and therefore have a measured weight of 32 lb). If the measured drag force is less than 3.2 lb, it becomes impossible to measure total force (approximately ball weight plus drag force) with any load cell of the stated accuracy and still maintain the requirement for 1% error in the drag force. For this reason, it may be necessary, in the case of small drag forces, to counterbalance the weight of the ball. Counterbalancing will be discussed below. If the measured drag force exceeds 5 lb, it is not necessary to counterbalance the ball weight, assuming a 50 lb load cell is available.

3.2.4 Counterbalance Weight

The use of a counterbalance weight has some attractive features if the drag force which we are trying to measure is quite small (less than several pounds). On the other hand, there are also many instances where a counterbalance weight can be quite annoying and provide little benefit to the measurement procedure. For simplicity of operation and for the minimization of possible mistakes in the data collection process, it is recommended that experiments be performed without the use of a counterbalance if at all possible. The ability to provide counterbalancing should be built into the system, and a simple spring mechanism is suggested. The use of the counterbalance in experiments should be at the discretion of the lead engineer and the counterbalance should only be employed in limited cases where data are unobtainable otherwise.

3.2.5 Ball Speeds

For measurements in the nonconvective region, ball velocities in the range from 0.05 to 2.0 cm/s are presently required. These ball speeds are required in order to ensure that measurements are made at low Reynolds numbers ($Re < 0.1$) where theories relating drag force and velocity to rheological properties are available. Continued investigation into model development may show that higher ball velocities can provide additional information, in which case this range of velocities may be extended. The acceptable error is 1% of the ball velocity. In the nonconvective region the ball velocity will be in the range from 1.0 to 100 cm/s with the same error. Higher velocities are required in order to obtain measurable drag forces. Acceleration of the ball to final velocity should be variable (programmable), since it is presently unclear if information is obtainable from drag force data acquired during acceleration. A typical acceleration for measurements in the nonconvective region is 1 cm/s^2 while for the convective or mixed region a value of 10 cm/s^2 would be more appropriate.

For density measurements, the ball will have to be held stationary while measurements of the apparent ball weight are obtained. The apparent weight of the ball will be about 91% of the true weight of the ball if the fluid density is about 1.6 g/cm^3 and the ball is tungsten. Under the best of circumstances we can expect to be able to measure fluid density to within 2% in the convective layer. Measurements in the nonconvective layer cannot be expected to be as accurate. Experiments with simulants have to date shown that errors in density measurements are around 10%. This error will increase as the yield stress increases.

4.0 Model Development

The system is equivalent to a falling-ball viscometer commonly used for Newtonian fluids. Similar viscometers also are used for suspensions (see, for instance, Abbott et al.

1991a, and Powell and Walla 1991). A schematic description of the system is shown in Figure 7.

Figure 7. Schematic of the system

The equation of motion for the sphere may be written as

$$M a = W - B - D - T - L , \quad (1)$$

where M is the mass, a is the acceleration, W is the weight, B is the buoyancy force, D is the drag force, T is the external force shown in Figure 7, and L is the system losses (depending on the number and arrangement of the pulleys).

If the sphere is moving with a constant velocity (V), Eq. (1) reduces to

$$T = W - B - D - L . \quad (2)$$

Finally, if the sphere is stationary, the drag force in Eq. (2) vanishes, and the equation reduces to

$$T = W - B . \quad (3)$$

In this system, the weight (W) of a given sphere is known. Also, it is assumed that the frictional losses of the system (L) can be obtained from a calibration test for the final system design. The measurable parameters are the external force T and the motion parameters of the sphere (a and/or V) (using the pulley's rotational speed, for example). The required data are the waste density (ρ) and the waste viscosity (μ). If applicable, the waste yield strength (τ) is another parameter that can be reduced from the above data. Obviously, none of the desired parameters are measured directly during the test. Therefore, they must be obtained by using models from the measurable parameters.

4.1 Data Reduction Methodology

In order to transform measured quantities (force and velocity) into fluid properties, we need to use physical models which form the relationships. The relationships depend upon the type of fluids which we are dealing with. Fluid types which we will consider include Newtonian fluids and several non-Newtonian fluids including Bingham plastic, generalized Bingham plastic, and power law fluids. It is presently believed that the convective layer can be adequately represented as a Newtonian fluid while the nonconvective layer can be approximately characterized as a generalized Bingham plastic. However, these beliefs may change as more information is learned about the waste. In any case, the drag force on the ball at some particular velocity depends on the nature of the fluid. In this section, we will outline how the drag force is related to fluid properties for the fluid types mentioned above. It should be noted that the theories about to be presented are all steady-state theories and do not consider transient behavior. If after further review it is learned that none of the models which will be described below are applicable to this problem, then another model must be found. Other models are available, and those discussed here should not be thought of as comprising all possibilities. Presently it is believed that one of them should be suited for our case.

The measured data must be converted to density, viscosity, and yield strength through models. The density can be obtained from Eq. (3), knowing the weight W and having measured the force T. The waste density (ρ_w) can be obtained as

$$\rho_w = \frac{6(W-T)}{\pi d^3 g} , \quad (4)$$

where d is the sphere diameter. However, we must note that this equation is not valid if some of the weight is carried by the material's yield strength in the NC layer. To measure the true buoyancy, we must fluidize the material around the sphere. The motion of the sphere may be sufficient to fluidize the material. However, if the material regains its strength very quickly after the motion ceases, this method will not work.

Furthermore, if the motion results in accumulation of a liquid layer around the sphere as the solids migrate away or if the solids are not freely suspended in this liquid, the measured density will not represent the actual density of the slurry.

Currently, the sphere must be designed to fit through one of the smaller risers (4-in. nominal ID) in Tank 101-SY. Thus, the diameter of the sphere would be approximately 3.6 in. The corresponding weight of a tungsten sphere of this size is 76 N (17 lbf). The waste density is expected to vary between 1400 and 1600 kg/m³. Thus, the net weight inside the waste would be between 70.5 and 71.3 N (15.9 and 16 lbf). Therefore, to measure the waste density accurately within this range, the load cell must be sensitive to variations less than 0.1 lbf (0.6% of the total weight). Thus, the load cell must be sensitive to variations at least an order of magnitude smaller than this value if we intend to do an accurate density measurement in the range of 1400 to 1600 kg/m³.

The capability of quantifying the drag force D in the above equations is key to obtaining the rheology parameters, such as viscosity and yield strength. The drag force can be written in terms of a drag coefficient (C_d) as

$$D = \frac{1}{2} \rho_w C_d V^2 \left(\frac{\pi}{4} d^2 \right). \quad (5)$$

However, converting the measured drag force and the velocity to viscosity requires knowledge of the type of fluid.

4.1.1 Newtonian Fluids

For a Newtonian fluid, the drag coefficient of a sphere is well quantified (see, for instance, Gerhart and Gross 1985) as a function of the Reynolds number (Re), defined as

$$Re = \frac{\rho_w V d}{\mu}. \quad (6)$$

The quasi-steady drag coefficient of a sphere is given by

$$C_d = \frac{24}{Re} + \frac{6}{1 + \sqrt{Re}} + 0.4 \quad (7)$$

for $Re < 2 \times 10^5$.

Figure 8. Drag force on a sphere with a diameter of 0.1016 m in a Newtonian fluid for various viscosities.

Figure 8 shows the drag force on a sphere moving in a Newtonian fluid. As indicated by this figure, the expected drag forces when the sphere is in the C layer are very small for the velocity and viscosity range of interest. Likewise, if we set a constant drag force, the resulting terminal velocities would be very large unless the drag force was set to a very small value. Note that if we operate at a high Re range, C_d approaches a constant, independent of μ . Thus, the drag data in this range cannot be used to obtain viscosity information. For best accuracy, we want to operate in the Stokes regime ($Re < 0.1$), where $C_d = 24/Re$. For a fluid with a 100-cP viscosity, $Re = 0.1$ corresponds to a velocity of less than 0.07 mm/s ($d = 0.1$ m, and $\rho = 1500$ kg/m³). The corresponding drag force would be $\approx 10^{-6}$ N (3×10^{-7} lbf). For such fluids, the required accuracy of the velocity and drag measurements are likely to be extremely high.

While the above methodology is only applicable for Newtonian fluids, we can use it to obtain an approximate estimate for the drag forces anticipated in the NC layer, which is believed to be non-Newtonian. If we use a constant apparent viscosity of 10^5 and 10^6 cP, the resulting drag forces also are shown in Figure 8. As shown, the drag forces can be quite large for such high viscosities. Note that for a 3.6-in. diameter tungsten sphere, the

net weight inside the waste is roughly 70 N (16 lbf). Thus, the terminal velocity of a falling ball corresponding to this value of the drag force would be less than 10 cm/s using a 10^6 -cP viscosity material.

4.1.2 Bingham Plastics and Generalized Bingham Plastics

The most common viscoplastic fluid is known as the Bingham plastic. The simplest fluid model for the Bingham plastic model can be described by the following equation:

$$\begin{aligned}\tau &= \tau_B + \mu_B \gamma \quad \text{for } \tau > \tau_B \\ \gamma &= 0 \quad \text{for } \tau \leq \tau_B\end{aligned}\tag{8}$$

where τ_B is the Bingham yield stress, μ_B is the plastic viscosity, and γ is the shear rate.

If a viscoplastic material shows a shear thinning, then the fluid behavior can be described by the Herschel-Bulkley model. Based on knowledge obtained about the waste to date, this model seems to be the most appropriate for a description of the NC waste. The Herschel-Bulkley model is a generalization of the simple Bingham model and replaces the linear shear rate dependence with a power law behavior. Thus, three parameters are needed to describe the fluid:

$$\begin{aligned}\tau &= \tau_B + \mu_o \gamma^n \quad \text{for } \tau > \tau_B \\ \gamma &= 0 \quad \text{for } \tau \leq \tau_B\end{aligned}\tag{9}$$

where μ_o is the consistency index (or zero-shear rate viscosity), and n is the power law index.

The drag force on spheres for Bingham plastics has been investigated experimentally. Analytical studies based on the solution of field equations also exist. A good summary of these works was recently reported by Chhabra (1993).

There are several empirical correlations formulating the functional relationship between the drag coefficient and pertinent dimensionless numbers. The choice of dimensionless parameters depends on the fluid model. For Bingham plastics, the important dimensionless number is the Reynolds number (Re_B), based on the Bingham viscosity (μ_B) and the Bingham number (N_B). In the case of generalized Bingham plastics (Herschel-Bulkley fluid model), these two numbers are modified to include the consistency (μ_o) and power law (n) indices to consider the power law nature of the shear-stress shear-rate relationship. Collapsing the family of drag coefficient curves into a single curve using a two-

dimensionless number (Bingham and plastic Reynolds numbers) has been attempted. This has been accomplished successfully in some cases.

An earlier correlation was provided by Andres (see Chhabra 1993) and was given as

$$C_d Re_B^{1.8} = 10^{12.26 - 0.78 He}, \quad (10)$$

where Re_B and He are the Bingham Reynolds number and the Hedstrom number is defined as

$$Re_B = \frac{\rho V d}{\mu_B}$$

$$He = \frac{\tau_B d^2 \rho}{\mu_B^2}$$

The applicability of this correlation is limited with the range $1 \leq He \leq 27$.

Pazwash and Robertson (see Chhabra 1993) express the difference between the values of drag coefficient for a Bingham fluid and that of a Newtonian fluid (C_{dN}) as

$$C_d - C_{dN} = 36 \frac{He}{Re_B^2}. \quad (11)$$

This correlation is given for a range of $920 < He < 3600$ and $60 < Re_B < 2000$. Equation (11) gave results in reasonable agreement with Ansley and Smith's and Pazwash and Robertson's data but overestimated the data of Valentik and Whitmore (Chhabra 1993).

Plešis and Ansley (Chhabra 1993) proposed a dynamic parameter of

$$Q = \frac{Re_B}{1 + N_B} \quad (12)$$

for a range of $0.7 < Re_B < 1200$ and $2.9 < N_B < 16.5$. The Bingham number N_B is defined as

$$N_B = \frac{\tau_B d}{\mu_B V}.$$

The drag coefficient was expressed as

$$C_d = 5 Q^{-0.49}. \quad (13)$$

As can be seen, this relationship does not approach Newtonian behavior as N_B goes to zero.

Later, Ansley and Smith (1967) modified this relationship and gave the dynamic parameter as

$$Q = \frac{Re_B}{1 + \frac{7\pi}{24} N_B}. \quad (14)$$

Equation (14) is not much different than Eq. (12) because the term $(7\pi/24)$ is equal to 0.91. Ansley and Smith gave the drag coefficient as

$$C_d = \begin{cases} \frac{24}{Q} & \text{for } Q < 20 \\ 0.4 & \text{for } Q > 20 \end{cases} \quad (15)$$

Equation (15) gave reasonable results for the data of Atapattu (1989) and Valentik and Whitmore but underpredicted the data of Pazwash and Robertson (Chhabra 1993).

The dynamic parameter, Q , is redefined by Hanks and Sen for a generalized Bingham plastic (see Chhabra 1993 for the suggested equation). Atapattu (1989) (see Chhabra 1993) suggested that Eq. (11) be used if the Re_B and N_B are redefined to consider the power law contribution for generalized Bingham plastics. He gave the drag coefficient as

$$C_d = \frac{24}{Q}. \quad (16)$$

where Q is defined as

$$Q = \frac{Re_{PL}}{1 + KN_{B,HB}} \quad (17)$$

The plastic Reynolds number (Re_{PL}) and Herschel-Bulkley Bingham number ($N_{B,HB}$) are defined as

$$Re_{PL} = \frac{d^n V^{2-n} \rho}{\mu_o} \quad \text{and} \quad N_{B,HB} = \frac{\tau_B d^n}{\mu_o V^n}$$

Equation (16) predicted Atapattu's own data, with average and maximum deviations of 30% and 48%.

Ito and Kajiuchi (1969) presented the drag force as a function of generalized Reynolds and Bingham numbers. There are additional studies reporting drag coefficients in Bingham plastics (Brookes and Whitmore 1968, 1969).

Direct solution of the field equation received very little attention. One of the earlier studies was reported by Yoshioka and Adachi (1971) and Adachi and Yoshioka (1973). Both papers used the stress and velocity variational principles to obtain upper and lower bounds on the drag coefficient. The calculated shape of the sheared zone was somewhat different than that suggested by Ansley and Smith (1967) and calculated by Beris et al. (1985). The estimated drag coefficient was tabulated as a function of the Bingham number. Chhabra (1993) compared his results with Ansley and Smith's data. This comparison indicated that Yoshioka and Adachi's (1971) upper-bound prediction agreed with Ansley and Smith's data.

Bhavaraju et al. (1978) obtained the drag coefficient for a bubble in Bingham plastics, as well as in power law fluids. Their analysis was based on a perturbation analysis in which the stream function, velocity, and deformation tensor were expressed in the form of a power series for the perturbation parameter of the Bingham number. A first-order solution gave the following equation for the drag coefficient:

$$C_d = \frac{16}{Re_{PL}} \left(1 + 3.22 \frac{N_B}{2} \right) \quad (18)$$

The term in parentheses can be assumed as the correction factor for the drag coefficient.

A more complete solution of the field equations was reported recently by Beris et al. (1985). They present a finite-element/Newton method for a sphere falling in a Bingham

fluid under a gravitational field. They used the calculated variational integrals suggested by Yoshioka and Adachi (1971) to verify the numerical results.

Beris et al.'s (1985) results indicated significant differences with the earlier approximate calculations. The predicted shape of the sheared region was similar to the description by Ansley and Smith (1967). The small unsheared region at 0° and 180° angles increased by increasing the yield stress parameter Y_g , defined as

$$Y_g = \frac{\pi d^2 \tau_B}{2F}, \quad (19a)$$

which reduces to

$$Y_g = \frac{3\tau_B}{d\Delta\rho g}, \quad (19b)$$

for a sphere sinking under the gravity force. In Eq. (19b), $\Delta\rho$ is the density difference between the sphere and the fluid.

In Eq. (19a), F is the external force acting on the sphere. The typical tangential velocity profile at a 90° angle was steeper for higher yield stress parameters and tended to follow the Newtonian profile as Y_g went to zero.

They presented the calculated drag coefficient as a function of the Bingham number and a yield-stress parameter. Their results indicated that the drag coefficient tended to infinity (sphere stops moving) as Y_g goes to 0.143. The numerically computed Y_g reached nearly a constant slope in the C_d - Y_g plane, except for very small values of Y_g . The calculated drag coefficient agreed reasonably with Ansley and Smith's data and the upper bound of Adachi and Yoshioka's (1973) prediction.

By fitting the numerical results, the drag coefficient is expressed as

$$C_d = 1 + 1.87 \sqrt{N_B} + 1.152 N_B. \quad (20)$$

More recently, Atapattu (1989) (see Chhabra 1993) used an optical technique and carried out quantitative and qualitative flow visualization experiments. He formulated the additional effect in the presence of a wall. The calculated shape of the sheared zone resembled qualitatively the previously postulated ones by Ansley and Smith (1967) and Beris et al. (1985). Atapattu's drag prediction was given by Eqs. (16) and (17).

The Reynolds number can be written as

$$Re_B = \frac{\rho V^2}{\mu_B V/d} \quad (21)$$

where the numerator is the dynamic pressure and the denominator is the shear stress. A more general form of the Reynolds number, which includes the yield stress, is therefore

$$Re_B = \frac{\rho V^2}{\tau}. \quad (22)$$

This definition may be more meaningful since the classical Reynolds number considers only the plastic viscosity. Often in this case the Hedstrom number is introduced as another correlation parameter to account for the yield stress. Dedegil (1989) compared this theory with Valentik and Whitmore's data and obtained a single drag coefficient curve as a function of Reynolds number. He suggested the following equations for spheres moving through a Bingham fluid.

$$\begin{aligned} C_d &= \frac{24}{Re_B} & Re_B < 8 \\ C_d &= \frac{22}{Re_B} + 0.25 & 8 < Re_B < 150 \\ C_d &= 0.4 & Re_B > 150 \end{aligned} \quad (23)$$

where

$$Re_B = \frac{\rho V^2}{\tau + \mu_B V/d} \quad (24)$$

Tran et al. (1993) conducted experiments and used Dedegil's suggestions to correlate the drag coefficient for Bingham fluids containing particles. Their results indicated that this formulation correlates the data very well.

4.1.3 Power Law Fluids

The drag force on a sphere moving in power law fluids has been investigated by various authors. The viscosity of a power law fluid is defined as

$$\mu = \mu_0 \gamma^{\bar{n}-1}, \quad (25)$$

For a detailed discussion of this subject, readers are referred to the studies of Chhabra (1983), Dazhi and Tanner (1985), and the textbook by Chhabra (1993). Theoretically, converting a drag force and velocity measurement into a viscosity model would require a finite element code [similar to that discussed by Dazhi and Tanner (1985)]. However, such numerical solutions already exist for the entire range of power law indices (n), ranging from 0 to 1 (see, for instance, Dazhi and Tanner 1985). A curve fit to such solutions can be used if we determine that the fluid of interest behaves as a power law fluid.

Because a power law fluid requires two parameters to be quantified (μ_0 and n), a minimum of two pair of data are required for velocity and drag force. It is also important to note that there appears to be a $\pm 30\%$ gap between the numerical predictions of the drag force and the experimental data. Not all of the blame for this discrepancy is on the theoretical model. There are a number of uncertainties associated with the experimental data reported in the literature. Primarily, wall effects, viscoelastic effects, and the power law approximation result in experimental uncertainties. Nevertheless, there are some empirical data, and an empirical model may also be used to convert the measured velocity and drag force into a viscosity model. Using either a numerical model or an empirical model, the drag coefficient for a power law fluid can be obtained in the following form:

$$C_d = F(Re', n), \quad (26)$$

where Re' is the generalized Reynolds number (accounting for the power law index).

Available studies to evaluate Eq. (26) can be classified into two categories: theoretical studies and empirical correlations. Theoretical studies consider the momentum equation for a creeping flow. They employ one of three methods: the variational principles method, the linearization (or perturbation) method, and the extended moment method. Details of these methods are not presented in this report. For more information, the reader should refer to Chhabra (1993).

There is a significant amount of experimental data in the literature. These data are listed by Chhabra (1993). The rheological behavior of test fluids was approximated by the Ellis model, as well as the Carreau model. From the comparison of experimental data and model predictions, using the Carreau fluid model gave very good results. By introducing the notion of a reference viscosity coupled with simple dimensional consideration, Bush and PhanTien (see Chhabra 1993) gave the following approximated theoretical expression:

$$Y = (1 + k^2 A^2)^{(n-1)/2}, \quad (27)$$

for a range of $1 > n > 0.4$ and $.0 < A < 400$. In Eq. (27), Y is the drag correction factor to be applied to the Stokes formula, A is the Carreau number defined as

$$A = \frac{2\lambda v}{d},$$

λ is the Carreau model parameter, and n is the power index.

Chhabra et al. (1981) indicated that the following expression correlated the values of the drag correction factor within 15% scatter:

$$Y = [1 + 0.5El^{1.65} (1 - \alpha)^{0.38}]^{-0.35} \quad (28)$$

for a range of $1 < a < 3.22$ and $0.1 < El < 141$. In Eq. (28), El is the Ellis number defined as

$$El = \frac{1.4\mu_0 V}{d\tau_{1/2}},$$

α is the Ellis model parameter that is a measure of the extent of shear thinning behavior, $\tau_{1/2}$ is the model parameter that denotes the value of shear stress at which the apparent viscosity has dropped to $\mu_0/2$, and μ_0 is the zero shear viscosity.

One important feature of the available studies is that they are all applicable to Stoke's regime, where the flow velocity is small. Consequently, this restriction should be kept in mind when using the waste viscometer data. At this time it should also be understood that there are a whole host of possible numbers and parameters with which a fluid can be characterized, depending on the applicable model. The flow Reynolds number is probably the most important parameter. In the NC layer the Reynolds number will be small, less than or about 0.1, so that we will operate in the Stoke's regime. In the mixed or C layer the Reynolds number will be from 100 to 1000, well outside the Stoke's regime.

Similar additional studies exist in the literature. The reader is referred to the study of Zhu and Satish (1992) on this subject as an additional reference.

5.0 Error Analysis

We essentially need to measure two quantities, the ball velocity and the drag force on the ball. For static measurements, we need the apparent weight of the ball. Velocity is measured by measuring the rotational velocity of the cable spool by use of an encoder. In order to obtain the ball velocity the spool diameter and the cable diameter must be known. All quantities can be measured to high precision and there is little doubt that we can measure velocity to within 1% over the range from 0.02 cm/s to 1 m/s. Position will be determined from the velocity measurement and should also be known to sufficient precision (1 ball diameter). Cable stretch due to loading has not been accounted for in position determination and remains as an open question. However, the error is expected to be relatively unimportant. Thus, we expect no difficulty in measurements of velocity or in the subsequent determination of ball position within the tank.

Errors in determination of the drag force on the ball and the apparent weight of the ball while immersed in the fluid are more complicated. The drag force on the ball will be some fraction of the total tension measured in the cable. We must account for other factors which affect the total load measured with the load cell. These include:

1. Pulley friction -- may be a function of load and speed
2. Weight of the spooled out cable -- depends on ball position
3. Buoyancy of waste -- depends on density and rheology - acts on ball and cable
4. Drag force on cable
5. Weight of pulley assembly supported by load cell

Some of these factors can be accounted for quite accurately and very simply in laboratory measurements, such as pulley friction, cable weight, and pulley weight. The drag force on the cable and the buoyancy force on the ball cannot be determined from in-tank measurements. Drag force on the cable can be estimated from tests with simulants and some results have already been obtained. In tests with a chemical simulant we have found that the drag force on a cable of about 1/8-in. diameter is about 1 N/m. The drag force in the same simulant on a 1-in. ball is about 2 N, so that for a 3.6-in. ball we expect a ball drag force of about 30 N. We can then expect that even at the deepest point in the tank (about 5 meters into the NC layer) the drag force due to the cable will be less than 20% of the drag force on the ball. Since the cable precedes the ball in raising ball tests, a part of the fluid will have already been sheared by the cable when the ball passes through it. The magnitude of this effect on the measurements has not been investigated and remains an issue which will be addressed in further laboratory investigations. It is expected that the effect will be small, but an accurate estimate of it is necessary in the reduction of the data.

The buoyancy force on the ball or cable when the ball is being pulled through the NC layer is difficult to determine from any experiment. Perhaps the best we can do is

assume that this force can be calculated from a knowledge of the fluid density and the total cable and ball volume involved. It cannot exceed this value. Fully deployed, the cable volume in the waste will be about 15% of the total (cable plus ball) volume occupied. The buoyancy force for the volume involved in a fluid of specific gravity 1.6 is about 7 N. The error in determining the buoyancy force is the most serious.

It should be noted that any errors made in the above quantities will occur systematically in all measurements. In other words, if the determined drag force measured at one ball velocity is in error due to inadequate compensation of the above quantities, then the drag force measured at a second or subsequent velocity will contain the same error. Such errors will result in an overall error in the determined yield strength of the waste, but will not affect the determined viscosity appreciably. At worst the total systematic error will be less than 10 N, so that if the drag force on the ball is 30 N or greater, the error in the determined yield stress would be less than 30%, which is acceptable.

It is presently not known exactly how errors in measurement of drag force and velocity will affect the final determination of rheological properties. The model relating these measurements to yield stress and viscosity as a function of strain rate has yet to be developed. If the waste fluid behaves nearly as an ideal Bingham plastic, then we can use the formulation developed by Beris et al. (1985) to obtain some idea of the effects of measurement errors. The expression relating the near-zero shear rate plastic viscosity and the yield stress to the drag force and ball velocity is:

$$T = 6\pi\mu_oRV \left[1 + 2.65 \sqrt{\frac{\tau_o R}{\mu_o V}} + 2.30 \frac{\tau_o R}{\mu_o V} \right] \quad (29)$$

where,

T is the drag force
 μ_o is the plastic viscosity
 τ_o is the yield stress
R is the ball radius
V is the ball velocity.

In order to obtain both yield stress and viscosity, measurements at two velocities are required, in which case,

$$T_1 = 6 \pi \mu_o R V_1 \left[1 + 2.65 \sqrt{\frac{\tau_o R}{\mu_o V_1}} + 2.30 \frac{\tau_o R}{\mu_o V_1} \right] \quad (30)$$

$$T_2 = 6 \pi \mu_o R V_2 \left[1 + 2.65 \sqrt{\frac{\tau_o R}{\mu_o V_2}} + 2.30 \frac{\tau_o R}{\mu_o V_2} \right] \quad (31)$$

where T_1 is obtained with velocity V_1 and T_2 is obtained with velocity V_2 .

For a generalized Bingham plastic, at least three measurements will be required. We have performed calculations to determine the expected drag force on a ball for a range of ball velocities, viscosities, and yield stresses. The results are shown in Table 1. The units for all quantities are cgs, so viscosity is in poise, yield stress is in dynes/cm², velocity is in cm/s, ball radius is in cm, and drag force is in dynes. In Table 1, T_1 goes with V_1 and T_2 goes with V_2 . The range of yield stress was from 700 dynes/cm² to 70,000 dynes/cm² (0.01 psi to 1.0 psi). The range of viscosity was from 100 poise to 1000 poise, or 10,000 cP to 100,000 cP. Ball velocity ranged from 0 to 1 cm/s. It is presently believed that the actual values for the tank wastes will be somewhere within these ranges, at least for the nonconvective region, and that the ball velocity will be approximately in the 0 to 2 cm/s range in most cases. The conclusions from the error analysis presented here assume that the values for yield stress and viscosity are within the above stated bounds.

Table 1 shows some interesting features. Even for the smallest yield stress and the largest viscosity, the yield stress is the main contributor to the drag force. This is evidenced by the fact that for all cases the drag force does not increase in proportion to the velocity. It increases at a much smaller rate. When the yield stress is very high, a doubling of the velocity results in an increase in drag force of less than 1%. It should already be clear that we will have difficulty making accurate viscosity determinations if the yield stress is very high. Except when the yield stress is very small the drag force is always in excess of 10⁶ dynes (10 N or 2 lb), so we should be able to make drag force measurements to within 1% with a 50 lb load cell. Even for the case with very low yield stress, the drag forces are sufficiently high that 2% measurements of the drag force are possible with a 50 lb load cell. This accuracy is probably acceptable.

Figures 9 and 10 show how the drag force varies over a selected range of viscosity and yield stress for two different velocities. All units in the plots are in cgs. Note the weak dependence on the viscosity and the strong dependence on the yield stress. The data in these figures are just a graphical representation of some of the data shown in Table 1.

Table 1. Calculated Values for Drag Forces (T_1 and T_2) for Specific Values of Velocity (V), Yield Stress (τ_0), Viscosity (μ_0), and Ball Radius (R). All units are cgs.

R	V_1	V_2	μ_0	τ_0	T_1	T_2
4.6	0.5	1	1.00E+02	7.00E+02	7.39E+05	7.81E+05
4.6	0.5	1	1.00E+02	3.50E+03	3.42E+06	3.51E+06
4.6	0.5	1	1.00E+02	7.00E+03	6.72E+06	6.84E+06
4.6	0.5	1	1.00E+02	3.50E+04	3.28E+07	3.30E+07
4.6	0.5	1	1.00E+02	7.00E+04	6.51E+07	6.55E+07
4.6	0.5	1	5.00E+02	7.00E+02	8.70E+05	9.77E+05
4.6	0.5	1	5.00E+02	3.50E+03	3.69E+06	3.91E+06
4.6	0.5	1	5.00E+02	7.00E+03	7.10E+06	7.39E+06
4.6	0.5	1	5.00E+02	3.50E+04	3.36E+07	3.42E+07
4.6	0.5	1	5.00E+02	7.00E+04	6.63E+07	6.72E+07
4.6	0.5	1	1.00E+03	7.00E+02	9.77E+05	1.14E+06
4.6	0.5	1	1.00E+03	3.50E+03	3.91E+06	4.22E+06
4.6	0.5	1	1.00E+03	7.00E+03	7.39E+06	7.81E+06
4.6	0.5	1	1.00E+03	3.50E+04	3.42E+07	3.51E+07
4.6	0.5	1	1.00E+03	7.00E+04	6.72E+07	6.84E+07
4.6	0.1	0.3	1.00E+02	7.00E+02	6.84E+05	7.16E+05
4.6	0.1	0.3	1.00E+02	3.50E+03	3.30E+06	7.37E+06
4.6	0.1	0.3	1.00E+02	7.00E+03	6.55E+06	6.65E+06
4.6	0.1	0.3	1.00E+02	3.50E+04	3.24E+07	3.26E+07
4.6	0.1	0.3	1.00E+02	7.00E+04	6.46E+07	6.49E+07
4.6	0.1	0.3	5.00E+02	7.00E+02	7.39E+05	8.15E+05
4.6	0.1	0.3	5.00E+02	3.50E+03	3.42E+06	3.58E+06
4.6	0.1	0.3	5.00E+02	7.00E+03	6.72E+06	6.94E+06
4.6	0.1	0.3	5.00E+02	3.50E+04	3.28E+07	3.33E+07
4.6	0.1	0.3	5.00E+02	7.00E+04	6.51E+07	6.58E+07
4.6	0.1	0.3	1.00E+03	7.00E+02	7.81E+05	8.94E+05
4.6	0.1	0.3	1.00E+03	3.50E+03	3.51E+06	6.58E+07
4.6	0.1	0.3	1.00E+03	7.00E+03	6.84E+06	7.16E+06
4.6	0.1	0.3	1.00E+03	3.50E+04	3.30E+07	3.37E+07
4.6	0.1	0.3	1.00E+03	7.00E+04	6.55E+07	6.65E+07

Figure 9. Calculated drag force (T) as a function of yield stress (τ_0) and viscosity (μ_0) for a ball velocity of 0.5 cm/s. All units are in cgs.

Figure 10. Calculated drag force (T) as a function of yield stress (τ_0) and viscosity (μ_0) for a ball velocity of 1.0 cm/s. All units are in cgs.

Equation (29) is difficult to handle for purposes of analytic error analysis. Another expression relating drag force to yield stress and viscosity for Bingham fluids is given by Ansley and Smith (Eqs. (14) and (15)) as,

$$T = 6\pi\mu_oRV \left[1 + 2 \frac{\tau_o R}{\mu_o V} \right] \quad (32)$$

This equation gives results similar to those predicted by Beris et al. (1985). Substituting values for the ball radius and evaluating in cgs units, we obtain

$$T = 86 \mu_o V + 788 \tau_o \quad (33)$$

The drag force is the sum of two terms, the first of which involves only the viscosity and velocity and the second depends only on the yield stress and ball radius. For the parameter range of interest here, the second term will always be much larger than the first term. If we neglect the first term, the expression for the fractional error is

$$\frac{\Delta \tau_o}{\tau_o} = \frac{\Delta T}{T} \quad (34)$$

This expression shows that the fractional error in the determined yield strength is the same as the fractional error in the measured drag force. This result has also been verified in numerical calculations using Eqs. (29-32) where small errors were assigned to the measured drag forces. Systematic errors due to improper accounting of buoyancy forces and drag force on the cable will be the dominant contributors to errors in the yield stress. Measurement errors are negligible in comparison. However, as discussed above even systematic errors are not expected to be so large as to cause unacceptable errors in the determination of the yield stress.

In Eq. (34) it has been implicitly assumed that there is negligible error in the measurement of the ball radius. Since this radius can be precisely measured beforehand, this assumption is justified so long as the ball radius remains constant throughout its deployment in the tank. Crystal growth or accumulation on the ball during the course of experiments may result in an effective change in the dimension of the ball. For this reason, a polyethylene coating will be applied to the ball to reduce the possibilities of crystal growth. Tests performed in the laboratory using a chemical waste simulant at 45°C have shown that crystal growth does not occur on either a polyethylene-coated or bare tungsten carbide ball over time periods of one month. Therefore, we will neglect uncertainty in ball radius as a contributor to measurement errors.

The fluid viscosity is determined from measurements at two different velocities. Using Eq. (33) the resulting expression is,

$$T_2 - T_1 = 86 \mu_o (V_2 - V_1) \quad (35)$$

Note that systematic errors in the measured drag forces will not contribute to errors in the viscosity, since they will cancel in subtraction of the two forces. If we solve for μ_o in the above equation and use standard error analysis methods we find

$$\frac{\Delta \mu_o}{\mu_o} = \frac{\Delta(T_2 - T_1)}{T_2 - T_1} + \frac{\Delta(V_2 - V_1)}{V_2 - V_1} \quad (36)$$

The fractional error in the velocities is around 1% and the velocity differences are comparable to the velocities, so the error induced in the viscosity due to velocity measurement errors is of order 1% and is therefore entirely negligible. For the parameter range of interest, the differences in drag forces at two different velocities is small compared to the drag forces themselves (see Table 1). Therefore the uncertainty in the difference can be large even if each individual drag force can be measured to good precision. To good approximation then,

$$\frac{\Delta \mu_o}{\mu_o} = \frac{\Delta(T_2 - T_1)}{T_2 - T_1} \quad (37)$$

Using values shown in Table 1 for the drag forces at two different velocities (0.5 and 1.0 cm/s) and assuming a measurement error of 1% in one of the drag forces, we can calculate the expected error in μ_o for a range of viscosities and yield strengths. The results are shown in Figure 11. The fractional error in viscosity increases with increasing yield strength and decreases with increasing viscosity. It appears that errors of the order of 10% to 200% can be expected in our determination of viscosity. This error can be reduced if the velocity range of the experiments is increased. In our calculations the upper limit on the velocity was 1 cm/s. From Eq. (35) it is seen that if the velocity difference is increased by some factor, then the error in viscosity will be reduced by the same factor. There may be some advantage in performing experiments at as high a velocity as possible consistent with remaining in the Stoke's regime. This is the reason why data collection at 2 cm/s was suggested earlier in discussions about experimental procedure.

It should be noted that if the yield stress and viscosity are outside the bounds assumed in our calculations, then the resulting errors will also be different. For instance, if the viscosity becomes much lower than 100 poise, the resulting error will increase dramatically. This is because the viscous contribution to the drag force becomes very small.

Figure 11. Fractional error in derived viscosity for a range of viscosities and yield stresses. A Bingham plastic fluid model is assumed.

Even if there were no yield stress at all, we would have difficulty measuring a drag force at a ball velocity of 1 cm/s and a viscosity of 100 poise. The viscosity will have to be at least 100 poise if the ball rheometer is to provide reasonably accurate results. Since estimates of the viscosity are around 1000 poise, we expect that we will be able to perform tests in the NC layer. In the convective or mixed layers, the drag will simply be too small to measure accurately unless the ball velocity is increased. It is for this reason that ball velocities on the order of 1 m/s are planned for this region.

The data will be used to determine a reasonable model for the fluid, with the present belief that a generalized Bingham fluid model may serve us quite well. However, if the viscosity and yield strength cannot be determined to sufficiently accurate precision, it may not be possible to choose among several models based on the data. The behavior of the viscosity as a function of strain rate is the most important ingredient for any model. For instance, it may not be possible to choose between a Bingham fluid model

and a generalized Bingham fluid model. On the other hand, it should be remembered that there is no strong requirement for precision modeling. A model which predicts the viscosity to about a factor of two is very acceptable to the currently identified data users community.

The sources for errors in the drag force have been described above. Some of them may be difficult to reduce. On the other hand, some of them will result in systematic errors which affect all measured drag forces in the same manner and these errors will not have a large effect on the derived viscosity. Systematic errors will include errors in the ball weight, the cable weight and drag force, the buoyancy force, and the pulley friction. Errors in load cell readings and errors due to waste inhomogeneity are examples of random errors. However, it is suspected that waste inhomogeneity will probably cause the largest confusion in interpretation and reduction of the data. Let us consider this factor.

The equations relating drag force and velocity to rheological parameters are steady-state equations. Therefore we must pull the ball until a steady-state condition is reached. On a plot of drag force vs. ball position, this will be evidenced by a relatively flat region in the plot. If fluid properties vary within the drag region, then the drag force will reflect these variations and it will be difficult to obtain a precise number for the drag force. Consider for example the data shown in Figures 12 and 13, obtained in the laboratory with a chemical simulant. Figure 12 indicates that a steady-state condition has been achieved and allows for a fairly precise determination of the drag force for the particular ball velocity employed. Figure 13, obtained with the same simulant, is quite different and it is clear that determination of the drag force to anything like 1% accuracy is not possible. In Figure 14 is shown a compendium of simulant data obtained over a range of velocities on two different days. If the Bingham plastic fluid model is applicable, then we would expect the drag forces to plot nearly linearly with velocity. The data at 1 cm/s do not fit very well with the other points. It would be difficult to claim that we have determined the drag forces to good precision. Inhomogeneities in the fluid itself are believed to be the cause of the experimental scatter observed in the data. Tingey (1992) has measured yield stresses which vary in excess of 10% in window C core samples of the NC layer. Thus, even careful accounting of errors and application of the best instrumentation available may not be enough to guarantee highly accurate determination of fluid rheological properties. However, it is believed that by suitable analysis of the data and the development of averaging methods, we will be able to determine the yield stress and zero shear rate viscosity to acceptable accuracy.

In fact, we will be able to measure total cable tension quite accurately, and the discussion above is not about measurement errors but rather points out limitations concerning modeling, the subsequent measurement procedure, and the nature of the waste. The waste may not be structured in a manner which permits simple reduction in terms of some fluid model.

Chem. Sim. Ref2 12-03-93
1" dia - 0.7 cm/sec

Figure 12. Drag force measured in a chemical simulant using a 2.5 cm diameter ball with a velocity of 0.7 cm/s. A steady-state flow is apparently obtained.

Chem. Sim. Ref2 12-03-93
1" dia - 1.0 cm/sec

Figure 13. Drag force measured in a chemical simulant using a 2.5 cm diameter ball with a velocity of 1.0 cm/s. No steady-state region is apparent.

Figure 14. Drag force measured in the same chemical simulant on different days.

The error analysis performed to date has shown that errors in the drag force measurements are the most critical in determining how well we can derive rheological parameters. Velocity measurement errors are unimportant if the velocity can be measured to 1% accuracy. Similarly, ball dimension error is expected to be unimportant. Errors in drag force measurement arise from two sources; compensation errors for forces which are not due to drag on the ball (such as cable and pulley weight, cable drag, pulley friction, and buoyancy) and errors due to accuracy limits on the load cells and the recording instruments. The compensation errors, which are systematic, will result mostly in errors in the derived values of the yield stress. Load cell measurement errors, which are random, will result in errors in the derived values for viscosity. The exact dependence of these errors on the drag force errors is dependent upon the model chosen to relate rheological parameters to the measured quantities. The analysis presented here assumed a Bingham plastic model. Other models can be expected to give somewhat different results, but qualitatively the results should be similar. Inhomogeneity of the fluid is expected to further add to the uncertainty in derived results.

6.0 Additional Laboratory Measurements

In the discussions presented above mention has been made of additional testing which will be required in order to prepare ourselves for the deployment of the ball rheometer and the subsequent analysis of the data. In this section we will briefly review these measurements.

6.1 Tests to Establish Expected Ball Rheometer Behavior

1. Test large ball in a simulant to determine expected pull distance needed to reach steady-state flow conditions. This test will require a fairly large volume of simulant in order to minimize boundary effects. A Bentonite clay mixture may be sufficient for this test. Tests should cover the range of Bingham numbers expected in actual waste. The effects of interfaces should also be examined in these experiments.
2. Perform tests to determine the expected drag on the cable. Repeat tests using only the ball and then the ball and cable. In this manner we can determine if the cable influences the drag force on the ball. Tests should be performed using a chemical simulant near tank temperature (about 50°C). Present tests have been performed at room temperature.
3. Perform falling ball experiments in a chemical simulant. Test both constant force-variable velocity and constant velocity-variable force options. These tests may provide insight on which method is more promising in a waste which has substantial inhomogeneity.
4. Devise test to determine inter-related effects of buoyancy and waste yield strength on drag force measurements in a chemical simulant. Since the drag force scales as the square of the ball radius while the buoyancy scales as the cube of the radius, experiments with different size balls may provide clues. Simulants should include a Bentonite clay mixture as well as a chemical simulant.
5. Perform tests to determine the expected rheological properties of a well mixed chemical simulant. Tests thus far have focused on the NC layer. We need spindle rheometer data on a mixed waste, in addition to ball rheometer data.

6.2 Model Development Tests

There is some belief that the initial overshoot in the drag force as the ball is being accelerated upwards may provide some rheological information, particularly about the fluid Bingham number. The existing theories on ball rheometry make predictions based on steady-state flow conditions. The overshoot is a transient phenomenon and has not

been studied in detail. Limited studies with simulants in the laboratory have not shown the initial drag force spike to be a strong function of Bingham number, and little difference in the magnitude of the spike is observed over variations of a factor of ten in Bingham number. Theoretical investigation of this transient behavior should be conducted to determine the expected dependence of the start-up spike on rheological parameters. These predictions should then be tested in the laboratory using well characterized fluids as well as a chemical simulant.

Experimental tests will also be performed expressly for the purpose of developing a fluid model which describes the tank waste. These experiments will be performed using a chemical simulant of the waste.

We will perform a series of falling-ball tests using x-ray radiography. These tests will be performed with a simulated waste, which yields with an external force exerted on it. When real and simulated wastes are allowed to settle, they form the convective and nonconvective layers. In the convective layer, the density and solid fraction are less than in the nonconvective layer. The nonconvective layer shows a yield stress owing to the crystal formation. We will perform falling-ball tests for both uniformly mixed waste, which is yielded by mixing, and waste in the nonconvective layer, which is not yielded. We will use the waste simulant previously developed by LANL.

From falling-ball tests, we plan to learn more about the unexpected problems regarding in-situ rheology measurements. This information will give us guidelines for these measurements and their evaluation. We also will perform falling-ball tests using a 3.5-in. diameter tungsten ball, as in in-situ testing, using x-ray radiography. Los Alamos will develop computer software for the data reduction for in-situ measurements. Below, we briefly detail these tests.

6.2.1 Waste Simulant Characterization Tests

The objective of these tests is to characterize the simulant in terms of densities and solid fraction as a function of a given initial recipe, temperature, and time.

6.2.2 Falling-Ball Tests with Yielded Waste Simulant

The objective of these tests is to measure the viscometric behavior of the uniformly mixed waste simulant with the falling-ball technique, using x-ray radiography as a function of temperature and solid fraction. A necessary objective is to verify that the yielded waste simulant can be characterized as a continuum.

6.2.3 Falling-Ball Tests with Unyielded Waste Simulant

The objective of these tests is to measure the viscometric behavior of the unmixed waste simulant after it has had sufficient time to stratify. The falling-ball technique, using x-ray radiography, will be used to probe the simulant as a function of temperature and solid fraction, assuming that the simulant can be characterized as a continuum.

6.2.4 Viscosity Measurements with Other Methods, Using the Yielded Waste Simulant

We intend to perform additional viscosity measurements, using different techniques to compare the falling-ball measurements with other techniques.

6.2.5 Flow Visualization in Falling-Ball Tests to Determine the Shape of Yielded Region

The purpose of this test is to determine the shape of the yielded envelope around a falling ball in the unyielded waste simulant experimentally. This information will verify the prediction of the choice of constitutive equation and, if needed, the numerical model.

6.2.6 Falling-Ball Tests with 3.6-in. Diameter Tungsten Ball

The objective of these tests is to obtain data for unyielded waste using a 3.6-in. diameter tungsten ball and x-ray radiography at representative conditions. Similar experiments will be conducted in a test setup in which the ball is pulled with a constant velocity.

7.0 Conclusions

Knowledge of the rheological properties of the waste material contained in Hanford Site high-level radioactive waste tanks is crucial for the success of many of the mitigation/remediation schemes. The ball rheometer is being developed as a means for obtaining in-situ rheological information about the waste. Initial deployment of this device will be in Tank 101-SY. In this report we have discussed the need for the ball rheometer and have described in some detail its mechanical structure, its mode of operation, and the factors which will influence its utility in the measurement of the waste's rheological properties.

Current rheology data has been shown to have significant uncertainty. For example, there is a considerable difference in the C layer viscosity for samples from windows C and E. Rheology measurements on core samples from NC layer have shown anomalous results. Typically, the rheograms show that the shear stress is a decreasing function of the strain rate at low strain rates. This behavior is not observed as a quasi-steady and stable rheogram for any other material (and/or slurries) investigated in the literature.

NC layer data also indicate that over a certain range of temperatures and strain rates, viscosity increases with increasing temperature, contrary to the behavior of most fluids.

The experimental method (cone-and-plate viscometer) previously used in obtaining the rheology data from the core samples also has a number of drawbacks. One of the most important is that the clearance of the cone-and-plate viscometer is on the same order as the crystalline sizes existing in the waste (the crystalline particles in the waste slurry are believed to be 1 to 100 μm in size). For a cone-and-plate viscometer used in the hot-cell measurements, this particle size is likely to interfere with the gap, resulting in erroneous viscosity or yield stress measurements.

In order to test the adequacy of cone and plate for the waste rheology measurements, a series of laboratory tests were performed using different viscometers and a chemical simulant of the waste. These tests showed that the cone-and-plate viscometer yields reasonably repeatable results for Newtonian fluids and non-Newtonian fluids with very fine particles. The measured values for these fluids using the cone-and-plate viscometer were also in good agreement with the values obtained using cylindrical spindles. The cone-and-plate viscometer gave significantly different readings from spindles for the simulated waste. The repeatability of a test for the cone and plate was also unacceptable and showed unacceptable scatter. Spindles, however, gave reasonably repeatable results for the same waste simulant. We concluded that with the crystalline sizes on the same order as the clearance of the cone and plate, the cone-and-plate viscometer will provide unacceptable measurements and therefore this rheometer is not recommended for the rheology measurement of the wastes. Although spindles gave repeatable results, the measured quantity was in question because of the concern associated with the particle migration in a shear flow field. Additional tests with a falling ball also were performed. These preliminary tests showed shear thinning behavior. However, the measured values were similar to those obtained using the spindle method.

The waste's yield stress was measured previously by the vane method and the method of measuring the shear stress at which flow first begins under constant shear stress or shear rate conditions. There are significant differences (about 100%) between values obtained from the vane method and the method of measuring the shear stress at the onset of flow under constant shear rate. When the values obtained from the two tests mentioned above are compared with the value obtained from an indirect method, they differ by orders of magnitude.

The need for better in-situ measurements of the rheological properties of the waste is therefore established. The advent of mitigation techniques such as the mixer pump have also created a need for instrumentation with which the effectiveness of a method can be measured. The ball rheometer can provide data from which the effectiveness of the mixer pump can be determined at least to some degree. Simple location of the boundary separating the convective or mixed layer from the nonconvective layer will allow a determination of the influence of the mixer pump on the waste.

We have pointed out some limitations on the capability of the ball rheometer. It is most likely to provide rheological information about the NC layer. The C or mixed layer may have a yield stress and viscosity which are too low to measure accurately, and it is possible that only upper bounds will be established. It is expected to provide a better measurement of density in the mixed or convective layer than in the nonconvective layer. Interfaces between fluid layers may introduce difficulties in the reduction of data. Stratified or inhomogeneous material in the nonconvective layer are also likely to present problems in the reduction of data.

Rheological properties of the waste can be measured in-situ with the ball rheometer. The yield stress and viscosity can be obtained from the measured drag force and ball velocity using a correlation for the drag coefficient. This approach will give reasonable results if the fluid behavior is identified correctly. For a generalized Bingham plastic, at least three tests with different ball velocities at the same elevation are necessary to evaluate the rheology of the waste from the measured drag force and velocity. If the solid and gas concentrations do not vary significantly over a distance of several feet (i.e., if the rheology is constant), then acceptably accurate determinations of yield stress and viscosity are possible. The ball rheometer will provide the most accurate results if the waste viscosity and/or the yield stress are appreciably high. Therefore it is expected to be most applicable to the NC layer. For low viscosities (less than 1000 cP), such as may exist in the convective or a mixed layer, and near zero yield stresses, the drag force on the ball becomes very small and is not a strong function of the ball velocity.

An analysis of errors and the manner in which they manifest themselves in the derived rheological values has been performed. This analysis shows that systematic errors are most important for the determination of the yield stress while even small random errors in the measurement of the drag forces can have a large effect on the determination of the viscosity. Choice of the most suitable model to describe the fluid behavior may be difficult based solely on the data. However, the magnitude of expected errors presently appears acceptable to users of the data, and there may be no strong need to determine the most appropriate model.

Additional testing in the laboratory with simulants is necessary before the ball rheometer can be expected to provide reliable information from in-situ measurements in the tank. Testing to determine the effects of ball and cable interaction and drag on the cable as well as the effective buoyancy in the fluid must be performed. In addition, the pull distance necessary to arrive at a steady-state condition needs to be determined. Several other tests have been described. Laboratory testing with chemical simulants is also necessary for development of a model which we believe will adequately describe the waste fluid and with which we can reduce the ball rheometer data. Development of a reasonably accurate fluid model will be very important in contributing to the success of the ball rheometer.

The ball rheometer will be successful if it can provide the following information:

1. density in the convective or mixed region,
2. location of the boundary between the convective and nonconvective region,
3. yield stress and viscosity of the nonconvective region to within 50% of true values, and
4. upper bound to the apparent viscosity of the convective or mixed region.

Accomplishment of the above may be difficult and depends somewhat on the nature of the waste material, which is not known to sufficient detail at present. For instance, if the yield stress of the NC layer is too high, it may be necessary to manually assist the ball to the bottom of the tank. If inhomogeneities are too great within the NC layer, we may have difficulty in reducing the drag force data. If the fluid nature of the waste cannot be captured in some fluid model, then reduction of the ball rheometer data may not be accomplished to within the required precision. The resolution of some of these issues will not be accomplished until actual in-situ data are acquired. However, it is presently felt that these issues can be dealt with and that the ball rheometer will accomplish the measurement goals for which it has been designed.

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APPENDIX D

TEST STRATEGY AND DATA REDUCTION

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August 3, 1994

MIT94:2083

Mr. J. W. Lentsch
Senior Project Manager
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Dear Mr. Lentsch:

Subject: Viscometer Test Plan

Attached is the test plan for initial operation of the viscometer in 101-SY, "Acquisition and Reduction of Data Obtained from Tank 101-SY In-Situ Ball Rheometer", PNLMIT:080394. This satisfies the deliverable for activity #330 on the schedule. This plan will form the basis for future tests in 101-SY and other tanks.

Sincerely,

C.W. Stewart, Manager
Hydrogen Mitigation Project

CWS:kah

Enclosure

cc: J Abbott (LANL)
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Acquisition and Reduction of Data Obtained from Tank 101-SY In-Situ Ball Rheometer

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Acquisition and Reduction of Data Obtained from Tank 101-SY In-Situ Ball Rheometer

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Abstract

Development of the ball rheometer to measure rheological properties and density of the waste in Hanford Tank 241-SY-101 will be completed around September, 1994. This instrument is expected to provide the first-of-its-kind in-situ measurements of the fluid properties, such as viscosity, of the waste contained within this tank that have been desired for years. Since the ball rheometer project began, a mixer pump has been installed in this tank, and by all accounts this pump has been very successful at mitigating the flammable gas problem associated with Tank 101-SY. Present plans now call for the use of mixer pumps in several other tanks.

The ball rheometer will serve as a diagnostic tool for judging the effectiveness of mixing in Tank 101-SY and others and will be one of few in-situ probes available for diagnostic measurements. The data requirements and basis of choice for the ball rheometer and the theory of the operation of the ball rheometer have been covered in previous reports (Pasamehmetoglu et al., 1993, Shepard, 1993, Shepard et al., 1994). The in-situ data collection strategy and the methods of data analysis and reduction are presented in this final report concerning this instrument. Based on experiments performed at Los Alamos National Laboratory and Pacific Northwest Laboratory, it is believed that a generalized Bingham fluid model (Herschel-Bulkley fluid model) may be useful for describing at least some of the waste contained in Tank 101-SY, and data obtained in the tank will initially be reduced using this fluid model. The single largest uncertainty in the determination of the drag force on the ball is the drag force which will be experienced by the cable attached to the ball. This drag can be a substantial fraction of the total drag when the ball is deep within the tank. Careful accounting of the cable drag will be important in the reduction of the data.

It is expected that the fluid properties may be history dependent, thus rheological properties of the undisturbed fluid may be different from the same properties after the fluid has been disturbed by passage of the ball. The data collection strategy allows the determination of the waste fluid rheology both in the undisturbed state and after it has been disturbed by the ball. Fluid density will be measured at regular intervals. Unlike the rheological parameters, measurement of density requires no model for its interpretation; however, the effects of yield stress may need to be accounted for. This measurement can be made with fairly good accuracy and may provide the most useful data in determination of mixer pump effectiveness.

1.0 Introduction

Since mid-1993 a team made up of staff from Westinghouse Hanford Company (WHC), Pacific Northwest Laboratory (PNL), and Los Alamos National Laboratory (LANL) has been developing a measurement instrument for determination of some of the fluid properties of the wastes contained in Tank 241-101-SY (hereafter abbreviated as 101-SY) on the Hanford Reservation. The ball rheometer was chosen for its simplicity, its ease of deployment, and its capabilities for providing data from which fluid density, yield stress, and apparent viscosity can be determined. The basis for its choice and the identified data requirements are outlined in an earlier report (Shepard 1993), while the underlying theory and practical application of the ball rheometer are given in other reports (Shepard et al. 1994; Pasamehmetoglu et al. 1993). The ball rheometer consists of a ball attached to a cable which is wound onto a spool. The system will be installed on a riser pipe through which entry into Tank 101-SY is obtained. The ball can be lowered into the waste or retrieved from the waste by rotation of the spool, which is mechanically connected to electric drive motors. The present ball is comprised of a tungsten alloy and is 9.1 cm in diameter and weighs about 16 lb (7.3 kg). It is likely that other balls of similar size but lower density, such as a steel ball, will also be employed. The cable is stranded stainless steel of diameter 0.32 cm (0.125 inches) and has a polyethylene coating. A diagram of the ball rheometer is shown in the following figure. The ball is deployed into the waste and retrieved by rotation of the take up spool. Typically the ball will be deployed at a constant velocity, which is adjustable over the velocity range from 0.1 cm/s to 100 cm/s. The cable passes over a pulley to which a load cell is attached. The tension in the cable, or actually twice the tension in the cable is measured by this load cell. We will measure the tension in the cable as the ball is being moved through the waste at different velocities. From these measurements, the drag on the ball due to movement through the waste can be determined. The amount of drag depends on the rheology (roughly the yield stress and the viscosity) of the waste fluid, and we are interested in determining the rheology of the fluid. Static force measurements obtained while the ball is at rest in the fluid will allow a determination of the fluid density. We intend to characterize the fluid at all depths within the tank.

Diagram of the Ball Rheometer System Showing the Ball, Cable, Take-up Spool, Pulley, and Load Cell. The instrument fastens to a riser pipe through which entry into the waste tank is obtained.

This report is largely concerned with the testing strategy when the ball rheometer is installed on Tank 101-SY. The strategy is based partially on the results of laboratory investigations conducted at LANL and PNL. The methods to be used for reduction of the data to obtain fluid properties is also a topic of interest here. Finally, some estimates of the accuracy we can expect in the derived fluid properties will be given.

In Section 2.0 of this report, we review the results obtained from laboratory investigations using chemical simulants of the waste. Experiments were performed at both LANL (primarily falling ball experiments) and PNL (primarily drag force measurements). These results are important for forming the tank testing strategy, which are presented in Section 3.0. The methods for reduction of the data to obtain fluid rheological parameters and fluid density are discussed in Section 4.0. Reduction of the data presently requires a fluid model, and we will initially assume that the fluid behaves as a generalized Bingham (Herschel-Bulkley) fluid and reduce the data to obtain parameters for the model. It should be noted that a time independent generalized Bingham fluid model may not adequately describe all or parts of the real waste. We can fully address the problem of data reduction only after we have acquired actual in-situ data. The actual tank waste may behave differently from the simulant tested in the laboratory. In Section 5.0 we present an estimate of the accuracies for the derived fluid rheological parameters and the fluid density. Conclusions and a summary are given in Section 6.0. An Appendix contains detailed information about the experiments performed at both laboratories, as opposed to the cursory review presented in the main body of this report.

2.0 Results from Laboratory Investigations

Experiments were performed at both PNL and LANL in support of the ball rheometer project. Experiments at PNL used an experimental setup which closely resembles the actual hardware being constructed by WHC. The primary purpose of these tests was to examine unresolved issues concerning the expected performance of the in-tank ball rheometer. Experiments at LANL were concerned with determination of the fluid properties of a chemical simulant of the 101-SY waste which is expected to behave similarly to the actual waste fluid. These experiments were aimed at determining the applicability of fluid models to describe the behavior of the simulant and at examining the fluid behavior of the simulant. The experiments will be described separately below.

2.1 Experiments Performed at PNL

The force measured by the load cell will not simply be the drag force on the ball. Other forces also contribute to the measurement. In the reduction of the force data to obtain the rheology of the fluid, the drag force on the ball is of primary importance. In the measurement of density, the buoyancy force on the ball must be determined. It is

necessary to determine all of the forces at work in these measurements and then determine which part of the total force is due to drag on the ball. As a result, the actual measured force will have to be corrected to account for quantities such as the weight of the ball, the weight of the deployed cable, the weight of the pulley, the friction in the pulley, and the buoyancy forces on both the cable and ball. Finally, the drag force on the cable has to be determined. Some of these forces can be obtained by laboratory measurements prior to deployment of the ball. For instance, the weights of all components and pulley friction should be well known ahead of time. Buoyancy can be reliably calculated from static measurements made in the tank. It turns out that only one force, the drag force on the cable, will present difficulties for measurement or calculation. This conclusion was reached independently at both laboratories.

A theoretical analysis was performed to identify the various forces measured with the load cell. Then, experiments were performed with simulants to estimate the contribution to the total force due to buoyancy and drag on the cable. In addition, constant velocity drag force experiments were performed using several ball sizes and simulants to determine how the drag forces on the ball varied with ball size and velocity for these fluids. These experiments simulate the manner in which data will be collected in actual work with the in-tank ball rheometer. Finally, we investigated the effects due to fluid boundaries (such as the air-fluid interface) and also transients that arise when motion of the ball is started and stopped. Experiments were performed with three different fluids: a chemical simulant of the waste, carbopol (a semi-clear polymer fluid containing no particles), and Bentonite clay (a mixture of clay and water having a high yield stress and viscosity) in order to span a reasonable range of Reynolds and Bingham numbers. We have attempted to parameterize the expected transient responses in terms of the fluid properties. Samples of the fluids were also characterized independently using a Bohlin rheometer, which consists of a pair of concentric cylinders with the sample contained in the gap between the cylinders. The results obtained with this instrument were then compared with results obtained by reducing the drag force data using theoretical relationships.

The equations giving the drag force on the ball in the case of a falling and rising ball are given respectively by (see Appendix),

$$D_b = B_b - C(z-z_0) - \int_{z_0}^z [A(z') - B(z')] dz' - \frac{\eta - \Delta R_f}{2} \quad \text{falling ball} \quad (1)$$

and,

$$D_b = -B_b + C(z-z_0) - \int_{z_0}^z [A(z') + B(z')] dz' - \frac{\eta + \Delta R_r}{2} \quad \text{rising ball} \quad (2)$$

where

D_b	=	drag force on ball
B_b	=	buoyancy force on ball
z_0	=	reference position of ball
z	=	ball position
A	=	drag coefficient for cable
B	=	cable buoyancy coefficient
C	=	weight per unit length of cable
η	=	pulley friction coefficient
ΔR	=	$R(z) - R_0$
R_0	=	load cell reading at reference location z_0 .

The above equations assume a reference measurement (R_0) of the cable tension. This measurement should be made just above the surface of the waste (at z_0) and includes the weight of the ball, pulley, and the deployed cable. In the experiments, ΔR will be a measured quantity. Some of the other quantities given in Eq. 1 and 2 will be well known but will not be directly measurable during experiments. The weight of the cable per unit length can be determined with prior measurements. Pulley friction as a function of load and speed can also be measured beforehand. Both the buoyancy on the cable and the drag on the cable may not be linear functions of the deployed cable length, since they depend on the fluid properties. If the density is known as a function of depth, then the cable buoyancy can be calculated as an integral over the cable length. For density measurements the drag forces and the pulley friction become zero and the density is calculated from

$$B_b = - \int_{z_0}^z B(z') dz' + C(z-z_0) - \frac{\Delta R}{2} \quad (3)$$

and the relation

$$\frac{\pi d^3}{6} \cdot \rho \cdot g = B_b \quad (4)$$

where ρ is the fluid density, d is the ball diameter, and g is gravitational acceleration. If the fluid density is measured at regularly spaced intervals, then the integral over the

depth can be performed to obtain the total buoyancy of the cable. Thus, static measurements allow a direct determination of the buoyancy forces and therefore the fluid density. Errors in the estimation of fluid density may result if the fluid has a significant yield stress and the ball is partially supported by this force, which is unaccounted for in Eq. 3. Laboratory experiments with a well mixed simulant have shown that the effect is negligible. The same may not necessarily be true in the actual tank waste, and this subject will be revisited when actual data are obtained. In examining Eq. 1 and 2 and in consideration of the above comments, it is seen that all terms in these equations can be accounted for except the cable drag coefficient (A).

