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Pacific Northwest National Laboratory
Operated by Battelle for the
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Prepared for the U.S. Department of Energy
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Summary

Pacific Northwest National Laboratory researchers developed a material balance assessment methodology based on conservation of mass to detect possible waste leaking and mis-routings during the pipeline transfer of double-shell tank waste with variable waste properties and tank conditions at Hanford. It is intended to be a backup method to pit leak detectors.

The main factors causing variable waste properties and tank conditions are waste density changes caused by chemical reactions and gas generation/retention/release, the existence of a crust layer, and waste surface disturbance due to mixer pump operation during the waste transfer. If waste properties and tank conditions were constant, this mass-based material balance methodology could be simplified to a volume-based material balance.

The material balance assessment methodology was applied to three waste transfers: AN-105 first transfer of 911,400 gallons of in-line diluted supernatant liquid; AN-105 second transfer with 673,000 gallons of liquid waste; and AZ-102 slurry transfer of 150,000 gallons. Three instrumentation setups were considered: (A) feed and receiver tank levels and diluent flow meter; (B) flow meter at the beginning of the transfer pipeline and receiver tank level; and (C) diluent, feed, and receiver tank levels.

For constant waste properties and tank conditions, the largest material balance error with optimum instrumentation is 2,200 gallons out of 911,400 gallons transferred (AN-105 first transfer) using instrumentation setup B with Micro Motion Elite CMF 200 or T150 mass flow meter in the transfer pipeline and an Enraf™ in the receiver tank.

When uncertainties due to variable waste properties and tank conditions were included in the analysis, the material balance errors became much larger, ranging from 13,600 gallons (1.5% error) with instrumentation setup B to 68,400 gallons (7.2% error) with instrumentation setup A for the AN-105 first transfer.

An alternative instrumentation setup to reduce these errors would be to have a Micro Motion Elite CMF 200 or T150 mass flow meter at the both ends of the transfer pipeline. Using this alternative setup with variable waste properties and tank conditions, the material balance error from the AN-105 first transfer is reduced to 3,900 gallons in the transfer pipeline. Thus, depending on the operational accuracy needs, one can select

- volume-based material balance equations for constant waste properties and tank conditions
- mass-based material balance equations for variable waste properties and tank conditions with one or combinations of the three instrumentation setups (A,B, C)
- mass-based material balance equations for variable waste properties and tank conditions with the alternative instrumentation setup having mass flow meters at both ends of the transfer pipeline.

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1.0 Introduction

The objective of this study was to develop a material balance calculation methodology for variable waste properties and tank conditions to detect waste leaking and misroutings during the double-shell tank (DST) waste pipeline transfer between and within the 200 East and 200 West Areas of the U.S. Department of Energy's Hanford Site. Waste will be transferred from a DST either to another DST or to a waste treatment (vitrification) plant storage tank. This methodology is to address a Final Safety Analysis Report's recommendation to be able to perform material balance calculations as a backup method to pit leak detectors.

The volume-based material balance historically has been used successfully for constant waste properties and tank conditions. However, volume-based material balance is not satisfactory for cases with variable waste properties and tank conditions. This limitation is evident for the waste transfer from Tank 241-SY-101 (SY-101) to Tank 241-SY-102 (SY-102) performed in December 1999. In this case, the estimated amount of waste transferred to SY-102 based on SY-101 waste depth changes is 23% greater than the amount estimated by waste flow discharge measured in the pipeline (Mahoney et al. 2000). The main causes of this large discrepancy are attributed to waste density changes due to chemical reactions, gas release, and the existence of a crust and its changes during the waste transfer. This clearly illustrates that a material balance methodology must be based on conservation of mass to handle variable waste properties and tank conditions.

Thus we developed a material balance assessment methodology for variable waste properties and tank conditions. We performed the following:

- Developed material balance equations for variable waste properties and tank conditions
- Evaluated effect of instrumentation errors only on material balance accuracy with constant waste properties and tank conditions
- Identified possible approaches to address factors affecting waste properties and tank conditions such as chemical reactions, gas release, dissolution of a crust, and the ability to measure waste level when the mixer pumps are running
- Evaluated effects of variable waste properties and tank conditions on material balance accuracy
- Developed an alternative waste instrumentation setup.

We applied the developed material balance equations to three tank waste transfers to demonstrate how this material balance methodology can be used to determine waste leaking and misrouting:

- Tank 241-AN-105 first liquid waste transfer
- Tank 241-AN-105 second liquid waste transfer
- Tank 241-AZ-102 slurry waste transfer.

In Section 2, we derive the material balance equations for variable waste property and tank conditions. Section 3 describes their three application conditions. Section 4 presents application results on material balance errors due to 1) the measurement instrumentation errors under the constant waste property and tank conditions and 2) variable waste properties and tank conditions. We also present an alternative measurement instrumentation setup and its benefits in this section. Summary and conclusions are presented in Section 5, and cited references are listed in Section 6.

2.0 Development of Material Balance Equations

The three instrumentation setups assigned are described in Section 2.1. General material balance equations based on conservation of mass to handle variable waste properties and tank conditions are derived and their integration forms presented in Section 2.2. Simplified material balance equations for constant waste properties and tank conditions are derived from the general material balance equations and presented in Section 2.3.

2.1 Instrumentation Setups

The waste transfers to be evaluated are 1) low-activity waste feed (supernatant with minimal solids) with and without in-line dilution and 2) high-activity waste feed with no in-line dilution. The waste transfer system consists of a waste feed tank, a diluent (water) supply source (water tank or water pipe), waste transfer pipeline, and a waste receiver tank, as shown in Figure 2.1.