The drag on the cable depends on the rheological properties of the fluid, which may be a function of depth within the fluid. This drag will also depend upon the length of cable immersed in the fluid. If the ball is deep enough into the waste, the drag on the cable may be a substantial fraction of the drag on the ball. At immersion depths greater than about 3 meters, the surface area of the cable in contact with the waste exceeds the surface area of the ball. We need to know the drag on the ball alone in order to determine the fluid rheology. This means that we need to correct measurements for the drag on the cable, but we can make this correction only if we know the fluid rheology. We presently have no theory with which to calculate the cable drag even if we can estimate the fluid rheology. Laboratory investigations are continuing in order to obtain some knowledge of how to account for cable drag. In the general case it does not appear possible to experimentally determine both drag forces independently in in-situ tests. However, this possibility will be explored. An iterative approach may provide a possible solution of this problem. Knowledge of the cable drag force as a function of position in the waste will allow the calculation of the integral for the total cable drag at any depth into the waste. We will discuss this problem in more detail in the Section 4.0, which deals with data reduction.

Experiments were performed to verify that the buoyancy of the ball is given by Archimedes Principle even when the ball is in motion through non-Newtonian fluids. These experiments verified that Archimedes Principle is applicable for these fluids and the measurement of fluid density will be possible in experiments conducted in the tank. Again however, if the fluid has a significant yield stress the accuracy of density determinations may suffer.

Experiments were conducted where only the drag forces acting on cables were measured. As with all of our experiments, the range of Reynolds number and Bingham number was limited. For experiments involving just the cables, the Reynolds number was always less than 0.1 while the Bingham numbers ranged from about 1 to 10. The results indicate that while the drag force per unit length of cable is small, the total force acting over a long cable may in some cases be comparable to the drag force on the ball. The drag force is dependent on the types of fluids tested, but appears weakly dependent on cable velocity. This result suggests that the drag is dominated by forces needed to yield the fluid, rather than by viscous drag. However,

no clear trends are apparent from the data. The drag force does not seem to correlate with the fluid yield stress, Bingham number, or Reynolds number. These experiments will be repeated in further attempts to understand the correlation between cable drag and fluid rheology.

There was concern that, for rising ball tests, the passage of cable through a region of fluid prior to the passage of the ball through the same fluid may affect the drag force on the ball due to the prior disturbance of the fluid. Experiments with the chemical simulant (well mixed), the bentonite clay, and the carbopol have shown that the effect is negligibly small. These experiments were mostly performed at Reynolds numbers less than 1.0.

In any experiment there will be a transition region where the ball accelerates to a constant velocity and steady state fluid flow is established about the ball. Available theory with which we will reduce the drag force data is based on steady state fluid flow. Experiments were conducted to examine the pull distance required before steady state drag is observed. The distance depends somewhat on the fluid rheology, but is typically of the order of one ball diameter, at least in our tests where the Reynolds number typically less than unity. The range of Reynolds numbers expected in actual testing in the tank may be substantially higher than 1, perhaps as high as $Re = 50$. In use of the ball rheometer in the waste tank, a pull distance of greater than one ball diameter will probably be required, and we plan initially to use at least three diameters. The required pull distance can be determined in actual in-situ testing, and adjustments will be made as necessary.

The effects of interfaces were also investigated in our experiments. For the fluids tested, a boundary (such as the fluid-air interface) begins to affect the measured drag forces when the ball approaches to within about one ball diameter of the interface. For experiments within the tank then, experiments should begin well away from known boundaries, such as the surface and the tank bottom. Interfaces within the fluid where the character of the fluid changes dramatically will be observed over a distance of several ball diameters over which it will be difficult to obtain reliable steady state data.

2.2 Experiments Performed at LANL

Primarily free-falling ball experiments were conducted in these tests. In addition, a significant effort was put forth to produce a large quantity of a chemical simulant. The primary focus of the experiments was to determine the applicability of continuum fluid mechanics in the analysis and reduction of ball rheometer data and to determine an appropriate fluid model with which to describe the fluid. Data were obtained with two simulants; an "aged" simulant which has been resident at LANL for years and a new simulant just recently prepared and chemically very similar to the older simulant. Tests show that the two simulants are not the same, but do not differ greatly. A generalized Bingham fluid model appears to be applicable for both of these fluids. The effect of

cable drag was also investigated analytically. Calculations based on the assumption of a Newtonian fluid indicate that cable drag can be a substantial fraction of the drag on the ball, in agreement with the experimental findings at PNL. Both laboratories have independently identified cable drag as a major factor in the reduction of the actual in-situ data. In addition, experiments were conducted with a settled simulant in order to observe how the particulates in the fluid settle and how the fluid rheology changes as a result of the settling. Results from this testing have contributed to the testing strategy which will be discussed below. For instance, based on these laboratory tests we will conduct experiments to probe the dependence of fluid properties on the shearing history of the fluid. It was observed in these experiments that the behavior of the fluid depends on this past history. Also, these tests showed that the undisturbed fluid can only be tested in falling-ball experiments, rather than with retrieving-ball experiments. Details of the laboratory investigations performed at LANL are given in the Appendix.

Experimental work at LANL required a considerable amount of simulant. Some existing waste simulant was available, but not nearly enough. Thirty gallons of new simulant was prepared following a procedure developed at LANL. The chemical composition of the new simulant is similar to other formulations used at PNL and is based on the chemical composition of the real waste as determined from sampling. Of course, radioactive components are omitted. While chemically very similar to existing PNL and LANL waste simulants, there was no assurance that all simulants would have exactly similar rheological properties. In order to assure that results obtained at PNL can be compared to those obtained at LANL, about 10 gallons of the new simulant was shipped to PNL for laboratory experiments. Future testing at PNL will be performed with this simulant.

Testing with the simulants was performed using free-falling ball rheometry. In addition, a Couette viscometer was used for an independent characterization of the simulant. Couette viscometry is based upon dissipative resistance in a fluid between two concentric cylinders with at least one of them rotating. Falling-ball tests utilized a variety of balls of different sizes and densities. The balls fell through a 5-cm diameter and 50-cm length column of waste simulant and the flight path of the balls through the column was recorded using x-ray radiography and a video recording system. The ball velocities were determined from the video images. Experiments were performed with well-mixed and settled simulants.

Experiments with a well-mixed homogeneous simulant showed very good reproducibility in the terminal velocities of similar balls dropped through the simulant in repeated tests. The conclusion drawn from these experiments was that the well-mixed fluid behaved as a continuum and was therefore amenable to theoretical treatment as a single phase fluid. In addition, the rheology for the well mixed simulants could be determined from these data. Both simulants ("old" and "new") appeared to behave as

generalized Bingham fluids. However the new simulant had a much higher yield stress.

Results from Couette viscometer tests with the same well-mixed simulants showed qualitatively similar results, but the viscosities were consistently lower by about a factor of two than viscosities determined by the falling-ball method. In addition, there were differences in the power law indices, with the indices being less using the Couette viscometer. The most likely cause for the discrepancy is that the simulant is not exactly described with the simple power law model. Small samples taken from a large volume of simulant were used for these tests, and non uniform sampling may also be a cause for the discrepancies.

Data obtained from falling-ball tests with a settled simulant suggest that the simulant is a history dependent non Newtonian fluid. The fluid apparently thins after being subjected to shear. In repeated falling ball tests through a simulant in which particles had been allowed to settle under gravity, the first ball through a region always dropped slower than subsequent balls dropped through the same region. A fluid model could not be determined for the settled simulant due to the variability of ball velocities in repeat tests. The experiments show that steps should be taken in actual experiments with the tank to determine the history dependence of the fluid rheological properties. As described below, these measurements will be obtained.

The additional complication introduced by the presence of a cable attached to the ball was addressed analytically. Both theoretical calculations and numerical calculations which include appropriate end effects indicate that drag on the cable when the ball is near the tank bottom may be a substantial fraction of the total measured drag. The calculations were based on a Newtonian model for the fluid, and improvements could be made by using non-Newtonian fluid models. However, these studies along with the experimental measurements obtained at PNL establish that cable drag will have to be accurately accounted for in the reduction of the actual in-tank data.

3.0 Data Acquisition Strategy

We desire to obtain a complete profile of the fluid properties from the top of the waste to the bottom. Measurements will be taken proceeding downwards, primarily with a falling ball operated at constant velocity. Once a complete test has been performed, we may desire to perform measurements from bottom to top in order to obtain repeat supplemental data. It should be noted that initially we will have incomplete knowledge the actual waste rheological character and the manner in which the rheology changes as a function of depth in the waste. The goal of the testing is to obtain this information and to establish as completely as possible the nature of the waste held within the tank, at least along one vertical dimension. Our testing strategy will reflect this goal.

We begin this testing description by assuming that the ball rheometer system is in place on the selected tank riser and ready for deployment.

3.1 Measurements in the Riser Pipe and Dome Space

With the ball fully retracted in the "home position," the ball position should be verified to be at distance zero, our reference position. After opening the gate valve which seals the instrument from the tank riser pipe, lower the ball at 1 cm/s for 1 cm and obtain a force measurement after the ball is stopped. The static density mode should be used for this measurement. This measurement determines the weight of the ball and the reading can be checked with the expected result. A reading which deviates from the expected value indicates that either an incorrect load cell has been installed (if there is a gross difference between measured value and expected value) or perhaps the calibration has shifted. The measurement is obtained near the home position so that immediate changes can be made if the measurement indicates a problem. It is fully expected that the measurement will be within tolerances, and the primary purpose of this measurement will be to detect long-term drifts in the apparent weight of the ball which could be due to instrument drift or waste buildup on the ball. Laboratory tests with a chemical simulant performed at PNL have shown that buildup of crystals and other material on the ball and cable occurs very slowly, and for durations of less than about a month buildup should not be a problem. However, our data analysis procedures will identify and quantify these effects.

The ball should then be lowered very slowly through the riser pipe (1 cm/s) while the load cell is monitored to observe reductions in the apparent weight of the ball. Such an observation would be an indicator that the ball is being impeded by the riser pipe or material within the riser pipe. No data are collected in this procedure. However, if the ball becomes stuck or begins to show signs that it is becoming stuck, the ball should be stopped and steps taken to understand the difficulty. Visual verification that the ball has passed through the riser pipe and into the dome space should be obtained utilizing the DACS camera. By the same means, it should also be verified that the cable is not in contact with the riser pipe after the ball has passed through the pipe.

After the ball has passed through the riser, it should be lowered by another 50 cm and brought to rest. A static measurement should then be obtained. Then four constant velocity measurements should be obtained: (1) lower the ball at 1 cm/s for 100 cm, (2) raise the ball at 1 cm/s for 100 cm, (3) lower the ball at 10 cm/s for 100 cm, (4) raise the ball at 10 cm/s for 100 cm. These tests are designed to check for pulley friction and the results should be compared to expected results based on previous laboratory testing. Long-term deviations may indicate a changing pulley friction. A static measurement should follow the final test.

The ball should then be lowered at 1 cm/s to very near the surface of the waste and another static measurement should be obtained. No data need be collected or recorded while the ball is falling. Approach to the surface can be verified by the DACS camera or by prior knowledge of the location of the surface and consideration of the amount of cable which has been released from the cable spool, and the measurement should be performed within several inches of the actual fluid surface. Exact position is not critical, but the ball should not be in contact with the waste. This measurement forms the reference measurement against which all other measurements will be compared. In Eqs. (1) and (2), this measurement provides R_0 . At this point we are ready for measurements in the waste fluid.

3.2 Measurements in the Waste

The first task is to remove a large enough volume of crust from the area immediately beneath the ball so that we can perform tests in the waste. There are several alternative methods for removing the crust. The first attempt will be to see if the ball itself can either push through or past the crust. If this fails, then water lancing will probably be the next option. In any event, the crust must be removed so that it does not interfere with the measurements.

Lower the ball at constant velocity (1 cm/s) for 20 cm while recording data. We should observe that the apparent weight of the ball changes by about 12 N as the ball travels from the dome space completely into the fluid. The spatial midpoint of this gradual change in cable tension marks the level of the fluid, and that level should be recorded on a data sheet. If the change is much larger than 12 N, then possibly the ball is either partially or totally supported by a crust layer. The DACS camera should be used to verify the condition. Steps should be taken to position the ball past the crust layer. Possible tactics include repeated high velocity (1 m/s) impacts of the ball with the crust or perhaps water lancing of the crust. It is essential that the ball travel into the liquid region beyond the crust. Lower the ball at 1 cm/s until the ball is 30 cm below the bottom of the crust layer. As the ball is falling, observe and record the drag force data. If there is a substantial drag, it may be due to friction between the cable and a portion of the crust. As much as possible utilize the DACS camera to help in making a determination. If the crust is impeding the cable, take steps to eliminate the problem. There is little point in continuing unless the cable is free from any influence due to the crust.

Perform a static density measurement. Now a series of repeated measurements will be obtained from this location throughout the entire depth of the tank. We will perform measurements at four velocities: 0.1, 1.0, 3.0, and 10.0 cm/s. These velocities are chosen to span as wide a velocity range as is reasonable practical, thereby providing data over a similarly broad range of strain rate. A minimum of three velocities are required in order to reduce the data in terms of a three-parameter model. A complete set of experiments will require 120 cm of distance in the fluid (30 cm for each velocity).

An implicit assumption in the reduction of the data will be that the fluid can be characterized by the same model parameters over the entire 120-cm distance spanned by a set of measurements. This assumption may not necessarily hold true for the entire depth of the waste. One means of observing changes which occur over a smaller distance scale is to group contiguous sets of data obtained at four (or three) velocities and perform essentially a running average over 120 cm (or 90 cm) every 30 cm.

Starting with the ball at about 30 cm beneath the bottom of the crust, lower the ball at 0.1 cm/s for 1 cm and at the highest data rate (100 samples/s). This step is taken to obtain the initial transient force spike which occurs during the initiation of ball movement and provides an independent estimate of the fluid yield stress. This step will be repeated at the beginning of each drop into undisturbed fluid. Now lower the ball at 0.1 cm/s for 30 cm and at standard data collection rates (15 samples/s). Retrieve the ball at the same speed. Repeat these measurements. From the graphic display, determine if there is any measurable change in the drag force between the two experiments. If a change is observed, repeat the experiment a third time and a fourth time if necessary. When these measurements are done, the ball should be back at its original location, about 30 cm beneath the crust surface. Increase the velocity to 1.0 cm/s and repeat the experiment twice. Repeat the procedure (i.e., two complete runs) at 3.0 and 10.0 cm/s velocities. The point of these measurements is to observe if the fluid changes character as a result of the shearing caused by the ball. Changes can be attributed possibly to mixing or to history dependent behavior (such as thixotropy). Also, by obtaining data at four velocities, some average character for the fluid in the 30-cm section should be obtainable. Lower at 1 cm/s for 30 cm and obtain a static density measurement. We are now at the lower point of the first set of experiments (the fluid immediately beneath the ball has yet to be probed) and are ready to repeat measurements with a different initial velocity. We first perform the drop test at 0.1 cm/s for 1 cm. We then repeat all measurements but start at 1 cm/s velocity (we perform up to four experiments at this velocity) and then proceed to 5.0, 10.0, and 0.1 cm/s. We then lower the ball 30 cm and perform another static density measurement. We are now ready to perform experiments at the third velocity, 3.0 cm/s. After the initial drop test at 0.1 cm/s for 1 cm, the exact same procedure is followed, with an initial velocity of 3.0 cm/s followed by 10.0-, 0.1-, and 1.0-cm/s velocity experiments. After lowering the ball and obtaining another static density measurement, the same procedure is followed with the velocity sequence of 10.0, 0.1, 1.0, and 3.0 cm/s. We then lower the ball 30 cm and obtain another density measurement. At this point a complete sequence has been obtained and we are ready to repeat the entire process again for the next 120 cm of waste. In such a fashion we should work our way downward through the entire tank.

It may happen that the drag force on the ball will increase as we proceed deeper into the waste such that it is no longer possible to obtain high velocities such as 10 cm/s with only gravity acting in the downward direction on the ball. If this event occurs, it

becomes necessary to reduce our velocity range. From the data we should be able to determine a reasonable estimate of the free-fall terminal velocity and then set a new upper limit which is somewhat less than this velocity. In such a case, the similarity between the upwards travelling experiments and the downwards travelling experiments will be broken. Only the velocities of the falling experiments need be adjusted and we will maintain the same velocity range for the retrieval measurements. If the free-fall terminal velocity falls below 1 cm/s, then it will be difficult to obtain sufficient data over a wide enough range of strain rate to adequately produce a rheological curve for the fluid, at least for the falling ball case. When this condition is reached, it is probably best to terminate the falling-ball experiments as described above. Choosing the constant force mode of operation and setting the force as low as possible, we will simply record the free-fall velocity for the falling ball case. Retrieval experiments will be conducted as before, however, so we will still be able to obtain a rheological curve from these data. Density measurements will be obtained at 30 cm intervals just as above.

It is planned that all experiments will be conducted over the same distances, namely 30 cm, and an implicit assumption is that this distance will be sufficient for obtaining a steady state condition. Laboratory experiments suggest that this distance will be sufficient, but these tests were not complete and the tank waste may not behave like the chemical simulants used in laboratory testing. For instance, no tests were performed at a ball velocity of 10 cm/s, nor were any balls greater than 5 cm in diameter used. If in the field we observe in any test that 30 cm is not a sufficient pull distance to achieve steady state then we will increase the distance to perhaps 60- or 90-cm. It may be that conditions are such that we never achieve steady state, in which case we will have to deal with reducing transient data, which will probably be a formidable task.

If the condition occurs where the ball simply will no longer fall through the waste at any velocity, then we will terminate the downwards travelling phase of the experiments and proceed with the retrieval phase of the measurements. Upon completion of the retrieval experiments, a decision will be made as to the viability of water lancing in order to obtain data from deeper in the tank.

A complete set of data obtained over 120 cm will require from about 30 minutes to 60 minutes to obtain, depending on the exact velocity sequence which is followed. If we assume an average time of 45 minutes per set, it will require about 6 hours to perform a complete profile of the tank from top to bottom. Retrieval experiments will require about the same time. For planning purposes, 16 hours of operation time should be allowed for a complete set of experiments and personnel should be so advised.

From the experiments above, we should have a very good notion of the ball weight which the fluid will support. If the apparent weight of the tungsten alloy ball never falls below about 80 N (measured), then a steel ball of the same diameter will also fall

through the waste. Subsequent experiments conducted at later dates should then be performed using a steel ball rather than the tungsten alloy ball. Use of the steel ball allows for use of a more sensitive load cell, such as the 15- or 25-lb full-scale load cell. The advantage gained from this configuration will be most evident in the determination of the fluid density, which can then be reliably determined to within 1%. Determination of model parameters may or may not be improved, but measurement capabilities towards lower viscosities and yield stresses should result. If the steel ball will sink under gravity through most of the tank, we can conclude that the fluid viscosity and yield stress are lower than the upper limits determined to date. An experimental procedure similar to the one described above should be followed.

The above experiments are conducted with the ball generally progressing in the downwards direction, although experiments with the ball in retrieval are performed along with the falling ball tests. A similar set of experiments will be performed with the ball generally heading in the upwards direction. These experiments can commence at any time after the falling-ball experiments are concluded. Experiments with the ball in retrieval will provide essentially the same information as the falling-ball experiments. The time-dependent behavior of the fluid can be probed by a comparison of results obtained for both sets of experiments. For example, if the fluid recovers its original characteristics within several hours after the initial passage of the ball through the waste, we should be able to observe this behavior in the retrieval experiments. In addition, a comparison of results may allow some insight into determination of cable drag in the waste. In retrieval the cable leads the ball and is pulled through relatively undisturbed fluid; while in the falling-ball experiments, the cable is always travelling in fluid which has been sheared by the ball. Except for this difference, the experiments will provide basically the same information and, at a minimum, provide a repeat of the falling ball experiments.

The experiments begin by first retrieving the ball 30 cm from its original position, which will be either at the tank bottom or the position of deepest travel in the falling ball runs. Obtain density information using the dynamic density mode. Raise the ball at 0.1 cm/s for 30 cm. Lower the ball at the same speed. Repeat these measurements. From the graphic display determine if there is any measurable change in the drag force between the two experiments. If a change is observed, repeat the experiment a third time and a fourth time if necessary. When these measurements are done, the ball should be back at its original location, about 30 cm above its deepest position. Increase the velocity to 1.0 cm/s and repeat the experiment twice. Repeat the procedure (i.e., two complete runs) at 3.0 and 10.0 cm/s velocities. The point of these measurements is to observe if the fluid changes character as a result of the shearing caused by the ball. Changes can be attributed possibly to mixing or to shear-dependent behavior (such as thixotropy). Also, by obtaining data at four velocities, some average character for the fluid in the 30-cm section should be obtainable. Raise the ball at 1 cm/s for 30 cm and obtain a density measurement. We are now at the upper point of the first set of experiments (the fluid immediately

above the ball has yet to be probed) and are ready to repeat measurements with a different initial velocity. We repeat all measurements but start at 1 cm/s velocity (we perform up to four experiments at this velocity) and then proceed to 5.0, 10.0, and 0.1 cm/s. We then raise the ball 30 cm at 1 cm/s and perform another density measurement. We are now ready to perform experiments at the third velocity, 3.0 cm/s. The exact same procedure is followed, with an initial velocity of 3.0 cm/s followed by 10.0-, 0.1-, and 1.0-cm/s velocity experiments. After raising the ball and obtaining another density measurement, the same procedure is followed with the velocity sequence of 10.0, 0.1, 1.0, and 3.0 cm/s. We then raise the ball 30 cm at 1 cm/s and obtain another density measurement. At this point a complete sequence has been obtained and we are ready to repeat the entire process again for the next 120 cm of waste. In such a fashion we should work our way upwards through the entire tank.

After completion of the retrieval experiments another short set of experiments should be performed. These experiments are done in order to obtain some information about cable drag. Starting at 1 cm/s velocity, lower and raise the ball through the entire depth of the tank four separate times. Repeat the procedure at 3- and 10-cm/s ball velocities. If there are regions over which the drag force varies linearly with pull or fall distance we can perhaps obtain an estimate of the contribution due to drag on the cable.

It should be clear that the rising ball experiments are exactly the same as the falling-ball experiments, except performed in the opposite direction. The same contingencies will apply in case the ball will not drop at the desired speeds. Experiments will terminate when we have reached a position within 30 cm of the bottom of the crust. The time required to perform a complete set of experiments will be very similar to the time taken to perform the falling-ball tests, estimated to be about 6 hours. If experiments are concluded and there is no desire to obtain more data, the ball should be retrieved back into the ball rheometer container. In retrieval through the dome space, the position of the fluid surface should be determined and the apparent weight of the ball should be measured at the reference position just above the fluid surface. If differences are noted these may indicate material buildup on the ball or cable or instrumental drift. In addition to rechecking these values, pulley friction should again be measured. The procedures for accomplishing these measurements are identical to those described earlier except that the waste surface location is determined with the ball going from fluid into the dome space. There is no need to repeat the initial measurement of the ball weight with the cable almost fully retracted. Rather, the ball should simply be returned to the home position. Extreme care should be taken as the ball approaches the riser pipe from below and full use of the DACS camera should be taken.

In the event that more data are desired later on, the ball should be stored in the rheometer enclosure unless retrieval data are needed, in which case the ball should be left as near to the bottom of the tank as possible.

4.0 Reduction of Data

Experimental work with chemical simulants along with rheological data obtained previously with core samples from tank 101-SY (Tingey 1992) have allowed the conclusion that the waste fluid can be modeled approximately as a history dependent generalized Bingham plastic fluid. In reality, many fluids are very complex in their fluid properties and cannot be exactly described by any of the standard fluid models. Fluid models have as their primary advantage a mathematical simplicity and, by virtue of parameters contained within these models, allow a description of the fluid in terms of these parameters. For instance, in the generalized Bingham fluid model, the parameters are termed the consistency index, the power law index, and the yield stress. These parameters only have meaning within the context of the model, and their relationship to fundamental physical parameters is not well established. It is not particularly important for the fluid model to describe the fluid except in a general sense. In our reduction of the data obtained with the ball rheometer, we will initially attempt to describe the fluid in terms of a generalized Bingham fluid, at least for regions where some mixing of the waste has occurred. Such a choice allows the great convenience of a fluid description with a very small number of parameters (three), and a more general reduction is probably not possible or advisable. A model which included all of the correct physics would better characterize the waste but inclusion of this type of model into other codes would be very difficult. For very general fluids, notions such as viscosity and yield stress begin to lose their meaning, and we then have to invent other terms with which to describe the fluid. A clearer picture of the fluid behavior would not likely result from such an endeavor, and informing data users (who want to hear terms such as viscosity) of the fluid properties could become quite confusing. However, it should be remembered that our description of the fluid will always be somewhat approximate.

The data reduction strategy outlined here represents our best present ideas of how to go about analysis of the drag force data. In fact the methods and models used to reduce the actual data may not be completely determined until these data are collected. Perhaps a generalized Bingham model will simply not be appropriate to adequately describe all of the waste. We are presently unsure of the best manner in which to account for drag on the cable, and laboratory investigations are continuing on this problem. Methods for reducing the data will evolve once data are collected in the field.

For a generalized Bingham fluid, the shear stress (τ) is related to the shear rate ($\dot{\gamma}$) by the following equation (Chhabra 1993):

$$\begin{aligned}\tau &= \tau_o + m \gamma^n \text{ for } \tau > \tau_o \\ \gamma &= 0 \text{ for } \tau \leq \tau_o\end{aligned}\quad (5)$$

Thus, there are three parameters in the model: the yield stress (τ_o), the consistency index (m), and the power law index (n). If $n=1$ then m is the viscosity and the fluid is a Bingham fluid. If $\tau_o = 0$ and $n=1$, then the fluid is Newtonian; while if $\tau_o = 0$ and $n < 1$, the fluid is a power law fluid. It is seen that the generalized Bingham fluid model contains as subsets three other fluid models. The relationship between the drag coefficient (C_d) and the drag force experienced by a ball of diameter (d) traversing the fluid at velocity (V) is given by, in the case of Newtonian fluids,

$$F_d = \frac{1}{2} \rho C_d V^2 \left(\frac{\pi}{4} d^2 \right) \quad (6)$$

where, in the limit of small Reynolds number, the drag coefficient is given by

$$C_d = \frac{24}{Re} \quad (7)$$

For non-Newtonian fluids, the typical approach has been to utilize Eq. 6 using a modified drag coefficient which depends on dimensionless model parameters such as the Reynolds number or the Bingham number. We will adopt the results of Attapattu (Chhabra 1993), who gives the Reynolds number as

$$Re = \frac{\rho V^{2-n} d^n}{m} \quad (8)$$

and the Bingham number as

$$Bi = \frac{\tau_o}{m \left(\frac{V}{d} \right)^n} \quad (9)$$

Attapattu relates the drag coefficient to a dynamic parameter by

$$C = \frac{24}{Q} \quad (10)$$

where

$$Q = \frac{Re}{1 + KBi} \quad (11)$$

Attapattu states that the correlation is valid over 8 orders of magnitude in the dynamic parameter. The parameter K is chosen so that, for any particular set of measurements, Eq. 10 is valid (i.e., the coefficient remains 24). This parameter probably depends on fluid rheology and is not a constant; however, Attapattu gives a value of very nearly one. If we assume that the power law coefficient is very nearly unity and further assume that the lowest viscosity of interest will be about 10 poise and that the lowest yield stress will be about 100 dynes/cm², we can estimate the range of the Reynolds number and the dynamic parameter for our in-tank experiments. Reynolds numbers range from about 0.1 (lowest velocity) to 10 (highest velocity) while the dynamic parameter ranges from 0.004 to about 2, if we estimate that K=1 in Eq. 11. The dynamic parameter is within the applicable correlation range given by Attapattu. Substituting for all quantities, we find that the drag force on the ball is given by

$$F_d = 3\pi m d^{2-n} V^n \left(1 + K \frac{\tau_0 d^n}{m V^n} \right) \quad (12)$$

There are three unknowns in Eq. 12; thus, if we obtain drag force data at three or more different velocities, we can solve for all three parameters. Eq. 12 will be the basic theoretical equation by which we relate measured drag force on the ball to the fluid properties. For $n = 1$ and $Bi = 0$ (i.e., $\tau_0 = 0$), the above expression reduces to the well-known result for Newtonian fluids in the limit of small Reynolds numbers.

Eq. 12 can be rewritten as

$$F_d = 3\pi d^2 \left(m \left(\frac{V}{d} \right)^n + K \tau_0 \right) \quad (13)$$

or

$$F_d = M \left(\frac{V}{D} \right)^n + B, \quad (14)$$

where M is a constant and B is nearly constant if K does not vary significantly over the range of shear rates spanned by the data. One method for determining the parameters M and B is to plot the drag force data against $(V/d)^n$ and then perform a least squares best fit of the drag force to a straight line where n is varied. The best fit gives n , and the resulting slope and intercept give M and B , from which m and τ_0 are determined.

Note that the method outlined for data acquisition allows some choices for the reduction of the data. We are obtaining data at four velocities rather than three; so if data from all four velocities are considered in the determination of the three model parameters, we will have four equations with three unknowns and the parameters are then overdetermined. A statistical analysis can then be performed to determine the parameter values which best fit each set of data obtained at four velocities. Alternatively, we can take any set of three measurements and determine the model parameters. It may make sense to fit the data to the model for the lowest three velocities (0.1, 1.0, and 3.0 cm/s) and then the highest three velocities (1.0, 3.0, and 10.0 cm/s) and compare results for the parameters. There should be reasonable agreement if the model is fairly representative of the fluid. The best average representation should be obtained by full consideration of all four data sets, however.

We can obtain a characterization of the fluid for each 30-cm increment, since multiple measurements at different velocities will be obtained for each increment. These characterizations will describe the fluid after it has been well sheared by the ball. Only the data obtained as the ball first traverses any 30-cm increment is representative of the undisturbed fluid. Clearly, we will have data at only one velocity for this case.

For the undisturbed fluid, drag force data obtained at four velocities over a distance of 120 cm will be reduced to obtain the average fluid properties over that distance. Since the ball velocities will be chosen sequentially, we can reduce any contiguous set of four separate measurements (or, for that matter, any set of three measurements). Thus, while the results represent data obtained over 120 cm, we can update the results every 30 cm.

There appears to be no satisfactory method to determine drag force on the cable other than by calculation. Given that the fluid properties are known, the drag on the cable can be calculated. For each 30 cm distance in the fluid, the drag on the cable will always be much smaller than the drag on the ball. One means of calculating the cable drag is to first reduce the data, assuming there is no drag, and arrive at the fluid description. Then we correct the apparent drag on the ball to account for the drag on the cable and recalculate the fluid properties (actually, the model parameters). In

order to use this method we need to understand the relationship between fluid rheology and the drag on the cable. We do not presently have this knowledge, but laboratory studies are continuing towards a solution to this problem. Assuming that we can account for cable drag, continued iteration will produce a consistent set of model parameters; and since the contribution of cable drag is incrementally small, convergence should occur very quickly. When the ball is subsequently lowered, we need to include the integrated cable drag calculated in all previous steps as a part of the correction. In this manner we can determine the cable drag just as we determine the model parameters, 30 cm at a time. We cannot, for each 30-cm increment, determine the cumulative drag on the cable from the single measurement. This method will only work if the data are reduced in a particular order, from the top of the fluid to the bottom.

Reduction of static measurement data to obtain fluid density is straightforward. Again, however, the data must be reduced in order, from the top of the fluid to the bottom, in order to perform the integral for the contribution to the buoyancy force due to the cable. The contribution due to the cable will be a small correction. Density measurements in regions of the fluid with a high-yield stress may be difficult, owing to residual stresses in the fluid which will contribute to the apparent weight of the ball. For this reason we will obtain density measurements in regions of the fluid which have already been well sheared by the ball.

5.0 Expected Accuracies

The accuracies we can expect to obtain in the determination of model parameters has been discussed in a previous report (Shepard et al. 1994), where it was assumed that a Bingham model for the fluid would be appropriate. The only difference between the model used in that report and the one used here is the addition of a power law index. This extra degree of freedom and the expected error in measuring the drag force on the ball will allow substantial errors in the calculated quantities, possibly making it difficult to differentiate the power law index from one. Experiments with well-mixed simulants have shown that the power law index is fairly close to 1.0, which is the Bingham fluid value. Given the restricted range of strain rates which will be experimentally available, it will be difficult to determine a power law index different from 1 unless it is much different from 1. Precise determination of this index is made especially difficult due to the expected large uncertainty in the effective viscosity. Therefore the analysis presented in the earlier report gives a realistic picture of the accuracies we can expect if we adopt a generalized Bingham fluid model. The drag on the ball is expected to be due primarily to yielding of the fluid with a small contribution due to viscous drag. As a result, it is expected that the fluid yield stress will be determined to good precision but there will be considerable uncertainty in the viscosity (perhaps as much as 50 to 100%).

The effect of cable drag as a source of uncertainty was not discussed in detail in the earlier report. It has since been recognized that this factor represents the most important and least accessible correction to the drag force data. The current plan is to attempt to calculate the correction. We will also perform in-situ experiments aimed at estimating cable drag. While the error in our calculation or measurement of cable drag may be incrementally small, the cumulative errors may be substantial, especially if we consistently overestimate or underestimate the cable drag contribution. For low Reynolds numbers (less than about 1) the total error in the cable drag force will affect the determination of the yield stress, but will introduce no significant error into the viscosity. It will appear as a systematic velocity-independent error in the reduction of any group of four data sets. Since the determination of viscosity relies on the velocity dependent part of the drag force, it will not be affected by the constant offset due to miscalculation of the cable drag. The yield stress is determined from the velocity independent part of the drag force and, therefore, the yield stress will reflect the error in the cable drag term. The error is estimated to be less than about 25%, based on the total expected cable drag as compared to drag on the ball. For higher Reynolds numbers the picture becomes more complicated because the drag on the ball due to yield stress may not be constant. We can probably expect Reynolds numbers of around 10 in actual experiments. In this case increased uncertainty in the calculated viscosities will probably result.

Errors in the determination of the density will depend primarily on the load cell used for the measurements. The load cells have a nominal rated accuracy of 0.1% of full-scale reading. If we use a 100 lb (450 N) range load cell, then the resolution is about 0.45 N. The fluid density is expected to range between about 1.4 and 1.6 g/cm³ (a rather limited dynamic range), so that the expected buoyancy force will be around 5.9 N. The pulley arrangement results in a doubling of this force, so we expect that we can measure density to within about 4% of true value with this load cell. As can be seen above, the expected total change in density will be about 13% of the mean value, and so resolution of 4% will produce relatively coarse results. Resolution on the order of 1% would be highly desirable, especially in view of the fact that the density data may provide the most reliable and interpretable information concerning the action of the mixer pump. It would be advantageous to use a more sensitive load cell (15- or 25-lb full-scale) which would allow for the desired accuracy. If the initial experiments demonstrate that drag forces are sufficiently small to allow use of more sensitive load cells, measurements will be repeated using such load cells and perhaps a lower density (steel) ball.

6.0 Conclusions

We have presented a plan for the collection of in-situ data with the ball rheometer and the subsequent reduction of these data. This plan is fairly detailed and, if followed, should allow the extraction of meaningful information about the waste fluid contained in Tank 101-SY. The plan implicitly assumes that we simply wish to determine fluid rheology and density from the top of the waste to the bottom, and is presented to accomplish this goal. Contingencies have been described to account for as many possibilities as could be imagined. It should be remembered that this plan is by no means complete or all inclusive. Only time and careful planning will determine the breadth of measurements we wish to make with this instrument. It is expected that it will be called upon to provide extended service as a diagnostic tool, since the availability of in-situ measurement instruments for the tanks is quite limited. It should be remembered that the ball rheometer can only directly measure fluid rheology and density, nothing more. The interpretation of what these quantities suggest, especially in judgment of mixer pump performance, will depend on other factors involving the use of the mixer pump.

We will reduce the drag force data to obtain fluid rheological parameters by assuming that the fluid can be adequately described with the generalized Bingham fluid model. It is expected that this model should be applicable, based on experimental results with chemical simulants of the waste. If actual data obtained from the tank indicates that this model is quite inappropriate, then the fluid model question will be revisited. Data will be obtained at four ball velocities so that determination of the three model parameters can be performed. Both the undisturbed fluid and the "well-mixed" or "highly sheared" fluid will be characterized.

We do not expect to obtain highly accurate rheological values, with expected errors of perhaps 50% for the viscosity and 25% for the yield stress. Viscosities below about 10 to 100 poise will be difficult to measure, as discussed in previous reports. Data users have consistently reported that such accuracies are sufficient. Unless residual stresses due to the yield stress of the fluid present difficulties, we expect to be able to make fairly accurate measurements of density, within 1% error if a low-range load cell can be used.

7.0 References

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Appendix A

EXPERIMENTS PERFORMED AT PACIFIC NORTHWEST LABORATORY AND LOS ALAMOS NATIONAL LABORATORY

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Results of Laboratory Experiments in Support of the Ball Rheometer Project

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1.0 Introduction

The ball rheometer is being developed in order to perform in-situ measurements of tank waste rheological properties, initially in Tank 101-SY. Previous reports have described the need for these data (Shepard 1993), rheological measurements of tank wastes (Pasamehmetoglu et al. 1993), and the theory of operation of the ball rheometer (Shepard et al. 1994). In this report we will concentrate on the reduction of the expected load cell data to obtain drag force on the ball and the methods we will employ to determine the waste's rheological properties from the drag force data. The ball rheometer consists of a ball attached to a cable which is wound onto a spool. The system will be installed on a riser pipe through which entry into Tank 101-SY is obtained. The ball can be lowered into the waste or retrieved from the waste by rotation of the spool, which is mechanically connected to electric drive motors. The present ball is comprised of a tungsten alloy and is 9.1 cm in diameter and weighs about 16 lb (7.3 kg). It is likely that other balls of similar size but lower density, such as a steel ball, will also be employed. The cable is stranded stainless steel of diameter 0.32 cm (0.125 inches) and has a polyethylene coating. A diagram of the ball rheometer is shown in Figure 1. The ball is deployed into the waste and retrieved by rotation of the take up spool. Typically the ball will be deployed at a constant velocity, which is adjustable over the velocity range from 0.1 cm/s to 100 cm/s. The cable passes over a pulley to which a load cell is attached. The tension in the cable, or actually twice the tension in the cable is measured by this load cell. We will measure the tension in the cable as the ball is being moved through the waste at different velocities. From these measurements, the drag on the ball due to movement through the waste can be determined. The amount of drag depends on the rheology (roughly the yield stress and the viscosity) of the waste fluid, and we are interested in determining the rheology of the fluid. Static force measurements obtained while the ball is at rest in the fluid will allow a determination of the fluid density. We intend to characterize the fluid at all depths within the tank.

The report is organized as follows. In Section 2 we examine the forces involved in measurements with the load cells. The goal is to identify the drag force contribution to

Figure 1. Diagram of the ball rheometer system showing the ball, cable, take up spool, pulley and load cell. The instrument fastens to a riser pipe through which entry into the waste tank is obtained.

the total force measured with the load cell. Not all of these forces will be measurable in the tank, and accurate estimates from laboratory measurements will have to suffice. We will present the results of laboratory tests to determine some of the forces involved in Section 3.

2.0 Determination of Drag Forces on the Ball

The load cell measures the total tension in the cable to which the ball is tethered plus frictional forces in the pulley plus the weight of the pulley assembly. Only part of the total force is due to viscous drag on the ball. It is imperative that we be able to account for all of the forces involved and separate out the drag force contribution, since this force can be related to the rheological properties of the fluid. We will begin with a theoretical description of the ball rheometer system.

2.1 Theory

We desire to understand and identify the forces which play a part in the Ball Rheometer. First consider the forces acting on the ball in the fluid and let upward forces be positive while downward acting forces are negative. Assume that the ball is falling at some constant velocity. The forces are shown in Figure 2.

Figure 2. Forces Acting on a Ball in Motion in a Fluid

where

T = tension in the cable at the ball

- D_b = drag force on the ball due to the liquid
 B_b = buoyancy force on the ball due to the liquid
 W_b = weight of the ball in air

The equilibrium condition is

$$T + D_b + B_b - W_b = 0 \quad (1)$$

Now consider the forces acting at the load cell, as shown in Figure 3.

Figure 3. Forces Acting at the Load Cell

where

- T' = tension in cable at pulley
 η = friction in pulley
 W_p = weight of pulley and other components
 F_c = counterbalance force
 R = force with which the load cell pushes back. This is the load cell reading.

The equilibrium condition is

$$R + F_c = 2T' - \eta + W_p \quad (2)$$

In general the tension at the pulley does not equal the tension at the ball.

$$T' = T + W_c - D_c - B_c \quad (3)$$

where

$$\begin{aligned} W_c &= \text{weight of deployed cable} \\ D_c &= \text{total drag force on cable} \\ B_c &= \text{buoyancy force on cable} \end{aligned}$$

Using Eq. (3) and substituting for T' in Eq. (2) gives

$$R + F_c = 2[T + W_c - D_c - B_c] - \eta + W_p \quad (4)$$

Using Eq. (1) and substituting for T in Eq. (4) gives

$$R + F_c = 2[W_b - D_b - B_b - D_c - B_c + W_c] - \eta + W_p \quad (5)$$

or, upon rearrangement

$$R = 2\left[\left(W_b - \frac{F_c}{2}\right) - (D_b + B_b) - (D_c + B_c - W_c)\right] - \eta + W_p \quad (6)$$

Eq. (6) shows that the counterbalance force can be viewed as equivalent to using a lighter ball of weight $(W_b - F_c/2)$. The cable-related force terms, D_c , B_c , and W_c , are not constant but will depend linearly on the amount of cable deployed in the waste.

Let z_o be the distance at which the ball is just above the surface of the waste. At this location,

$$R_o = 2\left[\left(W_b - \frac{F_c}{2}\right) + W_d(z_o)\right] + W_p$$

At some distance $z > z_o$, we have

$$R = R_o - 2[(D_b + B_b) + (D_c + B_c - W_c(z))] - \eta$$

If we assume

$$D_c = \int_{z_o}^z A(z') dz'$$

$$B_c = \int_{z_o}^z B(z') dz'$$

$$W_c = C(z - z_o)$$

where C is a constant and A and B depend on position in the waste, then we can write

$$\Delta R_f = R - R_o = -2 \left[(D_b + B_b) + \int_{z_o}^z (A(z') + B(z')) dz' - C(z - z_o) \right] - \eta \quad (7)$$

If we obtain the load cell measurement at z_o and concern ourselves with load cell measurement differences ($R - R_o$), then the situation is simplified somewhat. Solving Eq. (7) for D_b gives

$$D_b = - \left[B_b + \int_{z_o}^z (A(z') + B(z')) dz' - C(z - z_o) + \frac{\eta + \Delta R_f}{2} \right] \quad (8)$$

Thus, in order to determine the actual drag force on the ball, several parameters must be determined independently. These include:

- the buoyancy of the ball, which may depend on waste type
- the buoyancy on the cable
- the drag on the cable
- the weight of the cable
- the friction in the pulley, which may depend on velocity and load.

Eq. (7) and (8) hold for a falling ball. For a rising ball, the drag forces on the ball and cable as well as the pulley frictional force reverse in direction. Eq. (6) becomes

$$R = 2 \left[\left(W_b - \frac{F_c}{2} \right) + (D_b - B_b) + (D_c - B_c + W_c) \right] + \eta - W_p \quad (9)$$

Following the same procedure as before, Eqs. (7) and (8) become, for a rising ball, respectively,

$$\Delta R_r = R - R_o = 2D_b - 2B_b + 2 \int_{z_o}^z (A(z') - B(z')) dz' + 2C(z - z_o) + \eta \quad (10)$$

$$D_b = B_b + \frac{\Delta R_r - \eta}{2} - \int_{z_o}^z (A(z') - B(z')) dz' - C(z - z_o) \quad (11)$$

Equations (8) and (11) relate the drag force on the ball to other quantities. We will use Eq (7) and (10) in some of the analysis of data which follows. With the load cell we will measure ΔR . Pulley friction can be determined from laboratory measurements, as can the cable weight per unit length. Therefore only the buoyancy forces and the drag on the cable are not well known prior to deployment of the ball rheometer. Values for these forces may depend on the fluid properties and therefore cannot be determined ahead of time. We have performed laboratory experiments with several fluids in order to determine representative values for these forces, but their actual determination will have to be made in the tank if possible.

3.0 Results of Laboratory Investigations

Experiments were performed with several fluids to determine the ranges of parameters which we might expect in tests which will be performed in the tanks. Quantities such as the buoyancy forces and drag forces were measured with simulants which included a chemical simulant, Bentonite clay, and carbopol. The experimental arrangement was our standard configuration. The fluids were held in a 5 gallon bucket so that total fluid depth was about 30 cm and the bucket diameter was also about 30 cm. In most tests a steel ball was suspended over a pulley with a thin stainless steel braided cable normally used and marketed for fishing applications. The pulley and ball were supported by a load cell which measured total tension in the cable. These results are presented in this Section.

3.1 Buoyancy Force on the Ball

For static measurements in a material with a yield stress the buoyancy force on the ball may not necessarily be given by the change in the apparent weight of the ball, since the ball can be partially supported by the yield stress. In dynamic measurements it is not clear if the buoyancy is simply the weight of the displaced fluid, although it appears difficult to describe it otherwise. Due to this uncertainty, we performed experiments to determine the dynamic buoyancy of the fluids. The buoyancy force on the ball is most easily determined from total force measurements obtained while the ball is rising and while the ball is falling. For these tests we used a very thin wire for a cable, so that the drag, weight, and buoyancy of the cable could be neglected. Adding Eqs. (7) and (10) with the cable related terms set to zero we obtain

$$B_b = \frac{-(\Delta R_f + \Delta R_r)}{4} \quad (12)$$

Some of the relevant data are shown in Figures 4 through 8 for 0.5-, 1.0-, and 2.0-inch balls and for the chemical simulant and carbopol. All of the data show buoyancies, from Eq. (12), which are consistent with results obtained using Archimedes Principle. The measured densities of the chemical simulant and carbopol are 1.55 g/cm³ and 0.96 g/cm³ respectively. From Archimedes Principle we therefore expect buoyancies of 13.3 g and 106 g for the 1- and 2-inch balls in the chemical simulant and buoyancies of 1.0 g, 8.2 g, and 66.0 g for 0.5-, 1- and 2- inch balls submersed in carbopol. The data shown in these figures indicate buoyancies in close agreement. For the chemical simulant we determine buoyancies of 12.5 g and 103 g for the 1- and 2-inch balls while for the carbopol we determine buoyancies of 1.0 g, 8.5 g, and 67.5 g. We can conclude that the dynamic buoyancy force in these fluids is given by the weight of the displaced fluid.

In the data presented in Figures 4-8, the ball is initially in air and is then lowered into the fluid until the bottom of the container is approached. The ball is then retrieved at the same velocity. In order to apply Eq. (12) a reference value is needed (R_0). This value is the apparent weight of the ball prior to entering the fluid. For example in Figure 4, this value is 70 g in one case and 72 g in another.

Similar high quality data are not available for the Bentonite clay mixture because this fluid would not allow the free sinking of any of the test balls. This fluid had a very high yield stress, and its density was 1.05 g/cm³. The data which are available, shown in Figures 9 and 10, are consistent with the notion that the buoyancy is given by Archimedes Principle. Some comment is necessary to describe how these data were collected. Since the ball, which was formed from tungsten powder and had a diameter

Figure 4. Plot of ball drag force measured with chemical simulant with the 1 inch ball first falling and then rising at 0.5 cm/s

Figure 5. Plot of ball drag force measured with chemical simulant with the 2 inch ball first falling and then rising at 0.5 cm/s

Figure 6. Plot of ball drag force measured with carbopol with the 0.5 inch ball first falling and then rising at 0.2 cm/s

Figure 7. Plot of the ball drag force measured with carbopol with the 1 inch ball first falling and then rising at 0.2 cm/s

Figure 8. Plot of the ball drag force measured with carbopol with the 2 inch ball first falling and then rising at 0.2 cm/s

Figure 9. Plot of the ball drag force measured with bentonite clay with the 2 inch tungsten ball falling at 0.2 cm/s

Figure 10. Plot of the ball drag force measured with bentonite clay with the 2 inch tungsten ball rising at 0.2 cm/s

of 1.925 inches, would not freely sink, weights were attached to it using a platform and a thin hollow rod. One end of the rod rested on the ball while the other end held the weights on a platform which was well above the surface of the clay mixture. The ball was then lowered into the waste at 0.2 cm/s. The reference weight shown in Figure 9 was about 2200 g. Before retrieving the ball, the platform, weights, and rod were removed. Then the clay was moved to fill in the hole left behind while the ball was falling. The thin rod has little effect on the total drag while the ball is falling because of the large hole which the ball leaves in its wake. Very little material comes in contact with the rod. Therefore, in Figure 10, the weight of the platform and other weights (2044 g) should be added to the drag curve to compensate for their removal and to allow its use with Figure 9. As the plots show there is a large uncertainty in the buoyancy obtained from these data, since stable drag forces were not obtained. Using reasonable values from the plots we obtain a buoyancy of 64 g for the ball, while the expected value is 66 g. The uncertainty in the value obtained from the plots is about 15 g. Based on the results of measurements with all three fluids and especially the chemical simulant and carbopol, which also have a yield stress, we conclude that the buoyancy is given by the weight of the displaced fluid.

The verification that the buoyancy force is given by the weight of the displaced fluid regardless of fluid type allows the calculation of both B and $B(z')$ in Eqs. (8) and (11), since the fluid density will be measured as a function of ball position.

3.2 Drag Forces on the Cable

Drag force on the cable was measured in a relatively simple manner. A length of cable was placed vertically in the fluid and extended downwards to the bottom of the container. Three cable diameters were used, 0.013-, 0.125-, and 0.250-inches. Weighted stainless steel tubing was used for the larger sizes while a stiff stainless steel wire cable was used for the small size. The cables were then withdrawn at constant velocity while the drag force was monitored. The slope of the drag force as a function of distance or time (divided by two to account for the experimental arrangement) could then be used to obtain the drag force per unit length of the cable. In the cases of the 0.125- and 0.250- inch cables which have substantial weights, corrections were applied to the data to account for the increase in cable tension due to the withdrawal of the cable from the fluid and into the air, where there is no buoyancy. Representative data are shown in Figures 11 through 13, which show the drag on a 0.125 inch diameter cable at 0.5 cm/s velocity for the three different fluids. The results obtained from all of the data are summarized in Table 1.

For the chemical simulant the drag force on the cable does not seem to depend on the cable diameter or the cable retrieval speed. For the carbopol and Bentonite clay, both diameter and speed are important, but there is no apparent simple correlation. A more thorough discussion of these results will be presented after we discuss results obtained for the fluid rheological parameters. In actual practice in the tank, it is important to establish the drag force on the cable from in-situ measurements.

Figure 11. Plot of the drag force on a 0.125 inch diameter cable being withdrawn from the chemical simulant at 0.5 cm/s

Figure 12. Plot of the drag force on a 0.125 inch diameter cable being withdrawn from the carbopol fluid at 0.5 cm/s

Figure 13. Plot of the drag force on a 0.125 inch diameter cable being withdrawn from the bentonite clay at 0.5 cm/s

Table 1. Drag Force per Unit Length on Cable

Cable Diameter, (inches)	Cable Velocity (cm/sec)		
	0.1	0.5	1.0
	Drag Force (gm/cm)		
	Chemical Simulant		
0.013	0.05	0.04	0.04
0.125	0.09	0.09	0.10
0.250	0.10	0.10	0.09
	Carbopol		
	0.013	0.10	0.11
0.125	0.29	0.52	0.65
0.250	0.98	1.15	1.89
	Bentonite Clay		
	0.013	0.52	0.52
0.125	1.91	4.17	4.03
0.250	3.27	5.71	6.18

3.3 Drag Force on Ball

The drag force on balls of diameters 0.5-, 1.0-, and 2.0- inches at velocities of 0.1-, 0.5-, and 1.0-cm/s were measured for all three fluids. Results for the 1 inch ball at 0.5 cm/s velocity are shown in Figures 14 through 16. The results for all of the data are summarized in Table 2. For all fluids the velocity dependence of the drag force is very weak. The dependence on ball size is strong, scaling roughly as the square of the diameter. Both of these factors suggest that the drag force is dominated by the yield stress of the material. It is from data such as these that the model describing the behavior of the fluid must be obtained. The reduction of these data will be described below in the discussion of results obtained with the Bohlin rheometer.

Table 2. Drag Forces on Ball

Ball Diameter, (inches)	Ball Velocity (cm/sec)		
	0.1	0.5	1.0
	Drag Force (grams)		
	Chemical Simulant		
0.5	—	—	—
1.0	1.7	1.8	2.2
2.0	6.4	6.8	7.6
	Carbopol		
0.5	4.5	6.0	6.0
1.0	16	19	22
2.0	75	92	97
	Bentonite Clay		
0.5	44	48	50
1.0	138	150	155
2.0	562	600	655

3.4 Cable-Ball Interaction

There has been some concern that operation of the ball in the retrieval mode may lead to measurement errors due to the disturbance of the waste by the cable prior to the passage of the ball through the same waste. Clearly as the cable diameter approaches the ball diameter the drag on the ball will be diminished since the fluid would no longer have significant contact with the ball. However, in the case where the cable diameter is small compared to the ball diameter, which should always be the case, the effect should be very small unless the cable somehow changes the character of the fluid through which the ball will pass. We tested this concern experimentally. If the cable causes very little change in the character of the waste in the retrieval mode, then we should observe that the drag force on the ball plus cable system should equal the drag force on the cable plus the drag force on the ball measured independently. The

Figure 14. Plot of the ball drag force measured with the chemical simulant with the 1 inch ball being withdrawn completely from the fluid at 0.5 cm/s

Figure 15. Plot of the ball drag force measured with carbopol with the 1 inch ball being withdrawn completely from the fluid at 0.5 cm/s

Figure 16. Plot of the ball drag force measured with bentonite clay with the 1 inch ball being withdrawn completely from the fluid at 0.5 cm/s

results for the drag force on the cable and drag force on the ball have been presented above. In the measurements of the drag force on the ball, shown in Table 2, a thin stainless steel cable was used. The drag on this wire is negligible compared to the drag on the ball and so the results shown for drag force on the ball can be taken as due to the ball only. We performed experiments where cables of diameter 0.125- and 0.250-inches were attached to 1.0- and 2.0- inch diameter balls, and drag force measurements were made as these systems were pulled through the fluids at constant velocities. After accounting for the drag force on the cable, the drag forces on the balls were compared to the same drag forces measured with the thin wire. Within experimental error there appears to be no differences. These results suggest that the interaction between cable and ball is negligible and can be neglected.

Results for the 1 inch ball with the 0.125 inch diameter cable are shown in Figures 17 through 19 for all three fluids and a velocity of 0.5 cm/s. These plots have been corrected to account for the weight and buoyancy of the cable and the manner in which these change as the cable is being withdrawn from the fluid. The drag on the cable accounts for the apparent slope in the curves, and this drag decreases as the cable and ball are withdrawn from the fluid. The drag near the end of the pull where the cable is nearly completely withdrawn from the fluid represents the contribution of the ball to the total drag. It is this drag force which should be compared to the drag force measured when the ball was retrieved with the thin cable. The determination of drag forces from these plots is not simple, due to the fact that experimentally it is

Figure 17. Plot of the combined drag force due to 0.125 inch diameter cable and 1 inch ball being pulled through the chemical simulant at 0.5 cm/s

Figure 18. Plot of the combined drag force due to 0.125 inch diameter cable and 1 inch ball being pulled through carbopol at 0.5 cm/s

Figure 19. Plot of the combined drag force due to 0.125 inch diameter cable and 1 inch ball being pulled through bentonite clay at 0.5 cm/s

advantageous to allow for a flexible zero offset and this advantage was used to the fullest extent here. The results for all of the measurements are shown in Table 3. In nearly all cases the drag forces listed in this table are in close agreement with the corresponding drag forces shown in Table 2. There is no clear trend in the comparison of the data in these two tables. It is seen from Table 3, however, that, on average, the drag force measured with the 0.250 inch cable attached to the ball is somewhat less than the corresponding drag forces measured with the 0.125 inch cable. This would lend some support to the notion that a cable-ball interaction exists. It is clear that the effect, if any, is rather small. The conclusion from these data is that the cable has little influence on the drag force on the ball. For the case of the actual planned in-situ ball rheometer, where the cable diameter will be 0.125 inches and the ball diameter will be 3.6 inches, any effect should be entirely negligible.

3.5 Effects of Interfaces and Distances Required for Steady-State Flow

The drag force data can be related to expectations based on fluid flow models if the flow is a steady state flow. It requires some distance from the start of ball motion before steady state flow conditions are reached. This distance could conceivably depend on the fluid rheological properties as well as ball diameter and velocity. It is important to know these distances so that the distance over which a ball must be pulled or dropped at a constant velocity before steady state is achieved can be

Table 3. Drag Force on Ball with Different Cables

Cable Diameter, (inches)	Ball Velocity (cm/sec)		
	0.1	0.5	1.0
Drag Force on Ball (grams)			
Chemical Simulant/Ball Diameter = 1 inch			
0.125	1.5	1.5	2.0
0.250	1.4	1.5	2.1
Chemical Simulant/Ball Diameter = 2 inches			
0.125	6.0	6.5	6.0
0.250	6.5	6.5	6.5
Carbopol/Ball Diameter = 1 inch			
0.125	17	21	22
0.250	18	19	19
Carbopol/Ball Diameter = 2 inches			
0.125	80	87	100
0.250	76	84	101
Bentonite Clay/Ball Diameter = 1 inch			
0.125	140	150	165
0.250	130	135	150
Bentonite Clay/Ball Diameter = 2 inches			
0.126	600	625	625
0.250	575	625	625

estimated. The planning of experiments is aided with this information. In addition, the distance required for steady state flow to develop may be useful for the estimation of fluid properties, although this possibility has yet to be explored to any degree greater than simple speculation. In actual practice, the steady state pull distance will be determined empirically. It may provide some qualitative information about the nature

of the fluid which is independent of the drag force measurements. However, fluid properties must still be determined from the steady state drag force data.

Table 4. Pull Distances to Steady-State Flow

Ball Diameter, (inches)	Ball Velocity (cm/sec)		
	0.1	0.5	1.0
	Pull Distance (cm)		
	Chemical Simulant		
1.0	0.5	0.5	1.5
2.0	0.5	0.5	1.5
	Carbopol		
	1.0	4.0	5.0
2.0	7.0	7.0	7.0
	Bentonite Clay		
	1.0	2.0	7.0
2.0	4.0	4.0	10.0

The presence of interfaces in the fluid, such as an air-fluid boundary or a sludge-liquid boundary or the boundary between the bottom of the tank and the fluid can result in differences between the drag forces measured near the interfaces and those measured far away from the interfaces. We have two natural interfaces within our experiments, the fluid container bottom and the free surface of the fluid. In the natural course of experimentation both the steady state pull distances and the effects of interfaces have been investigated. We will first consider the pull distance necessary to reach a steady state flow condition. Results obtained from plots such as are shown in the figures presented here are given in Table 4. The pull distance to steady state is greatest for carbopol (most of the time), which has almost no yield stress and a viscosity between those of the chemical simulant and bentonite clay. The pull distance is least for the chemical simulant, which has the lowest viscosity. Except for one case with the bentonite clay, the pull distance does not depend strongly on velocity. Most of the data suggest that it scales with ball size, but not linearly. Examination of the

results in Table 4 show no correlation with the fluid Bingham numbers or the Reynolds numbers.

Table 5. Interface-Effects Distance

Ball Diameter, (inches)	Ball Velocity (cm/sec)		
	0.1	0.5	1.0
	Interface-Effect Distance (cm)		
	Chemical Simulant		
1.0	2.0	2.0	2.0
2.0	2.0	2.0	2.0
	Carbopol		
	1.0	2.0	2.0
2.0	2.0	2.0	3.0
	Bentonite Clay		
	1.0	3.0	3.0
2.0	7.0	8.0	8.0

The distance at which interfaces begin to affect the drag forces was also obtained from data plots. The results are shown in Table 5. This distance does not seem to depend on ball velocity. Both the carbopol and the chemical simulant give similar results and the results are similar for both ball sizes. The distance is largest for the Bentonite clay, for which case ball size seems to be important. Bentonite clay has a much larger yield stress than either the chemical simulant or the carbopol, and it would seem that yield stress may be the important factor in determining how close the ball can approach an interface before the drag force is affected. Again however, we have found no correlation with either the fluid Bingham numbers or the Reynolds numbers.

3.6 Fluid Rheograms

Samples were obtained for each fluid and rheograms were obtained with a laboratory Bohlin VOR rheometer. Results of such testing are shown in a separate report by Jon Phillips. Rheograms for the three fluids are shown in Figures 20 through 22. We will glean some of these results and compare them to the results determined from the ball rheometer as given in Table 2.

The data in Table 2 show that the drag force on the ball scales roughly as the square of the ball diameter and is a weak function of the ball velocity. These observations suggest that a Bingham or generalized Bingham fluid model may be useful in describing the fluids. A simple form for the equation relating drag force on the ball to viscosity and yield stress for a Bingham fluid is given by Bhavaraju et al. (1978) as

$$F_d = 3\pi\mu_o dV \left(1 + 1.6 \frac{\tau_o d}{\mu_o V} \right) \quad (13)$$

where,

F_d = drag force on ball

Figure 20. Rheogram for carbopol as measured with the Bohlin rheometer

Bentonite Clay - 13.5% (ball rheom) tests #2-4
T = 25°C, files = 042294.2-4.visc.data

Figure 21. Rheogram for bentonite clay as measured with the Bohlin rheometer

101-SY Chemical Simulant
T = 50°C, file = 050494.2-4.visc.data

Figure 22. Rheogram for chemical simulant as measured with the Bohlin rheometer

μ_o = zero shear rate viscosity
 d = ball diameter
 V = ball velocity
 τ_o = yield stress

Simplifying Eq. 13 we find that it contains a term which depends on viscosity and velocity (the usual Stokes term) and another which depends on the yield stress and the square of the ball diameter.

$$F_d = 3\pi\mu_o dV + 4.8\pi\tau_o d^2 \quad (14)$$

If we assume the applicability of this description of the fluid we can reduce the data contained in Table 2 and determine values for the yield stress and the viscosity. These values can be compared to results obtained with the laboratory viscometer. The comparison is shown in Table 6, where ranges of measured values are reported. Results with the Bohlin rheometer show that in all cases the viscosity is shear rate dependent. The shear rates obtained in the ball rheometer studies (ball speed/ball diameter) range from less than 0.1/s to less than 1/s, and in order to facilitate comparison, we chose the region of the flow curves between shear rates of 0.1/s and 1.0/s in order to obtain results from the Bohlin rheometer. The table shows that for the chemical simulant and the bentonite clay, both instruments provide comparable numbers for the yield stress but the viscosities determined with the ball rheometer are generally somewhat lower than those found with the Bohlin rheometer. In the case of carbopol, the yield stress given by the ball rheometer is much greater than the actual yield stress as measured with the Bohlin rheometer. Carbopol is known to be undescribable in terms of a simple Bingham fluid, and the disagreement here is not surprising. The disagreement in measured viscosities may be due to failure to include a power law term in the reduction of the ball rheometer data. The data obtained with the Bohlin rheometer indicate that the fluids are describable in terms of a power law model. Continued research at our laboratory has shown that both the bentonite clay and the chemical simulant can be described with a generalized Bingham fluid model. The carbopol cannot be so described. This study has yet to be completed, however all indications are that reduction of the actual in-situ data obtained from the tank should begin using a generalized Bingham fluid model.

4.0 References

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Table 6. Comparison of Experimental Results Obtained with Ball Rheometer and Laboratory Rheometer for Three Simulants

	Ball Velocity (cm/sec)	
	Yield Stress (Pascals)	Viscosity (Pascal-sec)
	Chemical Simulant	
Ball rheometer	1.5 - 1.6	2.2 - 2.8
Bohlin rheometer	<1.0	2 - 10
	Bentonite Clay	
Ball rheometer	135 - 170	60 - 200
Bohlin rheometer	130	200 - 1000
	Carbopol	
Ball rheometer	15 - 19	11 - 19
Bohlin rheometer	~2.0	20 - 30

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RHEOLOGICAL CHARACTERIZATION OF NUCLEAR WASTE USING
FALLING-BALL RHEOMETRY

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1.0. INTRODUCTION

Success of many of the mitigation/remediation and retrieval schemes proposed for the Hanford Site high-level radioactive waste tanks requires the knowledge of the rheological properties of the material contained within these tanks. The mitigation of Tank 101-SY received most of the attention because it releases flammable and toxic gases periodically. Over time, core samples have been taken from various regions of the tank to characterize the rheological and chemical properties of the waste (Tingey 1992).

The waste consists of a saturated salt solution containing solid salt crystals. Because of the various crystal types, the waste can be thought of as a suspension with various sizes and shapes of suspended particles. The settling time for the particles is slow.

Before mixer pump operation, the waste in Tank 101-SY exhibited four distinct layers: (1) crust, (2) convective (C) layer, (3) nonconvective (NC) layer, and (4) sludge at the bottom. The waste shows strong time dependency. This is believed to be caused by the continuous evolution of salt crystal structures and generation of gas. The salt crystalline structures trap gas generated by the waste in the lower, settled (NC) layer. This occurs until the NC layer has accumulated enough gas so that its average density is less than the C layer above it. The buoyancy of the less-dense NC layer eventually causes it to rise through the C layer in an event called a "rollover." The rollover shears the NC layer, releasing the trapped gases. Also, as the NC layer with trapped gas rises, the change in the pressure head (5 to 10 m) can cause expansion of the volume of waste in the tank before the gas is released. Understanding the rheological behavior of both layers will aid in understanding rollovers and in implementing mitigation, remediation, and retrieval of the waste.

Core samples (windows C and E) have been taken from various regions of the tank to characterize the chemical and rheological properties of the waste (Tingey 1992). However, the properties of these samples were not the same in either the C or NC layers. For example, there was a considerable difference in the C layer viscosity for windows C and E samples. Viscosity measurements for the NC layer showed scatter over one to two orders of magnitude. NC layer data also indicated that over a certain range of temperatures and strain rates, viscosity increases with increasing temperature.

Attempts have been made to obtain rheological properties of C and NC layers using a cone and plate viscometer (Tingey 1992). The results lacked reproducibility, probably because the clearances of the cone-and-plate viscometer were on the same order as the crystalline sizes existing in the waste (the crystalline particles in the waste slurry are believed to be 1 to 100 μm in size).

The waste, consisting mostly of seven different salts in water, were used to create a simulant that is chemically similar to the waste. The resulting simulant is used to test different viscometry methods. By comparing the results of viscosity measurements made by different methods, a suitable method can be identified for *in situ* measurements of the waste in the tank.

An additional study performed at Los Alamos National Laboratory (Pasamehmetoglu et al. 1993) demonstrated that the cone-and-plate viscometer yields reasonably reproducible results for Newtonian fluids and for non-Newtonian fluids with very fine particles. However, the reproducibility of the cone and plate data using a waste simulant had an unacceptable amount of scatter.

Spindles also were used to measure the viscous behavior of the waste simulant. Although spindles gave repeatable results, the measured quality was in question because of the concern associated with particle migration and wall slip in the shear flow fields.

Suspension viscosity in concentrated systems has been measured by using falling-ball rheometry (Mondy et al. 1986). Pasamehmetoglu et al. (1993) performed additional tests using falling-ball rheometry. These preliminary tests showed shear-thinning behavior. However, the measured values were similar to those obtained using the spindle method. To see if falling ball rheometry was a better technique than spindle tests, more accurate falling-ball experiments were necessary.

In most techniques, the bulk of the fluid is continuous sheared (cone and plate, spindle) or is shear at high rates for short amounts of time (capillary). However, the settling ball in a falling-ball experiment continuously encounters undisturbed fluid as it falls, and the bulk amount of the fluid is sheared very little, if at all. This minimizes suspended particle interactions, which can cause particle migration (Abbott et al. 1991b).

Because the waste exhibits a very complex time-dependent fluid behavior, the applicability of falling-ball rheometry was determined. The most important issue is whether the well-mixed waste can be treated as a homogenous media. If the waste behaves as a homogenous fluid, the apparent viscous behavior of the simulant can be determined using various sizes and densities of falling balls.

This study tests the reproducibility of falling-ball tests in the various waste simulants. The settling velocities are to be analyzed, assuming various shear-rate-dependent viscosities, until the assumed behavior matches the observed behavior. Two chemically similar simulants will be used to determine the characteristics of the mixed waste. The major difference between the two simulants is when they were created. Therefore, the differences will highlight any differences caused by aging.

The results of this study will be used to design an *in situ* viscometer and determine a procedure for determining the viscosity from *in situ* tests. A brief summary of state-of-the-art falling-ball rheometry will be given as it applies to concentrated suspensions. Also, some of the issues regarding our current experiments will be discussed. We will present the results and conclusions following the description of the simulant used in these experiments.

2.0. FALLING-BALL RHEOMETRY

Determining the viscosity of liquid from the terminal settling velocity of a ball is a well-known technique and has been the subject of numerous experimental, numerical, and theoretical papers. The solution of the equation of motion for a ball falling in an unbounded Newtonian fluid at a low Reynolds number ($Re < 0.1$, also known as creeping flow) is known as Stokes's law:

$$u_0 = \frac{d^2(\rho_b - \rho_f)g}{18\mu} \quad (2-1)$$

where u_0 is the terminal velocity, d is the sphere diameter, ρ_b is the sphere density, g is the gravitational acceleration, and ρ_f and μ are the density and viscosity, respectively, of the Newtonian fluid.

This equation is obtained by balancing the drag force on the sphere with its buoyancy force. Beyond a Reynolds number of 0.1, corrections for inertia are needed. Also, in many problems, wall effect corrections are needed. For Newtonian and many non-Newtonian fluids, these corrections are known. However, for materials exhibiting a significant yield stress or in large containers, wall effects can be insignificant.

Falling-ball rheometry recently has been used for dilute and concentrated suspensions by several researchers (Mondy et al. 1986, Powell and Walla 1991, Abbott 1993, Abbott et al. 1991b, Milliken et al. 1989a, Milliken et al. 1989b, and Mondy et al. 1990). Although suspensions are not always represented as Newtonian continua, they may be partially characterized by an apparent viscosity if the suspended particles only interact hydrodynamically. However, this assumes that a reproducible settling velocity can be determined. This definition originates from Einstein's (1906 and 1911) works, which concentrated on neutrally buoyant suspensions subjected to elongation. Subsequently, Burgers (1939) obtained an identical result for simple shear flow between parallel plates.

Suspensions differ from homogeneous fluids with the turbulence dissipation and migration of suspended particles caused by hydrodynamic interactions. The differences between suspensions and homogeneous fluids under turbulence are believed to be caused by the interaction between the particle size and the size of turbulent eddies.

As shown by the above-mentioned studies, suspensions exhibit Newtonian flow behavior at low Reynolds numbers. When we deal with higher Reynolds numbers, the inertial and turbulence effects must be considered. Suspensions are known to behave differently under turbulence, and any continuum model must reflect these differences. It is not clear whether all of these differences have been accounted for; direct numerical simulations of turbulence with particles have been able to reproduce only the results of modest amounts of turbulence owing to limitations on memory and time requirements necessary to solve these problems.

Particle migration occurs when initially well-mixed suspensions are subjected to inhomogeneous shear flows (Abbott et al. 1991b). The suspended particles migrate from regions of high shear rate to regions of low shear rate. This migration can occur over relatively short shearing lengths and results in the development of large concentration gradients.

The above test assumes that the suspensions could be modeled as a homogenous Newtonian fluid. From previous tests, the actual waste appears to have a yield stress and shear-thinning behavior. Therefore, models assuming Bingham and/or shear-thinning behavior will be tested while reducing the data. Again, homogenous fluid models may not be applicable to two-phase suspension media.

For the settled simulant, the C and NC layers will be analyzed separately. The C layer will be treated as a Newtonian fluid. Because of its low viscosity, capillary viscometers will be used to determine the viscosity. The settled layer will be treated like the well-mixed waste.

Preliminary experiments suggest that the NC layer, while exhibiting yield stress characteristics, may not be adequately modeled as a Bingham plastic. A Bingham plastic recovers its prestressed material properties instantaneously upon removal of external stress. This model works when the recovery time scale is short compared to the time scale of the motion. Preliminary experiments suggest that this time range may be from several minutes to as long as several days for the simulant. Thus, a history-dependent Bingham plastic model may be necessary.

If the waste behaves as a time-independent Bingham plastic, we have two options for reducing the data. First, we can operate at the Stokes regime and use the drag coefficient correlation of Beris et al. (1985), which is obtained analytically for creeping flow around spheres for Bingham fluid. This requires small-ball velocities (on the order of mm/s). The experimental average shear rate will be low for low-ball velocities. However, once we obtain the yield stress and Bingham plastic viscosity from two experimental data points, the extrapolation to evaluate the viscosity at higher shear rates is possible because we have already expressed the shear/stress-shear rate relation as obeying the Bingham relation; the analytical solution for the drag coefficient already was

obtained using the same relation. However, we can question the reliability of our estimate for the flow curve when it is used at higher shear rates if we get drag-vs-Reynolds-number data within a limited range of shear rates. In this case, we should extend the ball velocity range to higher desired shear rate values to confirm the flow curve.

Evaluation of yield stress and Bingham viscosity for high shear rates may not be obtained by the analytical solution of Beris et al. (1985) because of inertial effects. However, we also can reduce this data from empirical experimental correlations available by Ansley and Smith (1967), Ito and Kajiuchi (1969), and Brooks and Whitmore (1969); these researchers obtained the drag coefficient as a function of the Bingham number and plastic Reynolds number. Using clay and other types of Bingham plastics, they dragged the ball up to the plastic Reynolds number of 1000. Ansley and Smith (1967) were able to collapse all drag coefficient data to a single curve by defining a dynamic parameter in terms of the Bingham number and plastic viscosity number. Thus, tests theoretically can be run with high velocities if these correlations hold. The danger of this approach is the limited range of the dynamic parameter (between 0.01 to 2000) in Ansley and Smith's (1967) study because their Bingham fluids had very low yield stress. If the waste yield stress is high, as suggested, the dynamic parameter becomes very low for reasonable plastic viscosities. In this case, we may need to extrapolate the correlation, which always is difficult to justify. This extrapolation approach was taken in the preliminary drag force evaluation analysis of Pasamehmetoglu et al. (1993).

Our research attempts to answer questions asked above in a step-by-step approach. We have discussed some of our alternatives for data reduction. The final approach will be determined on the basis of experimental results we obtain from the tests.

3.0. SIMULANT CHARACTERISTICS

The wastes that were added to Tank 101-SY consist of double-shell slurry (DSS) and complexant concentrate (CC) waste, which were concentrated by evaporation before storage. The complexants added to the CC waste consist primarily of Na_4EDTA , Na_3HEDTA , sodium citrate, and sodium hydroxy acetate (glycolate). Both wastes consist mostly of precipitated, inorganic salts.

To adequately predict the behavior of the waste in the tank, falling-ball experiments must be performed with a representative waste simulant. A chemically similar simulant (described below) has shown that, like the waste, long periods of time (month to years) are necessary for the simulant to stabilize. Because this study needed to be performed in a 6- to 7-month time frame, an aged simulant was needed. Also, to perform large-scale experiments and determine the effects of aging, a fresh simulant was made. These two simulants are described below.

3.1. Composition

On the basis of chemical analysis of the core samples from Tank 204-SY-101, Agnew (1993) suggested the mixture shown in Table 1 as a chemically accurate reproduction of the waste in the tank.

Agnew (1993) prepared his simulant in a progressive manner. First, the least soluble components were added to an appropriate amount of tap water (complexants). Next, 2.3 M NaOH was added, which heated the solution. The aluminate (NaAlO_2) was added after the NaOH. However, Agnew later found that the sodium carbonate was much less soluble than the aluminate. As discussed later, we added the sodium carbonate before the aluminate when preparing our fresh simulant. After adding the aluminate, the sodium nitrite, carbonate, and nitrate were added. This mixture stood for a few days at 60°C in a 33.4-L model tank; then we observed that the settled solids were 2.54 cm deep. The total sodium was increased by increasing the amount of sodium hydroxide from 2.3 to 3.3 M to compensate for the lack of other cations that are present in the actual waste. Some of the components not added to the simulated waste are citrate, glycolate, nitrilo triacetate, phosphate, fluoride, chloride, other anions, potassium, calcium and other common cations, chromium, iron, and other transition metals. The simulated waste made by Agnew includes the major chemical species believed to adequately represent the physical and chemical nature of the tank slurry.

Agnew's slurry showed characteristics of four layers: (1) foam layer, (2) clear C layer, (3) soft slurry layer, and (4) a stiff bottom layer. This simulant waste was prepared approximately 2 yr ago and kept at typical tank temperatures in a model tank. As with the actual waste, the vast majority of the settled simulant was contained in the C and soft slurry layers.

TABLE 1. COMPONENTS USED IN AGNEW'S SIMULANT

Component	Concentration Moles/L (M)
NaNO_3	3.7
NaNO_2	3.6
NaOH	3.5
NaAlO_2	2.3
NaCO_3	0.5
Na_4EDTA	0.12
Na_3HEDTA	0.13

We obtained 4 L of this aged waste simulant from Agnew's model tank after the waste simulant was mixed homogeneously. These individual 1-L samples were kept in a vacuum oven to maintain ~50 to 60°C. Later tests showed that the temperature in the oven varied between 52 and 58°C in each cycle (about 30 min).

The 4-L samples are indicated as AS1, AS2, AS3, and AS4 (aged simulant). Each simulant taken from Agnew's tank was treated separately because each has a different temperature and shear history. For example, two of the samples were taken ~1 month after the first two. Also, all samples were at room temperature when they were moved.

To complete this study, 20 to 30 gal. of simulant was needed. Because there was less than 10 gal. of aged simulant, more simulant had to be created.

Using the recipe and procedure suggested above, a sample liter was made. The chemical components are listed in Table 2. The compositions given below are identical to those shown in Table 1, except in g/L vs mole/L.

The components are listed in the order they are added to the water. All salts dissolved at room temperature until the addition of the sodium nitrate. At 50°C, the carbonate (and possible the EDTA and HEDTA) came out of solution after the addition of the aluminate. The simulant then was transferred into a plastic container with a lid to reduce evaporative losses. The container was placed in the same oven with Agnew's simulants to maintain its temperature.

Using the test procedure given above, a 113.6-L (30-gal.) batch of simulant was made in a 55-gal. barrel. Initially, the temperature of the simulant caused by the heat of solution (mainly from the aluminate and sodium hydroxide) was 30°C.

TABLE 2. COMPONENTS USED IN THE FRESH SIMULANT

Component	Concentration g/L
Na ₄ EDTA	50.00
Na ₃ HEDTA	50.00
Na ₂ CO ₃	56.19
NaAlO ₂	196.07
NaNO ₃	317.05
NaNO ₂	244.95
NaOH	139.60
H ₂ O*	536.14

*amount calculated such that there would be 1590 g/L total.

Over 2 d, the simulant temperature was raised to the setpoint of 50°C. This mixture was constantly stirred using a barrel mixer. After several months, a sample of this simulant (fresh simulant, or FS2) was taken from the barrel.

To prepare the new simulant for experimental use, the simulant was taken to 70°C for a minimum overnight period. The simulant (still above 60°C) then was mixed vigorously for 30 to 60 min, then cooled to 50°C. At 70°C, the nitrate and nitrite salt crystals dissolved completely. When the temperature was reduced, the resulting crystals were more representative of crystals seen in the NC layer. This was equivalent to redistributing the sludge layer in the tank and diminished the variability of the simulant taken from the barrel at different times.

3.2. Density and Particle Shapes and Sizes

The shape and size of solid particles and the solid fraction are very important parameters controlling the rheological properties of suspensions. They also determine the settling rate of the suspension. Other physical properties are important, such as densities of the mixed simulant, saturated liquid, and the precipitated crystals.

For the simulant received from Agnew (1993), the densities were measured, along with information on the size and shape of the solid particles. Densities of Agnew's simulant and their comparison with waste measurements are given in Table 3.

Agnew's simulant showed a certain pattern of particle sizes that may be a trend for the actual waste. Larger crystals were made of sodium nitrate, sodium nitrite, and sodium carbonate. Sodium nitrate crystals are rhombohedral and tend to be very symmetrical prisms, while the sodium nitrite crystals are monoclinic and grow in a variety of different ways. Generally, they are flat, triangular plates,

TABLE 3. PROPERTIES OF AGNEW'S SIMULANT

Density (g/c ³)	Convective (g/c ³)	C Layer (g/c ³)	NC Layer (g/c ³)	Mixed (g/c ³)
Agnew's Simulant	1.51			1.59
E-Core Sample	1.50	1.57	1.70	
C-Core Sample		1.49	1.63	

although dendritic forms grow readily out of rapidly cooled solutions. The sodium carbonate crystals most often appear as needles clustered like haystacks (Agnew 1993). These forms only appear in waste that is cooler than -30°C , and the carbonate exists in another, much smaller crystal at the tank temperature.

The CC is present in Agnew's slurry primarily as small crystals because it is fairly insoluble in the 12-M sodium supernatant. HEDTA components could not be found in the actual waste or in Agnew simulant, even though they were present initially in both. We assume that the HEDTA degrades quickly into some as yet undetermined products (Agnew 1993).

The rate of crystal growth/dissolution is unknown. Indirect evidence, such as change in appearance and viscous behavior of the simulant, suggests that the rate is weeks, not hours.

In this study, the density of aged simulants was measured. The density of supernate at 50°C was determined to be $1.544 \text{ g}/\text{cm}^3 (\pm 0.004)$. The well-mixed simulant was measured as $1.593 \text{ g}/\text{cm}^3 (\pm 0.004)$ and $1.561 \text{ g}/\text{cm}^3 (\pm 0.004)$ for AS1 and AS2, respectively.

The solid fraction in a given simulant also can be changed by varying the temperature. Falling-ball tests were conducted at different temperatures with the well-mixed aged simulant to investigate the solid fraction effect. However, the amount of dissolved salts in the saturated liquid will decrease with decreasing temperature, causing a decrease in viscosity, whereas the viscosity of the supernate at a constant amount of dissolved salts will increase with decreasing temperature.

4.0. DESCRIPTION OF EXPERIMENTS

4.1. Falling-Ball Tests and Real-Time Radiography

A good description of falling-ball rheometry in opaque suspensions can be found in Mondy et al. (1986). Here, only the parts unique to this study will be presented.

The falling-ball paths were recorded using a standard VHS, editing video system. This system records 30 frames per second; the VCR could be advanced one frame at a time, yielding the highest accuracy within the limitations of the technique. The accuracy in position and time are estimated to be $\pm 0.2 \text{ cm}$ in the position and $\pm 0.03 \text{ s}$ in time, respectively. Because objects placed closer to the x-ray source will appear larger in the recorded image than objects further away, rulers with 0.32-cm-diam metal markers were placed in front on the right side and in back on the left side of the column. First-order corrections for errors due to perspective could be determined. Second-order corrections would be on the scale of other errors.

The test cylinder has an inside diameter of 5.08 cm and a length of 46 to 50 cm. A cylindrical jacket, through which water was pumped to maintain a constant temperature, surrounded the test cylinder. The water temperature was maintained by using a constant temperature bath that controlled the temperature in the bath to within $\pm 0.01^{\circ}\text{C}$ and in the column to within $\pm 0.03^{\circ}\text{C}$. The top of the test cylinder was covered with a lid to reduce evaporative losses.

The falling ball used in this study varied from 0.32 to 1.27 cm in diameter. Tungsten carbide, brass, steel, aluminum oxide (ruby), ceramic and aluminum balls were used to obtain various densities. Aluminum balls settled under a low shear rate, but the simulant (like the real waste) corroded aluminum. The initial experiments completely dissolved 0.64-cm aluminum balls in less than 3 d.

While inertial effects will be important in many of the experiments, the low Reynolds number data will be useful as a starting point to understand the more complex behavior at higher Reynolds numbers.

To obtain lower shear rates, 1.27- and 0.64-cm-diam plastic balls were used. These plastic balls had a density of 1.18, which is much less than the simulant density of 1.6. To increase the 1.27-cm-diam ball average density, 0.32- to 0.48-cm-diam holes were drilled in the ball and filled with various sizes of tungsten carbide, brass, and steel balls. These balls are referred to as PFBs. Similarly, 0.159-cm-diam holes were drilled in the 0.64-cm-diam plastic balls and filled with 0.159-cm-diam gold wire to increase the average density of the ball. These balls are referred to as PFGs. All holes were sealed with an acrylic epoxy.

4.2. Falling-Ball Tests

The purpose of these falling-ball tests was to get experience and anticipate the possible difficulties during *in situ* measurements. The tests are described below.

To see if it was practical to use a laboratory-scale apparatus to simulate the falling-ball system to be placed in Tank 101-SY, a small laboratory-scale model was made and tested. This apparatus would be used like the real system, except that the ball would rise or fall under a constant force. Initial tests were performed in a well-characterized Newtonian fluid under low Reynolds number flows to see if density and viscosity could be measured either through theoretical calculations or by calibration with another fluid.

In Fig. 1, a schematic of the falling-ball apparatus is shown. The major parts are a ball glued to a wire, which goes over two pulleys and then is connected to a counterweight. The counterweight can be adjusted so that the ball either will rise or settle into the fluid. Initially, standard pulleys were used. However, the frictional losses were much greater than the weight of the ball. To reduce these losses to manageable levels, air pulleys (like air bearings) were used. These had

Fig. 1. Picture of laboratory-scale falling-ball apparatus. The ball would either settle or rise under a relatively constant force.

very low frictional losses. However, the air flow in the pulleys would cause them to rotate without any load conditions. This force would depend on the rotation rate.

4.3. Couette Viscometer Tests

In addition to falling-ball tests, Couette viscometer experiments measured the viscous behavior of the simulant. Couette viscometry is based on dissipative resistance in a fluid between two concentric cylinders with at least one of them rotating. For a narrow-gap Couette viscometer, the shear rate is relatively constant, and the torque needed to rotate the cylinders specifies the shear stress. As mentioned previously, the particle migration and wall slip can be seen in the rotational viscometers. To compare the falling-ball results with results from a rotational viscometer, a Couette device was selected. The simulant used in Couette viscometer experiments was an aged simulant provided by Agnew (1993).

Approximately 200 ml of aged simulant (AS4) was provided to the Naval Air Warfare Center Weapons Division at China Lake to perform Couette flow tests. The sludge was sent in two 125-ml polyolefin screw-top bottles. When not in use, the sludge was stored at room temperature (20 to 25°C). Before making measurements, the bottles of simulant were stored for several days in an environmental chamber at the test temperature. The sludge was stirred by inverting or shaking the bottles. Air bubbles introduced by shaking were allowed to rise to the surface before pouring samples of the sludge into a viscometer for viscosity measurements. Only a few seconds were required to

allow bubbles to rise to the surface. It was noticed that the simulant gave off a slight ammonia odor at 40°C.

A Couette (cup and bob) viscometer was used, although a parallel plate viscometer was tried. The parallel plate was 50 mm in diameter. In loading the parallel plate viscometer, sludge was poured onto the center of the lower plate; the upper plate then was lowered to squeeze the sample to the edge of the plates. During the measurement, a crust appeared to form over part of the exposed surface at the edge of the sample. The torque was measured at various rotation rates. The torque appeared to decrease with increasing rates, which may have resulted from a breakup of the crust at higher rates. The torque also may have been influenced by sedimentation of the suspended particles. For these reasons, the parallel plate viscometer was not used further.

Samples measured in the Couette viscometer were loaded by pouring 28 to 29 g of simulant into the cup, mounting the cup into the viscometer, lowering the bob into the sample, and then spreading a layer of mineral oil on top of the sample. The mineral oil was added drop-wise from an eyedropper to form a 1- to 2-mm-thick layer floating on top of the simulant. This oil layer kept the simulant from evaporating and prevented the formation of any crust. For samples run without the oil layer, a crust was seen to form on the exposed surface; these runs showed higher and less reproducible torques than runs made with the oil layer in repeat experiments. The oil was low in viscosity (0.3 P at 23°C), and the layer was thin enough that its contribution to the measured torque was negligible.

The Couette viscometer was in a temperature-controlled environmental chamber heated by convection. A thermocouple in the base of the cup was used to measure the sample temperature. In all cases, the simulant was maintained at the test temperature in a separate environmental chamber before pouring it into the Couette viscometer. The Couette viscometer was allowed to equilibrate to the test temperature in its environmental chamber into which the sample was loaded.

4.4. Falling-Ball Experiments

For mixed-simulant tests, the simulant was poured into the circular cylinder after taking it out of the constant temperature oven. The column was maintained at a constant temperature, as described in Sec. 4.1. The stirring apparatus consisted of a hub with eight equally spaced rods projecting radially. A long axial rod connected the hub to a stirring handle. By moving the handle up and down while rotating it, the simulant was mixed for approximately 5 min. After mixing, the appropriate section of the column was imaged.

The balls were stored to within 2°C of the bath temperature before being used in an experiment. However, the column was normally 1 to 2°C cooler than the water bath because of convective losses to the surrounding air, so the temperature difference between the ball and the simulant was less than 2°C.

To remotely release a ball into the top of the simulant, a vacuum ball dropper was used. This conically shaped piece could accommodate balls as small as 0.32 cm in diameter. When the external vacuum pump was turned off, the pressure dropped slowly to atmospheric because of leaks in the hose. The ball then fell into the simulant.

Upon release of the ball, the x-rays produced an image of the ball's path through a 20-cm-diam window. These images were recorded so that the settling path could be determined. The motion of the ball also was displayed in real time on a monitor. Thus, decisions could be made for the next test based on results of previous tests.

The mixing was not performed for the settled-waste tests. As discussed later, the simulant originally was mixed as described above and allowed to settle to a specified compressive strength. The balls then were dropped.

4.5. Settling Experiments

To study the rheological effects of aging, three procedures were used. The first method involved an aging time of one week or less. The second method involved longer periods of time, typically more than one month. The third procedure used a centrifuge to accelerate the settling rate.

In the first method, the simulant would be mixed and allowed to settle for the aging time. Balls then would be dropped through the simulant. The most important data obtained would be from the first and second balls dropped. Here we were trying to determine how long the structure-yielding higher viscosity and yield behavior took to develop from the well-mixed case. Because short times were used, the experiments could be repeated by mixing the simulant and letting it settle again.

In the second method, the simulant would be allowed to settle for several weeks after mixing. Like the first method, balls then would be dropped in the simulant. However, at the end of the experiment, the simulant would not be mixed. Here, the waiting time would be how long the simulant took to recover. The objective was to see how much of the structure was caused by aging and how much by the higher concentration of crystals in the settled layer. If the rheological behavior of the simulant recovered in a few days to weeks, the structure then would be predominately caused by the increased concentration. The implication for the real waste would be that if the disturbance caused by the pump did not fully mix the tank, the waste could be much thicker than if the waste had been well mixed.

In the third method, a centrifuge was used to accelerate the settling. This method allowed several months of settling to occur in a matter of hours. Using this method, most of the simulants were tested for complete settling and the corresponding compressive strain.

4.6. Instrumentation Accuracy

The uncertainty associated with the evaluation of the terminal velocity in these experiments is derived from errors in estimating the distance between specified marks and the time of the flight between these marks. The accuracy of the flight time is set by the frame rate of the recording system (1/30 s). As mentioned before, this error is ± 0.03 s. The position could be estimated with an accuracy of ± 0.2 cm. The resulting error in the terminal velocities encountered in this work ranged from $\pm 2\%$ (caused by uncertainty in distance) to $\pm 10\%$ (additional 8% error in measuring time.)

The other measured parameters used in the data reduction method are the diameter and weight (or density) of spherical balls. Some balls (metal and ceramic) were fabricated to be almost perfectly spherical (within ± 0.002 mm), with variations between different balls being ± 0.006 . A ruby sphere had a uniform diameter to within our ability to measure (< 0.002 mm). Plastic balls were much less accurate and precise in shape, with diameters that deviated by 0.001 on a given sphere and that varied by ± 0.02 between balls. These nonmetallic balls were used to create densities close to that of the fluid. The center of moment of these balls is not perfect. Some of the data obtained using these balls showed considerable scatter. The weight was measured with a sensitive scale that had an accuracy of ± 0.0001 g. The range of ball densities in this study varied from 1.7 (PFG) to 15.2 (tungsten carbide).

The falling-ball accuracy will not be discussed because no reliable data were obtained.

5.0. RESULTS

The results of the pulling-ball, settling, falling-ball and Couette viscometer experiments are presented here. Falling-ball experiments yielded only qualitative conclusions because several sources of drag in the experiment could not be determined. Several simulants settled over a period of several months to quantify the settling rate and behavior of the simulants. Falling-ball experiments were performed with the well-mixed and settled simulants, while the Couette viscometer experiments were performed only with the well-mixed simulant.

5.1. Pulling Ball

5.1.1. Experiments

The first test measured the static load with the ball in air and then in water. This would give the displacement volume of the ball and wire. By placing the counter force on a balance, the differential load could be determined when the counterweight weighed more than the ball. The load on the balance kept decreasing with time, which was caused by the wire stretching. As the wire

stretched, the ball in the fluid settled lower, increasing the buoyancy force and lowering the load on the balance.

In trial runs under constant force in a Newtonian fluid, the ball would settle or rise more slowly at the bottom than at the top. Because this occurred both on settling and rising, it was related to the amount of wire in the fluid. However, the ball would not settle even at an approximately constant velocity, and it was not clear how to correct for the effects of the wire stretching and the force caused by the uneven flow in the air pulleys; thus, this set of experiments was abandoned.

5.1.2. Theoretical Analysis

In Newtonian fluids there exist analytical solutions for both a wire and a ball settling along the axis of an infinitely long circular cylinder. As a first-order approximation, the drag force on the sphere can be added to the drag on a wire, ignoring the effect of the sphere on the drag on the wire. This method should give an upper limit on the drag of a sphere being pulled by a wire.

The drag on a sphere in the cylinder is given by Happel and Brenner (1983) as

$$F_s = -\frac{3\pi\mu du_0}{\chi} , \quad (5.1)$$

where χ is the wall effect correction given by Faxen (1923)

$$\chi = 1 - 2.149\frac{d}{D} + 2.05\left(\frac{d}{D}\right)^3 - 0.95\left(\frac{d}{D}\right)^5 + O\left(\frac{d}{D}\right)^6 \quad (5.2)$$

and where d , u_0 , μ , and D are the diameter and velocity of the ball, the viscosity of the fluid, and the diameter of the cylinder, respectively.

The drag per unit length, l , on an infinitely long wire in a cylinder is given by (Phan-Thien et al. 1993) as

$$F_w = \frac{2\pi\mu v}{\ln(\varepsilon) + \frac{(1-\varepsilon^2)^2}{1-\varepsilon^4}} , \quad (5.3a)$$

with

$$\varepsilon = \frac{2r_w}{D} , \quad (5.3b)$$

where r_w is the radius of the wire. When the diameter of the tank becomes very large with respect to the radius of the wire, the force on the wire appears to go to

zero. The limitation of the above equation applies only when the flow is at a steady state. However, a wire in an infinite sea of fluid never reaches steady state; if it could, the resulting force would be zero because the fluid would be moving affinely with the wire. To model the real situations, the finite length of the wire and the transient nature of the calculation must be accounted for.

Two sets of calculations were performed. The first used the dimensions of the laboratory-scale setup described above, while the second set used the approximate dimensions of the tank. Table 4 lists both sets of dimensions.

Using Eqs. (5.1) to (5.3), the relative magnitude (x) of the wire contribution to the total drag is

$$x = \frac{F_w l}{F_s + F_w l} \quad (5.4)$$

Using the values in Table 4 with l equal to half of h , we find that x is 0.63 and 0.82 for the laboratory-scale and tank-scale models, respectively. This suggests that the drag on the wire may be more important than the drag on the sphere. In the laboratory-scale experiment, the large magnitude of the drag on the wire relative to the sphere is due to the relatively large size of the wire relative to the column diameter. However, in the tank simulation, it primarily is due to the length of the rod compared to the diameter of the sphere. Here, the drag caused by the wire probably is not an accurate estimate.

To verify that the drag on the wire will be on the order of the drag on the sphere, a numerical model that accounts for the finite length of the tank, the interaction between the wire and the sphere, and the non-Newtonian nature of the waste would be needed. As an incremental improvement, we have checked the above theoretical results with a low Reynolds number, Newtonian model.

TABLE 4. DIMENSIONS FOR THEORETICAL AND NUMERICAL CALCULATIONS

Variable	Laboratory Scale (in.)	Tank 101-SY (m)
$d/2$	0.25	0.04572
r_w	0.0075	0.0015875
$D/2$	1.00	10.9728
h	20.00	9.906

5.1.3. Numerical Calculations

To see what effects the finite size of both the laboratory-scale and the tank-scale experiments have on the relative drag between the wire and the sphere, a low-Reynolds number, Newtonian, boundary-element method code was used.

The code uses an integral boundary element method, which is named for replacing the boundary with a set of singularities representing the velocity and traction (the tangential component of the stress) on the boundary. By integrating over all the singularities, the partial differential equations reduce to a set of equations relating the strength of the singularities to each other. This reduces the order of the calculation by one dimension because now only the conditions on the boundary are important. However, the resulting matrices are dense vs the banded matrices resulting from finite-element methods. This technique also is limited to cases where the equations are linear. For linear problems, the gains made by reducing the order of the problem far outweigh the extra time needed to invert dense matrices. Therefore, this technique is good for solving Stokes equations (the linear form of the Navier-Stokes equations occurring from creeping flow conditions). This assumes that the stress-strain relationship is linear (Newtonian).

In the laboratory-scale experiment, the agreement is better than that seen for the tank-scale experiment because the theoretical equations neglect end effects. End effects typically arise only when the ball is within one-container radii from the bottom or top. Therefore, end effects are important throughout the entire tank because the length of the tank is comparable to its radius (see Fig. 2).

Further improvements in the calculations can be made using non-Newtonian fluid models outside of the creeping flow regime. While it might be constructive to separate the effects of inertia from the effects of nonlinear constitutive equations, from a modeling standpoint these are both nonlinear effects. This means that the boundary-element method used in the above calculations must be replaced by a nonlinear, time-dependent numerical method. Several packaged codes could be used if the constitutive relationships are shear-thinning and/or Bingham plastic. If esoteric constitutive equations such as a history-dependent Bingham plastic model are needed, then codes must be developed to account for these highly nonlinear effects. Currently, the amount of time necessary to complete such a project is unknown. To determine this, a fluid model either would need to be identified or created that correctly models the simulant behavior.

5.2. Settling Behaviors of Aged and Fresh Simulants

The repeatability tests for well-mixed simulants are relatively easy and quick to perform. However, the procedure takes significantly more time and care for the settled simulant.

(a)

(b)

Fig. 2. Comparison of the numerical results with the theoretical predictions. The two figures show results using laboratory-scale experimental dimensions (a) and tank dimensions (b).

Before pump operations, the settled (NC) layer in Tank 101-SY was reformed after each gas release event (GRE). The average period between GREs was ~3 months. At the end of this period, the NC-layer thickness was almost one half of the waste level. Following a GRE, a part of the NC layer mixed with the C layer.

The NC layer is formed by salt crystals in the waste settling. The settling process of particles in Tank 101-SY is complex because the particles have differences in shape, density, and size. Also, the salts can form crystal networks as a result of flocculation and aggregation. The rate of change of the height of the NC layer is available only indirectly through axial temperature measurements. Thermocouples do not provide enough resolution to track the interface between the C and NC layer. In addition, the gas generated in the NC layer causes the settled waste to expand, which pushes up the interface location. Although settling plays an important role in the formation of the NC layer, its rate is unknown.

Also, the settling behavior of the simulants is particularly important for the characterization of the state of a settled simulant. To demonstrate the repeatability of falling-ball tests in a settled layer, the simulant ideally should settle completely, which requires that the settling behavior be known. We must perform settling tests to identify the time required for a complete settling. In typical settling tests, the sample is mixed very well initially and allowed to settle. The height of the interface between the particle-rich and liquid-rich regions then are recorded. The ratio of the height of this interface to the height of the initially mixed suspension is called the compressive strength. The rate of change of the interface height is the settling rate. Initially, simulants with equivalent amounts of compressive strain will be compared.

The settling process of dilute systems are relatively well understood (Richardson and Saki 1954). However, settling of flocculated suspensions is not (Michael and Bolger 1962, and Glasrud et al. 1993). In fact, there are few works that report on nonhomogenous sedimentation. Glasrud et al. (1993) recently reported on the settling behaviors of iron oxide suspensions, using a suspension with needle-like particles. The average length of the particles was $0.5\ \mu$, and the average length-to-diameter ratio was 5 (extremely small particles). The continuous phase was mineral oil. Although the properties of the solid and liquid phases are very different from the properties of our simulant, this study reports interesting results. The settling rates decrease as the solid fraction increases, which was consistent with earlier works. Smaller tube diameters delayed settling. Air bubbles were found to accelerate the settling and had a larger effect at higher solid concentrations.

For the settling tests, the simulants were mixed very well and poured into circular cylinders with a diameter of 5.14 cm and a height of 46 to 51 cm. Simulants were kept in a larger closed container in a constant-temperature oven.

These cylinders were jacketed with circulating hot water to maintain a constant temperature, as shown in Fig. 3.

Settling experiments were performed with aged and fresh simulants. Reproducibility was only checked with the aged simulants.

Initial data were taken in a tapered cylinder. Data reduction to find equivalent time and/or equivalent settled distance in a pure cylindrical geometry was not obvious. The experiments were redone using cylinders for comparison with the settling experiments.

In Fig. 4, the relative settling behavior is seen to vary between the aged and fresh simulants, with the aged simulants settling more slowly than the fresh simulants. The same simulant (AS3) took various periods of time to start settling. When FS1 was allowed to settle at room temperature, it had many very large crystals (>1 mm), which probably contributed significantly to the fast settling rate. Until more results are available from the centrifuge experiments, the relationship between the fresh and aged simulants cannot be defined further.

Fig. 3. Sketch of settling tests.

Fig. 4. The settling behavior of aged and fresh simulants.

Because complete settling of the simulant takes months, we performed simultaneous experiments. Three cylinders were filled with simulants, two of them filled with an aged simulant and one filled with the fresh simulant. All cylinders settled for a few weeks. The interface between the supernate and the slurry was checked hourly for the first day, then for longer periods during working hours.

5.3. Falling-Ball Reproducibility

Experiments were repeated in well-mixed and settled simulants to determine reproducibility. Thus, below we discuss four cases: (1) well-mixed, aged simulant (AS1), (2) well-mixed, fresh simulant (FS2), (3) settled, aged simulant (AS2 and AS3), and (4) settled, fresh simulant (FS2). Falling-ball experiments were performed on both the aged and fresh simulants. The fresh simulant was more viscous than the aged simulant. This span of viscous behavior hopefully will contain the actual waste behavior.

5.3.1. Reproducibility

To simulate how the real waste would affect the settling force at a given settling velocity, falling-ball tests were performed using two simulants. These simulants and samples of a similar simulant made by Agnew (1993) are described in Sec. 3. These samples will be referred to as FS2 for the simulant made in this study, and AS1, AS2, AS3, and AS4 for the simulant samples obtained from Agnew.

Agnew's simulant was created over 2 yr ago and remained mostly at $\sim 50^{\circ}\text{C}$. The fresh simulant was mixed up only 4 to 5 months ago, so it still could be aging. The simulants differentiate from Agnew's tank because they behave differently and have different temperature histories.

Before the constitutive behavior can be determined, the reproducibility of the settling experiments must be checked. In Fig. 5, the results are shown for AS1, although equivalent experiments were performed on all simulants shown in this study. The first set of falling balls consisted of sets of 0.64-cm-diam aluminum, 0.32-cm-diam steel, and 0.48-cm-diam steel balls. To determine if the simulant behaved as a single-phase, homogenous fluid, each set consisted of three to five dropped balls. As seen in Fig. 5, the reproducibility of the settling times is within a few percent. Most of this error is due to the low resolution in time because of the rapid settling velocities in relation to the thirty frames per second used to tape these experiments.

Fig. 5. Balls of the same density and size give good reproducibility. The shear rate for 0.64 cm of aluminum, 0.32 cm of steel, and 0.48 cm of steel are 22, 70, and 78 L/s, respectively. (The frame rate was 30 frames per second; therefore, the above difference for a given ball type are caused by differences of ± 1 frame).

To determine the reactivity/corrosion of different balls in the simulant, the balls were recovered. The steel spheres did not appear to have been notably corroded (i.e., having the same mass, diameter, and surface quality). However, the aluminum balls were completely dissolved. Only some dark gray residue was found at the bottom of the simulant. Therefore, aluminum balls were never used again in this or any similar simulant after these initial experiments. Also, a large amount of foam developed in AS1 after a few days and before the balls were retrieved. This foam probably was caused by the initial off-gassing caused by dissolving/decomposition of the aluminum.

Using the fresh simulant (FS2), the PFB and PFG balls did not settle through the well-mixed simulants where they had settled in AS1. Higher shear rate balls settled reproducibly through the simulant. This bounded the yield stress. However, using 0.32-cm-diam ruby balls, the settling velocities were reproducible.

In earlier drops, a similar phenomenon was observed with the PFB and PFG balls in AS1. Also, occasionally a ball with a higher apparent density settled more slowly than a less-dense ball. At that time, it was assumed that the differences were caused by the nonuniform nature of the plastic ball (i.e., roughness, asymmetry, etc.). Also, some balls were not observed to settle when less-dense balls had settled. Because only 20 cm of the column can be observed at one time, the section observed was normally far below the upper interface where balls did get stuck in later drops. If a ball were trapped in this upper layer, stirring for the next ball would send it to the bottom.

The 0.32-cm-diam spheres were the best spheres used in this study, and they have given very reproducible results at high sphere rates. In FS2, their velocities were not constant over all the drops. In fact, the first ball settled twice as fast as the second ball. This suggests that the yield stress may not be uniform throughout the simulant or may not be uniform upon mixing. This would only manifest itself for balls that are near the yield point as they settle. A small change in the yield would cause large changes in the settling velocity. When using the *in situ* viscometer, this effect will cause a small change in the force required to pull the ball.

5.3.2. Settled Simulants

After settling for many weeks, the simulants were not settling noticeably over 24 h. At this point, balls were dropped in one of the aged simulants. This simulant then was mixed and shorter settling times were used to test how the structure developed from a well-mixed simulant. These shorter times gave reproducible results. From analyzing the data, it appears that the settled height was more important than the time settled. However, these experiments were performed only for ~100-h time periods.

The second column filled with the aged simulant was allowed to settle continuously. After the first set of falling-ball experiments were performed, the simulant was not mixed. Instead, a certain amount of time passed to see if the simulant would recover its undisturbed properties. This would be tested by repeating the same balls that were dropped initially. To determine if there was a critical waiting period, balls were dropped with increasing periods: 2 d, 4 d, 6 d, etc.

The first set of these experiments was not successful because temperature control was lost on three occasions. The first was when the column was transferred from the laboratory to the x-ray facility. This incident caused the formation of small crystals in the saturated liquid and caused a column of the settled layer to rise into the saturated liquid. After ~1 week, the column had settled back down on top of the settled layer. Tests run at this time showed very little difference between the resettled and undisturbed settled simulant.

The second time, temperature control was lost over the weekend, and an array of needle-like crystals had formed in the supernate layer. Upon restoring temperature control, the needles did not completely redissolve but settled mostly on top of the previously settled simulant. This layer of settled crystal needles had a significantly higher viscosity than the simulant below it.

At the same time, a sample of the saturated liquid was taken from the column. Using this sample, the viscosity and density of the saturated liquid was determined.

Because the top of the column was not sealed well, a solid layer formed on top of the simulant while the liquid was being analyzed. The liquid was poured on top of this layer and did not dissolve it. Upon breaking this relatively thin layer through which balls would not settle, the pieces settled down on top of the settled simulant.

The final temperature loss occurred only over a few hours, so it produced only small crystals. However, the whole set of layers had been continuously stiffening so that now the viscosity of the wiry layer was more than an order-of-magnitude higher yield stress than the undisturbed settled simulant. To get around this region, a tube was placed inside the cylinder so that balls could be dropped directly into the lower, undisturbed layer.

Similar experiments gave the same results at high shear rates in settled experiments and/or with FS2, as can be for AS3 in Fig. 6.

Fig. 6. Reproducibility in settled experiments for AS3. The shear rates for the 0.32-cm-diam ruby and 0.32-cm-diam steel are 24 and 70 s^{-1} , respectively. The 1.27-cm-diam balls ranged from 1.6 to 6.3 s^{-1} .

Near the yield point, the results become much less reproducible. Variations by a factor of two have been observed. This is not from the structure breaking down, because the second ball went more slowly than the first ball. This occurred while testing the well-mixed characteristics of FS2, so it is not due to the second ball sampling part of the undisturbed simulant. While evidence pointed to the behavior earlier in the study, it was not until these tests with balls of uniform density and size were performed that definitive conclusions could be made. This implies that to get good reproducibility, the *in situ* viscometer should operate at shear rate above 3 s^{-1} . This all depends on the characteristic shear rate at which results are needed. If they are needed in the lower shear rate regimes, more tests must be performed to determine both the average and deviations about the average.

5.4. Constitutive Equations for Well-Mixed Simulants

Above we demonstrated that the well-mixed simulant behaves as a homogenous fluid (continua). To estimate the flow curves (e.g., the relation between the shear stress and shear rate), various constitutive relationships will be tried. First, the simulant will be assumed to be a Newtonian fluid. Then the measured terminal velocity will be used to calculate the shear stress and shear rate. If the simulant is

a Newtonian mixture, the calculated effective (apparent) viscosity will not be a function of the shear rate. If the viscosity depends on the shear rate, then a non-Newtonian fluid model will be used. However, the apparent Newtonian viscosity behavior as a function of shear rate should be used as a guide for selecting the non-Newtonian models to test. For the simulant, the apparent Newtonian viscosity was shear thinning with a very low yield stress. Below, these cases will be discussed in a progressive order.

As a first iterate, the settling rate of the falling balls was analyzed assuming the fluid behaved as a Newtonian fluid at low Reynolds numbers. Making this assumption, the apparent Newtonian fluid viscosity can be calculated directly from the settling velocities using the drag on a sphere in the cylinder, which is given previously [Eqs. (5.1) and (5.2)]. However, all balls did not predict the same viscosity. From examining the apparent viscosity as a function of the shear rate, the fluid appeared to be a shear-thinning, and possibly a power-law fluid. While the drop at different temperatures and in the different simulant also could be subjected to a Newtonian analysis, they were not because the power-law analysis appeared to work satisfactorily.

From this first set of experiments, the Reynolds number was estimated to be significantly greater than 0.3 (the creeping flow limit for balls settling in a Newtonian fluid). To get closer to creeping flow conditions, 1.27-cm-diam plastic balls (PFB) with a density of 1.18g/cm³ were filled with 0.32- to 0.48-cm-diam brass, steel, and tungsten carbide balls such that the average density of the plastic balls ranged from 1.74 up to 2.0. Additionally, some 0.64-cm-diam plastic balls (PFG) were filled with 0.159-cm-diam gold wire. While these ball settled more slowly, only a few of the PFGs settled with Reynolds numbers below 0.3.

The next constitutive equation tried was for a power-law fluid, based on the behavior seen in the Newtonian analysis. The analysis assumes that the drag coefficient as a function of Reynolds number is the same for power-law fluids as for Newtonian fluids. Making this assumption introduces a 30% uncertainty into the results. While this is normally considered satisfactory, better results could be obtained if the drag coefficient depended on the Reynolds number and the power-law index. However, other proposed analysis methods that use drag coefficients that depend on the power-law index have not improved the accuracy of this seemingly first-order assumption.

The constitutive relationship for a power-law fluid is

$$\nu = m|\dot{\gamma}|^{n-1} \dot{\gamma} \quad , \quad (5.5)$$

where ν is the non-Newtonian viscosity, $\dot{\gamma}$ is the shear rate, and m and n are the fluid consistency index and power-law index, respectively. For $n=1$, the

Newtonian behavior is recovered with $m = \mu$. If $n < 1$, then the fluid is considered shear-thinning.

At moderate Reynolds numbers, the wall effects depend on the Reynolds number and the diameter of the settling ball relative to the diameter of the column. For a power-law fluid, the following relationships (Chhabra 1993) were used to determine the wall-effect f :

$$\frac{1/f - 1/f_{\infty}}{1/f_0 - 1/f_{\infty}} = \{1 + 1.3 \text{Re}_{PL,m}^2\}^{-0.33}, \quad (5.6)$$

where

$$f_0 = 1 - 1.6(d/D), \quad (5.7a)$$

$$f_{\infty} = 1 - 3(d/D)^{3.5}, \quad (5.7b)$$

$$f = \frac{u_0}{u}, \quad (5.7c)$$

and

$$\text{Re}_{PL,m} = \frac{\rho_f du}{m(u/d)^{n-1}} = \frac{\rho_f d^n u^{2-n}}{m}, \quad (5.8)$$

where u_0 is the measured velocity, u is the theoretical settling velocity in an infinite sea of fluid, and ρ_f is the density of the fluid. Also, the drag coefficient C_D is defined as

$$C_D = \frac{4(\rho_b - \rho_f)gd}{3u^2\rho_f}, \quad (5.9)$$

where ρ_b is the density of the ball and g is the gravitational constant. The densities of the simulant were measured and reported in an earlier section. Everything but the settling velocity was known *a priori*. The velocity used was the velocity corrected for wall effects, which depends on the Reynolds number.

The procedure consists of guessing a plastic Reynolds number, calculating the wall effect [Eqs. (5.6) to (5.7b)], modifying the velocity [(Eq. (5.7c))], determining the drag coefficient [Eq. (5.9)], and finally calculating the Reynolds number from the drag coefficient assuming Newtonian behavior. From data found in Perry's handbook (1984), the following inverse relationship was determined for $0.5 \leq \text{Re} \leq 50$:

$$\log(\text{Re}) = 2.0292 - 1.999 \log(C_D) + 0.60542 \log(C_D)^2 - 0.14072 \log(C_D)^3. \quad (5.10)$$

Higher Reynolds numbers were not encountered, and for lower Reynolds numbers the creeping flow result could be used where

$$C_D = \frac{24}{Re} . \quad (5.11)$$

Using the calculated Reynolds number as a guide, new Reynolds numbers were guessed until the calculated Reynolds number matched the guessed Reynolds number to three places. This procedure was repeated until all the different ball drops had self-consistent Reynolds numbers. From the plastic Reynolds number and the power-law index n , the apparent m was determined. By calculating the variance of m as a function of n , the best power-law index was determined. Because the wall effect is independent of the power-law coefficients m and n , the determination of the Reynolds numbers could be separated from the determination of the power-law coefficients.

In Fig. 7, the results of this analysis are shown. The power-law coefficients are 0.74 and 2.29 for the power-law and fluid consistency index, respectively. Next, the temperature was changed to 40.8°C, followed by a change to 25.2°C. After that, all balls except the aluminum balls were recovered. Because the off-gassing occurred during drops at 51.2°C (set A and B), the simulant was reheated to 50.0°C, and the initial tests were repeated (set C). The results can be seen in Fig. 8 and Table 5.

Fig. 7. Settling data reduced assuming power-law behavior and resulting wall-effects gives power-law behavior.

In Fig. 9, the stress vs strain was plotted to determine if the well-mixed simulant had a yield stress (either real or apparent). As can be seen in the figure, if a yield exists, it is less than 10 dynes/cm² or 1 Pascal. As shown in Fig. 10, FS2 is compared with AS1, and FS2 appears to have a yield stress greater than 10 dynes/cm². If the yield stress is subtracted from the overall stress, the two simulants have very similar behavior.

TABLE 5. POWER-LAW COEFFICIENTS DETERMINED BY FALLING BALL

Temperature (°C)	m [dyn s ⁿ / cm ²]	n
51.2	1.59	0.72
25.2	11.7	0.72
40.8	4.34	0.72
50.0	1.59	0.78

Fig. 8. Rheogram for AS1 at various temperatures. The first two tests at 50°C were performed while or soon after the aluminum balls were introduced into the simulant.

Fig. 9. Low shear behavior of AS1 shows that the yield stress is less than 10 dynes/cm² or 1 Pascal.

Fig. 10. Stress-strain diagram for two types of simulants. AS1 has a lower effective viscosity than FS2 due to a corresponding lower yield stress.

5.5. Constitutive Equations for Settled Simulant

For the settled waste, the viscosity of the simulant was not calculated because in most cases, a steady-state settling velocity was either not reached or not reproduced by the next settling ball. This implies that a history-dependent constitutive equation is necessary to accurately reduce the data. Also, both the settled and mixed simulants displayed yield stress; however, the settled waste had both a history-dependent and a history-independent value.

The settled simulants (AS2, AS3, and FS2) displayed certain common features. First, the first ball would settle more slowly than the second ball. Second, if the same type of ball were dropped until a steady-state settling velocity was achieved, this velocity would be lower than that observed in the well-mixed simulant. An exception was when a set of high-shear-rate settling balls was followed by a low-shear-rate ball with a diameter less than or equal to the high-shear-rate balls. The balls then would reproduce the well-mixed settling velocities.

To analyze the falling ball's behavior, several methods were used to reduce the falling ball's trajectory. The first was to locate the ball's position in each frame. This was used when the ball moved at least 0.32 cm per frame (or about 9 cm/s). A second method was to record the time, elapsed or actual, for every 0.64 cm the ball settled. Finally, if the same type of ball had been drop previously, the elapsed time for the ball to settle between predetermined points would be recorded. This would result in average settling speeds over a given number of sections, typical two or four sections.

The settling rates of similar balls did not always increase because balls fell down different channels in the settled simulant. Every time a ball settled more slowly through a section than the previous ball, a new hole could be seen in the interface between the supernate and the settled layers. However, most balls followed the pattern shown in Fig. 11 (the first ball dropped significantly slower than the second ball). Subsequent balls would settle at nearly the same rate as the second ball. However, if the simulant were mixed, balls dropped after mixing would settle faster than the balls before mixing. These effects are believed to be caused by some structure that forms in the settled layer over a period of days. Therefore, the first ball breaks down the fluid structure around its settling path. If the second ball follows the first ball path through the fluid, it dissipates most of its energy in the fluid sheared by the first ball. If a high-shear-rate ball is followed by a low-shear-rate ball, the high-shear-rate ball will have disrupted a large enough region so that the low-shear-rate ball will affect only sheared fluid. This is why such a ball would reproduce the well-mixed settling velocities. This only holds if the compressive strain is ~ 1 (no significant settling.)

Fig. 11. Effect of short-term history on the settling rate. The drop order shows that: (1) the first ball settles through a different suspension than subsequent balls, and (2) successive balls reach a plateau-settling velocity that is lower than the well-mixed velocity.

In Fig. 12, we see that there is a critical amount of time (between 10 and 16 h) below which the settled suspension behaves like the well-mixed suspension. For times less than the critical time, balls settle at the same rate as in the well-mixed suspensions. Furthermore, from Fig. 4, this also appears to be the time at which the interface starts forming. Thus, there does not appear to be any significant settling in the bulk of the simulant before the interface between the supernate and the settled layer forms.

5.6. Couette Viscometer Tests

The viscosity was measured using a Couette viscometer with a bob radius of 1.9 cm and a cup radius of 2.3 cm. The bottom of the bob was concave and captured a bubble of air beneath the bob to provide a shear-free surface. We therefore assumed that the measured torque was due only to the sample being sheared in the annular gap between the cup and the bob. The shear stress in the gap was not uniform. From the conservation of momentum, we can show that the shear stress varies as the reciprocal of the radius squared. Thus, the shear stress varied from its maximum at the surface of the bob to $(R_i/R_o)^2$ of the maximum value at the inner surface of the cup. For the Couette viscometer used, the ratio of the minimum stress to the maximum stress was 0.682.

Fig. 12. Velocity of first ball dropped to second ball dropped after suspension has settled for several hours. For times less than 16 h, the simulant did not change from its well-mixed state, so the first ball settled at the same speed as the second ball. For longer times, the second ball settled significantly faster.

The mean shear stress was calculated as the arithmetic average of the stress at the bob and the stress at the cup. The shear rate corresponding to this shear stress was calculated by using a series solution given by Mooney (1930). This series requires estimating the second derivative of the raw data. Derivatives were calculated by finite differences. Second derivatives were found to be small; thus, only the leading term was important in calculating shear rates. The series solution is valid assuming that:

- 1) the material has a yield stress lower than the minimum stress in the gap so that all the material in the gap is shearing,
- 2) the material does not slip at the wall, and
- 3) the material remains homogeneous (sedimentation and particle migration are negligible).

Data were consistent with a zero or very small yield stress (lower than is measurable on the viscometer used), and the entire sample appeared by visual inspection to be sheared during measurements. No wall slip was detected by visual inspection either through the transparent cup wall or at the top surface in

contact with the bob. Repeated runs on the same sample were reproducible to within $\pm 15\%$ except at the lowest torques, where the noise in the torque signal was a significant fraction of the measured torque.

The measured viscosities at the three temperatures are listed in Table 6 and shown in Fig. 13.

The viscosity was found to obey a power law relation [see Eq. (5.3)]. The power law parameters are listed in Table 7.

A comparison of results obtained from Couette and falling-ball rheometers is given in Fig. 14. As seen from this figure, the viscosity measured by the Couette viscometer at a given shear rate is less than measured by a falling-ball viscometer. Also, the power-law index obtained from the Couette viscometer is less (more shear thinning) than for the falling ball. There are five possible explanations for this effect: (1) particle migration, (2) slip at the walls, (3) yield stress with a short recovery time, (4) different histories (which makes comparisons between simulants futile), or (5) equations used to reduce data that are inaccurate.

TABLE 6. MEASURED VISCOSITY OF AGED SIMULANT USING
COUETTE VISCOMETER

Mean Shear Rate (1/s)	Mean Shear Stress (dyn/cm ²)	Viscosity (P)	Temperature (°C)
0.473	2.55	5.40	24.2
0.841	4.41	5.25	24.2
1.50	5.47	3.66	24.2
2.66	8.59	3.23	24.3
4.73	12.89	2.73	24.3
0.841	3.38	4.02	30.6
1.50	5.22	3.49	30.5
2.66	7.02	2.64	30.6
4.73	9.68	2.05	30.6
0.473	1.85	3.90	40.4
0.840	2.71	3.23	40.4
1.50	3.34	2.23	40.4
2.66	4.57	1.72	40.5
4.73	6.05	1.28	40.5

The first explanation would be a function of the amount of migration, stabilizing only upon reaching the steady-state concentration profile. As seen in earlier studies (Abbott et al. 1993), particle migration depends on the amount of shear, not the shear rate used to get there. These tests were performed by ramping up the velocity in a stepwise fashion from lowest to highest and then ramping down. Because the viscosities measured on the way up matched those on the way down, the particle migration would have to be completed during the first test at low shear rates. This seems unlikely.

The second explanation was tested for and not found. The third explanation was tested by using the Couette viscometer, stopping the viscometer, and waiting a short period of time (a few seconds up to a few minutes). The viscometer then was restarted and checked for an initially high torque. These tests did not show any recovery of the fluid with times up to 2 h. For the fourth reason, it seems more probably for our experience that the long times at room temperature would result in a more viscous, not less viscous, simulant.

Therefore, the final explanation needs to be tested with a well-characterized model fluid. However, as mentioned earlier, the data reduction already contains a 30% uncertainty caused by using the Newtonian drag vs the Reynolds number correlation to determine the stress. The largest possible source of error is that the well-mixed simulant (and the actual waste) is not adequately characterized by a power-law constitutive equation.

Fig. 13. Viscosity of Hanford waste sludge at the temperatures indicated.

6.0. SUMMARY AND CONCLUSIONS

To model the viscous behavior of the simulant at moderate Reynolds number, it was clear from the beginning that inertial effects would have to be accounted for. Additionally, because of the size of falling balls relative to the size of the column, wall-effect corrections would be important. The C layer is expected to behave as a Newtonian fluid. These falling-ball experiments performed with well-mixed waste simulants clearly show that the mixed waste and the NC layer are not Newtonian suspensions.

TABLE 7. POWER-LAW PARAMETERS OF AGED SIMULANT OBTAINED FROM COUETTE VISCOMETER

Temperature (°C)	m (dyn s ⁿ /cm ²)	n
24.2	4.45	0.678
30.6	3.89	0.600
40.4	2.79	0.503

Fig. 14. Comparing falling-ball viscosities with Couette viscosities. At a given temperature, the Couette viscosities determined in a Couette viscometer are less than half those determined by a falling ball.

At high shear rates, a power-law analysis appears to adequately model the data. For the fresh simulant, which has a higher yield stress, a correction for the yield stress appears to be necessary. As a function of temperature, the yield stress did not scale with the increased viscosity.

At low shear rates, a yield stress appears to exist. However, a Bingham plastic analysis did not improve the fit of the measurements. Part of the problem is that denser balls do not always settle faster than less-dense balls. This suggests that mixing the suspension does not make it homogeneous. Most of the mixing studies to date have concentrated on the uniform, single-material balls, which the latter explanation, the recovery time would have to be on the order of 1 min. This suggests that a history-dependent Bingham plastic model with multiple time scales may be necessary to reduce the actual tank data. These time scales do not appear to be shorter than seconds and longer than 2 h from the Couette viscometer experiments.