The material balance evaluation assumed that the instrumentation consists of one of the following three assigned configurations (see Figure 2.1):

- Measurement A: Tank waste levels (H_F and H_R) and diluent flow meter ($\rho_W Q_W$ or Q_W)
- Measurement B: Flow meter ($\rho_{FW} Q_{FW}$ or Q_{FW}) for diluted waste coming from the feed tank and waste tank level (H_R) in the receiver tank
- Measurement C: Tank waste levels (H_F and H_R) and diluent tank level (H_W).

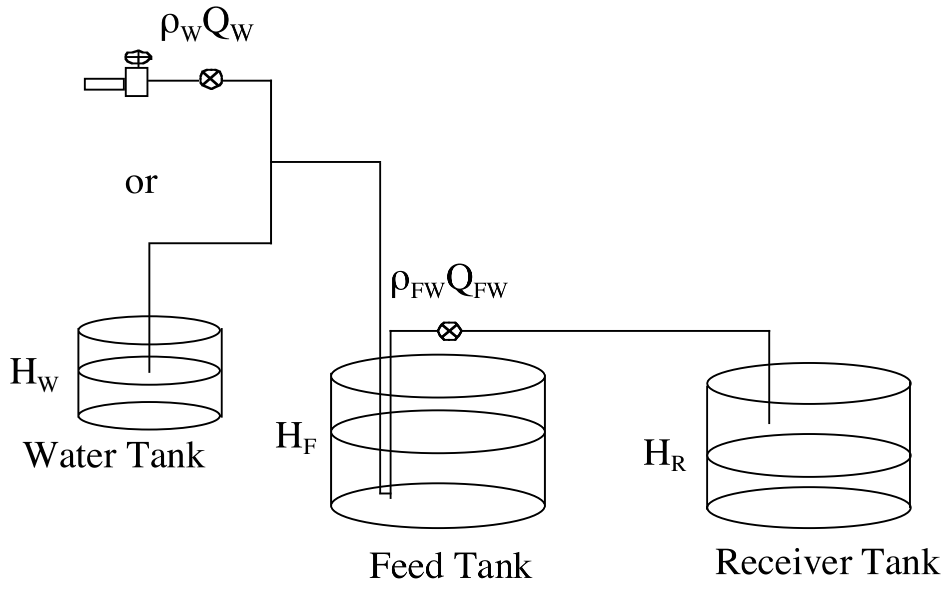

Figure 2.1. Waste Transfer System and Associated Instrumentation

where

H = height

Q = flow rate

ρ = density

and subscripts F, R, W = those of the feed tank, receiver tank, and water, respectively.

2.2 Material Balance Equations

Material balance equations were developed for each instrumentation setup. The assumptions made to develop the equations are given in Section 2.2.1. The general material balance equations are presented in Section 2.2.2, and their integration forms are given in Section 2.2.3.

2.2.1 Assumptions

To derive the material balance equations based on conservation of mass, we assumed

- variable waste and liquid densities
- variable water and waste feed flow rates
- variable cross sectional areas of water, feed, and receiver tanks
- water or waste initially contained in a receiver tank.

2.2.2 General Material Balance Equations

In the simplest terms, the conservation of mass states that

Loss of Feed Waste Mass + Water Mass Added = Mass Being Transferred
= Gain of Receiver Tank Waste Mass

or

Amount of Mass Error = Mass Being Transferred - Receiver Tank Mass.

We applied this conservation of mass to the three instrumentation setups.

- **Measurement A (known Q_w, H_F, H_R)**

Material balance error (including leaking or misroutings) over the transfer period may be expressed by

$$E = \int_{t=t_0}^{t=t_1} \rho_w Q_w dt - \int_{H_F=H_{F0}}^{H_F=H_{F1}} A_F \rho_F dH_F - \left[\rho_P \frac{\pi D_P^2 L_P}{4} + \int_{t=t_0}^{t=t_1} \rho_{FW} Q_{FW} dt - \int_{t=t_0}^{t=t_1} \rho_{PD} Q_{PD} dt \right] - \left[\int_{H_R=H_{R0}}^{H_R=H_{R1}} A_R \rho_R dH_R - A_R \rho_{R0} H_{R0} \right] \tag{2.1}$$

where

A = tank cross sectional area
D_P = pipe diameter
L_P = pipeline length
subscripts F0 and F1 = Feed tank values at the beginning and end of transfer
subscript PD = values at the downstream end of the pipeline
subscripts R0 and R1 = receiver tank values at the beginning and end of transfer
t, t_0, t_1 = time, time transfer began, and time transfer ended.

- **Measurement B (known Q_{FW}, H_R)**

Material balance error (including leaking or misroutings) over the transfer period may be expressed by

$$E = \int_{t=t_0}^{t=t_1} \rho_{FW} Q_{FW} dt - \left[\rho_P \frac{\pi D_P^2 L_P}{4} + \int_{t=t_0}^{t=t_1} \rho_{FW} Q_{FW} dt - \int_{t=t_0}^{t=t_1} \rho_{PD} Q_{PD} dt \right] - \left[\int_{H_R=H_{R0}}^{H_R=H_{R1}} A_R \rho_R dH_R - A_R \rho_{R0} H_{R0} \right] \quad (2.2)$$