The physics behind the time-dependent Bingham plastic appear to be related to structure formation of the precipitated salts. This would depend on the rate of crystal dissolution/recrystallization, which would increase with increasing temperature. This would explain why the yield stress did not increase with decreasing temperature.

7.0. REFERENCES

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APPENDIX E

DOSE RATE WORK

**Westinghouse
Hanford Company**

**Internal
Memo**

From: TWRHP Technical Support
Phone: 372-2842 R3-12
Date: June 27, 1994
Subject: 241-SY-101 VISCOMETER DOSE ESTIMATES

33300-94-050

To: K. L. Pearce L6-37

cc: S. L. Bump R3-12
P. Greenbaum S5-20
K. D. Haggerty T4-09
D. L. Kelly S5-20
PAO File/LB

- References:
- (1) Internal Memo, P. A. Olsen to K. L. Pearce, 33300-94-008, 241-SY-101 VISCOMETER DOSE RATE ESTIMATES, dated February 7, 1994.
 - (2) "Estimation of Waste Entrainment in the Viscometer Enclosure."
 - (3) Draft Design Drawing of Viscometer Container.
 - (4) Microshield Computer Code, Version 3.1, 1989.
 - (5) NUREG-1400, *Air Sampling in the Workplace*, February 1993.
 - (6) DOE Order 5480.11, *Radiation Protection for Occupational Workers*.

Dose rate estimates in relating to waste entrainment in the viscometer enclosure are provided for the safety assessment. This letter supplements original dose rate estimates. Reference (1) provided dose rate estimates when the riser is opened and the dose rate outside of the enclosure when there is a waste film on the cable. Tests performed and summarized in reference (2) reveal waste could become entrained in the cable, meaning more contamination in the enclosure. The design of the shielding plate has also changed yielding different dose rates through the shield plate. The attachment provides dose rate information for various waste entrainment possibilities and the internal dose potential when the enclosure is opened.

If there are any more questions please call me at the above number.

P. A. Olsen
Sr. Health Physicist

Attachment

Dose Rate Estimates for Viscometer Enclosure

Dose rate estimates in relation to the waste entrainment in the viscometer enclosure are needed to provide information in safety assessment. Tests performed and summarized in reference (2) reveal waste could become entrained in the cable, meaning possibly more contamination in the enclosure. There are two mechanisms by which waste can be removed from the outside of the cable: 1) as the cable is retracted it will be decontaminated by flushing the external surfaces of the cable and 2) as the cable is pulled through the orifice at the bottom of the enclosure, waste may be scraped off and deposited on top of the orifice plate. Waste may become entrained within the enclosure by waste scraping off of the cable as it passes through the orifice and by becoming embedded within the cable due to cracks in the coating. The enclosure will then need to be decontaminated, which means opening it. Personnel will be exposed to dry waste at this point. An estimate of how much contamination is in the enclosure can aid in determining internal dose to personnel.

Information and assumptions used in estimating dose rates were derived from references 1 and 2.

- The source is 1.23 E9 Bq/cc (554 microCi/cc) Cs-137 with a density of 1.62 g/cc.
- The height of the shipping enclosure is 64.34 cm (25.33 in.).
- The width of the shipping enclosure is 46.53 cm (18.62 in.).
- The enclosure is made of 0.3175 cm (1/8 in.) stainless steel.
- The mounting pipe is a stainless steel pipe with either a 0.601 cm (0.237 in.) or 0.827 cm (0.337 in.) thickness.
- The shielding plate (5.12 cm or 2.02 in. radius) has as a center whole with a top radius of 0.229 cm (0.09 in.) and bottom diameter of 0.483 cm (0.19 in.). The plate is made of stainless steel of 1.60 cm (0.630 in.) thickness except for four small areas of 0.795 cm (0.313 in.) wide and 0.832 cm (0.328 in.) deep. At these points the thickness of the plate is 0.335 cm (0.132 in.).
- The tungsten sphere has a radius of 4.57 cm (1.85 in.) and is housed in the mounting pipe.
- The length of the drum wrapped with cable is 18.1 cm (7.125 in.).
- The radius of the drum is 8.20 cm (3.227 in.).
- The cable is stainless steel coated with polypropylene yielding a radius of 0.158 cm (1/16 in.).
- A maximum of 40 grams (1.4 ounces) of waste could be on the outside of the cable if the wash mechanism were not operating.
- The cable could have as much as 791.68 grams (27.8 ounces) of waste in the interior of the cable.

The dose rate through the shield plate was calculated for the new design using reference (4). The dose rate is 12.3 mrem/hr in contact with the box and 11.8 at 30 cm from the top of the box with the riser open and the instrument in the waste.

The waste in the interior of the cable was varied from 32 grams (1.13 ounces) to 960 grams (33.8 ounces) to generate a dose rate versus gram of waste curve. The table lists the results generated using reference (4). The figure included on the following page can be used to determine when the contamination will yield a dose rate of 100 mrem/hr. The waste yielding this dose rate is approximately 65 grams for contact reading, 320 grams at a 30 cm reading, and greater than 1000 grams at 90 cm. The alarm set point for the area radiation monitor can be lowered to account for the distance from the source. At greater than 3 feet away, however, there will not be much value added in using it.

Waste Weight (grams)	Activity (Ci)	Dose Rate (mrem/hr)			
		Contact	30 cm	91 cm	304 cm
32	0.01	59	9.6	2	0.23
80	0.03	150	24	5	0.57
208	0.08	420	67	14	1.6
320	0.11	650	104	22	2.5
480	0.16	970	149	33	3.7
640	0.22	1280	203	44	5.0
800	0.27	1610	257	55	6.4
960	0.33	1930	311	66	7.7

References 5 and 6 were used to determine the intake potential associated with certain levels of contamination in the enclosure. The enclosure will have air flowing through it meaning the waste will likely be dry powder by the time the enclosure is opened. The following equation is found in reference (4).

$$I_p = Q \times 10^{-6} \times R \times C \times D$$

where Q = quantity of material,
R = release fraction, which is 0.01 for non-volatile powder,
C = confinement factor, which is 1 for open work areas, and
D = dispersibility, which is 10 for cutting, grinding, etc.

Although cutting and grinding is not going to take place this value was used for conservatism. The intake potential can then be related to the Annual

Limit of Intake (ALI) which is equivalent to a 5 rem dose over an entire occupational year of exposure. The other radionuclide present in the waste which could yield a high internal dose would be Sr-90/Y-90. The ALI for Sr-90/Y-90, which is 4.8 microCi, was used to relate the intake potential to dose. The maximum contamination level in the enclosure would be 831 grams. This equates to 0.26 Ci of waste. The intake potential would be 2.6 E-2 microCi and the dose would be 27 mrem as shown in the following equation.

$$\begin{aligned}
 \text{Dose} &= \left(\frac{2.6 \text{ E-2 } \mu\text{Ci}}{4.8 \text{ } \mu\text{Ci}} \right) (5000 \text{ mrem}) \\
 &= 27 \text{ mrem}
 \end{aligned}$$

Westinghouse
Hanford Company

Internal
Memo

From: TWRHP Technical Support
Phone: 372-2842 R3-12
Date: January 18, 1994
Subject: 241-SY-101 VISCOMETER DOSE RATE ESTIMATES

33330-94-005

To: K. L. Pearce L6-37

cc: D. B. Graves L6-38
P. Greenbaum S5-20
K. D. Haggerty T4-09
D. L. Kelly S5-20
R. J. Smith G2-02
R. N. Smith R3-12
PAO File/LB

- References:
- (1) Internal Memo 33300-93-089, P. A. Olsen to K. L. Pearce, 241-SY-101 VISCOMETER DOSE RATE ESTIMATES, dated November 22, 1993.
 - (2) Microshield Computer Code, Version 3.12, 1989.
 - (3) Draft Design Drawing H-2-818359 - Viscometer Container.

Dose rate estimates for inserting and retracting a tungsten sphere in tank 241-SY-101 through a 4 inch riser are included in the attachment. Reference (1) included dose rate and shielding estimates but the source term used in the original calculations was in error. This letter is submitted for similar dose rate calculations with the source term from the interim safety basis for 241-SY-101. There are three scenarios evaluated with the results listed in the attachment. The attachment includes the assumptions, results and recommendations. Reference (2) was used to calculate dose rates and estimate shielding. Reference (3) was used to determine dimensions and configuration of the source. If there are any more questions, please call me at the above number.

P. A. Olsen
Adv. Health Physicist

jlm

Attachment

241-SY-101 Viscometer Dose Rate and Shielding Estimates

Dose rate estimates for inserting and retracting a tungsten sphere into tank 241-SY-101 through a 4 inch riser are included. Reference (2) was used to generate the dose rate estimates. There are three scenarios evaluated:

- (1) The dose rate estimate while the tungsten sphere is in the tank.
- (2) The dose rate estimate outside of the mounting pipe which supports the viscometer enclosure and houses the tungsten sphere.
- (3) The contact dose rate estimate from the drum while the retracted cable is wrapped.

The following dimensions were used when calculating the dose rates in the above scenarios. This information was retrieved from reference (3) and cc:mail communications.

- The tank waste level is 34.1 feet (1041 cm).
- The distance of the void space is 126.8 in. (322 cm).
- The distance from the tank to the top of the riser through the soil is 126 in. (320 cm).
- The distance from the top of the riser to the bottom of the viscometer enclosure is 28.9 in. (73.4 cm).
- The height of the viscometer enclosure is 25.33 in. (64.34 cm).
- The enclosure is made of 1/8 in. (0.3175 cm) stainless steel.
- The mounting pipe is a stainless steel pipe with either a 0.237 in. (0.601 cm) or 0.337 in. (0.827 cm) thickness.
- The tungsten sphere has a radius of 1.80 in. (4.57 cm) and is housed in the mounting pipe.
- The length of the drum wrapped with cable is 7.125 in. (18.1 cm).
- The radius of the drum is 3.227 in. (8.20 cm).
- The cable is stainless steel coated with a high density polyethylene yielding a radius of 1/16 in. (0.158 cm).
- The thickness of the waste loaded on the cable and tungsten sphere were assumed to be 0.6 mils (1.5×10^{-3} cm).
- The source term is 508 microCi/cc of Cs-137 with a density of 1.62 g/cc from the interim safety basis for 241-SY-101.

(1) Dose Rate Through Open Riser

The assumptions considered the total distance to the top of the shipping container and the only shield the 0.3175 cm thickness of the viscometer enclosure. The estimated dose rate is 102 mrem/hr 30 cm from the top of the viscometer enclosure. This is a high radiation area and would require continuous manning if not locked. To decrease this dose rate to less than 100 mrem/hr another 0.3175 cm piece of steel could be added to the bottom of the viscometer enclosure.

(2) Mounting Pipe Dose Rate

The second request was for a dose rate estimate from outside the mounting pipe. Currently the thickness of this pipe has not been determined but it will be either 0.601 cm. thick or 0.856 cm thick. The sphere will likely have a layer of tank waste on it when it is extracted. The thickness of waste was assumed to be 0.0015 cm because of the short period of time that the sphere will be in the tank. The volume of the source is assumed to be 0.395 cc based on the above thickness. This would yield a source term of 200 microCi. For the purposes of running the Microshield computer program, the source was assumed to be uniformly distributed in the sphere. The dose rate on contact with the mounting pipe would be 20.3 mrem/hr and 17.5 mrem/hr for thicknesses of 0.601 cm and 0.856 cm respectively.

(3) Drum (with cable wrapped) Dose Rate

When maintenance is needed on the drum, contact with the drum will be required. Therefore a dose rate measurement is needed. The cable was also assumed to have 1.50×10^{-3} cm of waste loading. The length of the cable in the waste is 1041 cm. The total waste volume was calculated to be 2.29 cc yielding a source term of 1.16×10^3 microCi. For purposes of dose rate calculation the waste was assumed to be uniformly distributed throughout the drum. The waste will only be on 57% of the wrapped cable because that is the portion of the cable in the waste. The radius of the source is 8.19 cm and the length is 10.3 cm. The dose rate on contact with the drum was estimated at 83.9 mR/hr and the dose rate at 30 cm, 3 mR/hr.

The above information is to be used as a guidance. This should not take the place of actual measurements when performing work.

Westinghouse
Hanford Company

Internal
Memo

From: TWRHP Technical Support
Phone: 372-2842 R3-12
Date: February 7, 1994
Subject: 241-SY-101 VISCOMETER DOSE RATE ESTIMATES

33330-94-008

To: K. L. Pearce L6-37

cc: M. D. Clements G2-02
P. Greenbaum S5-20
K. D. Haggerty T4-09
D. L. Kelly S5-20
R. N. Smith R3-12
PAO File/LB

References: (1) Microshield Computer Code, Version 3.1, 1989.
(2) Draft Design Drawing of Viscometer Container.
(3) Internal Memo, P. A. Olsen to K. L. Pearce,
33300-94-005, "241-SY-101 VISCOMETER DOSE RATE
ESTIMATES," dated January 18, 1994.

Dose rates and shielding estimates for inserting a viscometer into tank 241-SY-101 through a 4 inch riser are included in the attachment per your cc:mail. The two estimates are dose rate estimates over the 4 inch open riser and expected dose rates on the outside of the box once the sphere and cable are removed. The attachment includes the assumptions and results. Reference (1) was used to calculate dose rates. Reference (2) was used to determine dimensions and configuration of the source. If there are any more questions, please call me at the above number.

P. A. Olsen
Adv. Health Physicist

jlm

Attachment

241-SY-101 Viscometer Dose Rate Estimates

Dose rates above a 4 inch riser in tank 241-SY-101 and the dose rates on the outside of the sphere and cable housing were estimated per your cc:mail using the reference (1) computer code. The following assumptions were made based on your cc:mail, and reference (2).

- The tank waste level is 34.1 feet (1041 cm).
- The distance of the void space is 126.8 in. (322 cm).
- The distance from the tank to the top of the riser through the soil is 126 in. (320 cm).
- The source term is 508 microCi/cc of Cs-137 with a density of 1.62 g/cc from the interim safety basis for 241-SY-101.
- The height of the shipping enclosure is 25.33 in. (64.34 cm).
- The width of the shipping enclosure is 18.32 in. (46.53 cm).
- The enclosure is made of 1/8 in. (0.3175 cm) stainless steel.
- The mounting pipe is a stainless steel pipe with either a 0.237 in. (0.601 cm) or 0.337 in. (0.827 cm) thickness.
- The tungsten sphere has a radius of 1.80 in. (4.57 cm) and is housed in the mounting pipe.
- The length of the drum wrapped with cable is 7.125 in. (18.1 cm).
- The radius of the drum is 3.227 in. (8.20 cm).
- The cable is stainless steel coated with a high density polyethylene yielding a radius of 1/16 in. (0.158 cm).
- The thickness of the waste loaded on the cable and tungsten sphere were assumed to be 0.6 mils ($1.5 \text{ E } -3 \text{ cm}$).

Using the first four assumptions, the estimated dose rate at the center of a 4 inch riser was calculated at 510 mrem/hr.

The dose rate estimate from outside the enclosure when the cable is in the enclosure and the viscometer is below the enclosure was also calculated for shipping requirements. The dose rate outside of the tungsten sphere enclosure was given in reference (3). The maximum dose rate on contact was calculated at 20 mrem/hr. At 30 cm this dose rate would be less than 2 mrem/hr. In contact with the top of the enclosure housing the cable, the dose rate was estimated to be less than 2 mrem/hr. The dose rate at the sides of enclosure was estimated to be 4.5 mrem/hr. The maximum dose rate will likely be from the tungsten sphere based on the results of reference (3) and those in this attachment.

The above information is to be used as a guidance when determining transport requirements. This should not take the place of actual measurements when performing work.

ALARA CHECKLIST

Object/Design Engineer Signature: _____

Date: 1/6/94

Work Package No.: 2W-94-XXXXX-W

I.	FACILITY DESIGN	CRITERIA	REMARKS
1.	Minimal contamination or hazardous waste production.	[na]	This is not a facility design DRAFT
2.	Designed for ease of contamination of hazardous waste control.	[na]	
3.	Surface coatings for ease of decontamination.	[na]	
4.	Designed to minimize exposure to uncontrolled areas.	[na]	
5.	Remote handling equipment provided.	[na]	
6.	Glove boxes required.	[na]	
7.	Solid and liquid waste systems designed for ease of operations.	[na]	
8.	Waste systems designed to minimize exposure to personnel and environment.	[na]	
9.	Sampling points in lowest practical exposure area.	[na]	
10.	Engineered controls for exposure and contamination controls.	[na]	
11.	Traffic patterns designed to minimize traffic through potentially contaminated areas or elevated exposure areas.	[na]	
II.	SYSTEM DESIGN		
1.	Equipment/instruments requiring routine maintenance calibration, servicing or inspection.		
	- Designed and located to minimize time of each task.	[Y]	Components are designed with quick releases for change-out.
	- Located in lowest practical radiation field.	[Y]	A shield plug is added to decrease dose rate at top of enclosure. Shielding will be provided by the structure for decreasing dose rate radially from the enclosure pipe.
	- Movable to a low radiation field.	[Y]	Instrument is designed to obtain data from tank waste, and must operate in that environment. However, the majority of service can be done in a lower radiation area after removing the assembly from the riser. Change out of load cells is expected while instrument is on the riser, but this will result in minimal worker exposure.
	- Located away from hazardous substances and conditions.	[Y]	Testing requires hardware to come in direct contact with tank waste. To minimize waste entrainment in the main viscometer assembly during equipment retraction, a decontamination system will be utilized.
2.	Valves, piping, process equipment designed to minimize leakage.	[Y]	All joints are sealed with gaskets.

1. *Chrysomelidae*
 2. *Chrysomelidae*
 3. *Chrysomelidae*
 4. *Chrysomelidae*
 5. *Chrysomelidae*

WHC-SD-WM-SDD-043
Rev. 0

APPENDIX F

MATERIALS

Westinghouse
Hanford Company

Internal
Memo

From: System Structural Integrity Assessments 23460-EBS-94-001
Phone: 376-4917 H5-52
Date: February 17, 1994
Subject: ESTIMATED CHEMICAL COMPATIBILITY OF TUNGSTEN BALL IN 241-SY-101
WASTE

To: T. I. Stokes H5-09

cc: W. F. Brehm H5-67
J. R. Divine H5-52
D. B. Graves L6-38
K. L. Pearce L6-37
K. V. Scott H5-52 *2118*
EBS:File/LB

Troy, I requested J. R. Divine, ChemMet Ltd., to assist in this quick-look assessment of the potential corrosion behavior of the tungsten (95% W, 2.5% Ni, 1.25% Cu, 1.25% Fe) ball in SY-101 waste. We have assumed that the ball may be in the approximately 120 °F waste for as long as two months. The following briefly describes the scope of the short-term investigation, the general findings and recommendations for resolving the general lack of tungsten corrosion data and in-tank experience.

Summary and Conclusions

Almost no data exist concerning corrosion of tungsten or tungsten alloys in caustic environments; no data were found concerning the effect of nitrate or nitrites. Corrosion staff at WSRL and WINCO do not know of any case where tungsten was used in their waste tanks. DST 241-SY-101 waste contains some chemicals that are commonly used to etch (or attack) tungsten. Cr or Ni plating would eliminate concerns about uniform corrosion. Galvanic and crevice corrosion concerns associated with a threaded stainless steel attachment could be evaluated by conducting corrosion tests in a waste simulant.

Investigation and Results

Jim and I scanned sixteen tungsten-related references and contacted 12 staff, both on- and off-site concerning corrosion of tungsten (references and names attached below).

Very little data were found concerning the corrosion behavior of tungsten and tungsten alloys in caustic solutions. Metal etching and limited metal cleaning information (from the ball manufacturer) indicate that certain chemicals in SY-101 waste could cause the ball to corrode. We cannot readily estimate how much corrosion will occur. A list of those etchants and one chemical cleaning agent vis-a-vis SY-101 waste is attached.

T. I. Stokes
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February 17, 1994

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Because the mixed state of these chemicals in SY-101 is unclear, it is possible that either corrosion inhibition or corrosion enhancement could occur. Conducting corrosion tests in an SY-101 simulant or placing corrosion specimens within the actual waste appear to be the only way to resolve this unknown effect.

You may want to make an estimate on how much tungsten you could lose from the ball and still not seriously affect the viscosity measurement data that is to be obtained.

Several other corrosion factors should be considered:

- 1) The ball contains a drilled and tapped hole, apparently to accept a threaded stainless steel bolt or equivalent. Jim and I did not find any data relating to either galvanic (2-metal) or crevice corrosion for a tungsten-SS couple.
- 2) The specific tungsten alloy is known to be very heterogeneous. The alloy starts out as compress of tungsten powder with Cu, Ni, and Fe powders within the w-powder interstices. During sintering the Cu-Ni-Fe "binder" takes up a substantial amount of the contiguous tungsten powder surface (perhaps about 20 %) while the tungsten takes up only very small amounts of them. The result is that the interfacial regions will act more like a Cu-Ni-Fe-alloy (that contains some W) in contact with mainly W. This could produce a galvanic-like or localized corrosion effect including cracking.
- 3) Stress level (and any residual stress) in the stainless steel cable could be important in that stress-corrosion might occur for a two-month exposure.
- 4) Chromium or nickel plating of tungsten appears possible; however, if there is a defect or holiday in the coating, an increased local corrosion might occur.

Details

Here's a list of etching solutions (chemical and electrolytic) and the cleaning agent used by Kulite Corp:

Chemical Etching Agents

- 1) Murakami's reagent: 10% NaOH and 10% potassium ferricyanide in water.
- 2) Potassium ferricyanide and caustic soda(Na_2CO_3) in water (acts like NaOH).
- 3) Copper sulfate and ammonium hydroxide.

T. I. Stokes
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February 17, 1994

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Electrolytic Etching Agents

- 4) 160 gm Trisodium phosphate (Na_3PO_4 o 12 H_2O) and water to make 1,000 ml of solution.
- 5) 100 gm NaOH in water to make 1000 ml of solution.

Cleaning Agent

- 6) Oakite (reported by Kulite to be a detergent and NaOH; Mr. Divine believes that Oakite is normally Na_3PO_4 and which acts as a caustic too. Mr. Manberg indicated that the solution makes their tungsten products bright and shiny. My interpretation of this is that the solution either completely dissolves the typical oxide (or equivalent) layer, or that it dissolves both that oxide layer and removes base metal too.

It is my understanding that the SY-101 waste contains:

- o about 10% NaOH (amount dissolved vs amount precipitated not known),
- o 1 - 2 % Phosphate,
- o Some carbonate,
- o Small amounts of ferricyanide
- o Some potassium,
- o About 20% Na, and
- o Ammonia is present.

In conclusion, the waste contains some of the chemicals that are commonly used to etch (or attack) tungsten.

No data were found concerning effect of nitrate or nitrite on corrosion of tungsten.

Recommendations

Here is one approach to resolving the lack of tungsten corrosion data:

- 1) Chrome or nickel plate the entire sphere. This appears possible, maybe within several weeks. Kulite Co. might be able to help in this matter. Until some corrosion data is developed (see 2 below) the ball should only remain in the tank for short periods of time; the ball should be rinsed, the threaded SS fitting disassembled and inspected for corrosion damage, and the entire assembly cleaned and dried.
- 2) Conduct corrosion tests at PNL in simulated SY-101 waste at 150 °F. If 95-5 material is readily available, and a level 4 impact rating is allowed, this work might be initiated within 2 to 3 weeks. K. H. Pool indicated that a SY-101 waste simulant solution is available at PNL for corrosion tests. M. J. Danielson (also PNL) would assist in conducting and evaluating the tests. Here is a brief initial description of the recommended approach.

T. I. Stokes
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February 17, 1994

- a) Obtain specimens for general (uniform) corrosion (UC) tests and galvanic/crevice (GC) corrosion tests.
 - b) Conduct fully immersed UC exposure tests of eight (or more) as-machined and eight (or more) as-machined and partially-plated specimens. Partial plating (say 3/4 to 7/8 of a given specimens surfaces) is recommended to see how well the plating works and to simulate the effects of a holiday (plating-tungsten interface) or crack in the plating. This test should also provide basic tungsten corrosion rate data (mils/week or mm/wk, etc.). If localized corrosion or cracking occurs then one would have to assume that cracking in-tank might also occur. Up to two specimens each would be removed after 2-wks, 8-wks and say, 26-wks.
 - c) Conduct GC corrosion tests of tungsten-stainless steel threaded joint specimens. This test should indicate if there is any galvanic (2-metal) effect combined with a crevice effect. Where the SS joins the tungsten, fluted ceramic washers would be used to promote a classic crevice corrosion effect. The threaded joint should provide a measure of any galvanic effect.
- 3) Stressed stainless steel. I do not know if any corrosion data exists for stressed, type 304 SS cable. This may not be a problem, however, if residual stress and dead load stresses are high enough, the SS cable might stress-corrosion crack under load. A larger cable may suffice, if actual stresses (in the initial cable) are determined to be high relative to SCC. Also, during the late 40's to early 50's plain carbon steel corrosion specimens were suspended in Hanford single-shell tank wastes using stainless steel wire. On at least several occasions specimens were lost to the waste, implying that the SS suspension wire failed. This could also be simulated at PNL.

List of References

- 1) ASM Metals Handbooks:
 - a) Vol 1, 8th Ed., Properties and Selection of Metals
 - b) Vol 3, 8th Ed., Machining
 - c) Vol 3, 9th Ed., Properties and Selection of Metals
 - d) Vol 9, 9th Ed., Metallography and Microstructure
 - e) Vol 13, 9th Ed., Corrosion
 - f) Vol 16, 9th Ed., Machining
- 2) ASM Handbook of Corrosion Data.
- 3) Corrosion Resistant Materials Handbook, 4th Ed., DeRenzo.
- 4) Smithells Metals Reference Book.
- 5) Uhlig, Corrosion Handbook.

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- 6) Fontana & Green, Corrosion Engineering.
- 7) Metal Finishing Handbook.
- 8) Brick & Phillips.
- 9) Tungsten, C. J. Smithells.
- 10) Alloy Digest (10 W-Alloys).
- 11) NACE Corrosion Data Survey, Metals Section, Sixth Ed.

List of Contacts

- 1) Westinghouse Savannah River Laboratory, C. Jenkins.
- 2) Westinghouse Idaho Falls Company (WINCO) R. Mizea.
- 3) Kulite Corp (Tungsten ball manufacturer), Richard Manberg.
- 4) Teledyne Sterling (Tungsten manufacturer), R. Kamper, R. Coles.
- 5) Westinghouse Hanford Co: R. Lobsinger, M. Anantatmula.
- 6) Battelle-Northwest: K. R. Sump, K. H. Pool, R. E. Westerman, M. J. Danielson, W. E. Gurwell.
- 7) National Institute of Standards and Technology, E. Escalante.

E. B. Schwenk

E. B. Schwenk, Principal Engineer
System Structural Integrity Assessments

ebs:emw

Project Number _____

Internal Distribution

File/LB

Date March 30, 1994

To Troy Stokes

From Chet Shepard *CS*

Subject Corrosion Testing of Tungsten Ball Material in
101-SY Tank Chemical Simulant

The 3.5-inch diameter ball fabricated for service with the ball rheometer is an alloyed material containing small amounts of copper and nickel with the remainder being tungsten. There is some concern that this ball may react chemically with the waste contained in Tank 101-SY. In order to examine this potentiality to the fullest extent possible without actually immersing the ball in the tank, experiments were performed using a chemical simulant of the waste and sample coupons of the ball material. These tests indicate that chemical reaction of the ball with the waste should not be a concern. A description of the testing is given below.

The simulant used for these tests was a chemical simulant containing, in the appropriate amounts, all of the chemicals found to be in the waste from actual tank samples with the exception of radioactive materials. After mixing the components, the simulant was heat treated according to the methodology developed by Rudy Allemann of PNL. The sample coupons were supplied by the manufacturer of the tungsten ball and are of the same chemical composition as the ball. Two coupons were used, one shaped as a disk and the other shaped as a bar.

In order to facilitate comparison, the coupons were stamped with a number using a dye and a hammer. The material was quite soft and easily stamped. Photographs were taken of the samples prior to their immersion in the simulant. These photographs focused on the stamped areas. The coupons were immersed in the simulant for 12 days and then they were removed for inspection. The simulant was kept at a temperature of 50°C for the entire duration of the test. Also, the coupons were positioned so that the stamped areas were accessible to the simulant fluid. The coupons were then photographed again and before-and-after comparisons could be made from these photographs. Sample photographs (before and after) are shown in Figure 1. In all photographs, there is no discernable difference in the surface features of the coupons after 12 days residence in the simulant. Some very slight discoloration of the coupons may have occurred. We can conclude that changes in the ball as a result of chemical reaction with the waste will occur on a time scale which is long compared to 12 days. From a practical point of view, these changes will occur slow enough so that chemical reactions will not affect the results of tests with the ball rheometer. Since the ball will also be coated with a polyethylene coating for further protection, it appears that we can dismiss this issue with complete confidence.

CLS:kh

Troy Stokes
March 30, 1994
Page 2

Figure 1. Before-and-After Photographs of Tungsten Coupon in an Area of Relatively Rough Surface Features

[58] From: Earl B Jr Schwenk at ~WHC240 4/29/94 2:09PM (4070 bytes: 3 ln, 1 fl)

To: Troy I Stokes at ~WHC207

Receipt Requested

cc: Dennis B Graves at ~WHC76, Kathleen L Pearce at ~WHC76, Keith V Scott at ~WHC74

Subject: DATA ON POLYETHYLENE

----- Message Contents

Text item 1:

Troy, attached are some data on room temperature tensile strength and heat resistance, continuous degrees F.
Regards, Earl.

Date: April 29, 1994

To: T. I. Stokes

cc. D. B. Graves
K. L. Pearce
K. V. Scott

From: E. B. Schwenk

Subject: TENSILE STRENGTH AND HEAT RESISTANCE OF POLYETHYLENES

Troy, here are some subject data on polyethylene. They came from Handbook of Plastics and Elastomers, C. A. Harper, Ed., McGraw-Hill, 1975. These properties will change somewhat when a conductive additive is blended in. If stainless steel powder were to be used (don't yet know exact additive) they apparently will not change significantly. Carbon may significantly change mechanical properties and stiffness.

Chapter 1, "Fundamentals of Plastics and Elastomers."

Table 24, Typical Mechanical Properties of Thermoplastics, pg 1-67.

	<u>Tensile Strength*</u> (Ksi)	<u>Heat Resis., Continuous</u> (°F)
Polyethylene, Low-density.	1 - 2.4	140 - 175
" " Med-density	1.7 - 2.8	150 - 180
" " High-density	2.8 - 5	180 - 225
" " High Molec. Wt.	2.3 - 5.4	180 - 225

* These appear to be for Room temperature.

Similar data were also presented in Chapter 3, "Mechanical Properties and Testing of Plastics and Elastomers," Table 3, Physical Properties - Thermoplastic Resins", pg 3-29.

<u>Property</u>	<u>Low Density</u>	<u>Medium Density</u>	<u>High Density</u>
Tens. Str.* (Ksi)	0.6 - 2.3	1.2 - 3.5	3.1 to 5.5
Resis. to Heat (°F, Continuous)	180 - 212	220 - 250	250

As you can see the tensile strength data and heat resistance temperature ranges are a little different from table-to-table. They probably came from different sources or labs and/or were tested under slightly different conditions. The heat resistance data suggest that periodic washing of the plastic with 140 - 175°F water should be satisfactory.

Also, the handbook did not indicate what the tensile strength values were in the heat resistance temperature ranges.

Battelle

Pacific Northwest Laboratories

WHC-SD-WM-SDD-043
Rev. 0

Project Number _____

Internal Distribution

File/LB

Date April 11, 1994

To Troy Stokes

From Chet Shepard/Larry Pederson *CS R P*

Subject Reaction of Aluminum with Gases Released by
Wastes in Tank 101-SY

There is some concern that gases emanating from the waste contained in Tank 101-SY may cause corrosion of aluminum components which are part of instrumentation located above a riser in this tank. Load cells which are part of the sensing system for the Ball Rheometer are clad with an aluminum housing and are at the focus of this concern. The Ball Rheometer is presently under development and scheduled for deployment at this tank in September 1994. In addressing the problem we will consider three gases: hydrogen (H_2), ammonia (NH_3), and nitrous oxide (N_2O).

By far the most favored reaction for aluminum in our atmosphere is the oxidation of aluminum to form Al_2O_3 . In air, the oxide layer is around 100 nm thick and is very passive. High quality optical mirrors use aluminum coatings which, after a short while, are Al_2O_3 coatings and these coatings are known for their resistance to degradation. Note that the oxide layer forms in the presence of a large amount of nitrogen and water vapor. It is very unlikely that nitrous oxide would disturb such a chemically resistant layer. One of the few inorganic compounds known involving aluminum and nitrogen is AlN . However, this compound will not form when aluminum is exposed to N_2O . Possibly aluminum may oxidize in the presence of N_2O , but this is no different than oxidation in air and cannot be considered as corrosion. Therefore we can eliminate N_2O as a possible corrosive gas for aluminum.

No compounds involving just aluminum and hydrogen are known to exist, and thus hydrogen by itself will not corrode aluminum. Hydroxides ($Al(OH)_3$) of aluminum will not form if there is already an oxide layer. If by some construction a hydroxide is formed, then the hydroxide will transform to the oxide with the release of water. Therefore hydrogen will not be a concern for corrosion of aluminum.

Ammonia by itself will not react with aluminum. However, ammonium hydroxide (NH_4OH) is a caustic. Aluminum is known to react with caustic solutions. For whatever reason, NH_4OH will not attack aluminum. This is according to Perry's Chemical Engineering Handbook, 6th edition, p23-26, where aluminum is listed as "unsuitable" in caustic and mild alkalies excluding ammonium hydroxide. Thus it is believed that ammonia will not cause a reactive problem with aluminum.

The conclusion reached here is that aluminum components are not at risk for any substantial reaction to the gases present in the atmosphere or in the tank

Troy Stokes
April 11, 1994
Page 2

dome space with the exception of oxygen, with which it forms the familiar oxide layer.

CLS:kh

DON'T SAY IT --- Write It!

DATE: November 4, 1993

TO: Kathleen Pearce

FROM: Bill Brehm

H5-67

Telephone: 376-9779

cc: WFB file

SUBJECT: Polyethylene in 101-SY

You requested an assessment of high-density polyethylene as a coating for a tungsten ball and stainless steel cable, to be used on a viscometer in 101-SY. The coating is to be applied to the ball and cable to retard crystal formation on them.

Summary: Polyethylene coatings on the cable and tungsten ball should show satisfactory performance in 101-SY for extended time periods. Satisfactory adherence of the polyethylene to the substrate at tank temperatures may be an issue and should be looked into.

I looked into the question from the following viewpoints: temperature, radiation resistance, chemical compatibility, damage resistance, and adherence.

Temperature: Polyethylene should not soften in the 135°F temperature in 101-SY, even under irradiation.

Radiation Resistance: Like all organic materials, polyethylene is subject to damage in ionizing radiation. Polyethylene tends to first become harder and stronger, but as the radiation dose increases, becomes "brittle and cheesy". (Ref. 1) The threshold dose, below which there is no effect of radiation, is quoted as 1.9 E9 ergs/cm (about 2.1 E7 rads, read 1.9 E9 as 1.9×10^9 , etc.) Polyethylene is subject to oxidation under irradiation; this is a surface effect so that thin films are degraded at lower radiation doses than thick ones. High-density polyethylene in thin films has a damage threshold about an order of magnitude lower than normal-density polyethylene.

If the lower damage threshold figure, approximately 2.1 E6 rads, is accepted, and the radiation level in 101-SY is 100 rads/hour (a guess) then the useful lifetime of the coating would be $(2.1 \text{ E6})/100 = 2.1 \text{ E4}$ or 21,000 hours.

Reference 2 is a newer work on radiation damage to polymers but says about the same thing. The work described in Reference 3, showing no damage to polyethylene at absorbed doses of over 1 E7 rads, support the discussion above.

Chemical Compatibility: Polyethylene is listed in Reference 4 as having acceptable behavior in up to 70% sodium hydroxide at up to 150°F, and acceptable behavior in sodium nitrate up to 150°F. Sodium hydroxide and sodium nitrate are two of the principal constituents of 101-SY waste. The aluminum salts and organics in 101-SY will not damage polyethylene. Reference 3 states that no damage was noted to a polyethylene coating after eight weeks in a simulated tank waste mixture; again, agreement between literature

findings and experiment was obtained. Therefore, the material is acceptable from a chemical compatibility perspective.

Damage Resistance: According to Reference 5, high-density polyethylene and ultrahigh molecular weight polyethylenes have good toughness, impact resistance, abrasion resistance, and wear resistance. Therefore, a polyethylene coating should have good resistance against damage when rubbed or bumped.

Coating Adherence: Again, according to Reference 5, adhesion of ultrahigh molecular weight polyethylene to substrates is poor. The section on high-density polyethylene did not mention adherence to substrates as a problem. It is not clear from the part of Reference 3 that I received, that the testing described therein was done at tank temperature rather than room temperature. The difference between room temperature and 135°F could be important. The thermal expansion coefficients between polyethylene and the substrate should be evaluated to see whether non-adherence at tank temperatures could be an issue.

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WHC-SD-WM-SDD-043
Rev. 0

APPENDIX G

STRUCTURAL ANALYSIS

Westinghouse
Hanford Company

Internal
Memo

From: Nuclear Fuel Evaluation
Phone: 376-4193
Date: April 29, 1994
Subject: SEISMIC ANALYSIS OF VISCOMETER ASSEMBLY WITH RESPECT TO TANK RISER
STRUCTURAL INTEGRITY

To: D. B. Graves L6-38

cc: R. E. Bauer L6-37
R. P. Omberg H0-40
K. L. Pearce L6-37
T. I. Stokes H5-09
J. R. Thiegles L6-38
A. E. Waltar H0-32
SLH File/LB

- References:
- (1) Memo, S. L. Hecht to K. L. Pearce, "Structural Analysis of SY-101 In-situ Viscometer Instrument", April 20, 1994.
 - (2) Hanford Plant Standard - SDC-4.1, Standard arch-Civil Design Criteria - Design Loads for Facilities, Rev 11, September 6, 1989
 - (3) R. P. Kennedy et. al., Design and Evaluation Guidelines for DOE Facilities Subjected to Natural Phenomena Hazards, UCRL-15910, June 1990.
 - (4) USNRC STANDARD REVIEW PLAN, NUREG-0800, Rev 1, July 1981

Per the request of Los Alamos National Laboratory (LANL), as result of their safety review, the impact of the viscometer assembly on the interfacing tank components during a seismic event is evaluated, herein. Specifically the 101-SY tank 4-inch risers, to which the Viscometer is attached, are evaluated for structural integrity under the Design Basis Earthquake (DBE) loading. It was previously WHC position^[1], that as seismic analysis is not required for temporary, short durations, instruments, as this represents a extremely low probability of occurrence event.

SUMMARY AND CONCLUSIONS

The evaluation given herein, provides a conservative treatment with respect to assumptions, classifications, loading and methodology. Here the tank riser is classified as a Safety Class 1 component. Hence, the following evaluation is based on the DBE damped response spectra for Non-reactor Safety Class 1 structures, i.e., a 0.2 g zero period horizontal acceleration, as given in reference 2, figure 3. 5% of critical damping is assumed and is likely to be quite conservative as the Viscometer design uses bolted connections and elastomer in the load path ($\geq 10\%$ defined in Ref. 3). Equivalent static analysis method (based on the fundamental natural

D. B. Graves

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frequency) are used, and the participation of the higher modes of vibrations treated is a conservative, well established, manner as defined in reference 4. These seismic loading and corresponding stresses and strains are combined with those due to dead weight.

The analyses, on the following pages of this memo, predicts that the tank riser structure, to which the Viscometer is attached, will maintain its structural integrity during a DBE. Furthermore, the riser should remain fully functional after a DBE, and can be returned to service. The maximum calculated stresses, during this faulted event, were predicted to be within the elastic range.

ANALYSIS

The fundamental natural mode of vibration, of the mounted assembly, is "apriori" speculated to be that of the 1st bending mode of the viscometer "cantilevered" on the riser extension pipe, spray decontamination and isolation valve system. This can be simply modeled, as the mass of the viscometer on a 62-inch long 4-inch SHD 40 pipe, fixed at the end (embedded in concrete). Though the Viscometer is supported by the riser extension and its jack support legs, the support from the legs is conservatively neglected for horizontal motion (no friction). However, for vertical loading, reactions at the legs are those given in reference 1. The fundamental natural frequency, f_n , is calculated below:

$$\text{mass, } m = W/g = 755 \text{ lb}/386.4 \text{ in/sec}^2 = 1.95 \text{ lb-sec}^2/\text{in}$$

stiffness of cantilever beam with end load, k

$$k = 3EI/l^3 = 3(30 \times 10^6)(7.23)/62^3 = 2,730 \text{ lb/in}$$

$$\text{then; } \omega_n = [k/m]^{1/2} = [2,730/1.95]^{1/2} = 37.4 \text{ rad/sec}$$

$$f_n = \omega_n / 2\pi = 6.0 \text{ Hz}$$

From the response spectra (see figure 1) the peak horizontal acceleration of 0.42 g's (for 5% damping) occurs in the frequency range of 1.6 - 8 Hz. As the calculated f_n is within this range, this peak 0.42 g value is to be used in subsequent calculations. The above evaluation was for mounting the Viscometer on riser 11 (in pit) with a extension pipe. The other option is using riser 4, in which case the cantilever pipe length is a considerably shorter, 30 inches. For this case the fundamental natural frequency is 18 Hz (ratio of the length to the -1.5 power), and the corresponding acceleration response is 0.3 g's. Therefore, the use of 0.42 g's will encompass all expected riser installations. Hence the maximum equivalent static horizontal force (F_H) is:

$$\text{due to fundamental mode: } F_{H-n} = Wa = (755 \text{ lbs})(0.42) = 317 \text{ lbs}$$

multiplying this value by a factor of 1.5 (per NUREG-0800, Ref 4)

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conservatively factors in the participation of the response of higher modes of vibrations. Then:

$$F_H = 1.5 * F_{H-n} = (1.5)(317) = 476 \text{ lbs.}$$

A similar treatment can be given to the vertical response. Here the natural frequency for compression-extension of the pipe ($k = AE/l$) will be much higher, and corresponding acceleration response lower, than that of the bending mode previously addressed. However, to be conservative the peak vertical acceleration value of 2/3 peak horizontal value (per Ref. 2) will be assumed. With the consideration of participation of higher mode contributions ($\times 1.5$) the equivalent static vertical force (F_V) is conservatively taken as:

$$F_V = (1.5)(2/3)(0.42) \times \text{dead weight vertical load}$$

With the maximum dead weight load seen at the bottom of the riser being 584 lbs^[1], then:

$$F_V (\text{seismic}) = (1.5)(2/3)(0.42)(584) = 245 \text{ lbs}$$

As the earthquake load coexist with dead weight loads, the total vertical (downward) load on the riser is:

$$F_V (\text{total}) = 245 + 584 = 829 \text{ lbs.}$$

Reactions at the riser (#11 which is worst case) are as follows:

due to F_H :

$$\text{bending moment, } M = F_H * l = (476)(62) = 29,510 \text{ in-lbs}$$

torsion, T , due to offset (9 in) from C.G. from riser

$$T = F_H * r = (476)(9) = 4,280 \text{ in-lbs}$$

$$\text{and shear} = F_H = 476 \text{ lbs.}$$

due to F_V :

vertical uniaxial compressive force, $F_V = 829 \text{ lbs.}$

and is conservatively to coexist, i.e., the peaks are in phase. The dynamic part of the load may^[3] be combined in a square root sum of the squares (SRSS) manner with the reactions due to horizontal loading.

As for potential damage to the tank, the top of the riser pipe, near the flange location, where it is embedded in concrete is the location where maximum stress will occur. The 4-inch SHD 40 pipe ($A = 3.17 \text{ in}^2$, $I = 7.23 \text{ in}^4$,

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$S = 3.21 \text{ in}^3$, O.D. = 4.5 in., I.D. = 4.026 in.) will have the following stress components:

$$\text{due to } M: \quad \max \sigma_b = M/S = 29,510/3.21 = \pm 9,190 \text{ psi}$$

$$\text{due to } T: \quad \max \tau = Tr/J = 2Tr_o/\pi(r_o^4 - r_i^4) = 2(4,280)(2.25)/\pi(2.25^4 - 2.013^4) = 670 \text{ psi}$$

$$\text{due to } F_H(\text{shear}): \quad \tau_{avg} = F/A = 476/3.17 = 150 \text{ psi (0 at outer fiber)}$$

$$\text{due to } F_V: \quad \sigma_a = F/A = -829/3.17 = -260 \text{ psi}$$

As the DBE is a extremely unlikely faulted design bases event, it is required that the structure remains structurally integral or intact, and issues such maintenance of lesser functional requirement, such as undeformed geometry, thought desirable, are not required. To assure this condition, with confidence the primary acceptance criteria used herein is that the elastically calculated values of maximum principal stress (σ_1), or the absolute value of the minimum principal stress (σ_3) not exceed the minimum ultimate tensile strength (S_u) of the material. Inherent conservatism is associated with this criterion when considering the main load is from bending (plastic shape factor) and the pipe is constructed of a strain hardening material, ASTM A53. The ASTM specification, for the A53 steel, for minimum tensile properties are $S_u = 60,000 \text{ psi}$, and S_y (yield strength) = 35,000 psi. Stress components of from the orthogonal directions are conservatively combined in a direct manner, rather than the prescribed SRSS fashion.

As the riser pipe is in axial compression, under worst case loading conditions, the absolute value of minimum principal stress is greater than that of the maximum principal stress, and hence will be evaluated. Here:

$$\sigma_3 = \sigma_a/2 - [(\sigma_a/2)^2 + \tau^2]^{1/2}; \text{ where } \sigma_a \text{ is the combined stress in axial direction} = -9190 - 260 = -9450$$

$$\sigma_3 = -9450/2 - [(-9450/2)^2 + 670^2]^{1/2} = -9,500 \text{ psi}$$

here the Safety Factor, S.F., = $60,000/9,500 = 6.32$
and should remain undamaged as $|\sigma_3| < S_y$

Additionally, the weld attaching the flange to the riser also need to be analyzed. The flange has a tight fitting collar, so as the bending moment is transmitted directly to the pipe, not loading the 3/16 fillet weld. The shear stress due to Torque, T is:

$$\tau = 2.83T/(hD^2\pi) = (2.83)(4,280)/[(.1875)(4.5^2)(3.14)] = 1,020 \text{ psi}$$

The normal stress, due to axial load, F_V , is;

$$\sigma_a = 1.414F_V/(\pi Dh) = (1.414)(829)/[(3.14)(4.5)(.1875)] = 440 \text{ psi}$$

These stress components values are acceptable as there quite low when compared to the material strength.

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The last component that needs evaluations is the bolts attaching the riser flange to the Viscometer assembly. There are eight 5/8 inch bolts ($A = 0.226 \text{ in}^2$ for tensile stress calculation - UNC) on a 7.5 inch bolt circle. The shear force, F_s , on a single bolt due to Torsion is:

$$F_s = T/nr ; \text{ where } n \text{ is \# of bolts and } r \text{ the radius of the bolt circle.}$$
$$= 4,280/(8*3.75) = 143 \text{ lbs each}$$

The corresponding average shear stress is ($A_s = 0.202 \text{ in}^2$) is:

$$\tau_T(\text{avg}) = F_s/A_s = 143/.202 = 706 \text{ psi}$$

This is combined (on the worst case bolts were the load direction are coincident) with the shear stress due to the shear force, F_H . Here:

$$\tau_F(\text{avg}) = F_H/nA_s = 476/(8*.202) = 295$$

the combined maximum average shear stress is 1000 psi.

The bending moment, causes the flange to pivot about a edge, and loads the bolts axially. The relationship between the bending moment and the maximum bolt axial load was derived in reference 1, and is given below.

$$F_{\max} = 0.0378*M, \text{ lbs}$$

The total moment, M , is that due to the general bending (29,510 in-lbs) less that of the downward axial force (829 lbs) acting at a moment arm of the distance from the center of the pipe to the edge of the flange (4.5 in), or 25,780 in-lbs. Therefore:

$$F_{\max} = (.0378)(25,780) = 974 \text{ lbs}$$

The corresponding axial stress is $974/0.226 = 4,310 \text{ psi}$.

A conservative acceptance criterion used here for bolt stress is the ASME B&PV Section III allowable for faulted conditions. Here the Primary Membrane Stress Intensity, P_m , is less than 120% of the design limit, S_m . Here:

$$P_m = 2\{ 4,310/2 + [(4,310/2)^2 + 1000^2]^{1/2} \} = 4,440 \text{ psi}$$

The ASTM A-307 bolts has a design allowable stress, S , value of 7,000 psi, which is generally more conservative, then the Class 1 S_m value. Therefore, the S.F. = $(1.2)(7,000)/4,440 = 1.89$.

S. L. Hecht
Nuclear Fuel Evaluation

FIGURE 1 RESPONSE SPECTRA - NON-REACTOR SAFETY CLASS 1
for 2, 5, 7, AND 10% CRITICAL DAMPING, 0.20g

Westinghouse
Hanford Company

Internal
Memo

From: Nuclear Fuel Evaluation
Phone: 376-4193
Date: April 20, 1994
Subject: STRUCTURAL ANALYSIS OF SY-101 IN-SITU VISCOMETER INSTRUMENT

To: K. L. Pearce L6-37

cc:	F. E. Bard	L5-01
	R. E. Bauer	L6-37
	D. B. Graves	L6-38
	R. P. Omberg	H0-40
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	J. R. Thiegles	L6-38
	A. E. Waltar	H0-32
	SLH File/LB	

The attached report " DESIGN SUPPORT STRUCTURAL ANALYSIS OF SY-101 IN- SITU VISCOMETER INSTRUMENT" is provided to support the Viscometer Assembly design. This evaluation addresses the structural integrity and related functionality of the Viscometer Assembly and interfacing waste tank components. The evaluation focuses on normal operations and handling conditions. One design bases accident is also addressed. Other structural safety analyses are outside the scope of this evaluation, and are to be address by LANL.

The Viscometer and interfacing tank components were shown to be structurally acceptable for design loading (normal and anticipated) conditions. The minimum Safety Factor on allowable stress was conservatively determined to be 4.8 (Design Margin = 3.8, or 380% over designed). Calculated deformations were found to acceptable, so as to assure that the Viscometer will function as intended. The "drop ball" accident was evaluated and shown to be acceptable with respect to tank structural integrity.

S. L. Hecht
Nuclear Fuel Evaluation

DESIGN SUPPORT STRUCTURAL ANALYSIS OF
SY-101 IN-SITU VISCOMETER INSTRUMENT

S. L. Hecht
February 1994

1.0 INTRODUCTION

The function of the In-situ Viscometer instrument, hereafter referred to as the Viscometer, is to make in-situ viscosity measurements of waste material in Hanford high level waste tanks. The initial plans are to use this instrument on tank 101-SY, however, the Viscometer may be potentially used on any tank which meet its interface requirements. The Viscometer will be mounted to a waste tank 4-inch riser. The device works by dropping and dragging a ball through the liquid waste, and measuring the corresponding drag forces and velocities. From these measurements, the viscosity of the liquid waste (layers) can be derived. A more detail description of the Viscometer and its factional requirements can be found in reference 1.

The Viscometer, shown in drawing H-2-818359, is comprised of at 3.6 inch diameter ball on a cable, the drive mechanism, instrumentation and control system. The equipment is mounted within a enclosure box, which intern is attached to the tank riser via a spool piece (with decontamination equipment).

The structural analysis, given herein, addresses the structural integrity of the Viscometer assembly, including functional aspects. Also considered is the structural integrity of tank interfacing components, due to loadings caused by the Viscometer attachment and operations. Structural evaluation of the drive mechanism components (e.g., motor shafts, couplings, reel drum) are outside of the scope of this evaluation. The analysis address mainly normal operations and anticipated events. The majority of, but not all of, the safety related structural analyses will be preformed by Los Alamos National Laboratory (LANL) and documented elsewhere. Furthermore, because the Viscometer is mounted to the tank for only a short time period, events with low probability of occurrence, such a earthquake, are not addresses.

2.0 DESIGN LOADINGS/EVENTS AND ASSUMPTIONS

The Viscometer is classified as a Safety Class 3 component. The natural phenomena design load for a Safety Class 3 component are wind and earthquake (seismic) loads (per HPS-SDC-4.1, Standard Arch-Civil Design Criteria; Design Loads for Facilities - Ref. 2). Since the Viscometer is a non-permanent component, used for only a short duration, earthquake loading is a extremely low probability event, and is hence, not evaluated here. Other loading considered are operational, dead weight, and installation loads. The only accident condition addressed is a dropped ball accident, as it is a design bases for this instrument. Each of these loadings, with corresponding stresses and design margins are addressed in Section 4. The assembly is assumed to be at a uniform constant temperature, with the maximum expected temperature not exceeding 150 F.

3.0 ACCEPTANCE CRITERIA

Allowable values of calculated stresses and or strains used in the evaluation given herein are those given in the American Society of Mechanical Engineers (ASME), Boiler and Pressure Vessel Code - Section III; Nuclear Vessels⁽³⁾. Other criteria are utilized in cases where they are more appropriate than the ASME code. These are cited in the particular application in Section 4. As ductile construction material are used in the design, and the loading is not cycled a significant number of times, peak stress and associated fatigue damage are not considered. Deformations are evaluated as to their impact on the functional requirements of the Viscometer.

4.0 LOADS, STRESSES AND DESIGN MARGINS

In the following subsections, 4.1 - 4.5, evaluations are made as to the loading, stresses and structural integrity of the Viscometer under various loading conditions. As individual load type rarely act independently, worst case combined loading (of sections 4.2, 4.3, ...) is addressed in section 4.6. Loads are calculated when necessary in respective subsections. Stresses are determined for the critical locations and are compared against allowable limits. Safety Factors (allowable/actual) are also determined.

4.1 Postulated ball drop accident

It is postulated that the Tungsten (W) ball either breaks from the cable or that the cable/spool mechanism either fails or releases so the ball free fall and impacts the bottom of the tank. The concern is that the ball could penetrate the bottom(steel plate) of the tank, thus causing the tank to leak.

Impact velocity and corresponding kinetic energy (KE) is conservatively based on determining the maximum velocity of the ball within the tank. For calculational simplicity, the maximum velocity is taken as the maximum of the terminal velocity of the ball in the tank waste, or in the maximum free fall velocity at the liquid level.

The terminal velocity (v_f) of the ball in the tank waste liquid, is conservatively used irrespective of the distance it falls. The terminal velocity would be limiting as long as the ball does not fall a significant distance through the vapor space above the liquid level. Terminal velocity is developed at equilibrium conditions between upward forces of buoyancy (B) and drag (D) and downward force of weight (W). This equilibrium free body equations is written:

$$W = B + D$$

Since D is a function of v_f this equation can be rewritten as:

$$D = W - B = V(\gamma_w - \gamma_f)$$

where V (volume of ball) = $\pi d^3/6 = .524(3.6^3) = 24.45 \text{ in}^3$

and γ_w and γ_f are the specific weights of the tungsten and tank liquid respectively.

$$W-B = 24.45 (.65-.036) = 15.0 \text{ lbs}$$

The drag force is given by:

$$D = C_D A \rho v_f^2 / 2 \quad \text{where;}$$

C_D , the drag coefficient is a function of the Reynolds Number (R) as shown in figure below^[4] and A is the projected cross sectional area. The tank waste fluid

properties of mass density (ρ) and kinematic viscosity (ν) are conservatively assumed to be those of water at 100 F. Because C_D is a nonlinear function of R (for $R > 10$), the determination of the drag coefficient and corresponding drag force involves an iterative calculation. As C_D is fairly constant over $10^3 < R < 10^5$, we will conservatively assume the minimum value of 0.4 for the first iteration. By rearranging and substituting we can solve for v_f . Here:

$$v_f = [2(W-B) / A \rho C_D]^{1/2}$$

$$= [(2)(15.) / (.0707)(1.9)(.4)]^{1/2} = 23.6 \text{ ft/sec}$$

checking R; $R = v_f d / \nu = (23.6)(3.6/12) / 7.4 \times 10^{-5} = 9.6 \times 10^4$

At this R, $C_D = 0.55$, therefore, the predicted terminal velocity based on a lower drag coefficient is conservative.

The resulting kinetic energy at impact would be:

$$KE = m v_f^2 / 2 = (24.45)(.65/32.2)(23.6)^2 / 2$$

$$= 137 \text{ ft-lbs} = 1650 \text{ in-lbs}$$

For the case where the ball free fall from it full up position to the top of the liquid level (-20 ft) and than through the liquid waste, the velocity and energy at the liquid level are:

The potential energy (PE) = WH

$$W = \gamma V = (.65)(24.45) = 15.9 \text{ lbs}$$

$$PE = (15.9)(20.) = 318 \text{ ft-lbs}$$

equating the kinetic and potential energy, we can solve for the velocity

$$v = [2PE/m]^{1/2} = [(2)(318)(32.2)/15.9]^{1/2} = 35.9 \text{ ft/sec}$$

Since this velocity is greater than the terminal velocity in the liquid, the velocity of the ball will be maximum after the free fall in air (35.9 ft/sec) and than decelerate to a constant minimum terminal velocity of 23.6 ft/sec. To be conservative we will use the maximum velocity and kinetic energy value in subsequent evaluation.

To determine weather or not the ball can penetrate the tank bottom plate (.5 inch ASTM A516 grade 65), empirical and design relationships were used. This data came primarily from armor-plate and ballistics test data.

Reference 5 gives relationship for penetration velocity of projectiles hitting metal plates. This relationship is shown in figure below, and involves the use of nondimensional parameter groups. The dimensionless projectile velocity is:

$$\rho_p V / (\sigma_t \rho_t)^{1/2} = (.65/386.4)(35.9)(12)/[(35000)(.29/386.4)]^{1/2} = 0.141$$

From the figure below the require thickness (h) for a 50% probability of penetration is $h/a = 0.05$. With $a = 1.8$ inches, than $h = (1.8)(.05) = 0.09$ inches thick.

Nondimensional Limit Velocity Versus Nondimensional Thickness
for "Chunky," Non-Deforming Fragments

The corresponding safety factor (SF) is $0.5/0.09 = 5.55$.

Additionally, reference 6 give a design equation for determining the penetration velocity (V_{p1}) for steel plate. Here

$$V_{p1} = [(1120000/W)(td)^{3/2}]^{1/2} ; \text{ ft/sec}$$

Where:

W = weight of projectile

t = thickness of plate (inches)

d = effective diameter of projectile (inches)

$$V_{p1} = [(1120000/15.9) \{ (.5)(3.6) \}^{3/2}]^{1/2} = 412 \text{ ft/sec}$$

This result gives a $SF = 412/35.9 = 11.5$ on impact velocity.

Additional margin is provided in that the tank bottom plate sit on low strength concrete and is within the outer steel bottom.

4.2 Dead Weight Loading

The Viscometer Assembly weight approximately 755 lbs. The center of gravity (c.g.) was determined to be approximately 9 inches from the riser center line, and about 17 inches from the jack supports, in the long direction. The c.g. is roughly located mid-way in the transverse direction. Because the assembly support base plate is fairly rigid in relationship to the riser, little bending moment is expected to be produced at the riser-flange bolted connection, and is therefore neglected. To determine the vertical force at the riser (F_r) and at the jack support legs (F_j), equilibrium conditions are imposed. Here;

$$\sum F_z = 0: F_j + F_r = W$$

and

$$\sum M_{c.g.} = 0: 17 * F_j = 9 * F_r$$

solving simultaneously with $W = 755 \text{ lb}$, we get

$$F_r = 494 \text{ lbs} ; \text{ and } F_j = 261 \text{ lbs or } 130 \text{ per leg.}$$

In addition to the Viscometer weight, the riser will see a portion of the weight of the decontamination unit and pipe extension ($W \leq 90 \text{ lbs}$). For conservatism the total weight of this unit is added to the 494 lb Viscometer load. Hence the total vertical maximum dead weight load on the riser is 584 lbs. For a number of components this load coexist with other loadings, and hence, the stresses and acceptability are evaluated in section 4.6, Combined Loading.

The support legs (screw jack) are attached to the Viscometer frame with two - 2 inch 3/16 fillet welds. Here, the maximum normal stress is⁽⁹⁾:

$$\sigma = 0.707P/(hl) = (.707)(130)/[(3/16)(2)] = 245 \text{ psi} , \text{ which is negligible}$$

4.3 Operating loads

One operating load is the drag force from the ball-cable which is transmitted to the Viscometer. The maximum specified drag load of 250 lbs. is concentric to the riser, and hence only add a vertical downward force to the riser. As this riser load coexist with other loading, the riser stresses and acceptability are evaluated in section 4.6, Combined Loading.

The 250 lb drag force on the ball is reacted by the cable and cable attachment. As the cable, including end components, is sized for this loading, only the attachment to the ball need be evaluated. The Cable Retainer (# on H-2-818359) is a threaded attachment to the ball. Of concern, is the potential of shearing off the threads (.437-14 UNC). Here the threads shear stress is:

$$\tau = 2F/(\pi d_r h) = 2(250)/[\pi(.3499)(.51)] = 892 \text{ psi}$$

The corresponding Primary Membrane Stress Intensity, P_m is 2τ or 1785 psi. The allowable for P_m is the Design Stress Intensity values, S_m , generally given in reference 3 for material and temperature of interest. For the 316 ss component at 100 F, $S_m(\text{min}) = 16,600 \text{ psi}$. Therefore; $S.F. = S_m/P_m = 16,600/1,785 = 9.3$. The threads on the W ball reacts with the load on the retainer. However, the shear stress is lower by the ratio of the thread major-to-minor diameters, or 1.25. Additionally, the strength of Tungsten alloy K1800 ($S_y = 90 \text{ ksi}$) is greater than that for 316ss, and hence is acceptable.

The other operating load on the Viscometer is the design internal pressure of 8.5 inches of water, or 0.307 psig. This pressure is contained within the sealed enclosure box (reel cover assembly). This 11GA 304 stainless steel enclosure is segmented, so it can open and allow access to equipment. The maximum stress will occur on the largest integral section, which is the front face of the top section. Because of near symmetry in the box shape, this panel can be conservatively consider fixed at all edges. The maximum bending stress is determined below from equation given in reference 7 (Table X - case 41).

$$\sigma_b = \beta p b^2 / t^2 ; \quad \beta = f(a, b)$$

here a (length) = 23 in., b (width) = 18.25 in. $a/b = 1.26 \Rightarrow \beta = 0.40$

$$\sigma_b = (.4)(.307)(18.25^2) / .12^2 = 2,840 \text{ psi} = P_b$$

$$SF = 1.5 * S_m / P_b = (1.5)(16600)/2840 = 8.8$$

The windows on the reel cover assembly are constructed of polycarbonate plastic ($S_u = 9000 \text{ psi}$), and because of its lower strength need to be evaluated. This nominal 10 x 6.5 x 1/4 plastic panel is mounted to the box via gasketed frame. Because of the gasket attachment, analyze as a simply supported rectangular plate with a uniformly distributed load (Ref. 7 Table X -case 36). Here:

$$\sigma_b = \beta p b^2 / t^2 ; \quad \beta = f(a, b)$$

here a (length) = 10 in., b (width) = 6.5 in. $a/b = 1.54 \Rightarrow \beta = 0.48$

$$\sigma_b = (.48)(.307)(6.5^2) / 0.25^2 = 100 \text{ psi, which is negligible}$$

The window assembly is attached to the box with ten steel clips. The total load on the window is $pab = (.307)(10)(6.5) = 20 \text{ lbs.}$ or 2 lbs per clip, which is not of concern.