- **Measurement C (known H_W, H_F , H_R)**

Material balance error (including leaking or misroutings) over the transfer period may be expressed by

$$E = -\int_{H_W=H_{W0}}^{H_W=H_{W1}} A_W \rho_W dH_W - \int_{H_F=H_{F0}}^{H_F=H_{F1}} A_F \rho_F dH_F - \left[\rho_P \frac{\pi D_P^2 L_P}{4} + \int_{t=t_0}^{t=t_1} \rho_{FW} Q_{FW} dt - \int_{t=t_0}^{t=t_1} \rho_{PD} Q_{PD} dt \right] - \left[\int_{H_R=0}^{H_R=H_{R1}} A_R \rho_R dH_R - A_R \rho_{R0} H_{R0} \right] \quad (2.3)$$

Equations (2.1) through (2.3) are general equations for variable waste properties and tank conditions. Waste densities, tank cross-sectional areas, and flow rates can vary during the waste transfer in these equations. In Section 4.2, we describe how these terms may be determined and apply them to the three transfer cases studied. The integral forms in Equations (2.1) through (2.3) may be calculated by as given in the following section.

2.2.3 Integration Forms

- **Integration forms for water tank mass flow, $\rho_W Q_W$ in Equation (2.1)**

Water mass, M_W, added to the waste is

$$M_W = \int_{t=t_0}^{t=t_1} \rho_W Q_W dt \quad (2.4)$$

With Simpson's rule (n = even integer),

$$M_W = \frac{\Delta t}{3}(\rho_{W0}Q_{W0} + 4\rho_{W0-\Delta t}Q_{W0-\Delta t} + 2\rho_{W0-2\Delta t}Q_{W0-2\Delta t} + 4\rho_{W0-3\Delta t}Q_{W0-3\Delta t} + ..$$
$$... + 2\rho_{W0-(n-2)\Delta t}Q_{W0-(n-2)\Delta t} + 4\rho_{W0-(n-1)\Delta t}Q_{W0-(n-1)\Delta t} + \rho_{W1}Q_{W1}) \tag{2.5}$$
$$\Delta t = \frac{t_1 - t_0}{n}$$

With the trapezoidal rule (n = integer)

$$M_W = \frac{\Delta t}{2}(\rho_{W0}Q_{W0} + 2\rho_{W0-\Delta t}Q_{W0-\Delta t} + 2\rho_{W0-2\Delta t}Q_{W0-2\Delta t} + 2\rho_{W0-3\Delta t}Q_{W0-3\Delta t} + ..$$
$$... + 2\rho_{W0-(n-2)\Delta t}Q_{W0-(n-2)\Delta t} + 2\rho_{W0-(n-1)\Delta t}Q_{W0-(n-1)\Delta t} + \rho_{W1}Q_{W1}) \tag{2.6}$$

Note that Simpson's rule produces more accurate integration values than the Trapezoidal rule does, but the latter may be easier to implement.

- **Integration Forms for Water Tank Height, H_W in Equations (2.2) and (2.3)**

Water mass lost in a water tank, M_W is

$$M_W = -\int_{H_W = H_{W0}}^{H_W = H_{W1}} A_W \rho_W dH_W \tag{2.7}$$

With Simpson's rule:

$$M_W = \frac{\Delta H}{3}(A_{W0}\rho_{W0} + 4A_{W0-\Delta H}\rho_{W0-\Delta H} + 2A_{W0-2\Delta H}\rho_{W0-2\Delta H} + 4A_{W0-3\Delta H}\rho_{W0-3\Delta H} + ...$$
$$+2A_{W0-(n-2)\Delta H}\rho_{W0-(n-2)\Delta H} + 4A_{W0-(n-1)\Delta H}\rho_{W0-(n-1)\Delta H} + A_{W1}\rho_{W1}) \tag{2.8}$$
$$\Delta H = \frac{H_{F0} - H_{F1}}{n}$$

With the trapezoidal rule:

$$M_W = \frac{\Delta H}{2}(A_{W0}\rho_{W0} + 2A_{W0-\Delta H}\rho_{W0-\Delta H} + 2A_{W0-2\Delta H}\rho_{W0-2\Delta H} + 2A_{W0-3\Delta H}\rho_{W0-3\Delta H} + ...$$
$$+2A_{W0-(n-2)\Delta H}\rho_{W0-(n-2)\Delta H} + 2A_{W0-(n-1)\Delta H}\rho_{W0-(n-1)\Delta H} + A_{W1}\rho_{W1}) \tag{2.9}$$

- **Integration Forms for Feed Tank Height, H_F in Equations (2.1) and (2.3)**

Waste mass lost in a feed tank, M_F is

$$M_F = -\int_{H_F = H_{F0}}^{H_F = H_{F1}} A_F \rho_F dH_F \tag{2.10}$$

With Simpson's Rule,

$$M_F = -\frac{\Delta H_F}{3}(A_{F0}\rho_{F0} + 4A_{F0-\Delta H}\rho_{F0-\Delta H} + 2A_{F0-2\Delta H}\rho_{F0-2\Delta H} + 4A_{F0-3\Delta H}\rho_{F0-3\Delta H} + \ldots \tag{2.11}$$

$$+2A_{F0-(n-2)\Delta H}\rho_{F0-(n-2)\Delta H} + 4A_{F0-(n-1)\Delta H}\rho_{F0-(n-1)\Delta H} + A_{F1}\rho_{F1})$$

$$\Delta H_F = \frac{H_{F0} - H_{F1}}{n}$$

With the Trapezoidal rule:

$$M_F = -\frac{\Delta H_F}{2}(A_{F0}\rho_{F0} + 2A_{F0-\Delta H}\rho_{F0-\Delta H} + 2A_{F0-2\Delta H}\rho_{F0-2\Delta H} + 2A_{F0-3\Delta}\rho_{F0-3\Delta H} + \ldots \tag{2.12}$$

$$+2A_{F0-(n-2)\Delta H}\rho_{F0-(n-2)\Delta H} + 2A_{F0-(n-1)\Delta H}\rho_{F0-(n-1)\Delta H} + A_{F1}\rho_{F1})$$

- **Integration Forms for Pipeflow Discharge, $\rho_{FW}Q_{FW}$ in Equations (2.1)~ (2.3)**

Diluted waste mass in at the pipeline upstream end, M_{FW} is

$$M_{FW} = \int_{t=t_0}^{t=t_1} \rho_{FW}Q_{FW}dt \tag{2.13}$$

With Simpson's rule,

$$M_{FW} = \frac{\Delta t}{3}(\rho_{FW0}Q_{FW0} + 4\rho_{FW0-\Delta t}Q_{FW0-\Delta t} + 2\rho_{FW0-2\Delta t}Q_{FW0-2\Delta t} + 4\rho_{FW0-3\Delta t}Q_{FW0-3\Delta t} + .. \tag{2.14}$$

$$\ldots + 2\rho_{FW0-(n-2)\Delta t}Q_{FW0-(n-2)\Delta t} + 4\rho_{FW0-(n-1)\Delta t}Q_{FW0-(n-1)\Delta t} + \rho_{FW1}Q_{FW1})$$

$$\Delta t = \frac{t_1 - t_0}{n}$$

With the Trapezoidal rule,

$$M_{FW} = \frac{\Delta t}{2}(\rho_{FW0}Q_{FW0} + 2\rho_{FW0-\Delta t}Q_{FW0-\Delta t} + 2\rho_{FW0-2\Delta t}Q_{FW0-2\Delta t} + 2\rho_{FW0-3\Delta t}Q_{FW0-3\Delta t} + ..$$

$$\ldots + 2\rho_{FW0-(n-2)\Delta t}Q_{FW0-(n-2)\Delta t} + 2\rho_{FW0-(n-1)\Delta t}Q_{FW0-(n-1)\Delta t} + \rho_{FW1}Q_{FW1}) \tag{2.15}$$

- **Integration Forms for Pipeflow Discharge, $\rho_{PD}Q_{PD}$ in Equations (2.1) ~ (2.3)**

Diluted waste mass at the pipeline downstream end, M_{PD} is

$$M_{PD} = \int_{t=t_0}^{t=t_1} \rho_{PD}Q_{PD}dt \tag{2.16}$$

With Simpson's rule,

$$M_{PD} = \frac{\Delta t}{3}(\rho_{PD0}Q_{PD0} + 4\rho_{PD0-\Delta t}Q_{PD0-\Delta t} + 2\rho_{PD0-2\Delta t}Q_{PD0-2\Delta t} + 4\rho_{PD0-3\Delta t}Q_{PD0-3\Delta t} + ..$$

$$... + 2\rho_{PD0-(n-2)\Delta t}Q_{PD0-(n-2)\Delta t} + 4\rho_{PD0-(n-1)\Delta t}Q_{PD0-(n-1)\Delta t} + \rho_{PD1}Q_{PD1})$$

$$\Delta t = \frac{t_1 - t_0}{n} \tag{2.17}$$

With the Trapezoidal rule:

$$M_{PD} = \frac{\Delta t}{2}(\rho_{PD0}Q_{PD0} + 2\rho_{PD0-\Delta t}Q_{PD0-\Delta t} + 2\rho_{PD0-2\Delta t}Q_{PD0-2\Delta t} + 2\rho_{PD0-3\Delta t}Q_{PD0-3\Delta t} + ..$$

$$... + 2\rho_{PD0-(n-2)\Delta t}Q_{PD0-(n-2)\Delta t} + 2\rho_{PD0-(n-1)\Delta t}Q_{PD0-(n-1)\Delta t} + \rho_{PD1}Q_{PD1}) \tag{2.18}$$

- **Integration Forms for Receiver Tank Height, H_R in Equations (2.1) ~ (2.3)**

Waste mass gained in a receiver tank, M_R, is

$$M_R = \int_{H_R = H_{R0}}^{H_R = H_{R1}} A_R \rho_R dH_R \tag{2.19}$$

With Simpson's rule:

$$M_R = \frac{\Delta H_R}{3}(A_{R0}\rho_{R0} + 4A_{R0-\Delta H}\rho_{R0-\Delta H} + 2A_{R0-2\Delta H}\rho_{R0-2\Delta H} + 4A_{R0-3\Delta H}\rho_{R0-3\Delta H} + ...$$

$$+2A_{R0-(n-2)\Delta H}\rho_{R0-(n-2)\Delta H} + 4A_{R0-(n-1)\Delta H}\rho_{R0-(n-1)\Delta H} + A_{R1}\rho_{R1}) \tag{2.20}$$

$$\Delta H_R = \frac{H_{R0} - H_{R1}}{n}$$

With the Trapezoidal rule:

$$M_R = \frac{\Delta H_R}{2}(A_{R0}\rho_{R0} + 2A_{R0-\Delta H}\rho_{R0-\Delta H} + 2A_{R0-2\Delta H}\rho_{R0-2\Delta H} + 2A_{R0-3\Delta H}\rho_{R0-3\Delta H} + ...$$

$$+2A_{R0-(n-2)\Delta H}\rho_{R0-(n-2)\Delta H} + 2A_{R0-(n-1)\Delta H}\rho_{R0-(n-1)\Delta H} + A_{R1}\rho_{R1}) \tag{2.21}$$

Time varying values of the water mass flow rate and those values in the water, feed, and receiver tanks must be estimated prior to the waste transfer, while those values in the pipeline may be measured during the transfer period to calculate these integrations.