4.4 Wind Loading

In evaluating wind loads and the corresponding stresses, it is conservatively assumed that there is no lateral (horizontal) support from the jack supports legs (no friction). This gives the maximum possible loading on the riser pipe. Evaluation looks at different (orthogonal) wind direction and conservatively used a worst case composite load as to produce worst case bending moment (M) and torque (T) on the riser. As for the two possible positions, riser 4A or 11, only the riser 11 position is evaluated as the bending moment-arm is significantly greater than that of riser 4A.

The wind load or drag (D) is given by:

$$D = C_D A \rho V_f^2 / 2 ; \text{ where:}$$

C_D is the drag coefficient, determined from Ref. 8
for the enclosure boxes:

$R = V_f d / \nu$; where ν their kinematic viscosity = 0.000143 ft²/sec
as d is in the order of 1 ft $R = (117)(1) / 0.000143 = 8.2 \times 10^5$
for this Reynolds No. and $1/d < 5$; $C_D < 1.2$

A is the projected cross-section area perpendicular to the flow direction
 ρ , the mass density, = 0.00251 lb_f-sec/ft² at 0 F (worst case properties)
 V_f is the wind velocity = (80 mile/hr)(hr/3600 sec)(5280 ft/mile) = 117 ft/sec

$$\text{Therefore: } D = (1.2)A(.00251)(117)^2 / 2 = 20.6A , A \text{ in ft}^2$$

The projected area, A , and drag force, D , in a front view are:

sealed enclosure box, $A = 27 \text{ in} \times 18 \text{ in} = 486 \text{ in}^2$; $D = 70 \text{ lbs}$
motor enclosure box, $A = 11 \text{ in} \times 24 \text{ in} = 264 \text{ in}^2$; $D = 38 \text{ lbs}$

in a side view are:

sealed enclosure box, $A = 27 \text{ in} \times 18 \text{ in} = 486 \text{ in}^2$; $D = 70 \text{ lbs}$
motor enclosure box, $A = 19.5 \text{ in} \times 11.5 \text{ in} = 224 \text{ in}^2$; $D = 32 \text{ lbs}$

The other component subjected to wind load is the decontamination unit (conservatively based on the larger older design). This cylindrical unit is approximately 16 inches long by 11 inches in diameter ($A = 176 \text{ in}^2$). Reference 8 gives $C_D \leq 0.8$. Therefore, for this component the maximum drag force (D) is:

$$D = (0.8)(176/144)(.00251)(117)^2 / 2 = 17 \text{ lbs}$$

The distance (moment arm) from the center of the wind load to the flange on Riser 11, based on worst case design configuration (may be a old design) are for the:

Sealed enclosure box = 86 in.
 motor enclosure box = 78 in.
 decontamination unit = 49 in.

The maximum bending moment (front view) at the riser flange is:

$$M = \sum D \cdot l = (70)(86) + (38)(78) + (17)(49) = 9,820 \text{ in-lbs}$$

As the sealed enclosure box and decontamination unit are approximately coincident with the riser pipe, the maximum torque would occur when the wind comes from the side. Here the moment arm to the center of the motor enclosure box to the center of the riser is approximately 18 inches. Here the torque (T) is:

$$T = D \cdot l = (32)(18) = 576 \text{ in-lbs.}$$

Evaluation of these loads is treated in section 4.6

The wind pressure on the enclosure box is 20.6 lb/ft^2 (see above) or 0.139 psi . This pressure is less than the internal operating pressure of 0.307 psig which was evaluated in section 4.3.

4.5 Installation and Handling Loads

The Viscometer is to be installed via a crane lowering the assembly unto the riser. The four lift eye attachment are used for this purpose. It is assumed that the jack screw legs are lowered into place, so the Viscometer is level and supported, before the crane is disengaged.

Conservatively assume that $1/2$ of the Viscometer weight is applied to one of the lifting fixture. In the worst case, this load would be a on one of the cantilevered $2 \times 2 \times .188$ tubular frame members ($A = 1.27 \text{ in}^2$, $I = 0.668 \text{ in}^4$, $S = 0.668 \text{ in}^3$, Ref. 10). Here, the maximum moment, M , and bending stress, σ_b , are:

$$\begin{aligned} M(\text{max}) &= (380 \text{ lbs})(5 \text{ in}) = 1900 \text{ in-lbs} \\ \text{and } P_b = \sigma_b &= M/S = 1900/0.668 = 2,840 \text{ psi} \end{aligned}$$

The tube material (ASTM A544) has a S_m of $26,700 \text{ psi}$, therefore:

$$SF = 1.5 S_m / P_b = (1.5)(26700) / 2840 = 14$$

This safety factor is more than adequate when considering any dynamic load factors.

A potential loading, associated with installation and possibly operation, is that of a worker leaning against the Viscometer. Assume that a 250 lb person lean against the top edge (40 inches above ground) at a 20° angle. For conservatism assume that the load is centered $2/3$ of the distance to the Viscometer, and that there is "zero" vertical reaction, i.e., 0 friction (gives maximum horizontal load, F). From moment equilibrium equations (about feet - rigid body), we get:

$$F = \tan(20)(2/3)(250 \text{ lbs}) = 61 \text{ lbs}$$

The moment arm above the riser is 101 in, so the $M = (61)(101) = 6,161 \text{ in-lbs}$. This bending moment, is less than that due to the wind load (section 4.4 and 4.6) previously evaluated, and as it does not coexist with the wind load is acceptable by comparison.

4.6 Combined Loading

The worst case credible combined loading is that due to combination of wind, operational, and dead weight loads. The critical location on the tank is the top of the riser. As the riser pipe is embedded in concrete near the flange location, the maximum stresses will occur at this location. The 4 inch SHD 40 pipe ($A=3.17 \text{ in}^2$, $I=7.23 \text{ in}^4$, $S=3.21 \text{ in}^3$, O.D. = 4.5 in., I.D. = 4.026 in.) then would have the following stresses due to wind load:

$$\text{due to } M: \quad \max \sigma_b = M/S = 9,820/3.21 = 3,060 \text{ psi}$$

$$\begin{aligned} \text{due to } T: \quad \max \tau &= Tr/J = 2Tr_o/\pi(r_o^4 - r_i^4) = 2(576)(2.25)/\pi(2.25^4 - 2.013^4) \\ &= 90 \text{ psi} \end{aligned}$$

The maximum downward axial loads, F_a , due to dead weight and operational load is $584 + 250 = 834 \text{ lbs}$. The corresponding axial stress is:

$$\sigma_a = P/A = 834/3.17 = 260 \text{ psi}$$

The combined axial stress is that due to bending and axial loads, or $3060 + 260 = 3320 \text{ psi}$. Here the combined Local Membrane + Bending stress Intensity ($P_L + P_b$) need to be evaluated. Here:

$$P_L + P_b = 2\tau_{\max} = 2*[(\sigma_a/2)^2 + \tau^2]^{1/2} = 2*[(3320/2)^2 + 90^2]^{1/2} = 3325 \text{ psi}$$

The allowable here is $1.5S_m$, which is 16,600 for ASTM A53 ($2/3 S_y(\text{min})$; $S_y(\text{min}) = 25,000 \text{ psi}$). Here,

$$SF = (1.5)(16,600)/3325 = 7.5$$

Additionally, the weld attaching the flange to the riser also need to be analyzed. The flange has a tight fitting collar, so as the bending moment is transmitted directly to the pipe, not loading the 3/16 fillet weld. The shear stress due to Torque, T is:

$$\tau = (2.83T)/(hD^2\pi) = (2.83)(576)/[(.1875)(4.5^2)(3.14)] = 137 \text{ psi}$$

The normal stress, due to the axial load, P , is:

$$\sigma_a = 1.414P/(\pi Dh) = (1.414)(834)/[(3.14)(4.5)(.1875)] = 445 \text{ psi}$$

$$\text{Here } P_L = 2[(445/2)^2 + 137^2]^{1/2} = 520 \text{ psi}$$

Considering a minimum weld quality factor (Q) or efficiency of 0.5, the Safety

Factor is:

$$SF = Q \cdot S_m / P_t = (.5)(16,600)/520 = 16$$

The bolts attaching the riser flange to the Viscometer unit needs to be evaluated. There are eight 5/8 inch bolts ($A = 0.226 \text{ in}^2$ for tensile stress calculations - UNC) arrange on 7.5 inch. bolt circle. The flange is 9.0 inches in diameter. The vertical downward axial load compresses the flange and does not load the bolts. Furthermore, this axial load reduces the total moment reacted by the bolts (see below).

The shear force, F_s on a single bolt due to Torsion is:

$$F_s = T/nr ; \text{ where } n \text{ is number of bolts and } r \text{ is the bolt circle radius}$$

$$= 576/[8 \cdot 3.75] = 19.2 \text{ lbs each}$$

The corresponding average shear stress is ($A_s = .202 \text{ in}^2$) is:

$$\tau(\text{avg}) = F_s / A_s = 19.2/.202 = 95 \text{ psi}$$

The bending moment, causes the flange to pivot about a edge, and loads the bolts axially. This force balance is shown in the figure below:

Here the bending moment (M) is related to the bolt axial force, so that;

$$M = d_1 F_1 + 2d_2 F_2 + 2d_3 F_3 + 2d_4 F_4 + d_5 F_5$$

assuming that the flange is rigid relative to the bolts, then from similarity;

$$\begin{aligned} F_1 &= (d_1/d_5) * F_5, \\ F_2 &= (d_2/d_5) * F_5, \\ &\vdots \\ &\text{etc.} \end{aligned}$$

by substituting and rearranging we can solve for the maximum loaded bolt, F_5

$$F_5 = M * d_5 / (d_1^2 + 2d_2^2 + 2d_3^2 + 2d_4^2 + d_5^2)$$

with $d_i (i=1,5) = 0.75, 1.85, 4.5, 7.15$ and 8.25 in.

$$F_5 = 0.0378 * M, \text{ lbs}$$

The total moment, M, is that due to the general bending (9820 in-lbs) less that of the downward axial force (834 lb) acting at a moment arm of the distance from the center of the pipe to the edge of the flange (4.5 in.), or 6070 in-lbs. therefore:

$$F_5 = (.0378)(6070) = 230 \text{ lbs.}$$

The corresponding axial stress is $230/0.226 = 1020$ psi. The combined P_m is than calculated at 1040 psi.

The bolts (5/8-11 UNC ASTM A-307) has a design allowable stress, S, value of 7000 psi. Therefore $SF = 7000/1040 = 6.7$

The base-plate upon which components, such as motors, are mounted was previously analyzed, in early scoping analysis, for combined dead weight + operating cable tension loading. In this scoping analysis, the plate was assumed to 0.625 inches thick, and was not supported by the tubular frame and gusset support to the riser extension. It is expected, that the design analyzed is not as stiff or as strong as the current design. This elastic finite element (plate) analysis, using the ALGOR⁽¹¹⁾, finite element code was used primarily to determine if the could be problems in the alignment of various drive components, due to excessive deformation. The results of this, now conservative analysis, predicted that various drive components are within 0.004 inches (vertical displacement) of each other. Hence, drive alignment problems are not expected. Calculated stresses were generally low ($\sigma_1 \leq 1500$ psi) except for the interface with the decontamination unit, which was conservatively modeled as infinitely rigid. Here, the σ_1 (bending) was calculated at a maximum value of 5135 psi, which is also Primary Membrane + Bending Stress Intensity value. For this 316 ss component, the Safety Factor is :

$$SF = 1.5 * S_m / (P_i + P_b) = (1.5)(16600)/5135 = 4.8$$

5.0 CONCLUSION

The Viscometer and interfacing tank components were shown to be structurally acceptable for design loading (normal and anticipated) conditions. The minimum Safety Factor on allowable stress was conservatively determined to be 4.8 (Design Margin = 3.8, or 380% over designed). Calculated deformation were found to be acceptable, so as to assure that the Viscometer will function as intended. The "drop ball" accident was evaluated and shown to be acceptable with respect to tank structural integrity.

6.0 REFERENCES

1. K. L. Pearce and T. I. Stokes, SY-101 In Situ Viscometer Instrument Engineering Work Plan, WHC-SD-WM-WP-242, October 1993.
2. Hanford Plant Standard - SDC-4.1, Standard Arch-Civil Design Criteria - Design Loads for Facilities, Rev 11, September 6, 1989.
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5. W. E. Baker, P. A. Cox, P. S. Westine, J. J. Kulesz and R. A. Strehlow, Explosion Hazards and Evaluation, Elsevier Scientific , 1983.
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7. R. J. Roark, FORMULA FOR STRESS AND STRAIN, 4th. edition, McGraw-Hill, 1965.
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9. H. A. Rothbart, MECHANICAL DESIGN AND SYSTEMS HANDBOOK, McGraw-Hill, 1964.
10. Manual of STEEL CONSTRUCTION, 7th ed. , AISC, 1970.
11. S. L. Hecht, ALGOR Computer Code QA, WHC-SD-GN-CSWD-321, August 1, 1991.

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APPENDIX H

DESIGN ANALYSES

**Westinghouse
Hanford Company**

**Internal
Memo**

From: J. D. Martin
Phone: 376-1949
Date: August 9, 1994
Subject: ADDENDUM TO VISCOMETER CABLE REEL DRIVE MOTOR SIZING CALCULATIONS

To: K. L. Pearce L6-37

cc: R. E. Bauer L6-37
D. B. Graves L6-38
L. M. McWethy N1-21
C. L. Shepard K5-25
T. I. Stokes H5-09

REFERENCES: 1. Internal Memo, "Review of Viscometer Cable Reel Drive Motor Sizing", L. M. McWethy to K. L. Pearce, December 2, 1993.
2. Design Calculations, J.D. Martin, "Viscometer Cable Reel Drive Motor Sizing", November 18, 1993.

The memorandum addresses the comment in Reference 1, and other, verbal comments regarding the design calculations and conclusions of Reference 2.

Based on vendor information, Reference 1 suggests that ball speed could be maintained over the 1000/1 speed range with a single motor. While both Electro-Craft and Aerotech literature indicate that their motor-controllers have a 1000/1 speed range, experience has been that speed regulation suffers at very low speed because the tachometer error voltage is so low. Conversations with applications engineers at both Aerotech and Electro-Craft confirmed that speed regulation at very low speeds was not as good as at high speed. Since speed regulation is vital to obtaining usable viscosity data, the decision was made to use two motors to cover the desired speed range. This not only provides for better speed regulation, but also gives some speed overlap and extends the slowest and fastest speed beyond what is required.

One requirement not adequately addressed in Reference 2 is the requirement to have low ripple (variation) in the ball speed. Ripple differs from speed regulation in that its cause is inherent to the design of the motor or controller. For example, motors driven by line frequency switched SCR controllers can exhibit some ripple at low speed and high loading conditions because there is not enough rotary inertia to maintain speed between current pulses. Personal experience indicates, and conversation with a Compumotor applications engineer confirmed, that direct current, brushed servo motors driven by linear controllers have the lowest ripple. The small (low-speed) motor uses a linear controller and so should be ripple free. Even though the large motor is driven by a pulse width modulated (PWM) controller, the 20 kHz switching frequency should provide ripple free speed control. While vendors could not supply any data, it is considered that the selected motor-controller combinations will minimize ripple.

T. Stokes

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August 9, 1994

Figure 3 in Reference 2 indicated that the high-speed motor would not meet the desired cable tension capability of 1100 Newton's. The data presented in that figure was for continuous duty, but the maximum torque capability is much higher. The attached tension capability figure shows the maximum short term tension capability to be more than adequate to meet the desired 1100 Newton's. In fact, electronic current limiting must be adjusted on both controllers to limit the torque to prevent excessive cable tension.

The data sheets for the Aerotech DSPS controller actually used have been added to Reference 2 as Attachment 5.

A handwritten signature in cursive script, reading "J. D. Martin".

J. D. Martin, Principal Engineer
TWRS Safety Programs Engineering Support

VISCOMETER CABLE TENSION CAPABILITY

From: Remote Systems Development
Phone: 376-9507 (L5-02)
Date: December 2, 1993
Subject: REVIEW OF VISCOMETER CABLE REEL DRIVE MOTOR SIZING

To: K. L. Pearce L6-37
cc: R. E. Bauer L6-37
D. B. Graves L6-38
J. D. Martin L7-04
LMM/File/LB

Reference: Design Calculations, J. D. Martin, "Viscometer Cable Reel Drive Motor Sizing," November 18, 1993.

The viscometer drive motor sizing (above reference) does not meet the requirements listed. Figure 3 of the above reference shows a window near 100 mm/s and 1000 N which does not meet the requirements.

From the data presented, a simpler design would meet these requirements. Motor Model 1960 (Attachment 3 of above reference), with a 1000:1 control range (as advertised), a 20:1 gear reduction and a 7-inch effective pulley diameter would meet all requirements.

Motor speed effective range: 2.15 - 2150 RPM

Geared speed effective range: .1075 - 107.15 RPM

With 7-inch effective diameter pulley:

Cable speed effective range: $Sc = Pix7x.1075x2.54/60 = .1 \text{ cm/s} \rightarrow 100 \text{ cm/s}$ (meets requirements)

Using J. D. Martin's assumptions of .85 gear torque efficiency and motor torques of:

@ 2150 RPM $\rightarrow 700 \text{ oz-in} = 43.75 \text{ lb-in}$
output torque is $43.75x20x.85 = 744 \text{ lb-in}$
cable force is $744/3.5 = 212.5 \text{ lbs} = 945 \text{ N}$
(meets requirement of 10 N)

K. L. Pearce
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@ 215 RPM - 900 oz-in = 56.25 lb-in
output torque is $56.25 \times 20 \times .85 = 956$ lb-in
cable force is $956 / 3.5 = 273.2$ lbs = 1215 N
(meets requirement of 1000 N)

L. M. McWethy
L. M. McWethy

jkt

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(4) Building NA (5) Rev. NA (6) Job No. N2B65
(7) Subject Viscometer Cable Reel Drive Motor Sizing
(8) Originator JD Martin Date Nov 18, 1993
(9) Checker _____ Date _____

(10)

SUMMARY

1. Maximum Cable Tension = 250 Lb or 1100 N
2. Cable Spool Effective Diameter = 167.1 mm or 6.579 in.
NOTE: Physical diameter of the spool is approximately the effective diameter minus the cable diameter.
3. Maximum Spool shaft torque = 822.4 lb-in
4. High-speed gearbox is 15:1 ratio worm gear type.
5. Low-speed drive is Electro-Craft E652 controller and 652-501-204 Gearmotor with 50:1 reduction, see Attachment #2.
6. High-speed drive is Aerotech Model 1960 Servo Motor (Attachment #3) and 16030-V Servo Amplifier (Attachment #4).
7. Usable Cable speed ranges are shown in Figure 2.
8. Cable tension capability is shown in Figure 3.
9. Assumptions and calculations are given on the following pages, 2 through 6.

End Summary

Nov 19, 1993 - The Aerotech 16030-V Servo amplifier has been replaced with a Model DSPS-A/DS16030-F15. The 16030-V has been discontinued but the new model provides the same voltage and current capabilities. See Attachment #5.

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Requirements: (See Attachment 1)

- a) Cable speed control from 1mm/s to 1m/s (1000:1 range)
- b) Continuous cable tension of 1000N during withdrawal.

Motors, gearboxes and other mechanical equipment are rated in English units. Conversion Factors are:

$$25.4 \text{ mm/in.}$$

$$0.2248089 \text{ Lb-Force/N}$$

Since cable reel diameter, gear ratio, rated motor speed and motor speed control range all affect the cable speed and speed range, values must be assumed to establish baseline motor-controller requirements.

Since it is unlikely that a single motor-controller combo can be found that provides the required torque and speed regulation over the full 1000:1 cable speed range, assume a dual motor drive. Each motor then only needs to regulate speed over a $\sqrt{1000}$:1 range or 31.623:1.

Slow-speed range: 1mm/s to 32mm/s

$$\text{"Center" speed} = \sqrt{31.623} = 5.623 \text{ mm/s}$$

High-Speed range: 32mm/s to 1000mm/s

$$\text{"Center" speed} = (5.623)(31.623) = 177.82 \text{ mm/s}$$

It is desirable to provide a cable speed range greater than the projected range in order to cover unforeseen contingencies. An overlap of the Low and High-speed ranges is also desirable to allow more flexibility in testing.

DC motor and Controller combinations providing regulated speed ranges of 50:1, or greater, are available from a number of vendors. The conservative assumption is that 50:1 regulated range is achievable.

If the 50:1 speed range is centered at the center of the required range, i.e., at 5.6mm/s and 177.8 mm/s. This will provide for both range overlap and extension of the minimum and maximum cable speeds. The "center" of the control range = $\sqrt{50} = 7.071$

$$\text{Low-speed range} = 5.623/7.071 \text{ to } (5.623)(7.071) \text{ mm/s}$$

$$= 0.795 \text{ mm/s to } 39.76 \text{ mm/s}$$

(Continued Page 3)

DESIGN CALCULATION

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(10) High-speed range = $177.82/7.071$ to $(177.82)(7.071)$ mm/s
 = 25.15 mm/s to 1257.4 mm/s

The preceding ball speed calculations are shown graphically in Figure 1

Assume an industrial (versus servo) motor will be needed for the high speed drive. Assume a 6 inch diameter for the cable reel so the cable can be taken up with a single layer. The single-layer arrangement eliminates the possibility of turn overlaps and provides a constant relationship of reel turns to ball vertical position.

Required cable reel shaft torque capability is then

$$T_L = \frac{D_R}{2} F_c \quad \text{where: } T_L = \text{Load torque}$$

$D_R = \text{Effective reel dia.}$

$F_c = \text{Cable force (tension)}$

$$T_L = \left(\frac{6 \text{ in}}{2} \right) (1000 \text{ N}) (0.2248089 \frac{\text{lb}}{\text{N}})$$

$$= 674.4 \text{ lb-in}$$

Design For 10% over required cable tension or

$$(1.10)(1000)(0.2248089) = 247.28 \text{ lb}$$

Use 250 lb for design. Thus,

$$T_L = (3)(250) = 750 \text{ lb-in.}$$

Assuming motor base speed of 1750 rpm, the center speed is nominally $\frac{1750}{\sqrt{50}} = 247.5$ rpm. Cable reel rotational speed is,

$$N_R = \frac{S_c}{\pi D_R} \quad \text{where: } N_R = \text{Reel rot. speed}$$

$S_c = \text{Cable Speed}$

$$N_R = \frac{177.82 \text{ mm/s} (60 \text{ s/min})}{\pi (6 \text{ in}) (25.4 \text{ mm/in})} = 22.28 \text{ rpm}$$

A gear ratio of $N_m/N_R = 247.5/22.28 = 11.1$ is required.

But, standard gear ratios are 10:1 and 15:1. Use 15:1 to minimize High-speed motor torque requirement.

$$T_m = \frac{T_L}{R e} \quad R = \text{Gear ratio}$$

$e = \text{Gearbox efficiency - Assume } .85$

(Continued on page 4)

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(10) Torque requirement for the High-Speed motor is then

$$T_m = \frac{(750)}{(15)(.85)} = 58.8 \text{ lb-in (Nominal)}$$

This is also the torque output requirement for the Low-Speed motor-gearbox.

The required gear ratio for the Low-speed motor is nominally 31.6:1. Standard ratios are 25:1 and 50:1.

The drive-reel design is to be optimized for the Low-speed range, so select a motor-gearbox-controller combination for that range first. A linear, closed-loop servomotor system using velocity feedback will provide the needed regulated speed range with minimum velocity ripple. A brush type motor will provide full torque capability over the entire speed range. The Electro-Craft E652 Controller and matching 652-501-204 gearmotor (see Attachment #2) meets the torque and regulated speed range requirements. The gearmotor has an in-line gearbox with a 50:1 reduction.

Size the cable reel to provide a cable speed of 35 mm/s at rated speed of the Low-speed gearmotor, 60 rpm.

$$D_r' = \frac{S_c R_H}{\pi N_L}$$

R_H = High-speed gearbox ratio = 15:1

N_L = Low-Speed Gearmotor output speed = 60 rpm

S_c = 35 mm/s

$$\text{So, } D_r' = \frac{(35 \text{ mm/s})(15)(60 \text{ s/min})}{\pi (60 \text{ rev/min})} = 167.1 \text{ mm or } 6.579 \text{ in}$$

The effective diameter of the reel, D_r' , is approximately the diameter of the centerline of the cable. If the cable diameter is 0.125 in, the diameter of the spool is $6.579 - 0.125 = 6.454 \text{ in}$.

Recalculate torque input to High-speed gearbox:

$$T_L = \left(\frac{6.579}{6.0} \right) 750 = 822.375 \text{ lb-in}$$

$$T_m = \frac{822.375}{(15)(.85)} = 64.5 \text{ lb-in.}$$

(Continued on page 5)

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- (10) The Electron-Craft 652-501-204 gearmotor has a torque rating of 178 lb-in, which is more than adequate.

Select the High-speed drive motor. Need 64.5 lb-in (1032 oz-in). A DC, brush, servomotor will provide the best torque capability. The highest torque servo motor that could be found is rated at 960 oz-in (see Attachment #3). The Aerotech Model 1960 servo motor. The -02 version has a torque constant of 80 oz-in/amp or $960/80 = 12$ amps at Full torque. The back EMF constant is 59 Volts/krpm (-02) so an armature voltage of $(59)(2750)/1000 = 162.25$ volts is required for full speed (2750 rpm). This power requirement (1947 watts) is beyond the capability of linear servo amplifiers. This leaves two options for the controller; industrial style SCR, or pulse-width-modulated (PWM) controller. A PWM controller is preferred because:

1. PWM controllers operate in the KiloHertz range, rather than at 120 Hz. The higher frequency should result in less velocity ripple, particularly at slowest speeds.
2. KiloHertz electrical noise is easier to filter out than is 120 Hz noise.

The only disadvantage of PWM servo amplifiers is a decreasing torque capability as speed increases, i.e., they develop full motor torque only at the slowest speed. This should be acceptable since the higher speeds will only be used when the ball is in the supernate.

From the torque-speed graph of Attachment #3, the Aerotech 16030-V controller should be used with the 1960 motor as it is for single-axis while the other models are rack mount for multiple-axis control. The graph indicates a usable maximum motor speed of 2150 rpm (the cross-over of the motor and driver torque limit curves).

(Continued on Page 6)

(1) Drawing NA (2) Doc. No. NA (3) Page 6 of 6
 (4) Building NA (5) Rev. NA (6) Job No. N2B65
 (7) Subject Viscometer Cable Reel Drive Motor Sizing
 (8) Originator JD Martin Date Nov 18, 1993
 (9) Checker _____ Date _____

(10) Recalculate High-speed cable speed

$$S_c = \frac{\pi D_m' N_m}{R} = \frac{\pi (167.1 \text{ mm}) (2150 \frac{\text{Rev}}{\text{min}})}{(15) (605/\text{min})} = 1254 \text{ mm/s}$$

While the Aerotech literature (Attachments #3 & #4) do not specify a regulated speed range, the vendor stated in a telecon that the speed range was 1000:1. This is the same as for the Electro-Craft E652 controller (Attachment #2).

Experience has shown that speed regulation error increases at the slower speeds. Thus, a usable speed range of 200:1 is more reasonable for this application. Thus,

$$\text{Low-Speed Range} = 35/200 \text{ to } 35 \text{ mm/s} \\ = 0.175 \text{ mm/s to } 35 \text{ mm/s}$$

$$\text{High-Speed Range} = 1254/200 \text{ to } 1254 \text{ mm/s} \\ = 6.27 \text{ mm/s to } 1254 \text{ mm/s}$$

See Figure 2.

Recalculate cable tension capability.

Low-Speed: The low-speed gear motor can supply more than enough torque for 250 lb ($\approx 1100 \text{ N}$) cable tension. The controller can be adjusted to limit the motor current and thus limit the cable tension.

High-Speed: Ref. Attachment #3 torque-speed graph.

At 2150 rpm, $T_m = 700 \text{ oz-in}$ (Nominal)

At $2150/200 = 10.75 \text{ rpm}$, $T_m = 900 \text{ oz-in}$ (nominal)

At 2750 rpm, $T_m = 0.2 \text{ oz-in}$, $S_c = 1254 \frac{2750}{2150} = 1604 \text{ mm/s}$

At 10.75 rpm, $S_c = 6.27 \text{ mm/s}$, Find cable tension

$$F_c = \frac{T_m R_e}{\frac{1}{2} D_s'} = \frac{2(900 \text{ oz-in})(15)(.85)}{6.579 \text{ in} (16 \text{ oz/lb}) (.2248 \text{ lb/N})} \\ = 969.8 \text{ N}$$

$$\text{At } 2150 \text{ rpm } F_c = \frac{700}{900} (969.8) = 754.3 \text{ N}$$

See cable tension capability, Figure 3.

(END)

Figure 1

50:1 Controllable Speed Range is Achievable.

J.D. Martin

Figure 2

LD Martin

VISCOMETER BALL SPEED CONTROL

With 6.579" Effective Spool Diameter
and 200:1 Usable Motor Speed Regulation Range. Nov 10, 93
Rev Nov 18, 93

VISCOMETER CABLE TENSION CAPABILITY

Nov 19, 73

WHC-SD-WM-SDD-043
Rev. 0

Figure 3

J D Martin

WHC-SD-WM-SDD-043
Rev. 0
Requirements for Viscometer

I. Ball Position (Elevation)

Required resolution: 5 cm

Desired accuracy: ± 5 cm at full cable payout

II. Constant Speed Tests

A. Ball Velocity

1. In the supernate

Desired range: 10 cm/s to 100 cm/s

Allowable ripple: 0.1 cm/s, rms

Required resolution: 0.1 cm/s

2. In the sludge

Desired range: 0.1 cm/s to 10 cm/s

Allowable ripple: 0.001 cm/s, rms

Required resolution: 0.001 cm/s

B. Cable Tension Due to Drag

1. In the supernate

Anticipated Range: 0 N to 10 N

Required resolution: 0.1 N

2. In the sludge

Anticipated Range: 0 N to 1000 N

Required resolution: 0.1 N

C. Measurement Frequency

1. In the supernate

100 samples/sec

2. In the sludge

10 samples/sec

D. Test Duration

1. In the supernate

100 seconds

2. In the sludge

100 seconds

III. Constant Cable Tension Tests

(assume this testing is done in the supernate only)

A. Ball Velocity

Desired range: 10 cm/s to 100 cm/s

Required resolution: 0.1 cm/s

B. Cable Tension Due to Drag

Anticipated Range: 0 N to 10 N

Required resolution: 0.1 N

C. Measurement Frequency

100 samples/sec

D. Test Duration

100 seconds

MOTOMATIC CONTROLS — PRECISE, ECONC

Attachment #2

E586-MODULAR CONTROL

- Closed-loop transistorized velocity feedback amplifier
- Speed range 1000:1 (5-5000 rpm)
- Full rated torque is maintained across the entire speed range
- Adjustable torque limit
- Adaptable to an external 0 to +10 VDC source for remote speed control
- Speed regulation* is 3% across the entire speed range (97% of the set speed)
- IR compensation (allows setting optimum regulation at speeds below 10 rpm)
- Regulation with line variations (105-125VAC), 3% or better
- Power transformer provides AC line isolation
- Input power — 115 VAC 50/60 Hz
- Fuse protected

E652-OPEN CONTROL

- Closed-loop completely transistorized velocity feedback amplifier
- Speed range 1000:1 (3-3000 rpm)
- Full rated torque is maintained across the entire speed range
- Adjustable torque limit
- Adaptable to an external 0 to + 10 VDC source for remote speed control
- Speed regulation* is 3% across the entire speed range
- IR compensation (allows setting optimum regulation at speeds below 10 rpm)
- Regulation with line variations (105-125VAC), 3% or better
- Fuse and thermal circuit breaker protection
- Power transformer provides AC line protection
- Input power — 115 VAC 50/60 Hz
- Dynamic braking
- Single polarity power supply is easily adaptable to a 110 to 130 VDC power supply

MATCHING MOTOR GENERATOR

Speed Range	Torque	Part Number
5-5000 rpm	24 oz-in	0586-30-500

See page 115 for motor specifications

E586-U ORDERING INFORMATION

Part Number	9078-0041
-------------	-----------

E586 MATCHING GEARMOTORS

Ratio	Part Number	Max Speed	Max Torque
6:1	586-501-102	833 rpm	6 lb-in
12.5:1	586-501-103	400 rpm	12 lb-in
30:1	586-501-107	167 rpm	26 lb-in
50:1	586-501-109	100 rpm	44 lb-in
100:1	586-501-113	50 rpm	79 lb-in
180:1	586-501-116	28 rpm	90 lb-in*
0586-30-501		Motor without gearhead	

Flange mounted — all gears steel — ball bearings — precision die-cast housing
 Lubricant: Grease

Maximum rated overhung load 25 lb 1/2" from mounting face

Maximum rated thrust load 15 lb

*Maximum rating of gearhead

See page 115 for Gear Motor specifications

MATCHING MOTOR GENERATOR

Speed Range	Torque	Part Number
3-3000 rpm	2.5 lb-in	0652-31-500

See page 115 for motor specifications

E652-O ORDERING INFORMATION

Part Number	9092-0004
-------------	-----------

E652 MATCHING GEARMOTORS

Ratio	Part Number	Max. Speed	Max. Torque
12.5:1	652-501-202	240 rpm	49 lb-in
25:1	652-501-203	120 rpm	89 lb-in
50:1	652-501-204	60 rpm	178 lb-in
90:1	652-501-205	33 rpm	290 lb-in
0652-31-501		Motor without gearhead	

Flange mounted — all gears steel — ball bearings — precision die-cast housing
 Lubricant: Grease

Maximum rated overhung load 25 lb 1/2" from mounting face

Maximum rated thrust load 15 lb

See page 115 for Gear Motor specifications

D-C SERVO MOTORS

Permanent Magnet
Models 1580, 1960

- 580 and 960 oz-in (4.1 and 6.8 N-m) stall torque
- High quality construction including stainless steel shaft, double-shielded ball bearings, and sealed brush holders
- Dynamically-balanced, skewed rotor assures vibration-free, cog-free performance
- Options include alternate windings, tachometer, encoder, and rear housings with connector or integral cable
- Fully-tested and run-in to assure rated performance

Specifications

PARAMETER	Motor Winding	SYM	UNITS	1580		1960	
				-01	-02	-02	-03
Stall Torque, Continuous		T _c	oz-in N-m	580 4.1		960 6.8	
Peak Torque		T _p	oz-in N-m	2400 16.9		4500 31.7	
Maximum Speed		N _{max}	rpm	2750		2750	
Maximum Power Output, Continuous		P	Watts	650		1160	
Torque Constant		K _t	oz-in/amp N-m/amp	45 0.31	65 0.45	80 0.56	100 0.7
			Volts/rpm	33.3	48.1	59	74
Back EMF Constant		K _b	Volts/rpm	33.3	48.1	59	74
Terminal Resistance		R	ohms	0.6	1.1	0.6	0.8
Armature Inductance		L _a	mH	1.3	2.3	4.5	7.6
Armature Moment of Inertia		J _a	oz-in-sec ² kg-m ²	0.26 1.8 x 10 ⁻³		0.37 2.6 x 10 ⁻³	
			rad/sec ²	9200		12000	
Maximum Acceleration at T _p		A _{max}	rad/sec ²	9200		12000	
Maximum Terminal Voltage		V _{max}	Volts	205		205	
Motor Constant		K _m	oz-in/Watt ^{1/2} N-m/Watt ^{1/2}	63.1 0.45		87.2 0.48	
Viscous Damping (infinite impedance)		D	oz-in/rpm N-m/rpm	9.1 0.06		8 0.06	
Stall Torque		T _c	oz-in N-m	23 0.16		40 0.28	
Time Constants	Mechanical	T _m	msec	10		4	
	Electrical	T _e	msec	2		8.5	
	Thermal	T _{th}	min	54		66	
Thermal Resistance		R _{th}	deg C/Watt	1.3		0.7	
Shaft Runout			inch mm		0.001 maximum, either end 0.03 maximum, either end		
Shaft End Play			inch mm		0.0005 max with 20 lb applied at either end 0.015 max with 89 N applied at either end		
Shaft Radial Load			lb N		40 maximum at maximum speed 178 maximum at maximum speed		
Brush Life			rev		3 x 10 ⁶ at maximum speed		
Weight		W	lb kg	25 11.5		37 16.9	

Note: See Tachometers section for tachometer performance specifications.

Do you need a custom-engineered solution for your application? Then call
AEROTECH's Systems Engineering Division (412) 963-7470

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Model 1960

Recommended Drivers: 16030-V, DS18030, DSL16020, U1SJ

Replaced by DSPS-A/16030-15

Motor and Motor/Tachometer Dimensions

MODEL NO.	A	B	C	D
15800C	14.00 355.6	19.04 270.3	-	-
16900C	17.20 438.9	13.84 351.5	-	-
1580LT	-	-	11.86 299.2	8.10 205.7
1980LT	-	-	14.98 377.4	11.20 287.0

TO ORDER: (412) 963-7470 Monday - Friday 8:00 am - 5:00 pm EST
Industrial Controls Product Group 101 Zeta Drive, Pittsburgh, PA 15238

Attachment #4
(2 pages)

D-C SERVO AMPLIFIERS

PWM, Single Axis

Models 6020-QS, 8020-QS,
10025-QV, 16030-V

- Output Voltages from $\pm 60V$ to $\pm 160V$ for control of virtually any d-c servo motor
- Highly efficient PWM operation and isolated power stages
- Patented* VARIBUS™ voltage control and adjustable peak current for optimized motor operation
- Full protection circuitry for motor and amplifier
- Self-contained, compact unit with integral 115/230VAC power supply

Ideal Single-Axis PWM Servo Amplifier

Aerotech's models 6020QS, 8020-QS, 10025-QV, and 16030-V d-c, pwm servo amplifiers are ideally suited to drive virtually any d-c servo motor in single-axis applications. Featuring output voltages from $\pm 60V$ to $\pm 160V$ and peak currents to 30A, these highly reliable amplifiers have a reconfigurable preamplifier section that accommodates a broad range of compensation/gain settings for velocity loop closure, as well as unity gain configurations for tachless systems.

VARIBUS™ For Optimal Motor Matching

The 10025-QV and 16030-V have the VARIBUS™ circuit which permits a range of bus voltages as low as 10VDC to be used without any alterations to the amplifier's circuitry.

Full Protection Circuitry

These amplifiers feature short-circuit protection circuitry with LED indicator and reset pushbutton. Adjustable current limiting and output current fusing protect the motor and amplifier from high currents. Directional current limits, initiated by switch or relay closures, decrease the output current in one or both directions. All amplifiers have an internal power supply. The 10025-QV and 16030-V require an external bus voltage transformer.

Isolated Drive Section Eliminates Ground Loops

All models feature full galvanic isolation of the power stages. This eliminates ground loops between the load and signal source and minimizes EMI/RFI noise generation and multiple axis crosstalk.

U.S. Patent No. 4,554,512

Simplified Schematic

Output Voltage vs Output Current

TO ORDER: (412) 963-7470 Monday - Friday 8:00 am - 5:00 pm EST
Industrial Controls Product Group 101 Zeta Drive, Pittsburgh, PA 15238

Models 6020-QS, 8020-QS, 10025-QV, 16030-V Specifications

MODEL		6020-QS	8020-QS	10025-QV	16030-V
Peak Output Current (2 sec)	Amps	±20	±20	±25	±30
Continuous Output Current	Amps	±10	±10	±12.5	±16
Output Fuse (3AG, slow blow)	Amps	10	10	12	15
Peak Output Voltage	Volts	±80	±80	±100	±160
Minimum Output Voltage	Volts	N/A	N/A	0	0
Peak Power Output	Watts	1400	1400	2250	4500
Continuous Power Output	Watts	700	700	1125	2250
Regenerative Energy Absorption	Joules	1	1	12	24
Operating Temperature	°C	0 to 50			
Storage Temperature	°C	-30 to 81			
Weight	lbs(kg)	14(6.4)	14(6.4)	16(7.3)	16(7.3)

Preamplifier

Offset (Gain max open loop)	dB	100
Drift (referred to input)	µV/°C	10
Offset	Volts	Adjustable to Zero

Power Amplifier

Gain	Amps/Volt	20	20	20	20
Bandwidth	kHz	1	1	1	1
PWM Switching Frequency	kHz	20	20	18	5
Current Limit ⁽¹⁾	Amps(Max)	1.8	1.8	1.8	1.8
Shutdown	Amps(Max)	0.3	0.3	0.3	0.3
Minimum Load Inductance	mH	2	2	2	5

Notes: 1. Requires a closure with current handling capability of 10mA.

Dimensions

MODEL	A	B	C
6020-QS	6.13" (155.8)	1.25" (31.8)	6.81" (173.0)
8020-QS	6.13" (155.8)	1.25" (31.8)	6.81" (173.0)
10025-QV	6.83" (168.3)	1.50" (38.1)	7.30" (185.4)
16030-V	6.83" (168.3)	1.50" (38.1)	7.30" (185.4)

Ordering Information

Model	Description	Price	Options
◆ 6020-QS-A-Fn/	Servo Amplifier, 60V, 10/20A	\$ 900	◆ -A 115VAC line operation (std.) N/C
◆ 8020-QS-A-Fn/	Servo Amplifier, 80V, 10/20A	\$ 900	◆ -B 230VAC line operation N/C
◆ 10025-QV-A-Fn/	Servo Amplifier, 100V, 12/25A	\$ 1,050	
◆ 16030-V-A-Fn/	Servo Amplifier, 160V, 15/30A	\$ 1,170 ⁽²⁾	

Notes: 1. Specify fuse current rating "-Fn" when ordering; see specifications for standard values.
 2. CHV1 inductor is recommended with 16030-V.

Accessories

◆ TV1.5	1.5kVA Transformer for 40V, 60V, 80V, 100V, 160V bus	\$ 370
◆ CHV1/	1.8mH inductor, 15A cont.	\$ 100

Look for this symbol: ◆ It stands for stock items shipped within 24 hours (ARO) AND FREE SHIPPING!

DS Series Mounting Chassis and Power Supplies

DSPS One-Axis Chassis

DSR Three-Axis Chassis

DSRF Six Axis Chassis

Compact Chassis/Power Supplies

One, three, four, six and eight axis chassis accommodate either the DS16020 or DS16030 amplifiers. The DSPS one axis chassis, DSR three axis chassis, and APRS-4 four axis chassis are designed for sub-panel mounting. The DSRF six axis chassis and APRFS-8 eight axis chassis are designed for either 19 inch rack or sub-panel mounting.

All chassis include a robust, fuse-protected, DC bus power supply plus logic level supplies. The DSPS has plugable screw terminals for easy power and control connections. DSR and DSRF chassis have a convenient backplane extension with screw terminals for power connections, and a 37 pin D-style connector for control connections. APRS-4 and APRFS-8 chassis use screw terminals for power connectors TB1 and TB2 and 15 Pin D connectors for control connections J5 and J6.

No transformer is required for 160 volt bus operation from 115 VAC. Bus voltages of 40, 60, or 80V can be provided in the DSPS from 115 VAC with the optional TV0.3 transformer or from 230 VAC with the TV0.4 transformer. With the optional TV1.5, TV2.5, and TV transformers, bus voltages of 40, 60, 80, 100 or 160V can be provided in each chassis from 115 or 230 VAC. Logic-level supplies require 115/230 VAC at 50/60 Hz.

Low Power Option Reduces Cost

All chassis include a 30 CFM blower and shunt regulator as standard. The low power LP option deletes the blower and shunt and is recommended for applications requiring 5 amps continuous current or less per axis. The low power option also saves cost by deleting the metal chassis cover.

Nonstandard Motor Load Fuse

The DS series amplifiers have an output fuse to protect the motor from overheating. To order a nonstandard fuse current rating, append "-Fn/" to the model number where n is the continuous current in amperes.

Current Command Configuration Option

Standard DS series amplifiers are configured as velocity command amplifiers. The amplifier generates a motor current proportional to the velocity error (difference of velocity command and tachometer feedback signals).

Some digital controllers derive a velocity command without the use of a tachometer and output a current command to the amplifier. Option "C" configures the DS series for a current command input voltage with 2A/V or 3A/V fixed gain. The user can modify this gain and add frequency compensation, if desired, by changing components on the plug-in personality module.

Parallel Operation Increases Power

When more than 30A peak/15A continuous per axis is needed, DS series amplifiers can be run in parallel. Two, three, or four amplifiers can be combined for up to 120A peak/60A continuous output current. Amplifiers can be run in parallel for both velocity command and current command applications. Option "P" specifies the parallel configuration.

Stepping &
Servo Drives

DSPS Single-Axis Chassis Specifications

Note AC power input direct from 115VAC line or via center-tapped or non center-tapped transformer

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AEROTECH, INC.
101 Zeta Drive, Pittsburgh PA 15238-2897
Phone: (412) 963-7470 FAX: (412) 963-7459

U.K. AEROTECH, LTD
Phone: (0734) 817274
FAX: (0734) 815022

Germany AEROTECH GMBH
Phone: (0911) 521031
FAX: (0911) 5215235

DS Series Chassis and Power Supply Specifications

Model		DSPS	DSR	DSRF	APRS-4	APRFS-8
Compatible Amplifiers		DS16020, DS16030				
Axes (max.)		1	3	6	4	8
Peak Power Output	Watts	1600	7200	14,400	12,000	24,000
Continuous Power Output	Watts	1000	4200	8400	7000	14,000
Blower Assembly		Standard				
Shunt Regulator		Standard				
Continuous Shunt Power	Watts		100			200
Operating Temperature	deg. C	0 to 50				
Storage Temperature	deg. C	-30 to 85				
Weight	lb (kg)	3 (1.4)	8.5 (3.9)	17 (7.8)	17 (7.8)	34 (16)

Output Voltage vs Output Current

Notes: 1. TV2.5 transformer with DSR power rating 14,400 W.
 2. TV1.5 transformer with DSR power rating 12,000 W.

Stepping &
Servo Drives

Ordering Information

To order an amplifier/chassis system append the code for operating voltage ("A" for 115VAC, "B" for 230 VAC) to the chassis number followed by "Xn-" (where n is the number of servo amplifiers) and the amplifier model number and fuse rating. For example, a three-axis, 115VAC DS16020 system is ordered as DSR-A/X3-DS16020-F10/. Two modules wired in parallel to form one axis with 30 amps continuous capability is ordered as DSR-A/X2-DS16030P-F30/. A one axis system with current command and low power option is ordered as DSPS-A-LP/DS16020C-F5/.

Model	Description	Price
DS16020-Fn ⁽¹⁾	DC servo amplifier module, 160V/20A	\$ 480
DS16030-Fn ⁽¹⁾	DC servo amplifier module, 160V/30A	\$ 570
DSPS-A/	1-axis chassis with power supply for DS16020, DS16030	\$ 470
DSR-A/	3-axis chassis with power supply for DS16020, DS16030	\$ 800
DSRF-A/	6-axis chassis with power supply for DS16020, DS16030	\$ 1,600
APRS-4-A-vvv ⁽²⁾	4-axis chassis with power supply for DS16020, DS16030	\$ 1,200
APRFS-8-A-vvv ⁽²⁾	8-axis chassis with power supply for DS16020, DS16030	\$ 2,400

Options

-A	115VAC line operation	N/C
-B	230VAC line operation	N/C
C	Torque (current) command configuration	N/C
P	Parallel configuration	\$ 100
-LP	Deletes blower, shunt and cover from DSPS, DSR, DSRF	\$ (75)

Accessories

TV0.3/	0.3 KVA autotransformer, 115VAC input operation with DSPS	\$ 135
TV0.4/	0.4KVA autotransformer, 230VAC input operation with DSPS	\$ 150
TV1.5/	1.5KVA isolation transformer	\$ 440
TV2.5/	2.5KVA isolation transformer	\$ 570
TV5/	5 KVA isolation transformer	\$ 840

Notes: 1. Specify fuse current rating "-Fn" when ordering.
 2. Specify bus voltage "-vvv" when ordering.

WHC-SD-WM-SDD-043
Rev. 0
VISCOMETER WEIGHT AND CENTER OF GRAVITY

COMPONENT	WEIGHT, LBS.	X, IN.	Y, IN.	W * X	W * Y
Base Frame	89	2	-2	178	-178
Base Plate 1	106	9	-2	954	-212
Base Plate 2	11	1	8	11	88
Gusset 1	2	16	0	32	0
Gusset 2	4	12	-5	48	-20
Jack Bracket 1	8	-9	12	-72	96
Jack Bracket 2	8	-9	-17	-72	-136
Pipe, 4 "	9	16	-5	144	-45
Spray System	2	16	-5	32	-10
Flange	3	16	-5	48	-15
Vacuum Valve	27	16	0	432	0
Adaptor Plate	55	16	-5	880	-275
Jack 1	32	-11	-18	-352	-576
Jack 2	32	-11	13	-352	416
Eye Bolts	2	6	-2	12	-4
Base Cover 1	2.5	1	-16	2.5	-40
Base Cover 2	2.5	1	11	2.5	27.5
Enclosure	76	14	-2	1064	-152
Purge System	28	12	-13	336	-364
Motor Cover	34	1	-2	34	-68
Large Motor Bracket	14	0	-8	0	-112
Small Motor Bracket	12	0	7	0	84
Encoder Bracket	7	-5	0	-35	0
Gearbox Plate	10	0	0	0	0
High Speed Motor	37	0	-14	0	-518
Low Speed Motor	13	0	10	0	130
Gearbox	21	0	0	0	0
Clutch 1	4	0	5	0	20
Clutch 2	4	0	-5	0	-20
Encoder	3	-8	0	-24	0
Drive Shaft	5	10	0	50	0
Couplings	2	0	0	0	0
Shaft Support	15	10	0	150	0
Shield Plug	14	16	-5	224	-70
Tungsten Ball	16	16	-5	256	-80
Load Cell Bracket	9	12	-4	108	-36
Load Cell	2	14	-4	28	-8
Pulleys	2	14	-3	28	-6
Drum Assembly	20	16	1	320	20
Level Winder	5	16	-3	80	-15
Cable	2	16	1	32	2
Electrical Components	5	0	0	0	0
TOTAL WEIGHT:	755		MOMENT:	4579	-2076.5
UNCERTAINTY:	+/- 20				
CENTER OF GRAVITY (FROM SHAFT AXES):			IN.	X 6.06	Y -2.75
CENTER OF GRAVITY (FROM RISER CENTERLINE):			IN.	-9.94	2.25

WHC-SD-WM-SDD-043
Rev. 0

APPENDIX I

SAFETY EQUIPMENT LIST

**Westinghouse
Hanford Company**

**Internal
Memo**

From: TWRS Project Safety Engineering
Phone: 376-8807 H4-70
Date: March 22, 1994
Subject: DEVELOPMENT OF SAFETY EQUIPMENT LISTS FOR VARIOUS TANK 101-SY
SUBSYSTEMS

LEJ-29300-001

To: C. E. Hanson H5-09

cc: R. E. Bauer	L6-37	D. R. Precechtel	L6-37
T. R. Benegas	H5-09	A. R. Schade	H4-60
B. W. Hall	H4-70	M. H. Shannon	H4-61
J. P. Hinckley	H4-66	T. I. Stokes	H5-09
E. H. Kohlman	H5-09	G. F. Vargo	H5-09
		LEJ File/LB	

As you know, the Safety Analysis and Engineering organization was recently restructured. Mr. Brett Hall has been assigned to the TWRS Project Safety Engineering organization. Mr. Hall is slated to support the Interim Pretreatment Module (IPM) Preliminary Safety Analysis Report (PSAR) and it is now time for him to assume his new responsibilities.

As discussed in the Statement of Work (attached) for the subject task, the safety equipment lists for the identified systems were to be completed in 4 phases, to support various stages in the design effort of each system. Based on the schedule in the statement of work, Phase II level analyses for all the systems, except the 101-SY camera system, are to be completed by April 15th. The Phase II analysis for the 101-SY camera is not due until the first of August. Phase III level analyses have already been completed for the multiport riser and the 103-SY and 101-AW camera systems. Phase III analyses on the remaining systems are not needed for several months.

The appropriate time to shift work responsibilities, then, appears to be April 15th. The phased approach outlined in the statement of work should allow this transition to occur smoothly. The phased approach was developed, in part, to allow the work to be split up among several analysts. The Phase II and III reports completed to date, and the Phase II analyses to be completed by April 15th, provide a sound basis from which to proceed with the remainder of the safety classification effort. Mr. Hall will provide his notes and the background information he has collected on the systems of concern to you or your designee.

Should you have any questions regarding this letter, please contact me at the above listed number.

L. E. Johnson, Manager
TWRS Project Safety Engineering

jwh

Statement of Work
for
Development of Safety Equipment Lists for Various Tank 101-SY Subsystems

Project Statement. Provide safety class 1 and 2 equipment lists for selected Tank 101-SY, 101-AW, and 103-SY subsystems, in accordance with the subsystem design/installation schedules.

Project Scope. This project will consist of reviewing available design media and pertinent, existing safety analyses to establish safety equipment lists for the tank farm subsystems shown in Table 1 (attached). It needs to be noted that these safety analyses are currently under revision, and that changes to the analysis may affect the SELs generated by this statement of work. Safety equipment lists will be developed for all safety class 1 and 2 items required for the operation of the as-installed subsystem. The level of detail, information, etc. of each of the lists will be as required by the MRP 5.46 "Safety Classification of Systems, Components, and Structures".

Successful execution of the project will require interaction between the WHC Safety Analysts assigned to this project, the individual cognizant engineers, and the individuals responsible for development of the safety analysis for each subsystem. This is particularly important when considering, for example, the potential interactions between the subject subsystem and other tank farm components during initial installation, operation, and maintenance activities. These interactions are not within the scope of the safety equipment list, but need to be fully documented in the Safety Analysis Reports.

Project Methodology. The work required to complete the SEL Project will be done in 4 phases. In the first phase the safety function, or "success criteria" for the subsystem of concern will be defined, and the safety classification for that function will be established. The appropriate safety classification will be assigned in accordance with the MRP 5.46, but will not be based on new safety analysis. The potential unmitigated consequences of applicable hypothetical accidents will be derived exclusively from existing Tank Farm safety analysis documents (eg., the Interim Safety Basis).

The second phase of the SEL project consists of breaking the subsystem down into major components, and determining which of these components are necessary to the subsystem's success in carrying out its assigned safety function. In order to complete this phase, some design information must be supplied by the designers. For phase 2, this information consists of design media and System Design Descriptions that will be developed to support the 60% design review. The output of the second phase will be an internal memo, with a copy sent to the Independent Safety review organization.

The third phase of the project consists of systems analysis of the essential components from the second phase. Fault Tree Analysis or other similar techniques will be used to identify individual components of the Safety Equipment Lists, and to verify that the system redundancy requirements have been satisfied. The environmental design requirements for each safety equipment item will also be determined, in a general sense. That is, for example, if an item is located inside the tank it will be noted that there will be radiation, corrosive atmosphere, etc. design requirements, but the

exact metrics of the requirements will be left to the designers. In order to complete this phase, some design information must be supplied by the designers. For phase 3, this information consists of design media and System Design Descriptions that will be developed to support the 100% design review. The output of the third phase will also be an internal memo, with a copy sent to the Independent Safety review organization.

The final phase of the SEL project will be to issue Engineering Change Notices to the Interim Safety Equipment List (WHC-SD-WM-SEL-026). An ECN will not, however, be released until the associated safety system is actually installed in the tank. The ECNs will be prepared by SSA, but it will be the responsibility of TWRS Engineering to coordinate the reviews, approvals, and releases of each of them.

Cost and Schedule. The overall cost of the SEL project, as currently defined, is estimated to be 8 man months. The work will be accomplished using Work Order #E63068. The schedule for completion of each of the project phases is shown in Table 1.

TABLE 1.

TANK FARM SAFETY EQUIPMENT LIST DEVELOPMENT PLAN

ITEM	Phase 1 Report	Phase 2 Report	Phase 3 Report	Phase 4 ECN	Cognizant Engineer	Safety Analysis
Multiport Riser	complete	complete	3/11/94	8/4/94	Prececht el	note 1
103-SY Camera	complete	complete	complete	2/28/94	Kohlman	notes 2, 3
101-AW Camera	complete	complete	complete	6/5/94	Kohlman	note 2
101-SY Camera	complete	8/1/94	9/1/94	9/20/94	Kohlman	note 4
Sonic Probe	complete	4/15/94	9/15/94	1/31/95	Vargo	note 1
Viscometer	3/15/94	3/15/94	5/15/94	7/22/94	Stokes	note 1
Void Frctn Meter	3/15/94	4/1/94	6/1/94	8/5/94	Stokes	note 1
101-SY Mxr Pump	complete	4/15/94	6/15/94	3/30/95	Benegus	note 1
101-SY NH3 Detector	complete	complete N/A	complete N/A	3/2/94	Bauer	note 5
DACS	3/15/94	TBD	TBD	TBD	Bauer	note 5

Note 1. LA-UR-93-1396

Note 2. WHC Internal Memo 29140-RJVV-94-003

Note 3. WHC-CM-SAR-061

Note 4. WHC-SD-WM-SAD-005

Note 5. No safety analysis exists or is planned which will explicitly consider this subsystem. It's functions are implicitly discussed in other Safety Analyses.

Westinghouse
Hanford Company

Internal
Memo

From: Systems Safety Analysis 29230-94-02
Phone: 376-2120 H4-66
Date: February 2, 1994
Subject: PHASE I REPORT, PRELIMINARY SAFETY CLASS ANALYSIS FOR SYSTEMS TO
BE INSTALLED IN SY FARM

To: J. W. Lentsch R2-78
C. W. Hanson H5-09

cc:	R. E. Bauer	L6-37	D. R. Precechtel	L6-37
	T. R. Benegas	H5-09	D. A. Smith	G6-16
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	E. H. Kohlman	H5-09	R. J. Van Vleet	H4-09
	SSA/LBFILE			

The attached summarizes the results of the first of three phases of analysis to determine equipment safety classifications for the following systems to be installed in the SY Tank Farm: the SY ammonia detector; the 101-SY, 103-SY, and 101-AW video camera systems; the 101-SY multi-port riser assemblies; the sonic probe; and the 101-SY permanent mixer pump.

The attached Phase I report identifies the "top level" Safety Class (i.e., SC-1 and SC-2) safety functions required of each of the systems of concern and provides the rationale behind determining these required safety functions. In a generic fashion, the items that must be Safety Class to provide or support the Safety Class safety functions are also identified. Guidance on the application of Safety Class criteria is provided, where unusual circumstances seemed to warrant such discussions.

The purpose of this Phase I report is to provide a basis from which to proceed with more detailed analyses. Agreement on this basis, by the cognizant system engineers, is sought before the analyses proceed in-depth. The Phase II and Phase III reports to follow for each system of concern will establish safety classifications at the subsystem and component levels, respectively. The Phase II and III analyses will include elements of the Data Acquisition and Control System (DACS) that are tied specifically to the systems of concern. The remaining DACS elements that are not involved with the systems of concern will be analyzed in a separate task.

If you have any questions, please feel free to contact me on 376-2120 or via cc:Mail.

B. W. Hall, Advanced Engineer
Systems Safety Analysis

mem

attachment

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Phase I Report, Preliminary Safety Class Analysis for Systems
to be Installed in the SY Tank Farm

1.0 Introduction

The letter report summarizes the results of the first of three phases of analysis to determine equipment safety classifications for several systems to be installed in the SY Tank Farm. The systems analyzed in this analysis include: the SY ammonia detector; the 101-SY, 103-SY, and 101-AW video camera systems; the 101-SY multi-port riser assemblies; the sonic probe; and the 101-SY permanent mixer pump.

This Phase I report identifies the "top level" Safety Class (i.e., SC-1 and SC-2) safety functions required of each of the systems of concern and provides the rationale behind determining these required safety functions. The items that must be Safety Class to provide or support the Safety Class safety functions are also identified, in a generic fashion. Guidance on the application of Safety Class criteria is provided, where unusual circumstances seemed to warrant such discussions.

The purpose of this Phase I report is to provide a basis from which to proceed with more detailed analyses. Agreement on this basis, by the cognizant system engineers, is sought before the analyses proceed in depth. The Phase II and Phase III reports to follow for each system of concern will establish safety classifications at the subsystem and component levels, respectively.

2.0 Approach

Available design documentation (Refs 4-7) was reviewed to become familiar with the systems and their intended functions, and to gain an understanding of the potential effects to be expected from system function failures or system misoperations. Pertinent safety analyses for the SY Tank Farm (Refs 1, 2, and 3) were also reviewed to determine the generic tank farm Safety Class functions that could be impacted by the systems of concern. The potential consequences of system function failure, as ascertained from the design documentation and the safety analyses, were compared against the safety class criteria in MRP 5.46 (Ref. 8) to determine the safety classifications appropriate to each safety function.

Generic safety class considerations germane to the systems of concern are summarized in Section 3. Section 3 also describes how these safety class considerations were factored into the definition of safety class functions for each of the systems of concern. Section 4 provides the results of the analysis--listing the safety class safety functions identified for each system, summarizing the rationale behind each safety class determination, and identifying some of the items needed to support the identified safety functions.

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3.0 Summary of Generic Safety Class Considerations

The systems considered in the analysis all have safety class implications in that they present potential interaction hazards to existing safety class systems in the tank farm or because they prevent, mitigate, or can cause hydrogen burn events in their respective tanks. Hydrogen burn events, depending on the amount of gas involved, can result in Safety Class-1 or -2 consequences.

3.1 Interaction Hazards

Reference 1 assigns safety classifications to the systems and selected components, parts and structures of the double-shell tank farm facility (AN, AP, AW, and SY Tank Farms). This reference determines that the primary and secondary shells and dome of each DST are SC-1 because their failure can result in liquid releases to the soil column in excess of MRP 5.46 SC-1 criteria. In addition, the primary tank ventilation system is found in Ref 2 to be SC-2 because an unmitigated release of particulate and aerosols from a tank could result in onsite exposures in excess of SC-2 criteria. Various instrumentation systems are also found to be SC-2 to support the operation of the primary ventilation system or to provide monitoring capability to implement emergency procedures to protect the onsite receptor and the environment.

The systems analyzed in this letter all present potential interaction hazards with the above mentioned Safety Class systems during their installation and operation in (and ultimate removal, where applicable, from) their respective tanks. For instance, various system equipment can be dropped during installation or removal, or potentially fail in service, in such a way as to compromise tank structural integrity or to compromise the safety function of the tank confinement system. Such interactions must be precluded or mitigated by design (or with administrative controls). Where design features are used to preclude interactions that can result in the loss of Safety Class functions, the safety classification of the design features should be designated accordingly.

3.2 Hydrogen Burn Events

The consequences associated with hydrogen burn events in 101-SY are estimated in Ref 2. For the purposes of this analysis, the consequences of hydrogen burns in tanks 103-SY and 101-AW are assumed to be of the same order-of-magnitude as hydrogen burn events in 101-SY. This assumption is necessary to conservatively assign safety classifications to the 103-SY and 101-AW camera systems.

Reference 2 determines the "maximum acceptable burp" (MAB) that can be ignited without failing the integrity of the 101-SY primary tank system. In determining this MAB, an open 42" (diameter) pressure relief path (through one riser) is assumed. Controls are established in the reference to ensure that hydrogen releases greater than the MAB are not caused by testing and operation of the temporary mixer pump.

The dose to the maximum onsite receptor following the MAB, with burn, is estimated in Ref. 2 to be about 5 rem. This is equivalent to the MRP 5.46 Safety Class-2 limit. A hydrogen burp and burn event (up to the MAB) is therefore judged to constitute a Safety Class-2 hazard for Tank 101-SY. Prevention of burp and burn events, involving gas releases up to the MAB, can correspondingly be defined as a generic safety class 2 consideration for all the systems to be installed in 101-SY.

A hydrogen burn event in 101-SY involving a hydrogen release greater than the MAB constitutes a Safety Class 1 hazard, since such an event could fail the SC-1 primary shell. Prevention of a hydrogen burn event in 101-SY, involving releases of gas in excess of the MAB, is a Safety Class 1 consideration for all the systems to be installed in the tank.

Since an open 42" pressure release path was assumed to establish the MAB, it must also be assumed that provision of such a release path, during a hydrogen burn event, is a Safety Class 1 consideration.

It should be noted that a burp, when there is no combustion of the gas, is not a Safety Class event. Ref. 2 shows that the radiological consequences associated with a burp (up to the MAB), when there is no combustion of the gas, is insignificant at the onsite and offsite receptor locations. The toxicological consequences from a burp are found in Ref 2 to be below SC-2 limits. A gas release event without combustion therefore constitutes a Safety Class-3 (facility worker) hazard.

Application to Systems of Concern

Summarizing the above discussion, the following generic safety class safety functions can be defined for 101-SY, relative to hydrogen burn events. These generic safety functions must be accommodated in the design of the systems to be installed in 101-SY.

1. Prevention of hydrogen burn events, involving gas releases up to the MAB is a Safety Class-2 (SC-2) function.
2. Prevention of hydrogen burn events, involving gas releases greater than the MAB, is a SC-1 function.
3. Provision of adequate pressure relief during a hydrogen burn event, involving gas releases up to the MAB, is a SC-1 safety function.

The hydrogen burn event requires a release of gases in concentrations above the LFL and the presence of an ignition source. Prevention of a hydrogen burn event can be accomplished two ways: by preventing the burp to begin with, or by precluding the presence of ignition sources in the tank, during periods when burps are possible. Of these two solutions, burp prevention is the preferred choice, since it is very difficult to eliminate all potential sources of ignition in the tank. The primary function of the permanent mixer pump is, of course, to prevent future burps from occurring in the

tank. This safety function is obviously SC-2. Pump components involved in providing this safety function are SC-2.

The permanent mixer pump, however, is the last of the systems analyzed in this letter to be installed in 101-SY. Ignition control is thus a SC-2 consideration for all the systems to be installed in Tank 101-SY prior to the pump. Items which preclude the presence of ignition sources from these systems during burps are SC-2.

Gas releases greater than the MAB are not anticipated to be possible in Tank 101-SY, unless the mixer pump and/or sonic probe are operated improperly. The mixer pump can initiate a burp exceeding the MAB if it is operated when the waste tank level is too high. The sonic probe can also presumably create a burp greater than the MAB if it is operated when the tank waste level is too high or if it is operated at too high a power level. The devices which ensure that such misoperations won't happen are thus SC-1.

Pressure relief during hydrogen burn events is the primary safety function of the multi-port riser. This safety function is obviously SC-1. The items which ensure the performance of this safety function (i.e., pressure relief panels) are SC-1. Items whose failure can compromise this safety class function (i.e., by plugging the release path or by preventing the pressure release doors from opening) are SC-1.

Summary

The important elements from the above discussions are summarized in the table below for the readers convenience. The table lists the four essential Safety Class (SC-1 or SC-2) safety functions that must be performed or accommodated by the systems to be installed in Tank 101-SY. A brief summary of the rationale behind classifying each safety function as SC-1 or SC-2 is also provided. The last column of the table lists the system(s)/subsystem(s) primarily responsible for (or involved in) performing the essential safety functions.

Safety Function	Safety Class	Rationale	System/Subsystem Responsible for Performing Safety Function
Prevention of burps up to the MAB.	SC-2	Burps up to the MAB, if ignited, could result in onsite exposures exceeding SC-2 limit. Ignition sources are not absolutely precluded in the tank.	Permanent Mixer Pump
Prevention of burps in excess of the MAB	SC-1	Burps greater than the MAB, if ignited, could fail the SC-1 tank containment system. (Credible ignition source is assumed).	Instrumentation/ Controls responsible for Permanent Pump and Sonic Probe operation
Provision of pressure release path during hydrogen burn events, involving gas release up to the MAB.	SC-1	The pressure release path ensures the integrity of the SC-1 tank containment system (i.e., primary shell) should a hydrogen burn event occur. The SC-2 mixer pump can not be credited with preventing this SC-1 hazard.	Multi-port Riser Assembly
Ignition Control	SC-2	Burp hazard exists until remediated by SC-2 permanent mixer pump, which is the last of the systems to be installed. Ignition control is defined as a SC-2 function to ensure that the systems included in this analysis will not contribute to a SC-2 event.	Applies to all systems to be installed as part of the activities covered in this analysis.

4.0 Results

Subsections 4.1 through 4.5 below summarize the Safety Class safety functions determined for each system (the three camera systems are analyzed together) and the rationale behind their determination. In a generic fashion, the items that must be Safety Class-1 or -2 to support the identified Safety Class functions are discussed. Guidance on the application of Safety Class design criteria is also provided, where warranted.

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4.1 Permanent Mixer Pump

It is logical to start with the permanent mixer pump first, even though it is to be installed last, because it will ultimately constitute the SC-2 remediation for the tank. Once installed, its presence affects the safety classifications of the other equipment to be installed in the tank.

4.1.1 Description

The permanent mixer pump uses a submerged liquid jet to induce flow of the waste tank fluid and to mix the tank contents. The intent is to impart energy to disrupt the nonconvecting slurry region sufficiently to allow a continuous release of hydrogen and to thus eliminate the burping problem in the tank. The permanent mixer pump is to replace the test mixer pump currently installed in the tank. It is expected that the mixing pump concept will be demonstrated to be capable of remediating the tank burping problem prior to the installation of the permanent mixer pump.

4.1.2 Safety Functions and Safety Classifications

The primary safety function of the permanent mixer pump is to, of course, prevent future burps in the tank. As discussed in Section 3.0, burp prevention is a SC-2 safety function. Note, however, that uninterrupted operation of the pump is not required to prevent tank burps. The gas must build up in the tank for an extended period of time before a burp hazard develops that can release hydrogen in concentrations above the lower flammability limit (LFL). The statement of safety function can therefore be worded as follows: continuous pump operation, except for periods not exceeding TBD (to be determined) days is required, to prevent a gas release with hydrogen concentrations exceeding the LFL. An analysis is needed to determine what the duration of inoperability can be. Pump components and associated instrumentation or control system components whose failure could result in loss of pump operation for periods in excess of this yet to be determined duration are SC-2.

As discussed in Section 3.0, gas releases greater than the MAB case evaluated in the test mixer pump safety assessment could result in failure of the SC-1 primary tank system. Pump operation when the tank waste level is above the range evaluated in the safety assessment could lead to gas releases larger than the MAB. The SC-2 function of the pump to operate can't be credited with preventing the SC-1 hazard presented by a release greater than the MAB. Another safety function associated with the pump, therefore, is to not operate when the tank waste level is too high. This safety function is SC-1. This can be accomplished with design features or with a TSR. The TSR would prohibit pump operation if the tank level is too high or if the tank level instrumentation is inoperable. (This may require that the tank level instrumentation be designated SC-1.)

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The need to restrict pump operation and to provide automatic shutdown of the pump during a tank burp (or during other tank conditions) will be evaluated in the safety assessment currently being performed to support pump installation and operation. Interlocks for automatic shutdown of the pump may be SC-1 as a result of the safety assessment.

The pump also presents a potential interaction hazard with the tank containment system. Drop of the pump during installation could compromise tank integrity. Since the tank is SC-1, prevention or mitigation of a drop is a SC-1 function. Items which prevent a pump drop or which limit the impact loading to the tank, should the pump be dropped, are SC-1. The pump can also transmit loads from wasteberg impacts to the SC-1 pump pit and tank dome (and from there to the SC-1 primary shell). In addition, a hydrogen burn event could force the pump or protective shell up, putting excessive loads on the pump pit coverblocks. An analysis is needed to determine if such loads can fail tank containment, either directly by failing the dome or indirectly by causing the pump to be dropped through the bottom of the tank. If such loads can fail tank containment, the items that isolate the loads from the primary tank system are SC-1.

4.1.3 Application of Design Criteria

The fact that continuous pump operation is not needed to prevent hydrogen burps allows some flexibility in the application of Safety Class design criteria to the mixer pump and associated instrumentation and controls. Some of the categories of Safety Class requirements are discussed below.

Natural Phenomena Hazards

The Safety class 2 items which could result in loss of pump operation do not need to be seismically qualified if it can be demonstrated that the items will be replaced with qualified spare components within the time period allowed for the pump to be inoperable. The storage for the spares is required to protect them from damage resulting from the seismic event (i.e., storage facility must be SC-2).

Environmental Qualification

The safety class equipment shall be capable of performing its intended safety function during normal, abnormal, or design basis accident conditions. This means that the pump shell must be designed against plugging and to withstand loading from the credible "waste berg" or it shall be designed to be replaced within the time period allowed for the pump to be inoperable.

Single Failure

Redundancy is not required for the safety class 2 items which could result in loss of pump operation if it can be demonstrated that the items will be replaced with qualified spare components within the time period allowed for the pump to be inoperable. Consideration needs to be given to the Technical

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Safety Requirements necessary to assure that the time period allowed for the pump to be inoperable is not exceeded.

Backup Power

The time period for which the pump is allowed to be inoperable is probably well in excess of the duration for which normal power may be credibly lost. Therefore, backup power is not required for continued pump operation if an analysis of the normal power shows that it is sufficiently reliable.

4.2 Sonic Probe

The Sonic Probe is being proposed as an alternative mitigation technique for 101-SY hydrogen problem. The Sonic Probe is a large rotary vibrator consisting of a shaft and eccentric weights (similar to a commercial concrete vibrator). The intent of the probe is to fluidize the waste sludge material within the tank by vibrational motion. The probe will be inserted into the tank before the permanent mixer pump discussed in the previous section and will be tested to see if it can release the hydrogen gas generated in the tank in a controlled manner.

The operating function of the probe is SC-3. It is not yet known if the probe is capable of adequately remediating the hydrogen burping problem in the tank. So the probe can not be assumed at this point to have a redundant, equivalent SC-2 safety function to that of the permanent mixer pump. Items whose failure could result in loss of probe operating function are nominally SC-3, except where higher safety classifications are required to prevent adverse interactions or to perform the conflicting function of shutting down the probe during dangerous conditions (see below).

The Safety Class concerns associated with the probe, as determined from early design reviews and various correspondence, are as follows:

- that the probe can cause an excessive gas release (burp) that can be ignited by other equipment in the tank, or by the probe itself,
- that the probe can ignite a naturally occurring gas release, or one caused by the probe or the test mixer pump,
- that the probe can adversely interact with other safety class items associated with the tank.

As discussed in Section 3, a hydrogen burn event presents a potential SC-2 or SC-1 hazard, depending on the quantity of hydrogen released. Both ignition control and burp prevention are defined as Safety Class functions for the probe. It takes both to ensure that the probe does not contribute to a Safety Class event, since neither the occurrence of burps nor the presence of ignition sources are absolutely precluded in the tank. (The test mixer pump cannot be credited with preventing burps since it is not SC-2). Using the approach applied on the permanent mixer pump, ignition control would be a SC-2 safety function for the probe. Prevention of burps

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greater than the MAB would be a Safety Class-1 function, accomplished via Safety Class-1 controls on probe operation.

Ignition of the burp can occur from sparks, static discharge, or extreme heat. Excessive heat could be generated due to such things as bearing failures in the probe. Sparks could be created by mechanical contact during the burp. For instance, the probe could be forced into the camera, or the drive shaft could fail and strike the tank. Electric discharge could occur from failed instrument wires. Items whose failure could cause ignition of a burp, via such mechanisms, are SC-2. The acoustical effects of probe operations on other equipment in the tank will have to be analyzed to determine if probe operation can create sparks sources elsewhere in the tank.

It is postulated that the probe can cause an excessive release of gas (burp) by operating at too high a speed, or by operating for too long a period of time. Another way is for the probe to be operated when the tank waste level is too high, as with the permanent mixer pump. Items whose failure can lead to loss of these controls are potentially SC-1. Such failures could cause gas releases in excess of the MAB which, if ignited, could fail the SC-1 tank containment system. Analyses are needed to determine the safe parameters for the probe controls.

Regarding interaction hazards, the following scenarios come to mind: the probe can be dropped during installation/removal onto Safety Class equipment; shaft failure can occur during operation, causing a portion of the probe to impact the SC-1 tank liner or other Safety Class equipment (e.g., permanent mixer pump) in the tank; shaft whirl could transmit loads to multi-port riser assembly, compromising the SC-1 safety function of the pressure release doors; the probe could also transfer loads to the multi-port riser assembly during a hydrogen burn event, causing it to flex enough that the pressure release doors fail to open. Loads could be transferred to the multi-port assembly from a wasteberg impact during a natural burp as well. The design of the probe will have to consider such interaction mechanisms. Design features used to prevent or mitigate such interactions would be Safety Class, if the interactions can lead to Safety Class consequences. The acoustic effects of probe operation on the electronics associated with the pump and on the ignition-proof electrical items in the tank will also have to be addressed.

4.3 Multi-Port Riser Assemblies

The multi-port riser assemblies are enclosed chambers which will be placed directly over the 42" risers on Tank 101-SY. These assemblies will be sealed to the existing riser flanges. Multiple penetration ports through the shielding plate on the top of each assembly will provide access to tank environment. The Sonic Probe discussed above and the 101-SY camera discussed in Section 4.4 will be installed through the penetrations in one of these assemblies. Relief doors are attached to the chamber area of each multi-port. The purpose of these relief doors is to relieve the overpressure in a hydrogen burn event.

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The multi-port riser assembly serves two basic safety functions: 1) to provide shielding and confinement during normal tank operation, and 2) to provide pressure relief in the event of a hydrogen burn.

Streaming through an open riser is not expected to result in exposure at the onsite receptor location (at 100 m) that would warrant making the shielding aspects of the multi-port SC-2. The multi-port only forms a portion of the confinement boundary for the tank. It is not expected that a significant release could occur through this part of the confinement boundary due to failures in the multi-port, except during burp events. Ref 2 shows that the onsite dose resulting from an open riser, even with the SC-2 primary tank ventilation system off, is only about 10^{-3} rem/hr. The shielding and confinement functions of the multiport are thus concluded to be SC-3. Items whose failure could result in the loss of these safety functions (e.g., shield plugs, gaskets) are SC-3.

During a hydrogen burn event, the pressure release function of the multi-ports is SC-1, because failure to relieve the overpressure in a MAB with burn could compromise the integrity of the SC-1 primary tank. The pressure release doors, which provide this pressure relief, are SC-1. The structural components of the multiport assembly that support the SC-1 function of these doors are also SC-1. For instance, the multiport assembly must not flex during burp and burn events to such a degree that the doors bind and do not open.

As with all the equipment analyzed in this report, interaction hazards associated with the multiport riser assemblies must be considered. The multiport riser assemblies can be dropped on Safety Class equipment in the tank farm, such as SC-2 ventilation components, during installation or removal. Controls and, potentially, Safety Class design features are needed to preclude drops that may compromise the safety functions of Safety Class equipment. The items which isolate loads from the riser during burps (including those involving burns) are SC-1, if the loads are potentially large enough to fail the dome via the riser. The loads produced by the Sonic Probe on the multiport during a burn event must be considered in analyzing this scenario. The pressures and energies associated with a burp can presumably cause movement in the instruments inserted through the multiports, and possibly movement of the multiport itself relative to the riser. The potential for mechanical contact to generate sparks energetic enough to ignite the burp needs to be considered in the design of the multiport and the instruments inserted through the multi-port.

4.4 101-SY, 103-SY and 101-AW Camera Systems

DSTs 101-SY, 103-SY and 101-AW all have been determined to have potentially combustible atmospheres. The camera systems to be installed in these tanks are to be of similar design and are to conform to National Electrical Code (NEC) Article 501 for use in a Class 1, Division 1, Group B atmosphere.

The camera systems will be remotely operated and will be used to observe and record the activities within the vapor spaces of each tank. Each camera system will be radiation resistant and will have one zoom camera mounted to

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a pan and tilt unit. Each system will also provide its own Class 1, Division 1, Group B atmosphere lighting. A nitrogen purge system will be used to provide ignition control for the mast, pan and tilt, feedback sensors, camera and housing, and other vapor space components.

The 101-SY camera fixture will be deployed through one of the multi-port riser assemblies described and analyzed in Section 4.3.. The 103-SY camera fixture will be deployed through a 42" riser (either 5A or the preferred riser 5B) in tank 103-SY. The 101-AW camera system will be deployed through a 20" riser in the 42" multi-flange assembly for that tank.

Safety Class Analysis

The safety analyses for the 101-SY, 103-SY and 101-AW cameras are currently being developed. The Safety Class (i.e., SC-1, SC-2) functions for these systems must thus be established using the information contained in existing analyses and by applying engineering judgement.

The primary function of the cameras is to observe and record activities within the vapor spaces of the tanks. This function has no Safety Class implications, by itself. The information garnered from the cameras is not used as the basis for any safety class activities (e.g., implementing emergency response procedures to limit doses to the onsite worker or the public). The items which support the monitoring function, are SC-3, since replacement of camera components would present an ALARA concern.

Although the primary function of the camera systems is not Safety Class, the camera systems do present a possible source of ignition during gas release events. For the purposes of this analysis it is assumed that the ramifications of a hydrogen burn in Tanks 103-SY and 101-AW are the same as for Tank 101-SY. As discussed in Section 3, a hydrogen burn in Tank 101-SY presents a potential SC-2 hazard, assuming controls are in place to prevent the pump and Sonic Probe (discussed above) from generating burps greater than the MAB. The probability and consequences of hydrogen burns in Tanks 103-SY and 101-AW have not yet been developed. This is being done as part of the safety analyses for the 103-SY and 101-AW cameras.

Prevention of a hydrogen burn in Tank 101-SY, prior to installation of the permanent mixer pump, is accomplished by precluding ignition sources in the tank. Since the consequences of a hydrogen burn are unacceptable at the onsite receptor location, ignition control is defined as a SC-2 safety function for the 101-SY camera system. Presumably, ignition control for the 103-SY and 101-AW systems is SC-2 as well. The items that provide or ensure this ignition control on all three systems are SC-2.

The nitrogen purge system prevents ignition of a burp due to the electrically active components of the mast, pan and tilt unit, camera and camera housing. This purge system is classified, at the system level, as SC-2. The items that ensure that this system performs its safety function when required are SC-2. Two options exist for ensuring that this system performs its safety function when needed. The first option is to designate all the items in the purge system that ensure its reliability during normal

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operations, DBAs, etc. to be SC-2. The other option is to interlock the electrical power supply to the cameras with detectors that detect loss of purge gas at the components located within the vapor space of the tank. This interlock would shut down all electrical in the event purge gas was lost. This interlock and the purge gas detector would be SC-2. The remainder of the system in this case would be SC-3.

The lighting fixtures are not similarly protected by a purge gas system. These systems must be inherently safe. The safety classification of the lighting systems is therefore SC-2. The items which ensure that the lighting systems are inherently safe are SC-2.

In addition to the electrical elements of the cameras, burps can be ignited due to static discharges or mechanically generated sparks. The items that preclude static buildup (e.g., those involved in grounding or bonding of the camera components to the tank) are SC-2. The camera systems should be designed to preclude mechanical contact with other items in the tanks during burps, if such contact can generate sparks energetic enough to ignite a burp. If necessary, the components which preclude mechanical contact are SC-2.

Interaction hazards must also be considered for the installation and removal of the cameras and lights from the tanks. As discussed in Section 3, the camera systems must not be dropped on and compromise the safety function of Safety Class equipment in the tank farm. The items most vulnerable would appear to be SC-2 instrumentation and controls associated with the tank ventilation systems. The camera is presumably not heavy enough to damage the SC-1 containment system for the tank. The items which ensure that adverse interactions cannot occur during installation or removal are thus designated to be SC-2. An analysis is needed to demonstrate that the 101-SY camera system cannot block or otherwise defeat the Safety Class 1 safety function of the multiport riser assembly it is installed through. Adequate pressure relief through this path is required to prevent damage to the SC-1 tank containment system.

Seismic Qualification

The Safety Class 2 purge and lighting systems may not have to be seismically qualified if another safety class item is used to shutdown electrical to the camera and lighting systems upon detection of an earthquake. Immediate shutdown is not required because, even if an earthquake could cause a gas release, there would be a lag time between the onset of the earthquake and the gas rollover. The safety classification of the shutdown would be SC-2, unless the potential burp caused by the earthquake could exceed the MAB, in which case the shutdown would be SC-1.

Reference 3 concludes that even if an earthquake could cause a gas release, the mechanical impacts generated in the earthquake would cease before the gas release occurred. The mechanical components of the camera and light may thus not need to be seismically qualified to prevent mechanically generated sparks. An analysis is needed to determine if a hot (but deenergized) filament from a failed light, following the earthquake, can ignite a burp.

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Other Considerations

For 101-SY, ignition control is not a Safety Class function during periods when the tank is sufficiently remediated. It may be possible, then, to relax the TSR requirements on the 101-SY camera and lighting systems after the SC-2 mixer pump is installed.

The assumption that hydrogen burns in tank 103-SY or Tank 101-AW produce similar consequences to those of a hydrogen burn in 101-SY is probably quite conservative. The magnitude of the hydrogen generation problem in Tanks 103-SY and 101-AW appears to be smaller than in 101-SY. The hydrogen quantities released for 103-SY and 101-AW are much smaller than in 101-SY and the duration of the releases is much longer than in 101-SY. This should result in much lower concentrations of hydrogen in these two tanks. Ref 2 shows that consequences of an MAB with burn in 101-SY barely qualify as a Safety Class 2 hazard. It is possible, then, that the consequences of a burn in tanks 103-SY or 101-AW, when determined, will only warrant classifying the items that prevent ignition in those tanks as SC-3. This possibility will be revisited when the safety analyses for the two tanks are further developed.

4.5 SY Farm Ammonia Detector

Ref. 2 estimates that the 15 minute normalized airborne concentration of ammonia at the onsite receptor location (100 m) following a hydrogen release event (window burp during pump installation or removal, no burn, ventilation not operable) location is 215 ppm. The SC-2 limit (ERPG-3) limit for ammonia is 1000 ppm. The IDLH concentration for ammonia is 500 ppm. Since the 15 minute TWA exposure to the onsite individual is well below the SC-2 limit and the IDLH value, it is judged that ammonia releases from 101-SY and 103-SY constitute only a SC-3 hazard. (Ref. 2 establishes an exclusion zone to limit worker exposure to < 500 ppm.)

The ammonia detector will be used primarily to protect tank farm workers. On high concentration indication, work in the tank farm will be restricted. The ammonia detector, presumably, will not be the primary device used to detect a burp. At this time, the ammonia detector is not planned to be used to initiate Emergency Response Plan actions or operator actions to place the tank farm in a safe shutdown condition following a burp. The operating function of the ammonia detector is thus classified as SC-3.

It is assumed that hydrogen and ammonia concentrations in the stack are not high enough during burps (with ventilation on or off) to propagate a flame front back into the 101-SY or 103-SY tanks. Thus, ignition control is judged to not be a Safety Class consideration for the ammonia detector. This assumption will have to be confirmed by analysis.

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5.0 Safe Shutdown Procedures

The safe shutdown and emergency response procedures for the 101-SY Tank Farm, relative to burping events, need to be developed. Such procedures have safety class implications, potentially regarding the systems covered in this analysis. The items that initiate safe shutdown (and emergency response) procedures and that perform the safe shutdown functions are Safety Class, if those procedures are necessary to prevent Safety Class consequences (see MRP 5.46).

For instance, the safe shutdown procedures to be followed following a gas release event need to be developed. Just following a burp, the tank is unstable enough that operating the temporary mixer pump or probe could release the residual gas in the tank, creating a second burp that could exceed the first in magnitude. The items that detect the burp and that initiate actions to shutdown and lock out the pump and probe (from being spuriously energized) need to be identified. These items are potentially Safety Class-1.

During a burp with burn, the multiport risers vent radioactive material to the environment. In such a burn, the tank would also vent through other release paths, such as the exhaust stack. As discussed above, the consequences of a burp with burn could exceed SC-2 limits at the onsite receptor location. It would appear, then, that emergency response procedures are needed to protect onsite workers following a hydrogen burn event--at least until the permanent pump is installed. Ref. 2 estimates that a burp and burn event is credible. SC-2 remediation will not be provided until the permanent mixer pump is installed.

A hydrogen burn event could compromise the effectiveness of the tank confinement system, such as by breaching the ventilation filters. The long term, unmitigated release that could occur following the burn event could result in an additional Safety Class-2 consequence to that produced directly by the burn event. Safe shutdown procedures may need to be defined to mitigate this secondary release to acceptable levels.

6.0 References

1. WHC-SD-WM-SEL-026, Rev. 1, "Double-Shell Tanks Interim SEL."
2. LAUR-93-1396, Rev. 5, "Safety Assessment for Proposed Pump Operation to Mitigate Episodic Gas Releases in Tank 241-SY-101."
3. WHC-SD-WM-SAD-005, "Safety Assessment for TV Camera and Lights Installation, Operation, and Removal in Tank 101-SY."
4. WHC-SD-WM-FDC-026, "Tank 101-SY Mixer Pump Functional Design Criteria."
5. WHC-SD-WM-ETP-0011, "Engineering Task Plan for 241-SY-101 Video Camera System."
6. "Multiport Riser 60% Design Review," Dec. 15, 1993.
7. "Sonic Probe Mitigation Demonstration, 30 % Design Review," Dec. 15, 1993.
8. WHC-CM-1-3, MRP 5.46, Rev. 4, "Safety Classification of Systems, Components and Structures," August 28, 1991.

**Westinghouse
Hanford Company**

WHC-SD-WM-SDD-043
Rev. 0

**Internal
Memo**

From: TWRS Project Safety Engineering
Phone: 376-8807 H5-37
Date: April 29, 1994
Subject: VOIDMETER AND VISCOMETER PHASE II REPORTS/CLOSEOUT OF 101-SY
SAFETY CLASSIFICATION EFFORT

LEJ-8D120-002

To: C. W. Hanson H5-09
L. M. McWethy L6-37
T. I. Stokes H5-09

cc: R. E. Bauer L6-37* D. R. Precechtel L6-37*
T. R. Benegas H5-09* M. H. Shannon H4-61
J. B. Crystal N1-42* D. A. Smith G6-16*
L. A. DellaRocco H5-09* T. I. Stokes H5-09*
B. W. Hall H5-37* E. K. Straalsund L6-37*
J. P. Hinckley H4-66* G. F. Vargo H5-09*
E. H. Kohlman H5-09* R. J. Van Vleet H4-09*
L. S. Krogsrud R3-08 LEJ: File/LB
* w/o attachments

- References:
- (1) Internal Memo, B. W. Hall to E. D. Kohlman, "Safety Classification of the 103-SY and 101-AW Camera Systems," dated April 28, 1994.
 - (2) Internal Memo, B. W. Hall to J. W. Lentsch and C. W. Hanson, "Phase I Report, Preliminary Safety Class Analysis for Systems to be Installed in SY Farm," dated April 15, 1994.
 - (3) LA-UR-93-1396, 1993, Revision 6, "Safety Assessment for Proposed Pump Operation to Mitigate Episodic Gas Releases in Tank 241-SY-101," Los Alamos National Laboratory, Los Alamos, New Mexico.
 - (4) LA-UR-93-1396, 1994, Revision 8, "Safety Assessment for Proposed Pump Operation to Mitigate Episodic Gas Releases in Tank 241-SY-101," Los Alamos National Laboratory, Los Alamos, New Mexico.

Transmitted herewith are the Phase II reports for the voidmeter and viscometer systems (see Attachments 1 and 2). This completes Mr. Hall's portion of the 101-SY Safety Equipment List development effort.

To summarize the work to date: The Phase III analysis for the multiport riser assemblies is included in the multiport functional design criteria document. The Phase II/III analyses for the 103-SY and 101-SY camera systems were previously transmitted via Reference 1. Detailed safety classification analyses, including fault trees, were performed and supplied to the appropriate cognizant engineers to support the 101-SY camera purge system design effort (the Phase II analysis on this system is not due until 9/1/94). These analyses are currently being used to upgrade the purge design to meet safety class redundancy requirements.

The recent change in hydrogen mitigation program strategy eliminated the need for Phase II analyses on the sonic probe and permanent mixer pump. The sonic probe discussion in the Phase I report (Reference 2) is considered to be sufficient to support the de-scoped sonic probe development effort. The permanent mixer pump analysis in the Phase I report can be extrapolated and applied to the test mixer pump, as deemed necessary.

Cautionary note: The analyses to date are based on the approach outlined in the Phase I Report (Reference 2), which was based on the consequence analyses contained in revision 6 of the Los Alamos National Laboratory Safety Assessment (SA) for the test mixer pump (Reference 3). Revision 6 of the SA determined that the maximum expected burp (MEB), if ignited, could not fail the Safety Class 1 primary tank system. The most recent revision of the SA, revision 8 (Reference 4), however determines that the MEB, if ignited, could fail the primary tank system. This means that if the test mixer pump is going to be used to remediate the tank, pump operation becomes a Safety Class 1 issue (instead of a Safety Class 2 concern as determined for the permanent pump in Reference 2). A waiver from or an interpretation of DOE Order 6430.1A safety class requirements will be needed to justify spare redundancy vs. in-place redundancy for pump components necessary to ensure pump operation. Ignition control for other systems in Tank 101-SY is no longer a safety class issue, if the mixer pump is qualified to Safety Class 1 requirements. Safety class and design guidance in the analyses to date, relative to ignition control, also become conservative if the pump is made Safety Class 1.

The work to date on the Data Acquisition Control System (DACS) is summarized in Attachment 3 (4/8/94 meeting minutes and DACS safety classification matrix). Mr. Hall is available, on a limited basis, to support the remainder of the DACS safety classification effort.

L. E. Johnson, Manager
TWRS Project Safety Engineering

jwh

Attachments 3

Viscometer Safety Classification Analysis, Phases I and II

1.0 Purpose

The purpose of this analysis is to identify potential Safety Class-1 (SC-1) and Safety Class-2 (SC-2) hazards associated with viscometer operation and to identify the major systems and components necessary to mitigate or prevent these hazards.

2.0 Scope

This analysis constitutes the first two of three phases of analyses on the subject system. It identifies the subsystems and major components which must be SC-1 or SC-2 to prevent significant harm--to the offsite public, onsite workers (outside the immediate vicinity of the SY tank farm), and the environment--from occurring due to viscometer operations. The more detailed Phase III analysis to follow on the viscometer system will identify the specific items that must be made SC-1 or SC-2 to support the safety function of each SC-1 and SC-2 system identified in this report.

The safety classification assigned in this analysis are preliminary in nature and are meant to minimize programmatic risk. The safety classifications are assigned based on engineering judgement and existing safety analyses assembled for different, but related, activities in Tank 101-SY. The consequence analyses for specific viscometer accident scenarios are yet to be developed. The approach to classifying systems relating to ignition control and burp prevention in this analysis is consistent to that outlined in the Phase I report (Hall 1994). It is intended that the safety classifications assigned in this analysis be revisited in the Phase III report, when the viscometer safety assessment is further developed.

This analysis is based on the 75% design review package for the viscometer, with the exception that the viscometer purge system is assumed to be as described in WHC (1994). (The purge system design was changed since the 75% design review package was released from an active pressurized system to a more passive arrangement that takes advantage of the tanks ventilation system.)

The analysis covers in-place operation of the viscometer only. Hazards posed during installation, removal, or maintenance are outside the scope of this analysis. Such hazards are assumed to be adequately covered by existing controls for intrusion into Tank 101-SY (defined in the mixer pump SA, Tank Farm ISB, etc) and by controls which will be defined specifically for the viscometer in the safety assessment (SA) currently being performed for the viscometer by Los Alamos National Laboratory (LANL). The safety class issues associated with the potential use of a water lance are also not covered in this analysis.

3.0 Identification of SC-1 and SC-2 Hazards

To identify the major subsystems and components that must be SC-1 or SC-2, it is first necessary to identify the potential SC-1 and SC-2 hazards posed by viscometer operation. LANL's draft safety assessment material provided in the 75% design review package was reviewed to identify potential SC-1 or SC-2 issues associated with the viscometer during in-place service. Specifically, Table 2, "Tank 101-SY Hazards Identification for Operation of the In Situ Viscometer," and the table labelled "Accident Scenario Listing for Viscometer Installation, Operation, and Removal" were reviewed (only the hazards identified for viscometer operation were considered for further analysis).

The hazards applicable to viscometer operation, identified from the SA review, are categorized and listed in the first column of the table below. The safety class implications of each of these hazards must be determined, at this point, using engineering judgement. The detailed consequence analyses for these scenarios are yet to be developed. LANL's test mixer pump safety assessment (LANL 1993) gives an idea of the consequences to be expected from many of the kinds of accident scenarios listed above. In many cases, the consequence analyses provided in this reference can be reasonably judged to bound the consequences of accident scenarios under consideration here.

The safety classifications judged to be appropriate for each of the hazards are designated in the second column of the table. The third column of the table justifies each safety class designation.

Hazards Matrix

Hazard	SC	Rationale
1.0 Category: Ignition of Burp Due to Viscometer Operation		
1.1. Spark source inside viscometer enclosure directly exposed to tank environment.	SC-2	All of the mechanisms listed have SC-2 implications. Ignition of a burp could potentially lead to a SC-2 consequence. LANL (1993) shows that consequences of a burp and burn, involving a gas release up to the MAB, approach 5 rem at the onsite receptor location.
1.2 Static discharge to tank or tank waste from plastic coated cable.		
1.3 Metal-on-metal sparks caused by moving viscometer components.		
1.4 Friction between riser and ball wire.		
1.5 Ignition of tank gases by viscometer equipment in weather enclosure (e.g., motors, tachometer).		

Hazard	SC	Rationale
2.0 Category: Burps Induced by Viscometer Operation.		
The possibility and potential consequences of the viscometer inducing a burp is not specifically addressed in the draft SA material. It is assumed that controls will be used to minimize the potential of viscometer induced burps. These controls are not defined yet, but presumably they will mirror those used on the test mixer pump. These controls will be assessed in Phase III.	SC-1/ SC-2	(Open Item) If found necessary, the controls used to minimize the chances that the viscometer can induce a burp greater than the MAB are SC-1. The controls used to minimize the chances that the viscometer will induce a burp up to the MAB are SC-2. It is assumed that non-SC equipment in the tank may ignite a burp, should one occur. LANL (1993) shows that ignition of burps is credible. The consequences of a burp and burn up to the MAB exceed 5 rem at the onsite receptor location (LANL 1993). Burp and burn events involving gas releases greater than the MAB may fail the primary tank system, which is SC-1.
3.0 Damage to Containment System		
3.1 Breach of tank due to viscometer ball impact.	SC-3	The viscometer ball is judged to be insufficiently heavy to breach the SC-1 primary tank system. It is likely that the damage that can be caused by the dropped ball is no worse than the tool drop scenario analyzed in test mixer pump SA (LANL 1993). This hazard is thus tentatively classified only as an SC-3 concern (retrieving the ball and repairing the viscometer presents ALARA concerns). The assumption that the ball will not fail the SC-1 primary tank will have to be confirmed by analysis.
3.2 Viscometer ejected during burp and burn.	SC-3	Viscometer items are judged to be insufficiently massive to do significant damage to the SC-1 primary tank system should the viscometer be ejected in a burp and burn. This will have to be confirmed by analysis.

Hazard	SC	Rationale
4.0 Breach of Confinement		
4.1 Breach of confinement provided by viscometer due to forces associated with burp and burn inside of dome--isolation valve open.	SC-3	The radiological consequences of a burp and burn could exceed SC-2 criteria. However, the confinement function of the viscometer housing is not really relevant during such an event. The burp and burn breaches confinement elsewhere in the tank and the multiport riser assembly ensures that the tank vents to the atmosphere during such an event. The incremental increase in material release that might occur due to the small extra leakage path presented by the viscometer is judged to be insignificant in comparison to the material releases elsewhere from the tank. LANL (1993) shows that the toxicological consequences (due to ammonia) resulting from burps, with or without burn, are below SC-2 limits. Failure of the viscometer enclosure presents ALARA concerns in that this would create an additional path to be sealed up after such an event.
4.2 Breach of confinement provided by viscometer due to forces associated with burp and burn inside dome--isolation valve closed.	SC-3	See item 4.1.
4.3 Structural failure of viscometer due to forces associated with hydrogen burn--isolation valve open or closed.	SC-3	Structural failure of the viscometer enclosure presents ALARA concerns after the burp and burn. Analysis will have to be performed to demonstrate that missiles will not defeat the SC-1 or SC-2 functions of nearby systems, such as the ventilation system or DACS.
4.4 Breach of confinement due to earthquake (or other natural phenomena) forces acting on viscometer or viscometer to tank interface.	SC-3	Breach of confinement is judged to be an SC-3 issue, if it is not accompanied by a burp and burn (see item 4.1). LANL (1993) shows that the unmitigated release through an open 42" riser (ventilation system off) is well below SC-2 limits.

Hazard	SC	Rationale
4.5 Hazardous material release from viscometer housing due to enclosure or enclosure penetration failure.	SC-3	The small amount of waste material inside the viscometer enclosure will not result in a significant onsite or offsite release should the enclosure fail.
4.6 Increase of internal tank pressure due to uncontrolled nitrogen supply from viscometer enclosure purge system.	NA	No longer applicable--active purge system removed from design after 75% design review.
5.0 Personnel Exposure		
5.1 Radiation exposure to personnel due to tank shine.	SC-3	Tank farm worker exposures are an SC-3 (ALARA) issue. None of these mechanisms are expected to result in significant exposures outside the immediate vicinity of the tank.
5.2 Personnel exposure to toxic or hazardous material while working on or with viscometer.		
6.0 Miscellaneous		
6.1 Tank floods due to ball and wire decon system.	SC-3	It is assumed that the decon water supply will be inherently limited to a quantity deemed acceptable (i.e., there will be a limited size supply tank). Significant onsite or offsite consequences (or tank damage) are not expected from the small amount of liquid that could flood the tank from this limited source.

Hazard	SC	Rationale
6.2 Incompatible material inside of viscometer housing exposed to tank atmosphere. (Cause: isolation valve open and purge air flow path blocked).	SC-3	It is possible for the aluminum components within the viscometer enclosure to be exposed to the tank environment. This could occur should the purge flow be blocked off while the isolation valve is open. The aluminum components are not qualified for the environment known to be inside the tank. The aluminum components cannot be assumed to function properly after exposure. The operating function of the viscometer is not SC-1 or SC-2, so failure of items necessary to ensure viscometer operation is not an SC-1 or SC-2 issue. Dropping the wire and ball into the tank was judged to be a SC-3 concern (see item 3.1 above).
6.3 Deposition of waste directly onto incompatible materials inside of viscometer housing.	SC-2	Contaminating the inside of the purge enclosure is an ALARA (SC-3) issue. Tank farm workers could also be exposed to ammonia on opening enclosure. Corrosion of viscometer hardware (should the purge system fail) is not considered to be a SC-1 or SC-2 concern because the operating function of the viscometer is not SC-1 or SC-2. The amount of material that could be deposited in the enclosure is insufficient to generate an LFL concentration of hydrogen during the period of time the viscometer may be in use.

4.0 Identification of SC-1 and SC-2 Systems

The only hazards found to have SC-1 or SC-2 ramifications in the above matrix were items 1.1 through 1.5, and 2.0. The systems and major components needed to mitigate or prevent these SC-1 or SC-2 hazards are discussed below. Many of these systems and components were identified from the "Mitigation Options" column of Table 2 in the draft SA material.

Item 1.1, Spark Source Inside Viscometer Enclosure. Currently, the vapor space of Tank 101-SY is designated as a Class 1, Division 1 environment when the waste level is above 406". Plans are to potentially operate the viscometer during Division 1 conditions. The viscometer enclosure (enclosure 3) directly communicates with the Division I tank atmosphere during

viscometer operation. Per NEC code, all items within the enclosure (e.g., load cell, pulley, and cable cylinder) must be "intrinsically safe." The implication is that these items could ignite a burp should they not be designed to be intrinsically safe. Since the consequences of a burp and burn can exceed SC-2 criteria, the intrinsically safe components inside the viscometer enclosure should also be designated SC-2. The particular aspects which ensure that these items are intrinsically safe should be designed and qualified to SC-2 requirements.

The proximity sensors and pressure switches are located within the riser just below the viscometer enclosure. These devices should be SC-2, designed to be intrinsically safe or explosion proof.

Item 1.2, Static Discharge in Tank. Static discharge between the viscometer items and the riser are primarily prevented via grounding and bonding jumpers. Since the burp and burn scenario is judged to have potential SC-2 consequences, the grounding and bonding items should be made SC-2.

Static charges can also buildup on the plastic cladding surrounding the wire used to support the viscometer ball. These static charges can discharge to the waste surface as the plastic clad wire approaches the surface. It is not yet known if such a static discharge will be energetic enough to ignite a burp. In addition, the high humidity in the tank helps to prevent static buildup. Analyses must be performed to show that credible static discharges from the wire cladding are insufficiently energetic to ignite a burp, or to show that the high tank humidity will suffice to prevent static discharge. If either of these cannot be demonstrated, plans are to redesign the plastic cladding to be conductive, or to provide a spray system to ensure that the wire always remains wet. The conductive cladding or the spray system, if found necessary, should be designated SC-2.

Item 1.3, Metal-on-metal sparks. The aspects which ensure that metal-to-metal sparks will not occur due to viscometer moving parts, during burps, are SC-2. Non-sparking materials are the preferred option.

Item 1.4, Friction Between Riser and Ball Wire. (Open item). Analyses must be performed to show that this is not a credible ignition mechanism, including during the ball drop and wasteberg impact scenarios.

Item 1.5, Ignition Due to Equipment in the Weather Enclosure. The weather enclosure (enclosure 2) contains the motors for the viscometer. The motors are direct current brushed motors capable of producing sparks during normal operation. These motors are enclosed but not sealed and are not qualified for operations in a classified (Division 1 or Division 2) space. The areas of the tank within 15 ft of each riser or vent are currently classified as Class 1, Division 2, Group B when the tank level is above 406 inches. The weather enclosure is located within the 15 ft radius. The weather enclosure is not sealed from the environment.

To prevent the motors from igniting a burp, a pressure switch/power interlock system is provided to shut off viscometer (motor) power any time the tank dome pressure goes above -1 in. of water. This pressure switch/power interlock

system is SC-2. Aspects of the system which ensure that it reliably performs its safety function are SC-2. These SC-2 aspects will be determined in Phase III. It is assumed that the pressure switch/power interlock reacts fast enough to shut off power before the plume reaches the motor enclosure (see open item in Section 5.0).

Note that in addition to performing its functional requirement to shut off power on rising pressure, the pressure switch components connected to the tank vapor space must be intrinsically safe. The aspects which ensure that the switches are intrinsically safe are SC-2.

The weather enclosure and viscometer enclosure are separated by 1.5 in. No channel exists between the two enclosures to transmit ignition-capable particles or flammable gases. It is considered incredible that ignition capable particles could be drawn into the Division 1 environment of the viscometer enclosure. The long, tortuous path such a particle would have to go through would ensure that the particle was extinguished.

Item 2.0, Viscometer Induced Burps. The items required to implement any needed SC-1 or SC-2 controls to prevent burps will be identified during Phase III.

5.0 Summary

The items inside the viscometer enclosure are intrinsically safe. These items (load cell, pulley, cable, cable cylinder, bearings, etc) are SC-2, with the functional requirement that they not produce flames, sparks, ignition-capable particles, or temperatures exceeding 280 C. The aspects which ensure that these items are intrinsically safe are SC-2.

The pressure switch/power interlock system is SC-2. This system is necessary to shutoff power to all non-qualified components during a burp. The components involved in this function are SC-2. In addition, the pressure switches (two are required to meet redundancy requirements) communicate with a potential Class 1, Division 1 atmosphere and must thus be designed to be intrinsically safe. The aspects necessary to ensure that the switches are intrinsically safe are SC-2.

Grounding and bonding items are SC-2 to prevent burp ignition due to static discharge. Analyses are needed to determine if credible static discharges from the plastic clad wire could be energetic enough to ignite a burp. If so, the plastic clad wire becomes an SC-2 item, and would have to be made conductive. Otherwise, an SC-2 spray system is needed to ensure that the wire always remains wet.

The aspects of the viscometer design that ensure that metal-to-metal sparks will not occur (between the viscometer and the riser) are SC-2. If non-sparking materials are used, controls are necessary to ensure that the components will not be replaced with spark-capable materials when maintained and repaired.

The remaining systems and items associated with the viscometer are designated, for now, to be SC-3. Most of the remaining items are necessary to minimize exposure to tank farm workers (i.e., they form part of the confinement boundary of the viscometer), or they present ALARA issues should they fail and need repair.

Open Items

The following open items must be resolved in the safety analyses being performed by LANL:

Response time of pressure switch interlock. An analysis is needed to show that the motors can be shut down fast enough to eliminate all ignition sources before the burp envelops the motor enclosure. This analysis should consider the amount of time it takes for the motors to coast to a stop, if there are credible spark sources from non-powered motors. If special devices are used to brake the motors, these devices should be considered for SC-2 designation.

Structural failure of viscometer due to hydrogen burn. An analysis is needed to determine if projectiles from the viscometer housing can defeat the safety function of SC-1 or SC-2 equipment in the tank farm, such as the DACS or the ventilation system.

Controls to prevent viscometer induced burps. The safety analyses must determine the necessary controls, if any, required to ensure that the viscometer cannot induce a burp. For instance, if it is determined that the viscometer must be shutoff when the waste level is high, to prevent it from inducing a burp greater than the MAB, the items necessary to detect this condition and to shut off viscometer power are SC-1.

Friction between viscometer wire and tank riser. Analyses are needed to demonstrate that the friction generated between the viscometer wire and the riser--during burps, wasteberg impacts, and uncontrolled lowering of the viscometer ball--is insufficient to generate sparks capable of igniting a burp.

Consequences of viscometer ball drop. An analysis is needed to determine the extent of tank damage should the viscometer ball be dropped or contact the tank wall due to wasteberg impact. It is currently assumed that the ball cannot breach the SC-1 tank. This assumption needs to be verified. The analysis should also consider the possibility that a dropped ball may adversely interact with the mixing pump in the tank.

Static discharge from plastic clad cable. An analysis is needed to quantify the potential buildup of static electricity of the plastic clad cable and to quantify the energy that could be released should such static buildup discharge to the tank or waste surface. If it is found that the discharge could be energetic enough to ignite hydrogen, SC-2 prevention or mitigation is required, as discussed in Section 4.0.

6.0 References

- Hall, B. W., 1994, Internal Memo 29230-94-02, "Phase I Report, Preliminary Safety Class Analysis for Systems to be Installed in SY Farm," to J. W. Lentsch and C. W. Hanson, April 15, Westinghouse Hanford Company, Richland, Washington. LANL, 1993, *Safety Assessment for Proposed Pump Operation to Mitigate Episodic Gas Releases in Tank 241-SY-101*, LA-UR-93-1396, Rev. 6, Los Alamos National Laboratory, Los Alamos, New Mexico.
- WHC, 1994, *title unknown*, WHC-SD-SM-DA-151, Westinghouse Hanford Company, Richland, Washington.

Voidmeter Safety Classification Analysis, Phases I and II

1.0 Introduction

The purpose of this analysis is to 1) determine the Safety Class-1 (SC-1) and Safety Class-2 (SC-2) subsystems and major components associated with the void fraction meter, and 2) define safety functions for the SC-1 and SC-2 subsystems and components. The analysis also identifies areas where deviations from the SC-1 or SC-2 design requirements appear to be justified.

This analysis constitutes the first two of three phases of analyses planned for the voidmeter system. The Phase III analyses to follow is to determine the specific items within each major subsystem that must be SC-1 or SC-2 to support the safety functions defined for the subsystems in this analysis. The Phase III report will also address the safety class implications of several open issues that could not be resolved in this analysis. These open issues are listed in Section 5.0.

The safety classifications assigned in this analysis are based primarily on engineering judgement. The detailed safety analyses for the voidmeter are currently being developed. The intent of this analysis is to minimize programmatic risk by identifying, at an early design stage, systems and system functions which are likely to be found to have SC-1 or SC-2 implications when the detailed safety analyses are completed. The SC-1 and SC-2 systems identified in this analysis can be reviewed amended as necessary to ensure that they will meet applicable SC-1 or SC-2 design criteria. The results of this analysis are to be revisited in Phase III.

2.0 Approach

The FDC for the voidmeter (as of 3/29/94) forms the design basis for this analysis. To identify potential SC-1 and SC-2 issues associated with the voidmeter, the draft hazards identification report produced by Los Alamos National Laboratory (Pasamehmetoglu 1993) was reviewed. Engineering judgement was used to assign a safety class designation to each hazard identified in the draft SA, based on the perceived consequences that could ensue if the hazard were not prevented or mitigated. In most cases, LANL's SA for the test mixer pump (LANL 1993) formed the basis for making judgements about the magnitude of radiological and toxicological consequences that could result from each hazard. The draft hazards identification report for the voidmeter (Pasamehmetoglu) was used to identify items (and controls) that prevent or mitigate each hazard. The systems and major components that should be designated SC-1 or SC-2 were determined based on this information and the functional requirements spelled out in the FDC.

The hazards review and safety class assignments are summarized in tabular format in Section 3.0. The SC-1 and SC-2 systems and major components are identified, along with their specific functional requirement(s) in Section

4.0. Section 5.0 identifies several open issues that must be resolved to support the Phase III analysis. Not enough information is available to assign safety classifications at this point for these issues.

3.0 Hazards Identification and Classification

The first column in the following table summarizes the hazards identified for voidmeter installation, operation, and removal from LANL's hazard identification report (Pasamehmetoglu). Included in the table are only those hazards that are initiated by voidmeter components (e.g., window burps and burp ignition caused by other tank components are excluded).

The second column in the table discusses the safety class implications of each hazard. The criteria listed in Table 1 of MRP 5.46 (WHC 1993) provide the bases for assigning the safety classifications associated each hazard in this column. Existing safety analyses [e.g., safety assessment for the test mixer pump (LANL 1993)] and engineering judgment were used to determine the potential unmitigated consequences that could result from each hazard.

The last column in the table summarizes the mitigation (or prevention) options available for each hazard. The focus in this column is on identifying hardware related prevention/mitigation. In some cases, however, administrative controls are the only proposed approaches to preventing a hazard. In other cases, further analyses are planned to demonstrate that the hazards pose acceptable risk.

Hazards Identification for the Voidmeter

Hazard	SC Implications	Mitigation Options
1.0 Hydrogen or Toxic Gas Release		
1.1 Release to upper housing owing to nitrogen feed line isolation failure	SC-3. Amount of material carried into housing is not expected to be large enough to cause an onsite (SC-2) effect, but it does constitute an ALARA hazard.	Check valves to prevent backflow. Lines vented to outside housing. Controls and analysis to demonstrate that consequences are below SC-2 limits.

Hazard	SC Implications	Mitigation Options
1.2 Release due to overpressurization of dome because of failure of nitrogen system (nitrogen injection to dome)	SC-3. ALARA issue. The amount of material released from the tank by this mechanism is expected to be much smaller than that forced out in a burp. The consequences of a burp (without burn) are well below SC-2 criteria (see LANL 1994).	Nitrogen quantity is limited to a few standard cubic feet. Not likely to result in significant change in dome pressure.
1.3 Release due to failure of pipe internal or external seals	SC-3. Release, without ignition, would be small and present a hazard only to facility personnel.	Controls and analysis to demonstrate acceptable consequences.
1.4 Release due to failure of nitrogen pneumatic control system lines and check valves	SC-3. See Item 1.3 above.	See item 1.3 above
1.5 Burp induced by voidmeter operation	SC-3. The consequences of a burp, without ignition, are insignificant outside the immediate vicinity of the tank.	Controls on voidmeter operation or analyses to demonstrate that voidmeter induced burps not possible.
2.0 Hydrogen or Toxic Gas Release With Burn		
2.1 Ignition of burp at surface due to crane/equipment operation, vehicle or crane/equipment impact.	SC-2. The consequences of a burp and burn, involving gas releases up to the MAB, could exceed 5 rem (the SC-2 limit) at the onsite receptor location. (See LANL 1993)	Controls on crane/vehicle operations. Voidmeter shaft and wiper seal on decon riser limit release of flammable gas through voidmeter riser.

Hazard	SC Implications	Mitigation Options
2.2. Accumulation of hydrogen in housing (due to leak in mast or pneumatic system) and ignition within housing (due to power system short or failure in voidmeter housing, operation of electric solenoid controlled valve, static electric discharge, or other design features that can produce sparks).	SC-2. Flame front could potentially propagate back down into the tank during naturally occurring burp. The consequences of a burp and burn (involving gas release up to the MAB) exceed 5 rem at the onsite receptor location (LANL 1993).	Items in housing are qualified for Division II environment, meaning they don't normally produce sparks. Shaft and lines leading to upper housing from sampler arm are seal-welded. Below waste cylinders are sealed. Nitrogen and pressurized water supply lines are small in diameter.
2.3 Ignition within tank, during burp, due to static electric discharge, metal-on-metal spark in tank and riser, friction between riser and voidmeter piping, or failure of thermocouples.	SC-2. The consequences of a burp and burn (involving gas release up to MAB) exceed 5 rem at the onsite receptor location.	Housing and components grounded/bonded. Analyses to be performed to determine if metal-on-metal sparks are possible and if friction can ignite burp. Compatible materials will be used on all parts that come in contact with each other. Thermocouples located in sealed wells.

Hazard	SC Implications	Mitigation Options
2.4 Voidmeter induced burp/and ignition due to other in-tank components.	SC-1/SC-2. Open item. Credible ignition sources exist within the tank. If the voidmeter induces a burp up to the MAB, the consequences of a burn could approach 5 rem at the onsite receptor location. If the voidmeter induces a burp > MAB (e.g., by operating when waste level is too high), the resulting overpressure in the burn could compromise the integrity of the SC-1 primary tank system.	Controls on voidmeter operation or analyses to demonstrate that voidmeter induced burps not possible.
3.0 Change in Tank Chemistry		
3.1 Excessive heating of the waste, resulting in a runaway reaction as a result of sudden pressurization.	Open Item (see Section 5.0)	--
3.2 Long term effects of voidmeter operation on the waste.	Open item (see Section 5.0)	--
4.0 Tank, Tank Components, and Riser Penetration		
4.1 Dropped voidmeter	SC-1. Voidmeter may be heavy enough to significantly damage SC-1 tank should it be dropped.	Controls and Structural Analysis. Impact limiter recommended.

Hazard	SC Implications	Mitigation Options
4.2 Damaging other tank components by voidmeter	SC-1. Voidmeter could be dropped through the bottom of the tank (see item 4.1). The voidmeter could also be dropped onto SC-2 tank ventilation system components during installation or removal. Failure of high pressure cylinder in housing could result in drop, or fail support mast, or generate missiles which could compromise safety function of other SC-1/2 items in the tank farm (such as the DACS and the ventilation system).	Administrative controls on voidmeter installation, operation, and removal procedures. Analysis of consequences of dropped voidmeter needed. Analysis of pressurized system failure modes and consequences needed.
4.3 Voidmeter cannot be retracted from tank due to retrieval system failure or binding	SC-3. ALARA issue-- increased exposure to tank farm workers.	Design features to allow manual retrieval.
4.4 Voidmeter cannot be retracted from tank owing to sampler arm failed out of vertical	SC-3. See 4.3 above.	See 4.3 above.
4.5 Voidmeter cannot be retracted from tank owing to wasteberg impact and bending	SC-3 See 4.3 above.	See 4.3 above. Analysis is needed to demonstrate that unacceptable loads will not be transmitted to primary tank system via the voidmeter due to the maximum wasteberg impact.

Hazard	SC Implications	Mitigation Options
4.6 Riser is damaged due to vibration of the voidmeter	SC-3. Extent of damage is not expected to be great enough to cause an SC-1 or SC-2 level release to the environment, but repair of riser presents ALARA concerns.	Structural Analysis.
5.0 Flooding of Tank		
5.1 Inadvertent water addition to tank associated with decontamination system	SC-3. Unlimited water addition could exceed hydrostatic limit for SC-1 primary shell. Total quantity of water supplied to decon system, however, is limited upstream to prevent significant consequences should decon system fail.	Controls and limited supply.
5.2 Excessive water addition due to failure of the high-pressure water injection system	SC-3. Quantity of water limited to 2 gal--insignificant addition to tank. Failure of system precludes implementing ALARA procedures.	Limited supply.
5.3 Excessive water addition due to the failure of water flush system to clean the pressure lines	see 5.2.	see 5.2.
6.0 Excessive Nitrogen Addition to the Tank From Voidmeter System		
6.1 Failure of nitrogen feed or pneumatic control system	SC-3. See item 1.2 above.	--

Hazard	SC Implications	Mitigation Options
6.2 Compression-initiated gas release/chemical reaction in the voidmeter due to the excessive gas temperature	SC-3. Amount or waste material involved is too small to create SC-1 or SC-2 consequence. ALARA concern.	Analysis to analyze consequences and probability.
7.0 Hazardous Material Spill		
7.1 Failure of decon system	SC-3. The small amount of material left on voidmeter would be insufficient to cause an SC-2 consequence, but the spill would constitute an ALARA concern.	--
7.2 Failure to operate decon system when required.	SC-3. See 7.1.	--
8.0 Ejection		
8.1 Voidmeter ejected from tank in burp and burn	SC-1, potentially. If heavy enough, voidmeter could significantly damage the SC-1 primary tank system upon landing back on the tank. Upon being ejected, the voidmeter may also induce significant damage to the tank dome.	Show by analysis that voidmeter is too heavy to be ejected. Or show that voidmeter cannot significantly compromise SC-1 tank integrity if ejected in a burn. (open item, see Section 5.0)

Hazard	SC Implications	Mitigation Options
8.2 Inadvertent high-pressure nitrogen release	SC-1, potentially. See 8.1 above. Failure of pressure vessels in housing could fail voidmeter shaft or cause crane to drop voidmeter, puncturing bottom of the tank (leading to an EHSC-1 release to the soil column). High pressure release may also generate missiles which could damage other SC-2 equipment in the tank farm (see 4.2).	Analysis to analyze credibility of accident and to analyze potential damage to voidmeter and tank.
9.0 Voidmeter Operation Hazardous Material Release		
9.1 Nitrogen pressure feed line isolation failure allows hazardous material to enter upper housing.	SC-3. Scoping calculations indicate that the amount of waste material that could be blown back into housing (by back pressurizing nitrogen line or due to burp and burn) through such small lines is insufficient to cause an SC-2 consequence. Such an event would create ALARA (SC-3) concerns however.	Analysis to show acceptable consequences.
9.2 Burn/explosion inside voidmeter sampling chamber as a result of self-ignition caused by rapid pressurization.	SC-3. (See also item 3.1). Reaction will be limited to very small fraction of waste. And will be rapidly quenched.	Analysis to determine credibility and consequences.

Hazard	SC Implications	Mitigation Options
9.3 Leak from upper housing.	SC-3. Increased exposure to tank farm workers. The amount of material that could be released is insufficient to cause an SC-2 or SC-1 consequence.	Analysis to demonstrate acceptable consequences.

4.0 Identification of SC-1 and SC-2 Items and Safety Functions

From the above table, only hazards 2.1 through 2.4, 4.1, 4.2, 8.1 and 8.2 were found to have SC-1 or SC-2 implications. The items in the voidmeter design that prevent or mitigate each of these hazards are discussed, in turn, below. The items recommended to be designated SC-1 or SC-2 at this stage in the design are identified and the specific safety functions to be performed by these SC-1 and SC-2 items are defined.

2.1 Ignition of burp at tank surface due to crane/equipment operation, and vehicle or crane/equipment impact. The crane electrical components are located outside the flammable regions (> 15') surrounding tank penetrations during burps. Crane equipment and vehicle operations around the tank are also administratively controlled to reduce the risk of ignition. The likelihood of vehicle or crane impacts occurring at the same time as a burp, given the administrative controls and low frequency of voidmeter measurements, is considered to be incredible. This will have to be confirmed by analysis. The materials used in the voidmeter construction are designed to be non-sparking should they contact the tank riser.

At this point no SC-2 hardware items were found necessary for this hazard. This issue will be looked into further in the Phase III analyses when more design details and safety analysis results are available.

2.2 Ignition of hydrogen accumulated in upper housing (SC-2). This hazard is a Safety Class-2 concern because a fire in the upper housing could propagate back into the vapor space of the tank during a burp. The burp is the likely driver for forcing hydrogen into the housing. The items in the housing are qualified for use in a Division 2 environment, but they are not intended to be designed to SC-2 criteria. From a safety class standpoint, they have to be assumed to be capable of igniting hydrogen should it build up in the housing. The consequences of a burp and burn at the onsite receptor location could exceed the SC-2 limit of 5 rem (see LANL 1993).

Hydrogen could migrate or be forced into the upper housing, conceivably, through leaks in the nitrogen supply lines, through leaks in the pneumatic cylinders located below waste level, or through leaks in the support mast. Hydrogen could also be forced into the housing during burps through leaks in

the housing itself, during a burp, since a plume of flammable gas is postulated to escape from the each tank riser during burps. A 15' radius around each riser is classified as Division 2 during burps. When taking measurements near the bottom of the tank, the upper housing will be within this 15' radius.