2.3 Simplified Material Balance Equations under Constant Waste Properties and Tank Conditions

For

- constant densities of ρ_w, ρ_F, ρ_{R0}, and ρ_{R1}
- constant Q_w
- no solids settling within a pipeline, and
- $\rho_{FW} Q_{FW} = \rho_{PD} Q_{PD} = \text{constant}$
- pipeline flushed at the end to remove the waste from the line, Equation (2.1) becomes

$$E = \rho_W Q_W t_1 + A_F \rho_F (H_{F0} - H_{F1}) - A_R (\rho_{R1} H_{R1} - \rho_{R0} H_{R0}) \tag{2.22}$$

Similarly, under these conditions, Equations (2.2) and (2.3) become

$$E = \rho_{FW} Q_{FW} t_1 - A_R (\rho_{R1} H_{R1} - \rho_{R0} H_{R0}) \tag{2.23}$$

and

$$E = A_W \rho_W (H_{W0} - H_{W1}) + A_F \rho_F (H_{F0} - H_{F1}) - A_R (\rho_{R1} H_{R1} - \rho_{R0} H_{R0}) \tag{2.24}$$

These simplified mass balance equations (2.22–2.24) were used for the actual applications in this study, as will be discussed in Sections 3 and 4.

3.0 Material Balance Applications

The equations presented in Section 2 are used to evaluate possible material balance errors during Hanford waste transfers. In Section 3.1, the specific waste transfer scenarios evaluated are presented. Section 3.2 presents the instrumentation considered and used, and Section 3.3 summarizes the material balance statistical assessment methodology.

3.1 Transfer Scenarios

Three distinctly different transfer scenarios out of Hanford double-shell tanks (DSTs) were considered. They include the transfer and in-line dilution of supernatant liquid, the transfer of diluted settled solids, and the transfer of a mixed slurry. The specific cases considered are listed below.

Transfer 1: The first transfer from Tank 241-AN-105 (AN-105) is expected to remove approximately 584,000 gallons of supernatant liquid from the tank. This waste will be diluted in-line with water at 56% by volume, yielding a total transfer of approximately 911,400 gallons. The waste will be transferred into Tank 241-AN-102 (AN-102). It is assumed that 0.305 m of water is initially in AN-102 at the time of the transfer.

Transfer 2: After the supernatant liquid has been removed from AN-105, an in-tank dilution of the settled solids with water is planned at 79% by volume, after which the tank will be mixed. Data from Herting (1997) indicates that this dilution amount will dissolve the bulk of the soluble solids. The second transfer from AN-105 will be conducted after any remaining solids in the tank have been allowed to settle. The subsequent supernatant liquid transfer is estimated to be approximately 673,000 gallons. Two different receiver tanks are considered. The first is an empty DST, while the second is an empty 46-ft-diameter tank at the vitrification plant.

Transfer 3: Tank 241-AZ-102 (AZ-102) will be mixed before and during transfer. The waste transferred will therefore contain solids at approximately 2% by volume, as determined from Schreiber (1995)and Bingham et al. (2000). The transfer batch size is 150,000 gallons. Again, two receiver tanks are considered: an empty DST and an empty 25-ft-diameter tank at the vitrification plant.

3.2 Instrumentation

Three different instrumentation setups were discussed in Section 2.1. Instrumentation setups A and B require both waste flow and surface level measurements, while instrumentation setup C requires waste and water surface level measurements only.

The options evaluated for obtaining flow rate measurements included Coriolis mass flow meters, electromagnetic (EM) flow meters, and ultrasonic technologies. Ultrasonic devices for measuring both density and fluid velocity within a pipe exist (Hylton and Bayne 1999; Greenwood and Bamberger 2000), but at its current stage of development, the technology does not appear to provide the accuracy or reliability that is obtained with commercially available

Coriolis and EM meters. No further discussion of ultrasonic technologies will be presented. EM meters only measure the fluid velocity; therefore, to obtain mass-flow measurements, the density must be known or obtained using a second device. Coriolis meters measure both the density and mass flow directly.

The waste and water surface levels are measured with an Enraf™ buoyancy gauge. These devices are already employed in the Hanford waste tanks, and Hedengren et al. (2000) note that the Enraf is potentially the most reliable surface level indicator because it is not subject to the build up of waste deposits, nor does it disturb the surface on which it rests.

3.2.1 Electromagnetic Flow Meters

Electromagnetic (EM) flow meters apply Faraday's Law for electromagnetic induction to obtain the velocity of a conductive fluid. As a conductive fluid passes through a magnetic field, a voltage results. The magnitude of the voltage is directly proportional to the fluid velocity, the magnetic field strength, and the pipe diameter. For in-line meters, the magnetic field and the fluid velocity are perpendicular; therefore, the velocity can be described by

$$U = \frac{V}{KBD} \tag{3.1}$$

where U is the average fluid velocity, V is the induced voltage, K is the proportionality constant, B is the magnetic field strength, and D is the pipe diameter.

EM meters are not affected by changes in the fluid density or viscosity (direct current meters have been susceptible to noise resulting from high-viscosity fluids) and result in negligible pressure drop because their flow channel is a short section of straight pipe. Both direct current (DC) and alternating current (AC) EM meters exist. Pulsed-DC systems operate at low frequencies (4 to 7 Hz), which allows the electronics to be re-zeroed between the pulses. However, the low sampling frequency of the meters makes them susceptible to noise from the flow of slurries, electrochemical reactions, and high viscosities.

AC EM meters reverse polarity at 60 Hz and are less susceptible to the noise from the flow of slurries. However, the AC meters do experience zero drift.

Yokogawa manufactures a dual-frequency EM meter that is intended to allow for continual re-zeroing while maintaining immunity to noise created by flowing slurries. The instrument has a carrier frequency of 7 Hz with a low pass filter and a 72-Hz superimposed high-frequency waveform. The accuracy of these meters is rated at 0.5% volume flow rate for a flow rate range of 20% of the span and higher. The accuracy of an EM meter depends on a uniform conductivity over the cross-section of the pipe. Variations in conductivity can occur with incomplete mixing of an added fluid such as in water dilution or stratification of a slurry flow. The stratification of slurries often results in reduced accuracy at higher percentages of the flow range than that specified by the manufacturer.

The Yokogawa EM meters can be installed in vertical or horizontal orientations. It is recommended that a vertical orientation be used for slurries. Flow should be upward through the vertically oriented meter. Five to 10 pipe diameters of straight pipe are required upstream of the meter, depending on the upstream pipe components.

A 2-in. Yokogawa EM meter, model AE14-Da1A/ff1/FN1, was installed in the temporary transfer line used for the waste transfer and back-dilution operations performed to remediate Tank 241-SY-101 in 1999 and 2000 (Estey 2000). The meter was installed as general service equipment as opposed to safety-class or safety-significant equipment. The meter operated successfully throughout the waste transfer sequences.

Yokogawa has not designed any of their instruments for a radiation environment. The wire insulation used in the sensors is either Teflon or polyvinylchloride (PVC), depending on the model. The meter was selected for the SY-101 application based on successful applications with core sampling trucks, the temporary nature of the application, and the safety class of the equipment.

3.2.2 Coriolis Mass Flow Meters

Coriolis meters measure both mass flow rate and density directly with the parameters of mass, time, and length being the bases of all measurements. Mass flow-rate measurements are accurate under conditions of changing viscosity, conductivity, density, and temperature of the flowing fluid. The principle of operation is based on Newton's second law.

The sensor contains a flow tube, which has a symmetrical flow path lying in a single plane. Common configurations of flow tubes have included D- and U-shaped geometries. Improvements in sensor technology and electronics now allow measurements to be obtained from straight flow tubes. The flow tube is vibrated at the natural frequency of the filled tube using a feedback circuit and drive coil. The vibration is induced at the midpoint of the flow tube such that the resulting motion of the tube is perpendicular to the plane of the flow tube.

As fluid enters the flow tube, it takes on the lateral momentum of the vibrating tube. As the fluid is accelerated in the lateral direction, a force is applied to the wall of the flow tube. As the fluid approaches the exit of the tube, it resists having its lateral motion decreased. The resulting force applied to the tube wall at the downstream side of the flow tube is opposite in direction to that imposed on the upstream half of the tube. These forces cause the flow tube to twist or bend. The forces applied to the flow tube switch direction with each half cycle.

The amount of twist or bend in the flow tube is directly proportional to the mass flow rate of material through the tube. The lateral velocities of both the upstream and downstream sides of the flow tube are measured. The time difference between the velocity detector signals appears as a phase shift and indicates the twist of the flow tube. The phase shift between the velocity signals indicates a mass flow rate. If no flow exists, than no twist is created in the flow tube and the measured velocities are in phase.

The density of the material in the flow tube is obtained from measuring the natural frequency of the system. The total mass of the tube and internal material is related to the natural frequency through the following relationship:

$$m_{Total} = \frac{k}{f^2 4\pi^2} \tag{3.2}$$

where k is the factory-determined spring constant and f is the natural frequency of oscillation. The density is obtained by subtracting the known mass of the tube and dividing by the internal volume of the flow tube.

An important fact to be noted about Coriolis meters is that they are not designed to obtain an average value over the length of the flow tube. The fluid properties over the length of the flow tube are assumed constant. High-frequency transients such as slug flow or rapidly fluctuating slurry concentrations result in inaccurate measurements. Length scales associated with the nonhomogeneity of the fluid must be significantly greater than the length of the flow-meter sensor tube.

Coriolis meters are not affected by upstream piping configurations other than geometries that may allow gas to accumulate, which can result in periodic releases of bubbles introducing noise in the measurements. Coriolis meters are manufactured by Krohne, Endress & Hauser, Foxboro, and Micro Motion. Micro Motion manufactures approximately 95% of the Coriolis meters currently in production. The majority of information pertaining to the application of Coriolis meters is associated with Micro Motion due to their overwhelming market share. Most of PNNL's experience within the DOE complex has been with Micro Motion meters, though there is some limited experience with Krohne meters (Reynolds et al. 1996; Enderlin et al. 1997; Powell et al. 1999). Based on these facts, various models of Micro Motion meters were evaluated to access the potential meter accuracy attainable.

The Elite® series models available for this flow range includes the CMF200 and CMF300, which are two- and three-inch models, respectively. The flow through both of these meters is routed through two channels with diameters considerably smaller than the nominal size of the meter. Based on vendor specifications, the accuracies attainable with these meters for mass flow rate are 0.16% and 0.18% of the reading for the CMF200 and CMF300, respectively. The specified uncertainty in density for both meters is 0.0005 g/mL.