Scoping calculations indicate that the amount of hydrogen that could migrate through the 1/8" and 1/16" pneumatic lines is extremely small--small enough that an LFL buildup in the housing is not considered credible during the time the voidmeter is planned on being used. The support mast on the other hand is probably large enough, should it fill with waste, to create a significant hydrogen buildup problem in the housing (there are no potential ignition sources in the mast itself). It is therefore recommended that the support mast be designated SC-2, with the functional requirement not to leak. The penetrations into the drywell of the support mast (which is 3" schedule 80 pipe) are seal-welded. These welds should be qualified to SC-2 requirements. No such requirements are judged to be necessary at this time for the pneumatic lines, cylinders, or check valves.

The third way in which hydrogen can buildup in the upper housing (i.e., through the housing seals during a burp) is an item for further development (See Section 5.0). Options include hermetically sealing the enclosure (with SC-2 seals), making the decon ring wiper seal SC-2 (to minimize leakage from the riser during a burp), extending the mast beyond the flammable radius around the riser, or making the housing "explosion proof."

2.3 Ignition of flammable gases within the tank. The voidmeter can ignite flammable gases within the tank via the mechanisms discussed above or because of static discharges from the voidmeter, metal-on-metal sparks between voidmeter and tank or riser, or friction between riser and voidmeter piping (SC-2), or arcing or high heat from failed thermocouples. The consequences of a burp and burn are sufficient to warrant SC-2 concern (see above).

Ignition of hydrogen in the upper housing and propagation back into the tank is covered in the discussion for item 2.2 above.

Static discharges are prevented by grounding and bonding the voidmeter components. The grounding and bonding jumpers should be designated SC-2. Metal-on-metal sparks are precluded with the use of non-sparking materials. Controls should be implemented to ensure that voidmeter components are not replaced with spark-capable materials. Analyses are needed to verify that credible friction developed between the voidmeter and riser can't generate enough heat to ignite a burp (see open item in Section 5.0). Any items found necessary to limit frictional heating should be designated SC-2.

The thermocouples are not intrinsically safe. However, they are located in wells. If electronic barriers are not going to be used to make the thermocouples intrinsically safe, the thermocouple wells should be classified SC-2, with the functional requirement to be leak-tight. If these wells were to leak, flammable levels of hydrogen could build up in the wells and be

ignited due to failure of the thermocouples. The alternative is to qualify the wells as explosion proof.

2.4 Burp induced by voidmeter. It may be possible for the voidmeter to induce a burp when the test chamber is pressurized or when the pressure is released from the test chamber. Should a burp be induced by the voidmeter, credible ignition sources exist within the tank. Depending on the size of the burp induced, the consequences of the burp and burn could exceed SC-2 or SC-1 criteria.

This is an item for further development. See Section 5.0.

4.1 Dropped voidmeter. If the voidmeter were dropped during in-place operation, it is presumably heavy enough and shaped in such a manner as to puncture the bottom of the SC-1 tank. If so, the amount of waste material that would seep into the soil column could exceed EHSC-1 limits (see MRP 5.46, Table 1, Appendix B). Precluding load drops with SC-1 crane hardware is extremely costly and difficult to do. It is therefore recommended that an SC-1 impact limiting device be included in the voidmeter design. This impact limiter would protect the tank while the voidmeter is being lowered or raised within the riser. The interface between the impact limiting device and the support mast should also be SC-1 to ensure that it will not fail and allow the voidmeter mast to fall through to the bottom of the tank. The impact limiter must also sufficiently absorb the energy of the drop to ensure that significant damage does not occur to the tank riser or dome. The support mast must be shown by analysis to be capable of withstanding the maximum credible wasteberg impact during a burp, at least to such a degree that the support mast will not be sheared off.

During installation or removal, the voidmeter could also be dropped onto the SC-2 ventilation system components or the dome of the tank. Controls on crane operations are the only planned means for preventing such occurrences. The impact limiter discussed above will not protect the tank dome and ventilation system components if the voidmeter is dropped outside the riser. Analyses must therefore be performed to demonstrate that the potential damage to the dome of the tank from such drops is acceptable, and that the potential damage to the ventilation system can be repaired within the required time period to prevent an SC-2 unfiltered release from the tank.

4.2 Missile Damage. Should the 2200 psi cylinder inside the housing fail, it could become a missile, damaging other SC-1 or SC-2 equipment in the tank farm, including the SC-2 ventilation system components, the DACS trailer, and the mixer pump, should it become an SC-1 or SC-2 device. The missile could also defeat the safety function of the SC-1 impact limiting device. Most often, such cylinders fail because their nozzles have been knocked off. It is therefore recommended that the supports that hold this cylinder in place be designated SC-1. These supports should be qualified to withstand the forces of a voidmeter drop (taking credit for the SC-1 impact limiter discussed above being in place), without transferring enough energy to the cylinder to cause its failure. The cylinder itself (including the nozzle) may need to be SC-1

(pedigreed for normal operating pressure) unless it can be demonstrated that the supports will prevent the cylinder from becoming a missile should the cylinder spuriously develop a leak (e.g., split along a seam).

There is a heater located within the housing. This heater must not cause the 2200 psi cylinder to overheat and rupture. The heater should be thermostatically controlled (with SC-1 devices), or SC-1 pressure relief should be provided on the cylinder.

8.1 Voidmeter ejection during burp and burn. This is an issue that must be resolved during detailed design. An analysis should be done to determine if the voidmeter can be ejected from the tank during a burp and burn, and if so, the extent of damage to the SC-1 primary tank system. This analysis should estimate the tank damage induced during ejection and the damage induced when the voidmeter components fall back down on the tank dome. If it is found that significant damage to the SC-1 primary tank system can result from the voidmeter ejection, the devices that secure the voidmeter in place should be made SC-1, designed to withstand the forces generated in a burp and burn.

8.2 Voidmeter ejected/dropped due to high pressure nitrogen release. A pressurized nitrogen release could possibly eject the voidmeter from the tank or shake the voidmeter enough to cause it to be dropped from the crane rigging. The impact limiting device discussed under item 4.1 should adequately mitigate the consequences from a drop, unless the impact limiter or interface between the impact limiter and the support mast were damaged by the missile discussed under item 4.2 above. The SC-1 cylinder supports discussed under Item 4.2 will prevent the missile scenario. Analyses are needed to determine if pressurized nitrogen releases can eject the voidmeter from the tank. If analyses show that this is possible and that significant damage to the SC-1 tank system or SC-2 ventilation system could occur, the ejection restraints discussed under item 8.1 above should be qualified to withstand the forces generated in all credible pressurized nitrogen release scenarios.

Summary of Safety Class Items

- Support mast (SC-2).. The support mast is classified, overall, as SC-2, with the functional requirement that portions of the mast within the dome of the tank not leak. The seal welds around the bulkhead penetrations at the bottom of the mast are SC-2. The "no leak" requirement is necessary to prevent hydrogen buildup in the upper housing, where it could be ignited and propagate a flame front back into the tank during a burp.
- Impact Limiting device and interface with mast (SC-1). An SC-1 impact limiting device is needed to protect the tank from damage should the voidmeter be dropped from the crane. The load bearing interface between the impact limiter and the support mast is SC-1, qualified to withstand the forces of the drop.

- Thermocouple Barriers (SC-2). The thermocouple dry wells are SC-2. The safety function is to prevent leaks of waste and hydrogen gas into the wells, which could be ignited by the thermocouples.
- Grounding and Bonding Jumpers (SC-2). The grounding and bonding jumpers are SC-2 to prevent static discharges between the voidmeter and the tank or liquid surface which could ignite a burp.
- Pressurized cylinder tie downs (SC-1). The supports which hold the 2200 psi "G" cylinder in place are SC-1 to prevent damage to the cylinder which may cause it to become a missile, or to restrain it in place should it be damaged. These supports must be qualified for the worst-case credible drop accident. The alternative is to show by analysis that missile impacts to SC-1 or SC-2 items in the tank farm are incredible or that the requisite repairs can be effected in time to prevent SC-1 or SC-2 releases to the environment.

5.0 Open Issues

The most important open issues identified in this analysis are summarized below. These open issues have potential SC-1 or SC-2 implications and must be resolved to support the Phase III safety class analysis.

1. **Flammable Radius Around Riser During Burps.** During burps, a flammable plume of gas may escape past the decon riser wiper seal. If the voidmeter housing is lowered within this plume, the electrical components in the housing may ignite the plume, and the resulting flame front may propagate back into the vapor space of the tank (back past the wiper seal). An analysis is needed to determine what the flammable radius is around the voidmeter riser during burps. This analysis should assume that the voidmeter is installed, but that the wiper seal has failed. If the upper housing can be lowered within the determined flammable radius, the support mast should be extended, the wiper seal should be made SC-2, or the seals on the housing should be made SC-2 to prevent leakage into the housing.
2. **Potential for Voidmeter Induced Burps.** An analysis should be done to determine if the voidmeter can induce burps under normal and accident conditions (such as when the pressure is relieved in the sample chamber, or if the pneumatic lines should break, under potentially 2200 psi of pressure). Credible sources of ignition exist in the tank. Should the voidmeter induce a burp, it is assumed that the burp will be ignited. Should the voidmeter induce a burp up to the MAB, which is then ignited, an SC-2 consequence could result. Should the voidmeter induce a burp greater than the MAB, which is then ignited, an SC-1 consequence could result (i.e., the SC-1 primary tank system could fail). If it is found that the voidmeter can induce a burp under abnormal conditions, the hardware items necessary to prevent these conditions are SC-1 or SC-2, according to the size of the burp that could be produced.

3. **Potential for Voidmeter Ejection.** An analysis should be done to determine the extent of damage to the SC-1 primary tank system if the voidmeter is ejected from the tank in a burp and burn event. This analysis should estimate the tank damage induced during ejection and the damage induced when the voidmeter components fall back down on the tank dome. If it is found that significant damage to the SC-1 primary tank system can result from the voidmeter ejection, the devices that secure the voidmeter in place should be made SC-1.
4. **Runaway reaction induced by voidmeter.** See item 3.1 in hazards matrix of Section 3.0. Analyses must be performed to examine the possibility that the voidmeter could induce a runaway reaction in the tank waste. It is postulated that this could occur due to compression heating of the waste in the test chamber. If credible, the consequences of the runaway reaction must also be estimated to ascertain the safety class implications of such an event.
5. **Long term effects of voidmeter operation.** The long term effects of voidmeter operation on the tank waste's chemical and physical properties should be assessed.

6.0 References

- LANL, 1993, *Safety Assessment for Proposed Pump Operation to Mitigate Episodic Gas Releases in Tank 241-SY-101*, LA-UR-93-1396, Rev. 6, Los Alamos National Laboratory, Los Alamos, New Mexico.
- Pasamehmetoglu, K.O., Letter TSA-6-93-820 (M115), "Hazard Identification for the In Situ Voidmeter," to T. Stokes, December 2, 1993, Los Alamos National Laboratory, Los Alamos, New Mexico.
- WHC, 1991, *Management Requirements and Procedures*, "Safety Classification of Systems, Components, and Structures," WHC-CM-1-3, MRP 5.46, Rev. 4, Westinghouse Hanford Company, Richland, Washington.

Attachment 3

MEETING MINUTES

Subject: 101-SY DACS Safety Classifications

TO:	Roger Bauer	L6-37	BUILDING:	306E
	Carl Hanson	H5-09		ETC2
	Thomas Pounds	H5-09		ETC1
	Dean Smith	G6-16		Vitro/RCHC
	Ross Truitt	L6-37		306E
	George Vargo	H5-09		ETC1
	Bob White	LANL		--

FROM: Brett Hall	H4-66	CHAIRMAN: George Vargo
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Dept-Operation-Component	Area	Shift	Meeting Date	Number
TWR/ENG	RCHN	Day	4-07-94	Attending
				7

The purpose of the meeting was to review the preliminary DACS Safety Classification Matrix (attached) and to discuss options for developing a detailed safety equipment list (SEL) for the DACS. The matrix, when finalized, is intended to provide the basis for developing the SEL. The SEL is needed to turn DACS operations over from EG&G to WHC.

The key points from the meeting are as follows:

- Due to the changing mission of the test mixer pump and the continually evolving safety analyses, general concurrence on the safety class assignments in the matrix could not be reached. However, it was generally agreed that SC-1 and SC-2 functions are associated with the DACS.
- Bob White agreed that LANL would review the matrix and identify those controls that should be designated SC-1 based on the current mitigation program strategy and the latest safety analysis results. It was suggested that the SC-1 and SC-2 DACS functions be documented in an appendix to the mixer pump SA.
- Since it was agreed that SC-1 and SC-2 controls and functions are likely to be associated with the DACS, several options were discussed regarding development of the SEL. These options included:

- o Designate the DACS as an SC-1 system. To meet SC-1 requirements, upgrade the DACS to resemble the computer configurations used in the CANDU reactors.
- o If the SC-1 functions identified in the LANL review are few, eliminate those functions from the DACS. For such functions, bypass the DACS with hard-wired interlocks.
- o Classify DACS items as SC-3, based on recovery time and operator action. Attempt to get a waiver from MRP 5.46 and DOE 6430.1A safety class requirements on this basis.
- o Classify DACS hardware items as IOSR items in a similar approach to that used for other tank farm items with potential SC-1 implications in the tank farm ISB. IOSR items are procured and maintained as SC-3 items, but have OSRs that require that they be operable during periods when they are needed. Brett Hall agreed to look further at the feasibility of this approach.

The approach to classifying the DACS will be revisited after LANL has reviewed the matrix and identified the controls intended to avert SC-1 and SC-2 consequences, given the new strategy to use the pump as permanent mitigation and the results of the latest safety analysis.

DACS Safety Classifications

The DACS monitors various tank conditions and pump parameters. Indication and alarms from the DACS are used to perform safe shutdown procedures. In many cases abort sequences are automatically implemented, via DACS logic, to shutdown various tank activities. Where these shutdown or abort processes are necessary to prevent significant harm to onsite receptors, the offsite public, or the environment, it is necessary to designate the relevant DACS components as SC-1 or SC-2, accordingly.

Potential SC-1 or SC-2 functions associated with the DACS were determined from LANLs Test Mixer Pump SA. Specifically, the level I and level II controls specified in SA were analyzed for SC-1 or SC-2 implications. The controls were looked at only for pump operation, post Phase B testing. Pump installation and removal controls were not considered. Phase A and B testing controls are irrelevant since these testing phases are complete.

The Level I and Level II controls are listed in the following matrix (column 1), along with the reference where the basis for each control can be found (column 2). The safety classification judged to be appropriate to each control is provided in the third column. The rationale behind each safety classification is provided in the 4th column. The specific DACS components necessary to implement each SC-1 or SC-2 control should be designated SC-1 or SC-2, accordingly.

Safety Classification Matrix

Control	Basis	SC	Rationale
Level 1 controls, Mixer Pump Operation, Post Testing Phase B			
Pump Motor Speed	SA (App. AN)	SC-1	Pump speeds above control limit are outside the safety envelope analyzed in the SA. Exceeding pump speed limit may induce burp > MAB. A burn involving a gas release > MAB could result in failure of the SC-1 primary tank system. (An ignition source from non-SC equipment is assumed).

Control	Basis	SC	Rationale
Test time duration	SA (App. AN)	SC-1	Test time duration must stay within the bounds of the analyzed safety envelope. Exceeding test time duration may result in burp > MAB. A burn involving a gas release > MAB could result in failure of the SC-1 primary tank system.
Waste Tank Level- -maximum pump operating limit	SA (App. BA, AN and T)	SC-1	This control restricts pump operation to limit the potential gas release to less than the MAB. A burn involving a gas release >MAB could compromise the integrity of the SC-1 primary tank.
Max. rate of level rise	SA (App. T and AN)	SC-1	The basis for this limit is that it is an indication that the pump operation has caused an increase in the rate of gas generation and/or retention. The control is permissive in nature, not abortive. It allows the pump to be operated only if the rate of level rise is below the control limit. Failure to control pump operation during a high rate of level rise could induce a burp exceeding the MAB. This control presumably involves the same DACS components as those used to control waste level above.

Control	Basis	SC	Rationale
Max. hydrogen conc. (< 0.6 vol%).	DOE 5480.4 and SA (App. T, AN)	SC-1	<p>This control prevents slow or steady-state conditions from presenting a flammability hazard during pump operation. This control is not designed to prevent an actual MAB because pump-induced rollover, once induced, may not be stopped by stopping the pump. The control also does not apply to a natural burp.</p> <p>This control, however, ensures that hydrogen concentrations in the vapor space, pre-burp, do not fall outside the bounds of the safety analysis. This control thus prevents hydrogen burn > MAB from occurring which could fail the SC-1 primary tank.</p>
Max. ammonia conc. < 3000 ppm	SA (App. AB)	SC-1	<p>Control is mainly for the protection of facility workers (SC-3). But control also ensures that the initial conditions for gas release, assumed in SA, will not be invalidated owing to high initial ammonia levels. Presumably, high ammonia levels during a burn could increase calculated burn energy enough to result in tank overpressures sufficient to compromise the integrity of the SC-1 primary tank.</p>
Level II Controls, Pump Operation			

Control	Basis	SC	Rationale
Primary Ventilation Flow rate: -Minimum flow*	Modified WHC standard Controls	SC-2	Control is intended to maintain a dilution flow for the release gases from tank 101-SY. If pump operation is not halted upon loss of ventilation, it is assumed that gases released can build up past the LFL. The consequences should these gases burn is presumed to be similar to that of the MAB (5 rem at the onsite receptor location).
-Maximum flow		?	Safety implications of ventilation flow rate exceeding max limit are unclear.

Control	Basis	SC	Rationale
Hydrogen concentration: - initiate operations when conc. < 500 ppm -TRG approval required to start testing if conc < 10 ppm	SA Appendix T, AN SA Appendix AN	SC-2 SC-3	This control prevents pump-induced releases when there is already a considerable amount of hydrogen in the dome space. It is assumed that a pump-induced burp when hydrogen concentrations are high could result in consequences similar that that of a burn involving the MAB. Other Level 1 controls prevent pump induced burp from exceeding MAB. This control is aimed at detecting conditions leading to increased gas retention as a result of pump operation. This control complements the control on rate of level rise (above) and is thus not required to be SC-1.
Ammonia Concentration < 500 ppm	SA Appendix AB	SC-3	This control ensures that the workers near the tank farm will not be exposed to an ammonia level that exceeds the 8-h exposure limit of 25 ppm.
Minimum Flow from Tanks 102-SY and 103-SY	Modified WHC Standard Controls	SC-3	Control is intended to maintain a dilution flow for the release gases from Tanks 102-SY and 103-SY. Van Vleet (1994) shows that the consequences expected from gas burns in these tanks are below SC-2 limits. Failure of this control, however, presents ALARA concerns.

Control	Basis	SC	Rationale
Availability of Auxilliary* (P28 exhauster)	WHC Modified Standard Controls	SC-2	Ventilation flow is critical for hydrogen dilution of Tanks 101-SY, 102-SY and 103-SY and should be restored as soon as possible. Pump operations and other tank activities must be shutdown to prevent the release of gases which may buildup to LFL. The consequences of a hydrogen burn in Tank 101-SY can lead to significant onsite consequences (5 rem at 100 m).
Waste Temperature Limit: - terminate pump operation if avg temp. > 125 F. - terminate pump operation if avg temp < 110 F.	SA App. Z and C SA App. Z	SC-3 SC-3	Temperature affects the total crystal mass in the tank, viscosity and shear strength of the fluids and slurry, and rate processes. High and low temperatures are indications of increased gas production and increased gas retention, respectively. These controls supplement the Level 1, SC-1 (above) controls on maximum hydrogen and ammonia concentration and maximum rate rate of waste level increase.
Mixer Pump - Discharge Pressure - Pump motor current - Pump motor temp - Pump Oil Moisture	SA App. T, AN SA App. T, AN Manufacturer Specification SA App. T, AN	SC-3 SC-3 SC-3 SC-3	These controls are used to protect the pump from internal damage. The mixing function of the pump is currently not a SC-2 function. Failure of these controls is not expected to cause an SC-1 or SC-2 consequence. Maintaining or repairing the pump (because of damage induced due to such control failures), however, presents ALARA concerns.

Control	Basis	SC	Rationale
Mixer Pump (continued)			
- Column Strain	Mixer Pump Structural Report	SC-3	Control shuts down pump before vibrations can cause column failure. Complete failure, such that the column drops to the bottom of the tank, is not expected. Repair and maintenance of the pump presents ALARA (SC-3) concerns. SA App. 0 shows that the tank bottom will not fail as a result of the 2' drop of the pump support column from its installed position. App. 0 also shows that the pump will not fall out of the riser and hit the primary liner of the tank. This will facilitate removing the damaged pump.
- Pump column pressure	FDC	SC-2	Control ensures pump is deenergized in the event purge gas is lost. Failure of this control could result in the pump igniting gases released into the vapor space of the tank. The consequences of such an event could approach 5 rem (the SC-2 limit) at the onsite receptor location.
MIT and VDTT			
- two strain gauges must be operable per MIT probe	SA App. AG	SC-3	Controls protect MIT and VDTT from being damaged because of pump operation. MIT and VDTT are not SC-1 or SC-2, but information garnered from them is useful in remediating the tank and in maintaining tank farm worker exposures ALARA.
- Measure strain less than allowable strains	SA App. AG	SC-3	

* These two controls are somewhat redundant and not necessary if ventilation system is made SC-2.

Reference

Van Vleet, R. J., 1994, Internal Memo 29140-RJVV-94003, "Transmittal of Unreviewed Safety Question Screening and Safety Evaluation Forms TF-94-0034-TV-FGWL-DST, REV. 1, and TF-94-0036-AUGER-FGWL-DST, Rev. 0," to R. B. Gelman, Jan 31, Westinghouse Hanford Company, Richland, Washington.

APPENDIX I SAFETY EQUIPMENT LIST

This safety equipment list has been developed by the project cognizant engineering personnel. The items listed are important to safety as indicated by the safety assessment. B. W. Hall's work (Internal Memo LEJ-8D120-002, attached to this document) also provided guidance during the development of this list.

Brett's work concluded spark control for SY-101 was a safety class 2 function. Preventing a tank leak was considered a safety class 1 function. A rule of thumb provided by Brett was that an active safety component, as defined by the MRP's, usually requires redundancy to qualify for SC 2 service.

As per the safety analysis LAUR-92-3196 Rev. 10 Addendum 1, the viscometer can not damage the tank's leak tightness. Therefore, there are no safety class 1 components.

The viscometer can severely damage the tank riser or other critical tank safety equipment if dropped from too high an elevation over these type components. Therefore, the critical lift has been required to make such accidents considered incredible in the safety analysis.

The below table breaks the viscometer assembly into the name of a general sub-system, an item #, specific component identifier, and the determined component safety class. Following the table is the rationale for each item's determined safety classification. If a component is not specifically listed, it is a safety class 4 item.

Table 1 "Viscometer Safety Equipment List"			
Name and safety class of system	Item No.	Drawing #, part #, and vendor reference #'s	Safety Class of Component
Pressure Switch System (SC 2)	1	Pressure Switches H-2-822165, Item 21 (H-2-818156 REF)	3
		Redundant Relays H-2-818150 Item 94	3
		"E-Stop" button H-2-818150 Item 60	3
Proximity Switch System (SC 2)	2	Intrinsic Barrier Pepperl+Fuchs MN-KHA6RW1/EX1 H-2-821311, Item 20	3
		Proximity Switch H-2-822165, Item 21	3

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Table 1 "Viscometer Safety Equipment List"			
Load cell system (SC 2)	3	Load Cells H-2-821312, Items 7-12 Intrinsic safety barriers H-2-821311, Items 16-20	3 3
Cable connecting ball to drum (SC 3)	4	H-2-818359, item 90	3
Drum & Pulley Assemblies (SC 3)	5	Metal parts H-2-818359, Items 2, 7, 27, 34, 50-54, 56, 58, 73-76.	3
Ventilation Systems (SC 2)	6	TIMERS 1&2 H-2-818150, Item 93	3
		Motor Cooling Fans H-2-818359, item 80	3
		Pitot tube (calibrated during ATP) H-2-822165, Item 24	3
		Pitot tube gauge H-2-822165, Item 19	3
		Ventilation system flow characteristics (3 cfm at 1" water gauge in the riser) (no specific drawing call out, must be tested)	3
		Orifice plate H-2-818359, Item 12	3
Special Materials (SC 3)	7	the plastic bag (no exposed aluminum)	3
Bolting & Gasketing (SC 3)	8	Orifice plate bolts H-2-818359, item 39	3
		Thick rubber gasket	3
Water Addition (SC 3)	9	decontamination water supply (some fixed amount, no specific drawing)	3
		Spray nozzle tips (gpm characteristics) H-2-821443, Item 19	3
Tank Isolation (SC 3)	10	Isolation valve H-2-818359 Item 85	3
		Enclosure pressure gauge H-2-822165 Item 19	3
		Enclosure flow rate gauge (pitot tube above)	3

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Table 1 "Viscometer Safety Equipment List"			
Waste Entrain (SC 3)	11	orifice plate (above)	3
		plastic coated cable 00 (above)	3
		radiation detector (no specific drawing)	3
Ball Speed (SC 3)	12	Software (ball speed aspects) WHC-SD-WM-CSRS-017	3
		fuse/current control device	3
Ball Load (SC 3)	13	Software (ball load aspects) WHC-SD-WM-CSRS-017	3
Contamination Control (SC 3)	14	HEPA filter H-2-822165 ITEM 22	3
		Enclosure gasketing	4
		Radiation Detector -Eberline Model EC4-X	4

Rationale:

Item 1: Pressure Switch System

This system exists to de-energize non-qualified electrical components (only on the viscometer) during a tank pressurization. It was stated in the NEC paper that the area immediately adjacent to the primary enclosure may become NFPA Class I, Division 2 Group B during a tank pressurization. This area has non-qualified equipment present. Thus, the non-qualified equipment presents a spark hazard, and the control system is thus classified as Safety Class 2.

Tank pressure is sensed (below the orifice plate and above the riser isolation valve) via two pressure switches. The two switches send signals via two separate wire runs to the control console. The control console has two separate relays that lock in when the correct pressure is sensed in the tank. If correct pressure is lost to either pressure switch, or a general power loss is experienced at the console, the relays open and prevent power from reaching the non-qualified electrical components in the potentially hazardous zone. Redundancy and fail safe are stressed here as this system is considered an "active" system per the WHC MRPs, and requires redundancy of active components to meet SC 2 criteria. The applicable electrical codes and the design concepts for compliance are discussed in detail by J. H. Bussell et al., (1994).

An emergency stop button exists that creates the same shut down conditions the

pressure switches cause, using many of the same components. The "E-Stop" button itself, and associated active components are SC 3 items.

The pressure switches are UL approved for Class I Division 1 Group A, B, C, and D locations. They are redundant as they are active. These switches are considered SC 3 items.

The wire runs between the pressure switches and control console are passive. They are considered SC 4 items.

The relays in the control console are redundant, and are SC 3 components.

Successful acceptance testing of this assembled system qualifies it for SC 2 service. Following any maintenance to any of these SC components, the ATP must be rerun sufficiently to assure the pressure switch system still functions per design.

Item 2: Proximity Switch System

A proximity switch is used to assure the ball is in the home position. This switch is mounted below the orifice plate, and is therefore exposed to a Div. 1 environment and presents a spark hazard. This system uses an intrinsic safety barrier similar to the load cells. This sensor/barrier combination came UL approved as a matched set.

Therefore, the proximity sensor and associated barrier is considered SC 3 item. The UL approval (Cl. I, Div. 1, Gr. B), acceptance testing, and visual inspection of fabrication by the Fire Protection Engineer assure these components are suitable to perform a SC 2 function.

Item 3: Load Cell(s)

There is one electronic component in the primary enclosure, the load cell and it's wiring. When the isolation valve is opened, the primary enclosure is in direct communication with the tank dome space. [The viscometer was designed as though the tank dome space had an NFPA Class I, Division 1 Group B environment at all times.] The load cell presents a spark hazard to the tank dome space. The load cell was made intrinsically safe by the use of Intrinsic Safety (shunt zener diode) Barriers. The intrinsic safety barriers are selected to protect the load cell for the above environment. See the NEC paper for detailed calculations of intrinsic safeness.

The load cell will be considered safety class 3, and must always be a simple apparatus as discussed in the above reference. Any change from the design drawing load cells requires the above reference be revisited to assure intrinsic safeness is not altered.

The intrinsic safety barriers must be UL approved, or equivalent. As such, they are considered safety class 3. After initial fabrication or any subsequent wiring modification, the "jurisdiction having authority" (currently WHC Fire Protection Engineering) must visually approve the wiring to assure the intrinsically safe design was fabricated correctly.

The combination of safety class three components, detailed analysis, visual inspection, and UL listed barriers qualifies the system to meet the safety class 2 spark control function.

Item 4: Ball Cable

The wire rope (7x19 stainless steel cable) is plastic coated to inhibit waste entrainment. A non-conductive plastic coating may create static sparks. Therefore, a conductive plastic coating has been specified. The wire rope with correct plastic coating is considered a SC 3 item. The plastic coated cable must have less than one Mega-ohm resistance between the outside of the plastic coating and the wire rope core to meet the intent of the safety assessment.

Sufficient quality assurance from the plastic's manufacturer through installation of the cable is sufficient to qualify the cable for SC 3 service with no special testing after delivery, other than a visual inspection.

Item 5: General Moving Parts

The mechanical motion of the cable drum, pulleys, bearings, etc. have the potential to become hot (if a failure occurred) and ignite the postulated Div. 1 environment. The SA assessed the viscometer as-built drawings, and found this accident incredible with current material selections and failure rates. [Also note that the ventilation system must by design be working and sweeping gases back into the tank, or all motion will stop. This system is detailed under the pressure switch system.]

All moving components are therefore considered safety class three to signify the importance of correct materials for replacement purposes.

Item 6: Ventilation Systems

During initial start up, or immediately following a tank pressurization, dome gas may have been allowed into the primary enclosure and must be ventilated back into the tank dome space. Gas may also get trapped in the immediate area around the primary enclosure after such an event, so must also be ventilated away from potential spark sources.

The primary enclosure ventilation is motivated by the low dome pressure (relative to atmospheric). At -1 inch of water gauge inside the tank, the flow rate through the primary enclosure was tested as 3.5 cfm. The flow control is

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inherent in the ventilation system design. Pressure drops occur largely over the inlet piping and orifice plate between the primary enclosure and the riser. Note that any enclosure leaks conservatively affect the indicated flow rate.

Appropriate flow rate is assured by use of a calibrated pitot tube and manually read differential pressure gauge. If the correct flow rate is occurring, the correct purge volume is assured automatically by the timers in the control console. When the pressure switches "see" the correct tank pressure (the switches sense below the orifice), they close, sending a signal to the console relays discussed above. The relays can not send power to non-qualified equipment until the timers have completed timing. The timers are redundant also.

Note: Ten volume exchanges of air are sought every hour per the NEC paper. The volume is approximately 4.9 cubic feet. At under 1" water gauge, the viscometer assembly will shut off from high pressure alarms. The timers will be set conservatively estimating 3 cfm at -1.0" tank pressure. Thus, the timer setting is 17 minutes. The pitot tube must be able to read out accurately over the flow range 2.5 to 4 cfm as a minimum.

The area around the primary enclosure is clearly open to the atmosphere or force ventilated using fans. The fans run at all times the pressure switches "see" the correct tank pressure. They are qualified to operate in a Div. 2 environment.

Therefore, the ventilation system flow characteristics (3 cfm at 1" water gauge in the riser) are SC 3.

The ID of the orifice plate (combined with cable OD) is also considered in the SA to limit possible waste entrainment accidents. The thickness of this plate is considered in the SA as worker shielding. Therefore, the entire orifice plate assembly is SC 3.

The pitot tube and local read out are SC 3 items to assure correct indication of flow. The interconnecting tubing and fittings are SC 4. The pitot tube differential pressure read out must be calibrated to cubic feet per minute.

The redundant timers are both SC 3 items. The correct timing duration must be verified via ATP.

The ventilation fans outside the primary enclosure are SC 3 items, in that they must meet Division 2 requirements. The wiring to the fan motors is SC 4.

Successful acceptance testing of the assembled ventilation, timing, and local indicator systems qualify them for SC 2 service. Following any maintenance to any of these SC components, the ATP must be rerun sufficiently to assure the ventilation systems still function per design.

Item 7: Special Materials

The load cells are constructed of aluminum. Aluminum will react with tank waste. The SA considered an exothermic reaction may ignite a Div. 1 environment. The SA requires the load cell be protected from waste contact. Direct contact with full strength waste is inhibited by the water decontamination system. A plastic bag placed around the load cell additionally protects the load cell from corrosion. The plastic covering (bag or equivalent) must be resistant to the waste being sampled, and must not be damaged. Therefore, the plastic bag is considered as safety class 3. [A damaged bag must be replaced to assure no waste contact can occur.]

The combination of waste resistant plastic covering, intermittent inspection, and the SA analysis qualifies this system for SC 3 service.

Item 8: Bolting & gasketing

The orifice plate bolts are a special material and size to prevent an ejection accident per the SA. These bolts are SC 3 items.

The thick rubber gasket is considered to have some impact limiting capabilities. It is a SC 3 item.

Item 9: Water addition

A tank truck shall be used to supply decontamination water. This is to prevent unlimited water supplies from flooding the tank. There is no SC attached to the tank truck, except it be some finite amount of water inside.

The allowed decontamination GPM may not exceed 3.5 gpm. This is controlled through quantity and sizes of spray nozzles. The spray nozzle tips are SC 3 items for these characteristics.

Item 10: Tank Isolation

The isolation valve must be able to close and seal the viscometer from the tank riser. The valve is SC 3. A SC 4 valve may be used if suitable materials investigation and acceptance testing is done to qualify it for SC 3 service.

The pressure in the enclosure will be monitored along with the ventilation flow gauge to determine if the isolation valve is indeed fully closed or open. The gauge is SC 3. A SC 4 gauge may be used if sufficient testing is completed to assure the gauge will work.

Item 11: Waste Entrainment

It was already discussed that the orifice plate and plastic coated cable OD were safety class items for waste entrainment considerations.

Along these same lines, a continuously operating radiation detector is required by the SA.

This detector in its entirety is SC 3. It may be SC 4 procured, but current calibration stickers and field HPT approval justify it for SC 3 service.

Item 12: Ball speed

Ball over speed is protected by software and hardware. The software that implements this control is SC 4. Acceptance testing justifies the software for SC 3 service.

A fuse/current control device is also implemented to prevent gross over speed/overload conditions. This fuse/device is SC 3. SC 4 components may be used if sufficient analysis and/or testing of the system assures the fuse/device will work.

Item 13: Ball overload

The software prevents cable tension from exceeding 250 lb. The software may be SC 4, but must be tested to meet SC 3 service.

Item 14: Contamination Control

The HEPA filter is for personnel protection prior to maintenance, and is SC 3.

Inside the primary enclosure may become contaminated. The gaskets and other seals between this area and the atmosphere are important. SC 4 components may be used (if material compatibility is assured).

APPENDIX J

DESIGN VERIFICATION OF PROJECT

APPENDIX J DESIGN VERIFICATION OF PROJECT

The viscometer engineering work plan stated that all the viscometer drawings would be released as 2SQ, which requires an "independent" technical review as well as independent safety and quality assurance reviews.

The viscometer design team conducted a 75% design briefing February 16, 1994. Several independent reviewers were present, among them were independent electrical and mechanical reviewers. The briefing announcement is attached. The briefing comments were submitted on RCRs, were dispositioned, and signed as closed by those reviewers. The RCRs are attached.

The mechanical design did not substantially change following the 75% design review. Therefore, the independent mechanical reviewer was not asked to re-review the final design drawings released on EDT 606726. The viscometer was "qualified by testing" as the final design verification, as documented by the acceptance test procedure and report. (WHC-SD-WM-ATP-089)

The electrical design changed substantially following the 75% design briefing. Therefore, our electrical independent reviewer was asked to review the final drawings to verify his acceptance of adequacy. His signature on EDT 141131 indicates the independent review was completed.

The electrical and control systems were sufficiently complicated to warrant documented acceptance testing. The testing was performed per WHC-SD-WM-ATP-079 Rev. 1. The acceptance test report concluded that the electrical and control equipment were ready for field service.

The site installation drawings were released slightly later than the viscometer drawings using EDT 607601. The technical content of the drawings was minimal, but independent safety and quality reviews were still performed.

The site power distribution skid was released using EDT 607602. Independent engineering, safety, and quality reviews were performed. The skid was used in the 306E building during testing to assure it functioned as designed, but was not the focus of a formal acceptance test.

[10] From: Troy I Stokes at ~WHC207 2/15/94 10:58AM (5681 bytes: 80 ln)
To: Laroy S (Steve) Krogsrud at ~WHC289, Michael L McElroy at ~WHC235,
John I Gould at ~WHC302, Larry A DellaRocco, Brett W Hall at ~WHC45,
Charles M Monasmith at ~WHC160, William B Anderson at ~WHC198, James R Biggs
at ~WHC69, James D (Jim) Robinson, Kay P Mortensen at ~WHC174,
Robert J (Bob) Thomas at ~WHC62
cc: Troy I Stokes, Dennis B Graves at ~WHC76, Michael (Mike) Gimera at ~WHC177,
Jack D (JD) Martin at ~WHC224, Kathleen L Pearce at ~WHC76, Roger E Bauer at
~WHC76, Carl E Hanson, Jack W Lentsch at ~WHC129, Richard P Johnson at
~WHC177, Chester L Shepard at ~PNL33, Andrew E Wilder at ~WHC340
Subject: Viscometer 75% independent design review briefing

----- Forwarded with Changes -----

From: Troy I Stokes at ~WHC207 2/3/94 11:13AM (4089 bytes: 69 ln)
To: Laroy S (Steve) Krogsrud at ~WHC289, Michael L McElroy at ~WHC235,
Julie R Robertson at ~WHC37, Larry A DellaRocco, Brett W Hall at ~WHC87,
Charles M Monasmith at ~WHC160, William B Anderson at ~WHC198, James R Biggs
at ~WHC69, James D (Jim) Robinson
Receipt Requested

cc: Troy I Stokes, Dennis B Graves at ~WHC76, Michael (Mike) Gimera at ~WHC177,
Jack D (JD) Martin at ~WHC224, Kathleen L Pearce at ~WHC76, Roger E Bauer at
~WHC76, Carl E Hanson, Jack W Lentsch at ~WHC129, Richard P Johnson at
~WHC177, Chester L Shepard at ~PNL33, Andrew E Wilder at ~WHC340
Subject: Viscometer 75% independent design review briefing

----- Message Contents -----

I've forwarded this as a reminder to all involved. I'll
also be attempting to contact each of the reviewers by
telephone today.

Thanks,
Troy Stokes

We have scheduled the above meeting to occur 2-16-93, 8 am,
at ETC-1, conference room 211 B. The viscometer assembly
will be put into temporary service on waste tank SY-101 in
September of 1994. The designs and hardware are being
developed under EP 2.4, as prototypes that will ultimately
be used in plant service.

Design Review packages will be distributed at the start of
the meeting. The 2-16-94 meeting is to brief the audience
on the project, design(s), and procedures (draft), and to
answer general questions from the reviewers.

Following the meeting, reviewers are requested to generate
their comments on RCR forms and to submit all comments by
2-25-94.

Depending on the quantity and nature of comments received,
individual comment dispositioning may be performed, or a
comment closure meeting may be called.

The meeting agenda, subject to content and/or schedule
changes, is as follows:

8:00 am Introduction/Schedule Troy Stokes, WHC
 Document Review and Strategy

8:15 Data need and Theory of Hardware Chet Shepard, PNL

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8:35	Functional Design Criteria	Troy Stokes, WHC JD Martin, WHC
8:55	I&C Design Status	JD Martin, WHC
9:15	Software Development Status	Mike Gimera, WHC
9:30	Mechanical Design Status	Dennis Graves, WHC
9:45	Break	
10:00	Installation, Operation, and Removal Procedures (DRAFT)	Troy Stokes, WHC
10:40	Safety Assessment Status	Jerry Bueck, LANL Cetin Unal, LANL
11:00	Question/Answer Period	Attendees
TBD	Meeting Wrap Up	Troy Stokes, WHC

List of Reviewers/responsibilities:

Steve Krogsrud	WHC, Tank Farm Independent Nuclear Safety
Mike McElroy	WHC, Quality Assurance
John Gould	WHC, Environmental
Brett Hall	WHC, Safety Analysis Engineering
JR Biggs	WHC, Tank Farm Operations
Larry Dellarocco	WHC, I&C independent review
Jim Robinson	WHC, Mechanical independent review
Chuck Monasmith	WHC, NEC compliance review
Bill Anderson	WHC, Fire Protection review
Bob Thomas	WHC, ALARA review
Kay Mortensen	WHC, Health Physics Field review

If you have any questions or comments relating to this meeting, please call me at 376-9436. [Rick, please see this gets forwarded to Jerry and/or Cetin.]

Thanks for your help,

Troy Stokes
Project Engineer
SY-101 Mitigation

[11] From: James D (Jim) Robinson 2/22/94 3:35PM (10589 bytes: 1 ln, 1 fl)
To: Troy I Stokes
Subject: RCR

----- Message Contents -----

Text item 1:

See attached

File item 2: TLS.RCR 2/22/94 3:34PM

[13] From: Larry A DellaRocco 2/23/94 3:28PM (12752 bytes: 1 ln, 1 fl)
To: Troy I Stokes
Subject: viscometer rcr

----- Message Contents -----

Text item 1:

see attached

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File item 2: VISCOMET.LDR 2/23/94 3:23PM

[14] From: Christopher L Cooley at ~WHC83 2/24/94 1:03PM (10225 bytes: 9 ln, 1 f
1)

: Kari L Leggett at ~WHC289, Cari L Minor, Troy I Stokes at ~WHC207

cc: Christopher L Cooley

Subject: DESIGN REVIEW SY-101 IN SITU VISCOMETER (183-94)

----- Message Contents -----

Text item 1:

Industrial Safety has completed a review of the Design
Review for the SY-101 In Situ Viscometer Instrument 75%
Design Review. Please see attached RCR for comments.

This document has been forwarded to Industrial Hygiene for
review.

Received 2-17-94, Returned 2-24-94

File item 2: 183-94 2/24/94 1:22PM

[15] From: Charles M Monasmith at ~WHC160 2/24/94 1:27PM (8570 bytes: 4 ln, 1 fl
)

: Troy I Stokes at ~WHC207, Jack D (JD) Martin at ~WHC224

Subject: SECOND TRY

----- Message Contents -----

Text item 1:

Once in a while I really zone out! I wonder if this lousy
white stuff effects my #\$\$#@& attitude!

CMM

File item 2: 3426.RCR 2/24/94 10:24AM

[16] From: Michael L McElroy at ~WHC235 2/25/94 1:50PM (10831 bytes: 11 ln, 1 fl
)

: Troy I Stokes at ~WHC207

Receipt Requested

Subject: VISCOMETER-75% INDEPENDENT DESIGN REVIEW COMMENTS

----- Message Contents -----

Text item 1:

Troy,

Attached please find an RCR for the above mentioned documents.

If you have any questions, feel free to give me a call.

Thank you.

Mike Mc
TWRS Program QA

WHC-SD-WM-SDD-043

Rev. 0

File item 2: VISCOMTR.069 2/25/94 1:38PM

[17] From: John I Gould at ~WHC302 2/27/94 11:06AM (17484 bytes: 26 ln, 1 fl)
To: Troy I Stokes at ~WHC207
 : Janyce C (Jan) Urie at ~WHC304, Rhonda J (Roni) Swan, Robert M Marusich at
 ~WHC150, Tony R Benegas at ~WHC208, Richard H Engelmann at ~WHC304
Subject: Revised RCR -- Viscometer Project, 75% stage
----- Message Contents -----

Text item 1:

Troy,

94-RPI-103

I HAVE MODIFIED THE RCR, IN THE ATTACHED FILE.
DISCARD THE RCR WHICH WAS SENT ON FRIDAY.

I am returning comments on the Viscometer Test, 75% design review package. See the attached RCR file.

The review was made in view of requirements for environmental compliance, summarized in manual WHC-CM-7-5.

I have to admit the review is not as complete as I would like.

I have had an extra amount of requests for my time; all of which were high priority.

I expect to be able to participate in the 100% review, at which time some additional effort can be made, looking for the details which may have been missed.

Call me if you have any questions.

John Gould
6-1157

WHC-SD-WM-SDD-043

Rev. 0

File item 2: VISCOMTR.75% 2/27/94 11:05AM

REVIEW COMMENT RECORD (RCR)

RECEIVED

FEB 17 1994

1. Date 2/17/94	2. Review No.
3. Project No.	4. Page 1 of 3

5. Document Number(s)/Title(s) WHC-SD-WM-WP-242	6. Program/Project/ Building Number	7. Reviewer LA DELLAROCO	8. Organization/Group 7E550	9. Location/Phone ETC-1/373-4928
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17. Comment Submittal Approval: 10. Agreement with indicated comment disposition(s) 11. CLOSED

Organization Manager (Optional)

Date

Reviewer/Point of Contact

Date

Reviewer/Point of Contact

Author/Originator

Author/Originator

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/ resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
	FDC, Section 5.2, page 5, N2 purge system, Enclosure 3 see following items.			
1	See figure 2 and 3. Use standard ISA symbols and nomenclature for instrument identification. As drawn can not identify some of the components function.			
2	See figure 2. A filter should be installed before PCV-1. This would protect PCV-1 from plugging up from dirt, rust etc. in N2 line.			
3	How do you determine enclosure N2 volume changes on purge meet requirements?			
4	PSLV-1 will open on loss of pressure and draw ambient air through the enclosure. Will this cause check valve V-1 to open and pull a vacuum on the N2 system?			
5	PV-1 purge valve is solenoid operated. PCV-2 enclosure pressure valve is not. How do you prevent N2 going through PCV-2 during purge? Both valves should be solenoid operated with interlock so if one is open the other is closed.			
6	As designed PSVH-4 has to open for purge system to work. PSVH-3 is designed to protect PCV-2. PSVH-3 would have to open before PSVH-4 to protect PCV-2. How would you get pressure high enough to activate PSVH-4?			

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WHC-SD-WM-SDD-043
Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date 2/17/94	2. Review No.
	3. Project No.	4. Page 2 of 3

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/ resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
7	Delete HEPA filter. Install a purge return line (Tee in just before PSVH-4) from the enclosure to the tank. HEPA filter has to be changed and tested periodically. Eliminating it would reduce the radiation exposure risk and reduce labor cost.			
8	Last sentence in Section 5.2 reads --- alarm device (see figure 3) Should read (see figure 4).			
9	Section 5.3 first sentence on page 8 reads --- alarm device (see figure 3) Should read (see figure 4).			
	FDC, Section 5.3, N2 purge system, Enclosure 2 see following items.			
10	PID shows filter YY-2 installed after PCV-3. Filter should be installed before PCV-3. The filter is used to remove oil, water etc. from the air supply. As shown to be installed it would not protect PCV-3.			
11	PV-2 purge valve is solenoid operated. PCV-4 enclosure pressure valve is not. How do you prevent air going through PCV-4 during purge? Both valves should be solenoid operated with interlock so if one is open the other is closed.			
12	As designed PSVH-6 has to open for purge system to work. PSVH-5 is designed to protect PCV-4. PSVH-5 would have to open before PSVH-6 to protect PCV-4. How would you get pressure high enough to activate PSVH-6?			
13	Where does purge gas exhaust during normal operations? Figure 3 shows it dead headed in to the pressure indicator.			
	FDC, Section 5.4, purge and interlock logic see following items.			
14	Section 5.4.2, System Startup, states K6-B and K7-B open and K6-A and K7-A close. This stops the purge cycle and closes the disconnect and power relays K1, 2, 3, and 4. How will this work? Do K6 and K7 have instantaneous contact closure or make before break contacts? If not how will system keep operating?			

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Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date 2/17/94	2. Review No.
	3. Project No.	4. Page 3 of 3

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/ resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
15	When the purge cycle is over K5 drops out. This causes K7 to drop out. When K7 drops out K7-A opens causing a power loss to the motor. How do you keep the system running?			
16	Section 5.4.3, System Shutdown reads: If either PLS-2 ----. Should read: If PSL-2 -----.			
17	PSL-3 gives alarm only. Shouldn't it trip the unit also?			
18	PAL-2 and PAL-3 Do these work off the normally open and normally closed contacts of PSL-2 and PSL-3? If so show on the logic diagram.			
19	Logic diagram shows PAL-3 in series with PSL-3. If PAL-3 works off of PSL-3 and PSL-3 does nothing but activate indicator lamp why is it series with it?			

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Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date 02/20/94	2. Review No. 1
	3. Project No.	4. Page 1 of 3

5. Document Number(s)/Title(s) Viscometer 75% Design Review Package	6. Program/Project/ Building Number N/A	7. Reviewer J. D. Robinson	8. Organization/Group Mechanical Equipment	9. Location/Phone ETC-1/6-4777
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17. Comment Submittal Approval: 10. Agreement with indicated comment disposition(s) 11. CLOSED

Organization Manager (Optional)

Date

Reviewer/Point of Contact

Date

Reviewer/Point of Contact

Author/Originator

Author/Originator

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
1.	The polyethylene material review conducted by Bill Brehm indicates that different thermal expansion rates between the polyethylene coating and the cable and ball should be evaluated (This could lead to the coating possibly coming off, my concern is that it may crack and actually increase the amount of contamination brought into the cabinet). Has this been completed? What were the results?			
2.	If I understand L. M. McWethy's comment (Review of Viscometer Cable Reel Drive Motor Sizing) correctly, it states that the high speed drive motor (Aerotech Model 1960 Servo motor, still shown as used on H-2-818359) does not meet all the requirements for speed and force (a window near 10 mm/s and 1000 N). He suggests an increase in drum size to seven inches. Drawing H-2-818359 in the review package shows drum diameter to be 6.454 inches. In this configuration the motor will not be able to deliver 10mm/s at 1000N.			

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Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date 02/20/94	2. Review No. 1
	3. Project No.	4. Page 2 of 3

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
3.	<p>The supplied P&ID of the purge system raises the following questions:</p> <p>1) How is a leak in the system detected (it appears that flow simply increases to maintain pressure)?</p> <p>2) A much simpler means of venting over pressure would be to route it back to the tank. Inclusion of a HEPA filter would complicate the system, i.e., a housing, testing, etc.</p> <p>3) Has the possibility of condensate formation on the drive motor enclosure been addressed? Does the filter (rr2 ?) shown on the drive motor purge P&ID include a dryer?</p>			
4.	<p>If I recall correctly, at the design review briefing it was mentioned that the viscometer may be used more than once on this tank and perhaps on others as well. The structural analysis states that seismic loading is not considered because of a low probability of occurrence (because of short use time). Is the analyst's statement correct or did I misunderstand the presentation at the initial briefing?</p>			
5.	<p>How is the instrumentation cabinet (H-2-818150, all sheets) mounted? Does it just set on the earth or is it fixed?</p>			
6.	<p>The Functional Design Criteria states that the viscometer is to be weatherproof, to allow operation in any expected climate for several days duration. The instrument cabinet door must be open for operation. How are the cabinet internals protected from the elements?</p>			

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Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date February 24, 1994	2. Review No. 3426
	3. Project No. N/A	4. Page 1 of 2

5. Document Number(s)/Title(s) VISCOMETER 75% DESIGN REVIEW	6. Program/Project/ Building Number SY-101 Mitigation /Safety	7. Reviewer CM Monasmith	8. Organization/Group Electrical Power systems Engineering	9. Location/Phone MO-262 /376-8109
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17. Comment Submittal Approval: 10. Agreement with indicated comment disposition(s) 11. CLOSED

Organization Manager (Optional)

Date

Reviewer/Point of Contact

Date

Reviewer/Point of Contact

Author/Originator

Author/Originator

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
1.	Drawing H-2-818155. Zone D-5. An "instrumentation receptacle strip" is shown connected to the secondary of isolation transformer T1. Consideration should be given to using isolated ground receptacles in this situation to continue the noise reduction gained by isolation transformer T1.	NO	The receptacle strip ground will be grounded through a separate wire.	MHC-SD-MM-SDO-043 Rev. 0
2.	Drawing H-2-818156. Zone D-6. Isolation transformer T1 does not show the neutral conductor (X2 and X4) grounded.	NO	Ground added.	
3.	Drawing H-2-818156. Zone D-6. Isolation transformer T1 is shown with only primary overcurrent protection. The OCP is only 5 amps. This seems more appropriate for a 1500 VA transformer rather than the 2500 VA specified for T1.	NO	The 2.5 KVA transformers were on hand and used, even though the instrumentation load is only about 1 KVA.	
4.	Drawing H-2-818156. Zone F-2. Isolation transformer T2 does not show the neutral conductor (X2 and X4) grounded.	NO	Ground added.	

[15] From: Charles M Monasmith at ~WHC160 2/24/94 1:27PM (8570 bytes: 4 ln, 1 fl)
)

REVIEW COMMENT RECORD (RCR)	1. Date 2/25/94	2. Review No. 94-069
	3. Project No. N/A	4. Page 1 of 2

5. Document Number(s)/Title(s) VISCOMETER-75% INDEPENDENT DESIGN REVIEW	6. Program/Project/ Building Number HMT/241-SY-101	7. Reviewer M.L. MCELROY	8. Organization/Group TWRS PROGRAMS QA/38220	9. Location/Phone 200E/M0234/3-5588
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17. Comment Submittal Approval: Organization Manager (Optional)	10. Agreement with indicated comment disposition(s) 4/11/94 Date	11. CLOSED 4/11/94 Date
	M.L. McElroy Reviewer/Point of Contact	M.L. McElroy Reviewer/Point of Contact
	Author/Originator	Author/Originator

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
1.	QUESTION-How will the weight and drag force of the cable be accounted for?		Weight and drag force and buoyancy of the cable will be accounted for by measurement of these quantities (per unit length) in the laboratory using simulants. We plan tests with three simulants spanning a range of rheological parameters. In the experiments the cable or a substitute will be drawn through the simulants and the drag force and buoyancy will be measured. The weight of the cable (per unit length) is easily measured. In the reduction of the data the buoyancy, drag force, and weight of the deployed cable will be accounted for. These quantities will clearly depend on the amount deployed, and cable drag force will probably be velocity dependent. In addition, the buoyancy of the ball as well as pulley weight and friction will be accounted for.	Closed

REVIEW COMMENT RECORD (RCR)		1. Date 2/25/94	2. Review No. 94-069
		3. Project No. N/A	4. Page 2 of 2
12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)
2.	The Safety Assessment will have to address the prolong use of the viscometer if it is allowed to stay in the tank for long periods of time and while the pump is in operation, ie. the interface between the operating pump and the viscometer, the chemical corrosion of the unit, etc.	MLM	Accept. LANL is considering ball/cable tangling issues, and proposed mixer pump controls (alignment, speed, or ?) to address this issue.
3.	The tank seal must be addressed, while the viscometer is in the tank. Also, the SA should possibly address this.	MLM	Accept. Under normal operation, the tank will be sealed sufficient to hold 5 inches of water vacuum up to nearly 1 atm of pressure. Under installation, removal, or accident conditions, the dome space may be in brief communication with the surrounding atmosphere. The SA will address these issues.
4.	QUESTION-Will the tank dome pressure affect the density data? Will this be factored into the calculations?		Tank dome pressure will not affect the density measurements. According to Archimedes Principle, the ball is buoyed up by the weight of the displaced fluid. The weight of the displaced fluid depends only on its density. Since the density is independent of the pressure on the fluid (i.e., it is incompressible), the tank dome pressure will not matter. We neglect small differences due to the gas content of the waste (gas is compressible). The gas volume will vary inversely as the dome pressure plus the hydrostatic head. In the NC layer where gas can be held it will take variations of several PSI in the tank dome space before the density measurements are significantly affected.

CLOSED

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Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date 2/25/94	2. Review No. 94-069
	3. Project No. N/A	4. Page 3 of 2

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
5.	QUESTION-How will the twisting/spinning of the "ball" be controlled?		<p>The ball is not expected to twist or spin. The cable was not specifically procured to be an anti-rotation type. We haven't seen load rotation when reeling a 200 lb load onto a winch. Slight rotation at slow speeds will not significantly affect drag loads, which provide the key data from this instrument.</p> <p>Twisting and spinning of the ball are not specifically controlled. However, this behavior can only occur if the cable is wound onto the spool in certain ways. Level wound lines such as ours are resistant to storage of torsional energy. The fluid will not cause any significant twisting of the line unless there are gross deviations from sphericity in the ball, which there are not.</p>	Closed
6.	The interface with the "dewar" nitrogen system must be controlled.	MLM	The new purge system design will not interface with the "dewar" nitrogen system.	

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REVIEW COMMENT RECORD (RCR)	1. Date 2/25/94	2. Review No. 94-069
	3. Project No. N/A	4. Page 4 of 2

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
7.	The scenario of the viscometer being lanced into a "wasteberg" and becoming stuck or unmovable should be addressed. Especially, if the ball is stuck and the wasteberg moves accross the tank, as with the thermocouple tree during window G.	MLM	<p>Accept.</p> <p>If the ball will not sink under its own weight, a water lance will be used to sluice a ball pathway. If the ball will still not sink, the lance can be rigged to push the ball to tank bottom. Under the last scenario, the ball may have to remain at tank bottom for three or four days prior to withdrawal to provide meaningful data. LANL is addressing this in the SA. The waste yield strength is not expected to be greater than 1 psi, and is really predicted to be about .05 psi. At 1 psi, the cable would need to pull about 200 lb line tension to free the ball.</p> <p>If 200 lb tension will not free the ball, the electric motor will be disengaged. A special fitting and torque wrench will be used to manually crank the ball out of the tank. If the ball has somehow gotten caught around an MIT or pump, the strain gauges will indicate so. The cable will separate from the ball at about 800 lb line load. A ball in the tank has been shown acceptable in the LANL SA being developed. A ball with cable floating in the waste is a management problem. Our goal is that if the ball is irretrievable stuck on an MIT for instance, we will crank the cable up taught, and leave the device in place, or somehow replace the device with a permanent fixture to hold the cable taught while the viscometer is deployed elsewhere. This procedure and safety implications will be developed in the</p>	CLOSED

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 Rev. 0

REVIEW COMMENT RECORD (RCR)			1. Date 2/25/94	2. Review No. 94-069
			3. Project No. N/A	4. Page 5 of 2

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment, and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status

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[16] From: Michael L McElroy at ~WHC235 2/25/94 1:50PM (10831 bytes: 11 ln, 1 fl)
 To: Troy I Stokes at ~WHC207
 Receipt Requested
 Subject: VISCOMETER-75% INDEPENDENT DESIGN REVIEW COMMENTS
 ----- Message Contents -----

Text item 1:

Troy,

Attached please find an RCR for the above mentioned documents.

If you have any questions, feel free to give me a call.

Thank you.

Mike Mc
 TWRS Program QA

WHC-SD-WM-SDD-043
 Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date	2. Review No.
	2/25/94	94-069
	3. Project No.	4. Page
	N/A	6 of 2

File item 2: VISCOMTR.069 2/25/94 1:38PM

REVIEW COMMENT RECORD (RCR)	1. Date 02/20/94	2. Review No. 1
	3. Project No.	4. Page 1 of 4

5. Document Number(s)/Title(s) Viscometer 75% Design Review Package	6. Program/Project/ Building Number N/A	7. Reviewer J. D. Robinson	8. Organization/Group Mechanical Equipment	9. Location/Phone ETC-1/6-4777
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17. Comment Submittal Approval:	10. Agreement with indicated comment disposition(s)	11. CLOSED
Organization Manager (Optional)	Date <u>4/21/94</u> Reviewer/Point of Contact <u>J.D. Robinson</u> Author/Originator	Date <u>4/21/94</u> Reviewer/Point of Contact <u>J.D. Robinson</u> Author/Originator

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
1. Page 1-30	The polyethylene material review conducted by Bill Brehm indicates that different thermal expansion rates between the polyethylene coating and the cable and ball should be evaluated (This could lead to the coating possibly coming off, my concern is that it may crack and actually increase the amount of contamination brought into the cabinet). Has this been completed? What were the results?		The polyethylene coatings on the ball and on the cable are different. In the case of the ball, the coating is applied at a high temperature (150 C). It is essentially melted onto the ball from a dry residue powder covering the ball. The ball then cools to room temperature and the coating is formed. Before we even received a coated ball, the coating had gone from 150 C to room temperature. It was observed that its adherence was very acceptable. Clearly thermal expansion differences are not a concern for the ball. It has also been found that this coating chips away (when attempts are made to remove it) rather than tear or peel. Not only that, the ball is	

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Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date 02/20/94	2. Review No. 1
	3. Project No.	4. Page 2 of 4

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
1.			<p>not a particularly good host for the waste, and we have found that a chemical simulant of the waste does not adhere well to even the bare ball. Thus, (1) the coating should adhere well even with thermal cycling, (2) the coating chips away, so that waste cannot become entrained between the coating and ball, and (3) the waste adheres poorly to both the ball and the coating so that washing should remove the waste very effectively.</p> <p>The case for the cable is probably not as strong and no testing that I'm aware of has been performed except waste adherence testing. The waste adheres poorly to the coated cable. The expansion coefficient for polyethylene is about $1.8E-4/^\circ C$, while for stainless steel it is about $1.8E-5$, a factor of 10 less. For a 30 $^\circ C$ increase in temperature, a 10 m length of cable would become 10.005 m (wire) and 10.054 m (coating). If the cable coating is constrained not to expand then the extra length of 5 cm must be distributed over the 10 m length of cable.</p>	

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Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date 02/20/94	2. Review No. 1
	3. Project No.	4. Page 3 of 4

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
2.	If I understand L. M. McWethy's comment (Review of Viscometer Cable Reel Drive Motor Sizing) correctly, it states that the high speed drive motor (Aerotech Model 1960 Servo motor, still shown as used on H-2-818359) does not meet all the requirements for speed and force (a window near 10 mm/s and 1000 N). He suggests an increase in drum size to seven inches. Drawing H-2-818359 in the review package shows drum diameter to be 6.454 inches. In this configuration the motor will not be able to deliver 10mm/s at 1000N.		<p>1. The Aerotech Model 1960 is the largest DC servo motor that could be found.</p> <p>2. The experimenters were informed about the inability to produce the full 200 lb cable tension with the high speed motor and they found it to be acceptable.</p>	
3. Page J-32	<p>The supplied P&ID of the purge system raises the following questions:</p> <p>1) How is a leak in the system detected (it appears that flow simply increases to maintain pressure)?</p> <p>2) A much simpler means of venting over pressure would be to route it back to the tank. Inclusion of a HEPA filter would complicate the system, i.e., a housing, testing, etc.</p> <p>3) Has the possibility of condensate formation on the drive motor enclosure been addressed? Does the filter (rr2 ?) shown on the drive motor purge P&ID include a dryer?</p>		<p>The purge system design presented at the 75% Design Review has been changed. The new design does not require a purge system for tank safety. The new purge system design will be submitted for review.</p> <p>Motors are no longer purged.</p>	

WHC-SD-WM-SD-043
 Rev. 0

REVIEW COMMENT RECORD (RCR)		1. Date 02/20/94		2. Review No. 1	
		3. Project No.		4. Page 4 of 4	
12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)		16. Status
4.	If I recall correctly, at the design review briefing it was mentioned that the viscometer may be used more than once on this tank and perhaps on others as well. The structural analysis states that seismic loading is not considered because of a low probability of occurrence (because of short use time). Is the analyst's statement correct or did I misunderstand the presentation at the initial briefing?		There are no Hanford Site requirements for seismic analysis of a component which is meant for temporary service and performs no safety function. The potential of such a component to damage a permanent structure from a seismic [or other accident] event will be considered in the LANL SA. The viscometer itself need not survive a seismic event and will not be analyzed for seismic loading.		
5.	How is the instrumentation cabinet (H-2-818150, all sheets) mounted? Does it just sit on the earth or is it fixed?		The instrumentation cabinet will sit on the earth.		
6.	The Functional Design Criteria states that the viscometer is to be weatherproof, to allow operation in any expected climate for several days duration. The instrument cabinet door must be open for operation. How are the cabinet internals protected from the elements?		A tent or other portable enclosure will be deployed around the cabinet during field test performance. Testing will not be conducted on very windy days, or other days that operators are not allowed field access. All equipment will be prevented from contact with rain. Dust and temperature are the main considerations. The cabinet is a NEMA 12 upgraded to a NEMA 4 which is weatherproof when closed. Instruments will not be used in inclement weather. The cabinet has a heater and air conditioner for temperature control.		