Based on working experience and the review of process data for homogeneous slurries, the uncertainty in mass flow rate for the CMF200 is predicted to be 0.2% over the range of 1000 to 2000 lb/min. The accuracy of the CMF300 is questioned due to the operating range of the meter. The process flow rate range specified for the waste transfers (e.g., AN-105 and AZ-102 waste transfers) was 1000 to 2000 lb/min. The CMF300 operating range is 0 to 10000 lb/min compared with 0 to 3200 lb/min for the CMF200. For application to slurries, significant deviations from vendor specifications for accuracy have been observed at flow rates less than 20% of the meter range. Figure 3.1 plots meter accuracy and percent of meter full-scale flow rate. The vendor-specified accuracy is presented along with two plots that have been obtained from experimental testing at PNNL.

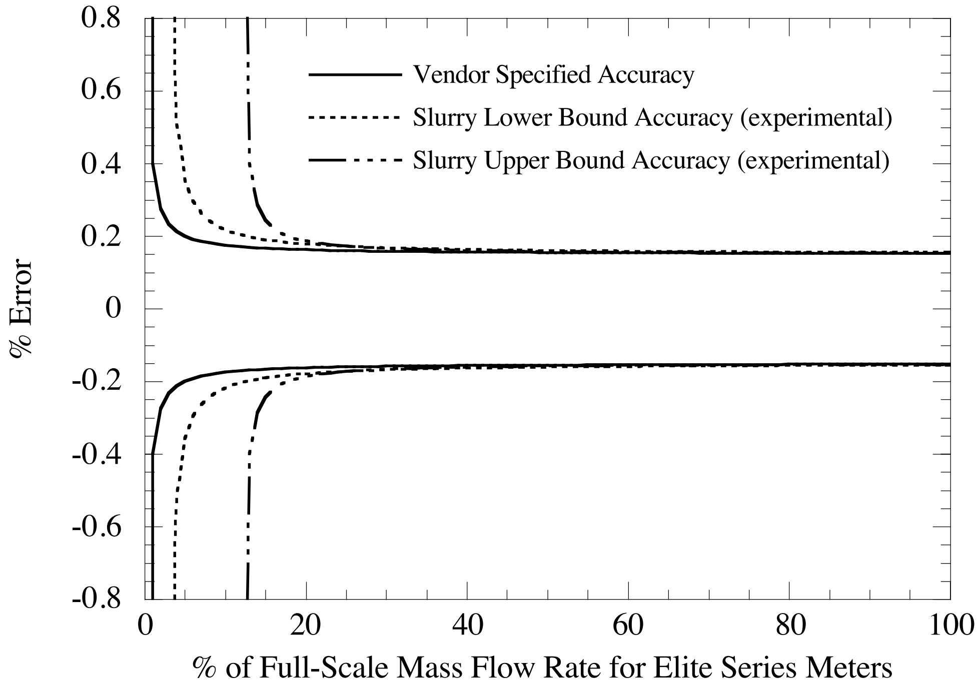

Figure 3.1. Percent Error as a Function of the Percent of Full-Scale Mass Flow Rate for Elite Series Micro Motion Flow Meters

The two plots of experimental data shown in Figure 3.1 represent the upper and lower bounds of meter accuracy that have been observed during tests with suspended slurries. Testing has been conducted with slurries containing granular material such as zeolite and silica sand and cohesive material such as kaolin clay. The carrier fluids have consisted of water and mixtures of water, sugar, and salt. The specific gravities of the slurries have ranged from 1 to approximately 1.5. The bounding results presented are based on experimental work conducted at PNNL that has yet to be published.

It is unclear how the observed deviations between the vendor specified accuracy and the experimental results are related to various slurry properties such as particle concentration, particle settling velocity, or size particle distribution. No attempt has been made to analyze the results obtained.

Testing of a CMF300 was performed at PNNL for Project W211 at Hanford (Reynolds et al. 1996) for flow rates of approximately 1500 to 2200 lb/min. The accuracy of the meter for mass flow rate was determined to be on the order of 8%. Several items were considered to contribute to the high uncertainty, including the range of flow rates tested relative to the span of the meter. The results of the W211 testing were not considered in the development of Figure 3.1.

The T series of Micro Motion meters consists of a single straight flow tube. The model T150 is the largest-diameter straight-tube configuration currently produced by Micro Motion. It has an internal diameter of 1.37 in. The vendor-specified accuracy for a flow rate of 1000 lb/min is

0.2% of the reading; for the T150 the density accuracy is 0.002 g/mL. PNNL has no experience or process data obtained with a T-series meter.

The Micro Motion sensors are not sensitive to a radiation environment. The associated transmitters have not been hardened for a radiation environment, but the transmitters can be located up to 1000 ft from the sensor.

The Micro Motion meters are capable of measuring the flow rate in either direction through the meter. Programming options allow the meter to indicate positive flow in the forward, reverse, or both directions (i.e., all flow through the meter yields a positive value). No sacrifice in accuracy is incurred with the various options.

Two-inch straight tube Coriolis meters are reported to be manufactured by both Krohne (Model 800 G+) and Endress and Hauser (Promass 40 E). The Promass 40 E has a range of 0 to 2600 lb/min and accuracy in mass flow rate of 0.5% of reading or higher depending on flow rate. The 800 G+ has a range of 33 to 3520 lb/min and a specified accuracy of 0.16% of reading or higher depending on flow rate.