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Rev. 0

REVIEW COMMENT RECORD (RCR)	1. Date 2/25/94	2. Review No. 94-RPI-103
	3. Project No. SY-101 Viscometer	4. Page 1 of 7

5. Document Number(s)/Title(s) TANK SY-101, IN-TANK VISCOMETER, 75% DESIGN REVIEW (Troy Stokes, H5-09)	6. Program/Project/ Building Number SY-101 Hydrogen Mitigation Charge: N2117	7. Reviewer JI Gould	8. Organization/Group (Environmental) Regulatory Program Integration, 88110	9. Location/Phone 2440 Stevens Center, H6-30 376-1157
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17. Comment Submittal Approval: <i>John Gould for JRR</i> Organization Manager, JR ROBERTSON	10. Agreement with indicated comment disposition(s) 4-11-94 Date Read 4-25-94	11. CLOSED <i>John I. Gould</i> Reviewer/Point of Contact 4-25-94 Date	 <i>John I. Gould</i> Reviewer/Point of Contact Date
Author/Originator		Author/Originator	

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
	THE FOLLOWING COMMENTS WERE NOTED DURING THE BRIEFING MEETING ON 2/16/94:			

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REVIEW COMMENT RECORD (RCR)

1. Date 2/25/94	2. Review No. 94-RPI-103
3. Project No. SY-101 Viscometer	4. Page 2 of 7

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
1.	<p>It was verbally stated (by C Shepard/PNL) that the viscometer test would only be effective (or valid) for the pumped slurry portion of the tank (also known as the conductive "C" layer).</p> <p>Eventually, waste form information will be needed for the bottom sludge (also known as the non-conductive "NC" layer).</p> <p>Provision for performing the test, at least in the "pulled" mode, should be considered for the bottom "sludge, also.</p> <p>Indications are that it takes at least two weeks for the settling process to make a readily distinguishable separation between the NC & C layers.</p> <p>The idea of "lancing in" the ball, as deeply as possible with a push rod has a lot of appeal.</p>		<p>The viscometer will be effective in all portions of the waste. It will be most effective at determination of the C layer density and the NC layer yield stress and viscosity. It may have difficulty in making precision determinations of the C layer viscosity because this viscosity is expected to be low. It may have difficulty in measurement of the NC layer density because the ball may be partially supported by the yield strength of the fluid.</p> <p>We intend to obtain waste from information throughout the whole tank.</p> <p>We do not know what the condition of the tank waste will be when the ball rheometer is deployed. We will probe the waste "as is". The primary purpose for deployment of the ball rheometer is to characterize the waste, rather than to prove the ball rheometer, although both activities will certainly occur. It may be that it takes two weeks to form distinguishable C and NC layers. If this is the case and if data from an NC layer is desired for whatever reason then we must let the tank sit for two weeks.</p> <p>Lancing in the ball has some advantages in terms of minimal corruption of the existing waste form. However, from an operational point of view water lancing is much simpler to accomplish, and the advantages are such that water lancing is presently preferred.</p>	

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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
2.	<p>I appreciated the realization that the waste could not be treated as an idealized ("Newtonian") fluid, but I would also like to know how the "Bingham" fluid behavior and associated model will impact how the data is used.</p> <p>Since the measured data can be evaluated with software, off-line, it would be useful to make several evaluations, and determine parameters for both fluid types.</p>		<p>If the fluid turns out to be "Bingham", or, more generally, if it has a yield stress then the value of the yield stress is important to modelers of the tank behavior. The yield stress is not of great importance to structural analysts, who still need the viscosity. An accurate description of the fluid shear stress-vs shear rate behavior is desirable by all parties. Fluid descriptions such as Bingham, Yield - Pseudoplastic, Newtonian, or Power-Law all convey a picture of the shear stress - shear rate curve. We hope to be able to produce such a curve from the data.</p> <p>The observation that we can evaluate several different fluid models is exactly correct and will be performed. It is anticipated that, among the models attempted, one will fit the data better than the others, so that we can claim that the fluid has a particular behavior.</p>	

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REVIEW COMMENT RECORD (RCR)		1. Date 2/25/94		2. Review No. 94-RPI-103	
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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)		16. Status
3.	<p>It was mentioned during JD Martin's part of the briefing (my notes, here), that The hazards evaluation may be the only place in the project documentation, where any environmental criteria are addressed.</p> <p>This project needs to meet all the environmental compliance requirements in manual WHC-CM-7-5. It must have either an environmental assessment made, or a designation/inclusion letter from Mr. Richard Engelmann, (manager NEPA Documentation, 376-7485) that the action is covered by existing NEPA analysis and designation.</p> <p>When a safety assessment has been done by an off-site contractor, it is still useful to ask the regulatory analysis support staff to determine if a complete evaluation has been done for environmental compliance issues. Please contact Ms. Julie Robertson, (manager Regulatory Program Integration, 376-8162) to arrange for an environmental Point-of-Contact (POC) checklist. The POC checklist provides a permitting strategy, if needed.</p>		<p>Comment not-accepted.</p> <p>The project has been in frequent communication with Richard Englemann's group, specifically Sherm Tifft. They have verbally stated, and through CC:mail I'm sure, that the "Jansky Generic" EA will cover the viscometer work scope. This EA was recently released as DOE/EA-0915, and received a FONSI back from HQ on incoming correspondence no. 9402034 B.</p> <p>Los Alamos National Laboratories (LANL) will prepare a letter [or include in the viscometer safety assessment] stating verifying that installation, operation, and removal of the viscometer will not cause a more significant environmental impact than that which is currently covered by the "Jansky Generic" EA.</p> <p>We will pursue the POC checklist far enough to see if we need any special permitting not covered by the EA described above. We had hoped that you could identify if any special permitting would be required as part of your design review participation.</p>		

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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
4.	<p>Strange phenomena department:</p> <p>Hydrogen will diffuse "up gradient" against the low pressures that are being mentioned (a few inches of water-gauge) due to its relatively small mass. This means that the pit can become a collecting place for finite concentrations of flammable gas. This possibility would seem to be of a higher concern, than is being given in the draft narratives.</p>		<p>Comment not-accepted.</p> <p>We are not placing the viscometer in any pit. The entire viscometer assembly will be above grade at all times. An air purge is currently planned to pass by the load cell area into the tank vapor space. This purge is nominally at 1.5 cfm when a 10 inch water differential is present. It is not anticipated hydrogen will enter the box with such flow rates through the orifice plate geometry.</p>	
5.	<p>Please clarify whether you plan to build a HEPA filter into the above-ground enclosure.</p> <p>When the gate valve is opened, the purge gas can exhaust into the tank riser. However, it's possible that there may be conditions where the purge needed to be "flowing" and the riser valve is closed.</p> <p>Suggest this potential be evaluated and a procedure interlock applied, if necessary.</p>		<p>The new design uses enclosure purge only for equipment protection and operator safety (SC-3) to allow access to the load cell/cable system for maintenance. A HEPA filter is provided for venting the enclosure when not connected to the tank.</p>	<p>MHC-SD-MM-SDD-043 Rev. 0</p>

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REVIEW COMMENT RECORD (RCR)	1. Date 2/25/94	2. Review No. 94-RPI-103
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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
6.	<p>The test strategy allows for the winch and other above-ground equipment to become "contaminated equipment." This equipment becomes a secondary solid waste stream for the tank farm.</p> <p>This is contrary to the requirement of "waste minimization," which is required to be considered by DOE Orders 5820.2A; 5400.1 and 5400.3 at Hanford.</p>		<p>Comment not-accepted.</p> <p>This is not contrary. The waste has several unknown parameters and requires several tests be run to ultimately allow continued safe storage and retrieval. It would be impossible to accomplish safe storage and retrieval without gathering more tank waste data.</p> <p>Devices that touch the waste become contaminated. This contamination is either at acceptable levels, or is decontaminated back to acceptable levels. The viscometer should survive several years of service prior to becoming so contaminated as warranting disposal. It has also been developed following ALARA principles, and will be far less complicated than the core sample truck, or other sampling mechanisms.</p> <p>Your comment would lead the reader to believe that the contamination can spread without bound above the tank. An enclosure above the tank will capture all potential contamination within the viscometer itself.</p>	MHC-SD-MM-SD-043 Rev. 0

REVIEW COMMENT RECORD (RCR)			1. Date 2/25/94	2. Review No. 94-RPI-103
			3. Project No. SY-101 Viscometer	4. Page 7 of 7
12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
7.	<p>Have cold tests demonstrated the adequacy of spray rinse for the cable? The spray should sufficiently clean the waste off the cable and sphere to allow workers to contact-handle the enclosure, during test tear-down.</p> <p>Unless the proposed spray arrangement can be assured of keeping the contamination inside the enclosure to less than ALARA dose/exposure levels for the test operators, it may be necessary to add a second set of spray nozzles in order to clean the cable, sufficiently.</p>		<p>Comment not-accepted.</p> <p>Though a valid concern, our past experience with decontamination of equipment leaving SY-101 tank indicate all waste buildup is highly water soluble. LANL testing has also indicated waste buildup is next to nothing once the cable has been dipped in water.</p> <p>All design information to date indicates that it would take several full ball extractions with zero decontamination effort before the viscometer enclosure would become so contaminated as to become a "high radiation" area. Field radiation monitoring as part of standard operation will prevent unexpected radiation dose to personnel.</p> <p>A 4" stainless steel pipe was withdrawn last July through a spray system of similar power to the viscometer. It came out 2 mR/hour contact, and a smear resulted in 8000 counts/second or minute, I can't specifically recall, but it was clean enough to wipe with rags by hand.</p>	MHC-SD-MM-SDD-043 Rev. 0
8.	<p>A transport/storage receiver should be purchased for the enclosure as soon as possible. Suggest contacting Package Safety Engineering (Greg Fields) for this requirement.</p> <p>We do not want the tank farm to become a lay-down yard for hot equipment.</p>		<p>A 7A Box is being procured through Packaging Safety Engineering (PSE). This box will be used to transport and store the viscometer. PSE will also prepare the Documentation and Analysis for Packaging (DAP).</p>	

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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
9.	<p>The Test Plan should include a description of the "safe shutdown criteria," in case there are waiting periods between first installation and final retrieval/demobilization of the test.</p> <p>The installation of interface cables and utility hookups (eg, purge gases) needs to be laid out and checked for non-interference with current SY-101 tests and monitoring.</p>		<p>Accept.</p> <p>The safe shut down criteria will be listed in the operations and maintenance manual as well as the LANL safety assessment. The first definition will be cultivated in the NEC code compliance internal memo currently under development.</p> <p>The field routing of cabling will be highly temporary, and stand alone from all other systems. The need for a nitrogen purge has disappeared, so interface with this system is not anticipated at this time. Field routing has already been investigated at the design engineering level.</p>	WHC-SD-WM-SDD-043 Rev. 0
10.	<p>WHC-SD-WM-WP-242, Work Plan:</p> <p>Page 9, section 2.5: "Impact levels" (per MRP 5.43) are no longer being used. Review designators are now controlled by manual CM-3-5.</p>		<p>Accept.</p> <p>The numbering system has disappeared. The document, if revised at some future point in time, will have the numbers deleted in accordance with new standards. A revision at this time is not warranted for this point alone.</p>	
11.	<p>Data Users' Requirements, PNL MIT #111593:</p> <p>"Accuracy" needs -- should be accounted for by carrying along the upper 2-sigma band, where applicable, and reporting any "out-liers" beyond the 95% level of confidence. While these practices will be done by any competent researcher, the demand for speed in reporting often allows them to be skipped.</p>		<p>The statements on accuracy are justified and will be complied with where possible. It may be that we can apply the stated criteria only to the density data. In regards to viscosity and yield stress, the answers we obtain will depend upon the model chosen to describe the fluid. There may be great difficulty in ascribing an accuracy to the values for these parameters.</p>	

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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
12.	It seems that at least two or three cold runs should be done in a test facility/tank to verify software and motor control interfaces, before installing in the SY-101 waste.		Agree. An acceptance test plan to run the equipment through its paces is being developed as this comment is being written. Several non-documented tests will be performed during a period of time call "calibration, grooming, and alignment" on the schedule. The ATP will document a series of specific tests, and their success.	
13.	Safety Classification draft, page 11 of 13: Items 2-4 & 2-6 need to be considered in same light as comment #5, above. Purge flow, regardless of how minimal, and regardless of how minuscule the contamination might be needs to be accounted for. An unfiltered release would have to be reported as an "off-normal occurrence," with all of the associated paperwork.		The purge system design presented at the 75% design review has been modified. New design description will be submitted for review.	WHC-SD-WM-SDD-04B Rev. 0
14.	Letter 29230-94-02, page 14, last paragraph: Justification for the assumption regarding hydrogen and ammonia concentrations in the stack should be supplied. "Best operator memory" is usually insufficient.		NOT Accepted Document was included for information only. The ammonia detector is not part of the viscometer project.	

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REVIEW COMMENT RECORD (RCR)		1. Date 2/25/94	2. Review No. 94-RPI-103
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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)
Page J-43	15. WHC-SD-WM-HC-010, page 5, section 3.2, first statement states that the present mixer pump controls the level by mixing the C & NC layers. This doesn't quite conform to the Los Alamos Gas Generation model, which assumes that the "buoyancy" is what controls the level, and the mixer pump controls the gas generation, which feeds the buoyancy.		Comment not-accepted. Document ...HC-010 may not have been specific enough to fully provide a connection between LANL work and what ...HC-010 was trying to justify. In short, the mixer pump is mixing the tank, causing small controlled gas releases. Trapped gas in the waste leads to some level of bouyancy of a given tank layer. At some point, without mixing, the bouyancy becomes so great as to cause amassive tank rollover. The waste just generates gas of its own accord with the radiolysis playing some major portion in gas generation. The mixer pump has nothing to do with gas generation, but through mixing, causes high shear areas in the waste which breaks up the waste structure and allows trapped gases to migrate towards the top of the tank.
	16. Drawing H2-818152: Clarify where the motor cooling fans (zone C-3) circulate clean or contaminated air. If the exhaust the cooling air externally, the diagram should include a HEPA filter.		The fans circulate ambient air. Filters are included, but not HEPA quality.
	17. Drawing H2-818154: It appears that the position transducer is a direct-gearred assembly and produces an electric signal via a "make-break" operation. An optical sensor should be considered, where the make-break is done on a light beam, with no possibility of sparks.		The position sensor is an optical type.

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REVIEW COMMENT RECORD (RCR)	1. Date 2/25/94	2. Review No. 94-RPI-103
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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
18.	<p>Letter 33330-94-005, Dose Rate Estimates:</p> <p>Item (3), for the drum, assumes a uniform residual coating of 1.5E-3 cm thickness on the cable.</p> <p>From my observations of borehole logging, where the cable was inserted in a slurry of drilling mud, there is a tendency for more waste to cling to the cable than is allowed here. In addition, there will be "globs" of several millimeter extent, that get past the spray and drip cleaning. An order of magnitude upper limit increase is suggested.</p> <p>This would allow a nine-fold increase in the waste thickness on the cable, and an 80-fold increase in the cable-to drum transfer potential. A quick estimate on my part is that the contact dose rate would be increased to 6.7 R/hr and 240 mR/r at 30 cm.</p>		<p>See item 7 for discussion of efficiency of decontamination system.</p> <p>In the event the decon spray system does not work, there is a possibility of pulling waste into the enclosure during retraction of the sphere. LANL has conducted tests that show the amount of waste accumulation in the enclosure is limited by the shield plate orifice size. Build-up also depends on the number of times the sphere is retracted.</p> <p>Additional dose rate calculations will be performed using the test results from LANL to determine upper limit dose rates.</p>	

[17] From: John I Gould at ~WHC302 2/27/94 11:06AM (17484 bytes: 26 ln, 1 fl)
 To: Troy I Stokes at ~WHC207
 cc: Janyce C (Jan) Urie at ~WHC304, Rhonda J (Roni) Swan, Robert M Marusich at ~WHC150, Tony R Benegas at ~WHC208, Richard H Engelmann at ~WHC304
 Subject: Revised RCR -- Viscometer Project, 75% stage
 ----- Message Contents -----

Text item 1:

Troy,

94-RPI-103

I HAVE MODIFIED THE RCR, IN THE ATTACHED FILE.
 DISCARD THE RCR WHICH WAS SENT ON FRIDAY.

REVIEW COMMENT RECORD (RCR)	1. Date 2/25/94	2. Review No. 94-RPI-103
	3. Project No. SY-101 Viscometer	4. Page 12 of 7

I am returning comments on the Viscometer Test, 75% design review package. See the attached RCR file.

The review was made in view of requirements for environmental compliance, summarized in manual WHC-CM-7-5.

I have to admit the review is not as complete as I would like.

I have had an extra amount of requests for my time; all of which were high priority.

I expect to be able to participate in the 100% review, at which time some additional effort can be made, looking for the details which may have been missed.

Call me if you have any questions.

John Gould
6-1157

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		2/25/94	94-RPI-103
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File item 2: VISCOMTR.75% 2/27/94 11:05AM

REVIEW COMMENT RECORD (RCR)	1. Date February 24, 1994	2. Review No. 183-94
	3. Project No. 101-SY	4. Page 1 of 2

5. Document Number(s)/Title(s) 75% Design Review for SY-101 In Situ Viscometer Instrument.	6. Program/Project/ Building Number 101-SY	7. Reviewer Chris L. Cooley	8. Organization/Group W.T.S.S.	9. Location/Phone 2751E/ 372-3271
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17. Comment Submittal Approval:	10. Agreement with indicated comment disposition(s)	11. CLOSED
Organization Manager (Optional)	<u>13 Apr 94</u> Date Reviewer/Point of Contact Author/Originator	<u>13 Apr 94</u> Date Reviewer/Point of Contact Author/Originator

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
1 Page J-47	Mechanical section. The viscometer assembly includes various rotating components (i.e. shafts and pulleys). Most of the components will be housed in enclosures, however, it appears that some of the rotating components may be exposed. If so, guards that fully enclose the components should be used. Guards should comply with OSHA 29 CFR 1910.217 Table O-10.		NOT Accepted Between the reel enclosure (H-2-818360) and the motor cover (H-2-816361) all rotating components will be enclosed. If the enclosures are removed for maintenance, all power to the viscometer will be disconnected.	
2	Human Factor Engineering (Ergonomics) should be considered prior to fabrication and installation of the equipment.		Accept. Ergonomics have been and will continue to be considered during design of the viscometer.	

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REVIEW COMMENT RECORD (RCR)		1. Date February 24, 1994	2. Review No. 183-94
		3. Project No. 101-SY	4. Page 2 of 2

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status

[14] From: Christopher L Cooley at ~WHC83 2/24/94 1:03PM (10225 bytes: 9 ln, 1 f
 1)
 To: Kari L Leggett at ~WHC289, Cari L Minor, Troy I Stokes at ~WHC207
 cc: Christopher L Cooley
 Subject: DESIGN REVIEW SY-101 IN SITU VISCOMETER (183-94)

----- Message Contents -----

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Text item 1:

Industrial Safety has completed a review of the Design Review for the SY-101 In Situ Viscometer Instrument 75% Design Review. Please see attached RCR for comments.

This document has been forwarded to Industrial Hygiene for review.

Received 2-17-94, Returned 2-24-94

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Rev. 0

<p align="center">REVIEW COMMENT RECORD (RCR)</p>	<p>1. Date</p> <p align="center">March 4, 1994</p>	<p>2. Review No.</p> <p align="center">183-94</p>
	<p>3. Project No.</p>	<p>4. Page</p> <p align="right">1 of 1</p>

5. Document Number(s)/Title(s)	6. Program/Project/ Building Number	7. Reviewer	8. Organization/Group	9. Location/Phone
SY-101 In Situ Viscometer 75% Design Review	Tank Farms	L.S. Krogsrud	WTSA / NS	2751 / 372-2302

17. Comment Submittal Approval:	10. Agreement with indicated comment disposition(s)	11. CLOSED
 <u> </u>	 <u> </u>	 <u> </u>
Organization Manager (Optional)	Reviewer/Point of Contact	Reviewer/Point of Contact
	Date	Date
	<u>K.L. Pearce for T.I.S.</u> Author/Ori ginator	<u>K.L. Pearce for T.I.S.</u> Author/Ori ginator

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
1.	The design and consequences of failure of the air purge to the motor compartment are not covered.		The purge system design presented at the 75% Design Review has been changed. The new design will be submitted for review.	

14. Hold Point	15. Disposition (Provide justification if NOT accepted.)
	The purge system design presented at the 75% Design Review has been changed. The new design will be submitted for review.

16.
Status

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REVIEW COMMENT RECORD (RCR)		1. Date		2. Review No.	
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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)		16. Status
2.	The tungsten ball is 1.25% copper. Exposure of the metal to waste containing ammonia would cause "leaching out" of the copper due to its oxidation and formation of soluble copper salts.		How the ball will react chemically to the waste is not well known. The memo from E.B. Schwenk to Troy Stokes dated Feb. 15, 1994 points out some of the uncertainties. It is certainly possible that some chemical reaction may occur between the copper alloyed with the tungsten in the ball and the waste. An experiment was performed to address this issue. Samples of materials identical in composition to the ball were obtained from the ball vendor. These samples were immersed in a simulant of the waste which is as close a chemical replica to the Tank 101-SY waste as we can make, excluding radiative components. The samples were kept in the waste simulant (at 50 C) for 12 days and then examined. Photos were taken of the before-and-after samples. No discernable differences were found in the surface features of the samples. There appeared to be no etching or pitting or changes of any sort except a slight change in color. Perhaps a much longer test would reveal some changes, but this test was of sufficient length to assure us that any changes will occur slowly compared to the time it takes to perform a series of experiments in the tank. In addition, the ball will be coated with a polyethylene coating which will inhibit reactions except at locations where it has been damaged. We are confident that the ball will not undergo changes due to chemical reaction which can affect the results of in-situ measurements.		

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REVIEW COMMENT RECORD (RCR)		1. Date March 4, 1994	2. Review No. 183-94
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12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
3.	Safety class of components is not identified.		Accept We are working with Brett Hall to develop a safety equipemtn list. In our System Design Description (SDD), we will include this safety equipment list, which is a list of safety related components of the viscometer and their appropriate safety classification.	

REVIEW COMMENT RECORD (RCR)	1. Date 3-4-94	2. Review No. EAQAMAM94-002
	3. Project No. Viscometer	4. Page 1 of 2

5. Document Number(s)/Title(s) WHC-SD-WM-WP-242 REV.0	6. Program/Project/ Building Number VISCOMETER	7. Reviewer MA MCGHAN	8. Organization/Group EAQA/QA	9. Location/Phone M0902/376-2986
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17. Comment Submittal Approval: 10. Agreement with indicated comment disposition(s) 11. CLOSED

Organization Manager (Optional)

4-19
Date

Kathleen Pierce
Reviewer/Point of Contact
Mark McGhan
Author/Originator

4-19-94
Date

Reviewer/Point of Contact
Mark McGhan
Author/Originator

12. Item	13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/resolve the discrepancy/problem indicated.)	14. Hold Point	15. Disposition (Provide justification if NOT accepted.)	16. Status
1 Page J-52	Page 9 section 2.5 second sentence change Impact levels to Approval designators, MRP 5.43 to CM-3-5. Third sentence change impact level to approval designator. Second paragraph change impact level to approval designator.	MAM	Reject. Though the approval indicator system has changed, the content of the engineering work plan is not misleading, and does tell how the drawings will be finally released, as 3SQ. From a practical point of view, there is no difference between 3SQ versus SQ. Those names listed are aware of the procedural change.	

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Rev. 0

Per discussion with Kathleen on 4-19 this document has been released and these comments I have noted will be addressed in a ECR.

ENGINEERING DATA TRANSMITTAL

2. To: (Receiving Organization) Special Projects	3. From: (Originating Organization) TWRs Safety Programs Eng. Support	4. Related EDT No.: N/A
5. Proj./Prog./Dept./Div.: Viscometer, SY-101	6. Cog. Engr.: D. B. Graves	7. Purchase Order No.: N/A
8. Originator Remarks: The purpose of this EDT is to release the drawings listed in block number 15.		9. Equip./Component No.: N/A
		10. System/Bldg./Facility: 241-SY-101/Tank Farms
11. Receiver Remarks:		12. Major Assm. Dwg. No.: H-2 822165
		13. Permit/Permit Application No.: N/A
		14. Required Response Date: 7-15-94

15. DATA TRANSMITTED					(F)	(G)	(H)	(I)
(A) Item No.	(B) Document/Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	Approval Designator	Reason for Transmittal	Originator Disposition	Receiver Disposition
1	H-2-818145	1	0	Viscometer, SPI-15 Load Cell Assembly	SQ	2	1	
2	H-2-818145	2	0	Viscometer, SPI-15 Load Cell Assembly	SQ	2	1	
3	H-2-818146	1	0	Viscometer, SPI-25/50 Load Cell Assembly	SQ	2	1	
4	H-2-818146	2	0	Viscometer, SPI-25/50 Load Cell Assembly	SQ	2	1	
5	H-2-818147	1	0	Viscometer, SSB-250 Load Cell Assembly	SQ	2	1	
6	H-2-818147	2	0	Viscometer, SSB-250 Load Cell Assembly	SQ	2	1	

16. KEY									
Approval Designator (F)		Reason for Transmittal (G)				Disposition (H) & (I)			
E, S, Q, D or N/A (see WHC-CM-3-5, Sec.12.7)		1. Approval	4. Review			1. Approved	4. Reviewed no/comment		
		2. Release	5. Post-Review			2. Approved w/comment	5. Reviewed w/comment		
		3. Information	6. Dist. (Receipt Acknow. Required)			3. Disapproved w/comment	6. Receipt acknowledged		
(G)	(H)	17. SIGNATURE/DISTRIBUTION (See Approval Designator for required signatures)						(G)	(H)
Reason	Disp.	(J) Name	(K) Signature	(L) Date	(M) MSIN	(J) Name	(K) Signature	(L) Date	(M) MSIN
2	/	Cog.Eng. D. B. Graves	<i>[Signature]</i>	7/15/94	L6-38				
2	/	Cog. Mgr. R. E. Bauer	<i>[Signature]</i>	7/20/94	L6-37				
2	/	QA M. A. McGhan	<i>[Signature]</i>	7/20/94	L6-35				
2	/	Safety L. S. Krogerud	<i>[Signature]</i>	7/20/94	R3-08				
2	/	Proj. Eng. T. I. Stokes	<i>[Signature]</i>	7/20/94	H5-09				

19. <i>[Signature]</i> T. I. Stokes 7-21-94 Authorized Representative Date for Receiving Organization	20. <i>[Signature]</i> R. E. Bauer 7/22/94 Cognizant Manager Date	21. DOE APPROVAL (if required) Ctrl. No.
Signature of EDT Originator D. B. Graves 7-18-94	Date	

ENGINEERING DATA TRANSMITTAL

(CONTINUATION PAGE)

5. Proj./Prog./Dept./Div.: Viscometer, SY-101	6. Cog. Eng. D. B. Graves	1. EDT 606726	Page 2 of 3
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15. DATA TRANSMITTED				(F)	(G)	(H)	(I)	
(A) Item No.	(B) Document/Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	Approval Design- nator	Reason for Trans- mittal	Orig- inator Dispo- sition	Receiv- er Dispo- sition
7	H-2-818148	1	0	Viscometer, SSB-500 Load Cell Assembly	SQ	2	1	
8	H-2-818148	2	0	Viscometer, SSB-500 Load Cell Assembly	SQ	2	1	
9	H-2-818359	1	0	Viscometer Assembly	SQ	2	1	
10	H-2-818359	2	0	Viscometer Assembly	SQ	2	1	
11	H-2-818359	3	0	Viscometer Assembly	SQ	2	1	
12	H-2-818359	4	0	Viscometer Assembly	SQ	2	1	
13	H-2-818359	5	0	Viscometer Assembly	SQ	2	1	
14	H-2-818359	6	0	Viscometer Assembly	SQ	2	1	
15	H-2-818359	7	0	Viscometer Assembly	SQ	2	1	
16	H-2-818359	8	0	Viscometer Assembly	SQ	2	1	
17	H-2-818359	9	0	Viscometer Assembly	SQ	2	1	
18	H-2-818359	10	0	Viscometer Assembly	SQ	2	1	
19	H-2-818359	11	0	Viscometer Assembly	SQ	2	1	
20	H-2-818359	12	0	Viscometer Assembly	SQ	2	1	
21	H-2-818359	13	0	Viscometer Assembly	SQ	2	1	
22	H-2-818359	14	0	Viscometer Assembly	SQ	2	1	
23	H-2-818360	1	0	Viscometer Cable Drum Cover Assembly	SQ	2	1	
24	H-2-818360	2	0	Viscometer Cable Drum Cover Assembly	SQ	2	1	
25	H-2-818360	3	0	Viscometer Cable Drum Cover Assembly	SQ	2	1	
26	H-2-818361	1	0	Viscometer Motors Cover	SQ	2	1	
27	H-2-818361	2	0	Viscometer Motors Cover	SQ	2	1	
28	H-2-818361	3	0	Viscometer Motors Cover	SQ	2	1	
29	H-2-818361	4	0	Viscometer Motors Cover	SQ	2	1	

(CONTINUATION PAGE)

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606726

[illegible]

DISTRIBUTION SHEET

To Special Projects		From TWRs Safety Programs Eng. Support		Page 1 of 1	
Project Title/Work Order Viscometer SY-101 Mitigation Project		EDT No. 606726		Date 7-14-94	
ECN No.					
Name	MSIN	Text With All Attach.	Text Only	Attach./ Appendix Only	EDT/ECN Only
R. E. Bauer	L6-37				x
D. B. Graves	L6-38	x (3)			
C. E. Hansen	H5-09				x
L. S. Krogsrud	R3-08				x
J. W. Lentsch	S7-15				x
M. L. McElroy	S1-57				x
M. A. McGhan	L6-35				x
T. I. Stokes	H5-09	x (+ 3 sets 1/2 size)			

<p>JUL 26 1994 20</p> <p>ENGINEERING DATA TRANSMITTAL</p>	<p>Page 1 of 2</p> <p>1. EDT No 141131</p>
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<p>2. To: (Receiving Organization) Special Projects</p>		<p>3. From: (Originating Organization) TWRS Safety Programs Eng. Support WTE620</p>		<p>4. Related EDT No.: N/A</p>							
<p>5. Proj./Prog./Dept./Div.: Viscometer SY-101 Mitigation Project</p>		<p>6. Cog. Engr.: J. D. Martin NABIR</p>		<p>7. Purchase Order No.: N/A</p>							
<p>8. Originator Remarks: The purpose of this EDT is to release the drawings listed in block number 15.</p>				<p>9. Equip./Component No.: N/A</p>							
<p>11. Receiver Remarks:</p>				<p>10. System/Bldg./Facility: 241-6Y-101/Tank Farms</p>							
				<p>12. Major Assm. Dwg. No.: H-2-818150</p>							
				<p>13. Permit/Permit Application No.: N/A</p>							
				<p>14. Required Response Date: 07/08/94</p>							
<p>15. DATA TRANSMITTED</p>											
(A) Item No.	(B) Document/Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	(F) Impact Level	(G) Reason for Transmittal	(H) Originator Disposition	(I) Receiver Disposition			
01	H-2-818150	1	0	Viscometer/Void Fraction Control Console Assy.	SQ	2	1				
02	H-2-818150	2	0	Viscometer/Void Fraction Control Console Assy.	SQ	2	1				
03	H-2-818150	3	0	Viscometer/Void Fraction Control Console Assy.	SQ	2	1				
04	H-2-818150	4	0	Viscometer/Void Fraction Control Console Assy.	SQ	2	1				
05	H-2-818150	5	0	Viscometer/Void Fraction Control Console Assy.	SQ	2	1				
06	H-2-818150	6	0	Viscometer/Void Fraction Control Console Assy.	SQ	2	1				
<p>16. KEY</p>											
Impact Level (F)		Reason for Transmittal (G)			Disposition (H) & (I)						
<p>1, 2, 3, or 4 (see MRP 5.43)</p>		<p>1. Approval 2. Release 3. Information 4. Review 5. Post-Review 6. Dist. (Receipt Acknow. Required)</p>			<p>1. Approved 2. Approved w/comment 3. Disapproved w/comment 4. Reviewed no/comment 5. Reviewed w/comment 6. Receipt acknowledged</p>						
(G)	(H)	<p>17. SIGNATURE/DISTRIBUTION (See Impact Level for required signatures)</p>						(G)	(H)		
Reason	Disp.	(J) Name	(K) Signature	(L) Date	(M) MSIN	(J) Name	(K) Signature	(L) Date	(M) MSIN	Reason	Disp.
2	1	Cog. Eng. J.D. Martin	<i>J.D. Martin</i>	7-6-94	L7-04						
2	1	Cog. Mgr. R.E. Bauer	<i>R.E. Bauer</i>	7/6/94	L6-37						
2	1	QA M.L. McElroy	<i>M.L. McElroy</i>	7-11-94	S1-57						
2	1	Safety L.S. Krogsrud	<i>L.S. Krogsrud</i>	7-11-94	R3-08						
		Env.									
2	1	Proj Eng T.I. Stokes	<i>T.I. Stokes</i>	7/11/94	H5-09						
2	1	Indep Rev L.A. Dellarocca	<i>L.A. Dellarocca</i>	7/11/94							
<p>18. <i>J.D. Martin</i> J.D. Martin 7-6-94 Signature of EDT Originator Date</p>		<p>19. <i>T.I. Stokes</i> T.I. Stokes 7-11-94 Authorized Representative Date for Receiving Organization</p>		<p>20. <i>R.E. Bauer</i> R.E. Bauer 7/6/94 Cognizant/Project Engineer's Manager Date</p>		<p>21. DOE APPROVAL (if required) Ltr. No. ☐ Approved ☐ Approved w/comments ☐ Disapproved w/comments</p>					

ENGINEERING DATA TRANSMITTAL

(CONTINUATION PAGE)

5. Proj./Prog./Dept./Div.:	6. Cog. Eng.	1. EDT	
Viscometer SY-101 Mitigation	J. D. Martin	141131	Page 2 of 2

15. DATA TRANSMITTED					(F)	(G)	(H)	(I)
(A) Item No.	(B) Document/ Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	Impact Level	Reason for Trans- mittal	Origi- nator Dispo- sition	Receiver Dispo- sition
07	H-2-818150	7	0	Viscometer/Void Fraction Control Console Assy.	SQ	2	1	
08	H-2-818150	8	0	Viscometer/Void Fraction Control Console Assy.	SQ	2	1	
09	H-2-818151	1	0	Viscometer/Void Fraction Cable Assemblies	SQ	2	1	
10	H-2-818151	2	0	Viscometer/Void Fraction Cable Assemblies	SQ	2	1	
11	H-2-818151	3	0	Viscometer/Void Fraction Cable Assemblies	SQ	2	1	
12	H-2-818151	4	0	Viscometer/Void Fraction Cable Assemblies	SQ	2	1	
13	H-2-818152	1	0	Viscometer/Void Fraction Loop Diag. Motor Drive	SQ	2	1	
14	H-2-818152	2	0	Viscometer Loop Diagrams Controls	SQ	2	1	
15	H-2-818152	3	0	Viscometer Loop Diagrams Position Encoder	SQ	2	1	
16	H-2-818152	4	0	Viscometer Loop Diagrams Misc. Signals	SQ	2	1	
17	H-2-818152	5	0	Viscometer/Void Fraction Loop Diag. V/F Inst. Power & Cont.	SQ	2	1	
18	H-2-818153	1	0	Viscometer/Void Fraction Control Console Connection Diagram	SQ	2	1	
19	H-2-818153	2	0	Viscometer Instrument Cabinet Conn. Diagram	SQ	2	1	
20	H-2-818153	3	0	Viscometer/Void Fraction Control Console Connection Diagram	SQ	2	1	
21	H-2-818154	1	0	In Situ Viscometer Block Diagram	SQ	2	1	
22	H-2-818154	2	0	Viscometer Block Diagrams	SQ	2	1	
23	H-2-818156	1	0	Viscometer/Void Fraction Elementary Diagram	SQ	2	1	
24	H-2-818156	2	0	Viscometer/Void Fraction Elementary Diagram	SQ	2	1	
25	H-2-818157	1	0	Viscometer/Motor Controllers Schematic Diagrams	SQ	2	1	
26	H-2-818157	2	0	Viscometer Motor Controls Schematic Diagrams	SQ	2	1	
27	H-2-818157	3	0	Viscometer Motor Controls Schematic Diagrams	SQ	2	1	
28	H-2-821308	1	0	Viscometer Motor Controller A13 Assembly	SQ	2	1	
29	H-2-821309	1	0	Viscometer Motor Controller Connection Diagrams	SQ	2	1	
30	H-2-821309	2	0	Viscometer Motor Controller Connection Diagram	SQ	2	1	
31	H-2-821312	1	0	Viscometer Load Cell Modification	SQ	2	1	
32	H-2-821313	1	0	Viscometer Motor Controller A14 Assembly	SQ	2	1	
33	H-2-821310	1	0	Viscometer Intrinsic Barrier Wiring Diagram	SQ	2	1	
34	H-2-821310	2	0	Viscometer Motor & Load Cell Box Wiring Diagrams	SQ	2	1	
35	H-2-821311	1	0	Viscometer Intrinsic Barrier/Amplifier Enclosure Assembly	SQ	2	1	
36	H-2-821311	2	0	Viscometer Instrument Assembly	SQ	2	1	

ENGINEERING DATA TRANSMITTAL

Page 1 of 1

1. EDT 607601

2. To: (Receiving Organization) Special Projects	3. From: (Originating Organization) TWRS Safety Programs Eng. Support	4. Related EDT No.: N/A
5. Proj./Prog./Dept./Div.: Viscometer/Void Fraction SY-101 Mitigation Project	6. Cog. Engr.: J. D. Martin	7. Purchase Order No.: N/A
8. Originator Remarks: The purpose of this EDT is to release the drawing listed in block 15.		9. Equip./Component No.: N/A
		10. System/Bldg./Facility: 241-SY-101/Tank Farms
11. Receiver Remarks:		12. Major Assm. Dwg. No.: N/A
		13. Permit/Permit Application No.: N/A
		14. Required Response Date: 07/29/94

15. DATA TRANSMITTED					(F)	(G)	(H)	(I)
(A) Item No.	(B) Document/Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	Impact Level	Reason for Trans- mittal	Orgi- nator Dispo- sition	Recov- er Dispo- sition
1	H-2-818363	1	0	In Situ Viscometer/Void Fract. Instr. Systems Inst.	SQ	2	1	
2	H-2-818363	2	0	In Situ Viscometer/Void Fract. Instr. Systems Inst.	SQ	2	1	
3	H-2-818363	3	0	In Situ Viscometr/Void Fract. Instr. Systems Inst.	SQ	2	1	
4	H-2-818363	4	0	In Situ Viscometer/Void Fract. Instr. Systems Inst.	SQ	2	1	

16. KEY					
Impact Level (F)		Reason for Transmittal (G)			Disposition (H) & (I)
1, 2, 3, or 4 (see MRP 5.43)		1. Approval	4. Review	1. Approved	4. Reviewed no/comment
		2. Release	5. Post-Review	2. Approved w/comment	5. Reviewed w/comment
		3. Information	6. Dist. (Receipt Acknow. Required)	3. Disapproved w/comment	6. Receipt acknowledged

17. SIGNATURE/DISTRIBUTION (See Impact Level for required signatures)										(G)	(H)
Reason	Disp.	(J) Name	(K) Signature	(L) Date	(M) MSIN	(J) Name	(K) Signature	(L) Date	(M) MSIN	Reason	Disp.
2	/	Cog. Eng. J.D. Martin	<i>J.D. Martin</i>	7-26-94	L7-04						
2	/	Cog. Mgr. R.E. Bauer	<i>R.E. Bauer</i>	7/28/94	L6-37						
2	/	QA M.L. McElroy	<i>M.L. McElroy</i>	8-1-94	S1-57						
2	/	Safety L.S. Krogsrud	<i>L.S. Krogsrud</i>	8-2-94	R3-08						
		Env.									
2	/	Proj Eng T.I. Stokes	<i>T.I. Stokes</i>	7/29/94	H5-09						
2	/	Indep Rev L.A. Dellarocco	<i>L.A. Dellarocco</i>	7-26-94	H5-09						

18. J.D. Martin Signature of EDT Originator	19. <i>T.I. Stokes</i> 7-29-94 Authorized Representative for Receiving Organization	20. (above) R.E. Bauer Cognizant/Project Engineer's Manager	21. DOE APPROVAL (if required) Ltr. No. ☐ Approved ☐ Approved w/comments ☐ Disapproved w/comments
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DISTRIBUTION SHEET

To Special Projects	From TWRS Safety Programs Eng. Support	Page 1 of 1 Date 07/25/94
Project Title/Work Order Viscometer/Void Fraction SY-101 Mitigation Project		EDT No. 607601 ECN No.

Name	MSIN	Text With All Attach.	Text Only	Attach./ Appendix Only	EDT/ECN Only
R. E. Bauer	L6-37				X
L. A. Dellarocco	H5-09				X
E. Hansen	H5-09				X
L. S. Krogsrud	R3-08				X
J. W. Lentsch	S7-15				X
J. D. Martin	L7-04	X			
M. L. McElroy	S1-57				X
T. I. Stokes	H5-09	X + 4 sets "half size"			

APPENDIX K

CONSTANT TENSION DESIGN ANALYSIS

This design was not fully implemented or tested. It is attached for potential future use information only.

VISCOMETER INSTRUMENT MOTOR CONTROL DESIGN DERIVATION FOR CONSTANT-TENSION CONTROL

1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this appendix is to document the derivation of the design of the constant-tension control circuits.

1.2 MOTOR/CONTROLLER DESCRIPTION

Figure 1. Viscometer Motor Control Block Diagram

The block diagram for the Viscometer motor control is shown in Figure 1. Two standard permanent magnet, DC servo motors and servo amplifiers (motor controllers) are used to provide a precisely controlled speed range from less than 1 mm/s to greater than 1 m/s. Unity gain isolation amplifiers are used to electrically isolate the computer control and data lines from the more noisy motor control circuitry. Electromagnetic clutches are used to couple the appropriate motor to a common 15:1 worm gear speed reducer driving the cable take-up reel. Cable tension is measured by running the cable over an idler pulley mounted on a load cell. There are six load cell/idler assemblies that can be installed, ranging in capacity from 67 N (15 lb) to 2224 N (500 lb).

The servo amplifier for the high-speed motor is a bipolar, pulse-width modulated amplifier. Thus, direction is controlled by the polarity of the control signal, and the pulse width -- proportional to the input level -- determines the average voltage applied to the motor. Conversely, the low-speed motor servo amplifier is a linear, unipolar amplifier, so reversing relays (Direction Control) must be used to control direction, and the applied motor voltage is proportional to the input control voltage. The low-speed motor is a gearmotor with a 50:1 reduction, while the high-speed motor is direct drive to the worm gear reducer.

Figure 2. Simplified Tension Control Loop Diagram

A simplified motor control loop diagram -- applicable to either the low-speed or high-speed motor -- is given in Figure 2. The motors can be operated in either of two modes: constant speed or constant cable-tension. For constant-speed mode, the control, e_c , and tachometer, e_g , signals are feed directly to the servo amplifier in a standard "speed control" configuration. If the motor slows down due to increased load, the tachometer voltage decreases, which in turn causes an increase in the motor drive voltage, e_m . In the constant-tension mode, the amplified load cell voltage, e_t , and control voltage are feed to the separate Tension Control Feedback Amplifier whose output goes to the servo amplifier control voltage input. A change in cable tension results in a change in e_t , with a corresponding change in the motor drive voltage to bring the tension back to the control setting. This mode is similar to constant-torque control except that the feedback signal is not zero when the motor is stopped.

1.3 PHYSICAL PARAMETERS

The physical parameters affecting design of the Viscometer motor/controller system are given in Table 1. Other design parameters are provided in following sections as needed.

TABLE 1. Ball Rheometer Physical Parameters

PARAMETER	VALUE
Ball Diameter	9.144 cm (3.60 in)
Ball ¹ Density	17.756 g/cc (0.64145 lb/in ³)
Ball Weight	69.706 N (15.67 lb)
Ball Mass	7.108 kg (0.4870 slugs)
Waste Density	1.4 to 1.7 g/cc (.0506 to 0.0614 lb/in ³)
Waste Viscosity	0.5 to 10,000 poise
Cable Reel Diameter	16.71 cm (6.579 in)
Cable Diameter ²	3.175 mm (0.125 in)
Cable Weight	29.6 g/m (1.99 lb/100 ft)

NOTES: 1. Ball is solid tungsten with a high density polymer coating.
2. 2.38 mm (3/32 in) diameter stranded stainless steel cable with extruded high density conductive polymer sheath.

2.0 CABLE TENSION DYNAMIC EQUATION

2.1 NEED

In order to design the control circuits, it is necessary to first gain an understanding of the nature of the dynamic loads involved. Thus, we first derive the dynamic equations for the cable tension and subsequent load cell output.

2.2 BASIC DERIVATION

Let the motion of the ball be in a downward direction. The forces acting on the ball will then be as illustrated in Figure 3, where:

Figure 3. Forces Acting on the Viscometer Ball

T = cable tension
 F_b = buoyancy force
 F_d = drag force
 m = ball mass
 g = gravitational constant
 mg = ball weight
 V = velocity

and the weight and buoyancy of the cable are ignored for this analysis.

From D'Alembert's Principle we may write

$$\sum F_x - ma = 0 \quad (1)$$

$$\text{where: } a = \frac{d^2x}{dt^2}$$

The summation of forces in the X direction is

$$\sum F_x = mg - F_d - F_b - T \quad (2)$$

where :

$$F_b = \frac{1}{6} \pi D^3 \rho \quad (\text{buoyancy force of the ball}) \quad (3)$$

D = ball diameter
 ρ = waste density

$$F_d = \frac{1}{2} \rho C_d v^2 \frac{\pi D^2}{4} \quad (\text{drag force on the ball, from Streeter-1958}) \quad (4)$$

C_d = drag coefficient.

Assuming the fluid density is uniform over the distance being considered, Equation 2 may be rewritten as

$$\sum F_x = W' - F_d - T \quad (5)$$

where:

$$W' = mg - F_b \quad (\text{effective weight}). \quad (6)$$

Equation 1 then becomes

$$W' - F_d - T - m \frac{d^2x}{dt^2} = 0 \quad (7)$$

or, the cable tension is given by

$$T = W' - F_d - m \frac{d^2x}{dt^2} \quad (8)$$

The theoretical drag coefficient (from Gerhart-1985) is given by

$$C_d = \frac{24}{N_R} + \frac{6}{(1 + \sqrt{N_R})} + 0.4 \quad (9)$$

where:

μ = fluid viscosity

N_R = Reynold's number, $\rho VD/\mu$.

Substituting the Reynold's number expression into Equation 7, we have

$$C_d = \frac{24\mu}{\rho VD} + \frac{6\sqrt{\mu}}{(\sqrt{\mu} + \sqrt{\rho VD})} + 0.4 \quad (10)$$

The range of drag coefficient that may be encountered is shown in Figure 4.

Figure 4. Anticipated Range of Drag Coefficient

2.3 SIMPLIFICATION

To gain an understanding of the contribution of each term in the dynamic equation, it is helpful to have a simpler form of Equation 10. To that end, we now simplify the expression for the drag force.

Assume the Reynold's number range of interest is such that the first term of Equation 10 dominates. Substituting that term into Equation 4, we have

$$F_d = \frac{1}{2} \rho \left(\frac{24\mu}{\rho VD} \right) V^2 \frac{\pi D^2}{4}$$

or

$$F_d = 3\pi\mu VD, \quad (11)$$

which is in agreement with Equation 15, Article 337 of Lamb-1932. Equation 8 may now be written as

$$T = W'' - 3\pi\mu D \frac{dx}{dt} - m \frac{d^2x}{dt^2}. \quad (12)$$

Note that W' has been replaced by W'' (tare weight), where $W'' = W - F_o - F_c$, and F_c is the counterbalance force used on only the 15, 25 and 50 lb capacity load cells.

2.4 CABLE TENSION FORCES

Each of the three terms in Equation 12 contribute to the net cable tension. Knowing the possible range of each of the terms provides some insight into the importance of each of the terms. (Remember that the "measured" cable tension is twice the actual tension.)

- Tare weight (W''): Ranges from zero to 69.706 N (15.67 lb).
- Drag force (second term of Equation 12): The possible range of the viscous drag force is shown in Figure 5. It ranges from near zero at very low speeds up to nearly 10,000 N (2,248 lb) at maximum viscosity and speed.
- Acceleration force (third term of Equation 12): Under steady state conditions, the acceleration term is zero. However, the high-speed motor is capable of accelerating at 12,000 radians/s/s. Neglecting the inertia of the brake, couplings, gears, and cable reel drum and shafting, this translates into a linear acceleration of 6.8 g's. If the acceleration is upward, this would produce a maximum cable tension of 474 N (107 lb).

At relatively low speeds, acceleration will be the main contributor to changes in cable tension, at least during the start and stop periods. It could also dominate under varying drag conditions as the controller attempts to maintain constant tension.

Figure 5. Anticipated Ball Drag Force Range

2.5 RISING BALL

When the ball is being raised, the sign of the velocity term will be negative so the tension will increase. Similarly, upward acceleration will be negative, again increasing tension as expected.

2.6 LOAD CELL VOLTAGE

Referring to Figure 2, the Load Cell Amplifier output voltage can be written as

$$e_c = 2k_{LC}k_A T. \quad (13)$$

The amplifier gain (k_A) is set for 210, but the load cell sensitivity (k_{LC}) depends on which of the six load cell/idler assemblies is installed. Substituting the tension expression of Equation 12 and the k_A constant into Equation 13, we have the final expression for the voltage output from the load cell amplifier,

$$e_t = 420k_{LC}(W'' - \pi\mu Ddx/dt - md^2x/dt^2). \quad (14)$$

The values for k_{LC} are given in Table 2.

For understanding the dynamics of the motor/controller systems, it is more desirable to have Equation 14 in terms of motor shaft displacement rather than the given linear motion. Let S be the motor shaft rotational speed. We then have

$$dx/dt = 2\pi rk_g S \quad (15)$$

and

$$\frac{d^2x}{dt^2} = 2\pi rk_g \frac{dS}{dt}, \quad (16)$$

where: r = effective radius of the cable reel, i.e., the diameter of the centerline of the cable,

k_g = gear ratio, 1/15 for the high-speed motor and 1/750 for the low-speed.

TABLE 2: Load Cell Sensitivities

LOAD CELL RATING		LOAD CELL SENSITIVITY - k_{LC}	
lb	N	mV/N	mV/lb
15	66.7233	0.4397	1.956
25	111.2056	0.2672	1.189
50	222.4111	0.1329	0.5912
100	444.8222	0.0678	0.3016
250	1112.0555	0.0267	0.1188
500	2224.1110	0.0137	0.0609

Substituting Equations 15 and 16 into 14, we have

$$e_t = 420k_{LC}(W'' - 6\pi^2\mu Drk_g S - 2\pi r m k_g \frac{dS}{dt}) \quad (17)$$

Note that idler frictional forces are considered to be much smaller than the dead weight tension and are ignored.

3.0 TENSION CONTROL FEEDBACK AMPLIFIERS

The required transfer function for the Tension Control Feedback Amplifier when the ball is being lowered (see Figure 2) is of the form:

$$e_s = k_1 e_c - k_2 e_t \quad (18)$$

where it is assumed that a "positive" e_s drives the motor in the right direction. Note that k_1 and k_2 may be complex impedances and could also be negative. The form of Equation 18 for each of the four motor direction combinations and positive values of k_1 and k_2 are derived in Table 3.

The total loop gain of the summing amplifier plus servo amplifier must be considered in determining the values for k_1 and k_2 . While simulation analyses can provide a range of required values, testing must be performed to adjust the values as required to give the desired overall system behavior.

Table 3: Constant-Tension Control Parameters

DRIVE SYSTEM	BALL DIRECTION	SET CABLE TENSION ¹	SIGNAL POLARITY			e_s CHG.	REQUIRED CHG. ²		SUMMING AMPLIFIER EQUATION FORM
			e_c	e_t	e_s		$\bar{S}^3$	e_s	
LOW SPEED	DOWN	$W' - \epsilon$	+	+	+	↑	↑	↑	$k_1 e_c + k_2 e_t$
						↓	↓	↓	
	UP	$W' + \epsilon$	+	+	+	↑	↓	↓	$k_1 e_c - k_2 e_t$
						↓	↑	↑	
HIGH SPEED	DOWN	$W' - \epsilon$	-	+	-	↑	↑	↓	$k_1 e_c - k_2 e_t$
						↓	↓	↑	
	UP	$W' + \epsilon$	+	+	+	↑	↓	↓	$k_1 e_c - k_2 e_t$
						↓	↑	↑	

- NOTES: 1. $(W' - \epsilon) > 0$ and $2(W' + \epsilon) < \text{load rating of installed load cell}$, where ϵ is the expected drag force.
2. Required changes to restore tension to preset value.
3. Absolute value of motor speed.
4. ↑ signifies an increase in value, while ↓ signifies a decrease in value.

The conceptual circuits satisfying the equations in the right most column of Table 3 are shown in Figures 6 and 7. The low-speed circuit requires a reversing relay and two operational amplifiers in order to obtain the correct

Figure 6: Conceptual Low-Speed Constant-Tension Summing Amplifier

voltage to the unipolar controller. The high-speed circuit requires only one operational amplifier for the bipolar controller. The resistor values were selected to provide a gain of 100, although this may result in a total loop gain which is too high.

4.0 CONTROL VOLTAGE

4.1 BACKGROUND

The constant-tension mode is somewhat analogous to the more common constant-torque control, except for one major difference; the feedback signal is not zero when the motor is not running because of the effective static weight of the ball. To minimize acceleration effects, the motors should start with minimum speed -- ideally zero -- and ramp up to the speed required to produce the desired tension.

4.2 DISCUSSION

The only way to achieve zero initial speed is to initially have zero output voltage from the summing operational amplifiers. This is accomplished by offsetting the tare weight voltage with an equal voltage from the computer. Thus, the motor run control sequence should be as given below.

Figure 7: Conceptual High-Speed Constant-Tension Summing Amplifier

1. Set the mode control relay on the controller to constant-tension.
2. If the low-speed motor is being used, set the direction control relay for the desired direction.
3. Read the load cell voltage and save the value for later use when stopping.
4. Output a control voltage to the appropriate controller that is equal to the load cell voltage.
5. Close the controller enable relay.
6. Engage the clutch.
7. Ramp the control voltage to the desired set point tension voltage.

The stopping sequence should be roughly the inverse of the run sequence.

1. Ramp the control voltage to the load cell voltage read when starting.
2. Deenergize the clutch.
3. Open the controller enable relay.
4. Reset mode and direction relays, and control voltage as desired.

Figure 8 illustrates the behavior of the control, feedback and motor-drive voltages when lowering the ball. When raising the ball, the voltages will be similar except the load cell amplifier output voltage, e_t , will be greater when the ball is moving than it is when it is stopped.

5.0 LOAD CELL SIMULATOR

5.1 NEED

The motor/controller must be tuned for the constant-tension mode before placing the instrument into service. Operation of the Viscometer in simulated waste of any reasonable depth does not provide sufficient time to observe behavior and make any tuning adjustments -- moving 300 cm (9.84 ft) at 10 cm/s takes only 30 seconds. Further, since this control mode involves unproven circuits (Figures 6 and 7), uncontrolled ball motion could occur with the potential for equipment damage or personnel injury. Thus, for initial testing the motors must be disconnected from the cable reel, and a simulation of the amplified load cell signal must be used instead of the actual signal which is not available.

Figure 8: Constant-Tension Mode
Voltages When Lowering
the Ball

5.2 DERIVATION

Equation 17 can be simulated using standard operational amplifier circuit elements. The tachometer output from each of the motors provides the electrical signal proportional to the motor speed, S . We can now break down the various terms in Equation 17 into their analog equivalent.

The term outside the parentheses is simulated by an amplifier with fixed gain. However, there are six possible load cells (see Table 2), so this stage will have six different gain settings. This stage will be feed by the sum of the simulations of the terms within the parentheses.

The coefficient on the speed term, S , is represented by a gain stage. Since the viscosity, μ , is the quantity being measured and is anticipated to be somewhere within a four decade range, this amplifier must have variable gain in order to simulate a wide variation in viscosity. There will also be separate amplifiers for each drive motor/controller since each motor has a different gear ratio, k_g .

Figure 9: Conceptual Load Cell Amplifier Output Simulator

The simulation for the coefficient of the acceleration term, dS/dt , is a differentiator -- that is, a circuit that acts on only the rate of change in speed. The "W" term is equivalent to a constant voltage or offset. The operational amplifier equivalent expressions for the terms in Equation 17 are given in Table 4. The circuit for the simulated load cell output is illustrated in Figure 9. AR1 is an inverting differentiator for the acceleration

term and AR2 is a variable gain inverting amplifier for the velocity term. AR3 sums the dead weight voltage, e_w , with the output from AR1 and AR2. The voltage inputs to AR3 have a simulation units scaling factor of Volts/Newton. AR4 provides the fixed gain for the individual load cells. The equation for the analog equivalent of Equation 17 is (see Figure 9 for component designations)

$$e_t = \frac{R6}{R2} (e_w - \frac{R6}{R2} k_g S - R6C3k_g \frac{dS}{dt}) \quad (19)$$

The voltage swing and maximum input voltage for the operational amplifiers is $\pm 10V$. Since the maximum dead-weight and velocity terms are greater than that (see Table 4), a constant factor must be used to reduce those values to less than the allowable. The gain of AR4 can be increased a like ratio to reestablish the correct overall gain. Thus, Equation 17 can be rewritten as

$$e_t = 10(420)k_{lc} \quad (W''/10 - 6\pi^2\mu Drk_g S/10 - (2\pi mk_g dS/dt)/10) \quad (20)$$

$$\begin{array}{ccccccc} \text{so that} & \downarrow & & \downarrow & & \downarrow & \\ e_t = & R6/R2 & & (e_w - & (k_t R6/R2)S & - & (k_t R6C3)dS/dt) \quad (21) \\ & \downarrow & & & \downarrow & & \downarrow \\ & \text{AR4} & & & \text{AR2} & & \text{AR1} \end{array}$$

Table 4. Analog Equivalents of Equation 17 Terms and Their Anticipated Range of Values.

TERMS (1)		ANTICIPATED VALUE	
EQUATION 17	ANALOG EQUIV. (2)	MINIMUM	MAXIMUM
420 K_{lc} [V/N]	R_f/R_i [ND]	0.00577	0.1847
W'' [N]	e_w [V]	0.0	69.71
$6\pi^2\mu Drk_g$ [Ns]	$k_t R_f/R_i$ [Vs]	1.3572 E-3 2.7144 E-5	30.16 (3) 0.6032 (4)
$2\pi r m k_g$ [Ns ²]	$k_t R_f C_i$ [Vs ²]	4.9782 E-3 (5)	0.2489 (6)

- NOTES: 1. Units are given in brackets, where ND means non-dimensional.
2. The i and f subscripts indicate input and feedback, respectively.
3. High speed drive min/max.
4. Low speed drive min/max.
5. Low speed drive
6. High speed drive

The values for the components for the amplifier stages AR1 through AR4 of Figure 9 are given in Tables 5 and 6. The tachometer voltage constants are:

High Speed Motor, $k_t = 0.1825$ V/Rev/Sec
Low Speed Motor, $k_t = 0.1674$ V/Rev/Sec.

Table 5. Component Values for Simulator Circuits AR1 and AR2 of Figure 9

REFERENCE Eq. 21 & FIG. 9	LOW-SPEED			HIGH-SPEED			UNITS
	AR1	AR2-MIN	AR2-MAX	AR1	AR2-MIN	AR2-MAX	
$k_g R6C3$	4.978 E-4			2.489 E-2			v_s^2
R6C3	29.74 E-4			0.1364			s
C3	0.1 E-6			10 E-6			Farads
R6	29.4K			13.7K			Ohms
R7	29.4K			13.7K			Ohms
$k_g R6/R2$		2.714 E-5	6.032 E-2		1.357 E-4	0.3016	v_s
R6/R2		1.622 E-4	0.3603		7.437 E-4	1.653	ND
R2		1.00M	1.00M		100K	100K	Ohms
R6		162	360K		75	165K	Ohms
R7		1.00K	1.00K		1.00K	1.00K	Ohms

6.0 REFERENCES

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Table 6. Component Values for Simulator Circuits AR3 and AR4 of Figure 9

REFERENCE Eq. 21 & FIG. 9	AR3	AR4						UNITS
		LOAD CELL						
		SPI-15	SPI-25	SPI-50	SPI-100	SSB-250	SSB-250	
R2, R3, R4 & R6	10.0K							Ohms
R7	4.99K							Ohms
(e _w)MAX	6.971							Ohms
R _x	1.K							Ohms
R _y	1.15K							Ohms
4200k _{LC}		1.847	1.122	0.5582	0.2848	0.1120	0.0577	V/N
R2		10.0K	--	--	--	--	--	Ohms
R6		18.2K	11.3K	5.49K	2.80K	1.13K	576	Ohms
R7		2.00K	--	--	--	--	--	Ohms

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UP: $e_s = 100(e_c - e_t)$

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