3.2.3 Enraf Buoyancy Gauge

The Enraf buoyancy gauge sits stationary on the waste or water surface. The instrument consist of a displacer suspended on a retractable/extendable wire connected to a force transducer. From Archimedes' principle, the displacer, when partially immersed in the waste surface, is buoyed up by a force equal to the weight of the displaced fluid.

The device operates by measuring the apparent weight of the displacer after partial immersion into the waste surface. This apparent weight is programmed into the device. In equilibrium conditions, the apparent weight of the displacer matches that measured by the force transducer. With changing waste level, the force transducer will experience a change in weight. The wire is then retracted/extended until the programmed apparent weight of the displacer is again measured by the force transducer. The change in wire length then gives the change from the reference level, allowing for determination of the new waste level.

Yokogawa and Micro Motion flow meters and the Enraf buoyancy gauge were considered in this study. Measurement errors associated with these devices are given in Table 3.1.

Table 3.1 Instrumentation Errors

Device	Error	Distribution
Yokogawa (AM400)	± 1.0 %	uniform
Yokogawa (AM300D)	± 0.5 %, water	uniform
Micro Motion (R Series)	± 0.5 %	uniform
Micro Motion (Elite CMF200 or T150)	± 0.2 %, waste ± 0.25 %, water	uniform normal
Enraf	± 0.00254 m	uniform

3.3 Statistical Assessment Methodology

A Monte Carlo simulation approach was used to investigate the error propagation associated with tank waste transfers. When adequate sampling is not achievable, Monte Carlo simulation studies can be employed to obtain good estimates of uncertainty.

Input distributions and their appropriate parameters are identified and determined, based on physical and engineering knowledge, to create scenarios that could possibly occur given every known possible combination of events. Each value used for the inputs is randomly sampled from an infinite population featuring the specified distribution and appropriate parameters. The typical distributions used for these inputs were uniform and normal (bell-shaped) distributions.

For each case, 2.5 million simulation runs were conducted. Sampling a large number of cases increases the chance that every possible combination of inputs is exhausted. The outputs represent all possible physical scenarios given the conditions constrained by the inputs. However, despite the number of runs conducted for each case, there is low probability that the extreme values for each parameter will be combined. Typically, therefore, the 100% interval results from these simulations are 0.5 to 10% less than conservative and highly unlikely point-estimation values, which combine all extreme parameter values.

4.0 Application Results and Evaluations

The equations given in Section 2.2 were applied to the three specific transfer scenarios outlined in Section 3.1. The material balance error solely due to the instrumentation is discussed in Section 4.1. In this case, the waste properties and tank conditions are held constant. In Section 4.2, the waste properties and tank conditions are varied and the instrumentation errors altered to account for in-tank conditions to determine the total expected material balance error.

4.1 Constant Waste Properties and Tank Conditions (instrumentation error)

Material balance errors due solely to instrumentation error dictate a limit above which any material balance error identified could be attributed to effects other than the instrumentation. In other words, if the material balance error due to the instrumentation is larger than the error due to effects other than actual leakage or mis-routing, no definitive leak detection is available from the material balance. In this section, material balance errors are evaluated under constant waste properties and tank conditions.

4.1.1 Summary of Input Data

The constant waste properties and tank conditions for the three transfers are given in Table 4.1. Instrumentation errors are taken from Table 3.1. The waste data are taken or determined from Hedengren et al. (2000), Herting (1997), Schreiber (1995), and Bingham et al. (1999). Note that, in order to achieve the total transfer volume for Transfer 2 and 3, multiple transfers may be required for the vitrification plant tanks.

Table 4.1 Transfer Parameters

Parameter (units)	AN-105 First Transfer	AN-105 Second Transfer	AZ-102
Feed Waste Volume (gal)	584,000	673,000	150,000
Dilution Water Volume (gal)	327,400	NA[(a)]	NA
Dilution Water Density (kg/m^3)	992	NA	NA
Feed Tank Diameter (ft)	75	75	75
Feed Waste Density (kg/m^3)	1430	1280	1147
Feed Tank Initial Height (m)	10.41	7.58	7.92
Feed Tank Final Height (m)	5.02	1.37	6.54
Receiver Tank Diameter (ft)	75	75 or 46	75 or 25
Receiver Tank Initial Height (m)	0.305	NA	NA
Receiver Tank Initial Density (kg/m^3)	1,000	NA	NA
Receiver Tank Final Height (m)	8.711	6.21, DST	1.38, DST
Receiver Tank Final Density (kg/m^3)	1269	1280	1147
(a) NA denotes not applicable.			

4.1.2 Waste Material Balance Results

The material balance errors due to the instrumentation were evaluated using Equations (2.22), (2.23), and (2.24). As discussed in Section 3.3, a Monte-Carlo simulation approach was used for error propagation.

Three sets of measurements and three different transfer scenarios were considered, as presented in Sections 2.1 and 3.1. In addition, different flow meters and receiver tanks are considered. To facilitate the presentation and discussion of the results, these different cases are denoted in the following manner:

- **Measurement Sets**

A. Waste tank levels and diluent flow totalizer
B. Flow totalizer for diluted waste and receiver tank level
C. Waste and dilution tank levels

- **Transfer Scenarios**

1. AN-105 first transfer, 911,400 gallons
2. AN-105 second transfer, 673,000 gallons
3. AZ-102, 150,000 gallons

- **Flow Meters**

MM1. Micro Motion (R Series)
MM2. Micro Motion (Elite CMF 200 or T150)
Y1. Yokogawa (AM400)
Y2. Yokogawa (AM300D)

- **Receiver Tanks**

VPT. Vitrification plant tank
No designation of a receiver tank indicates that it is a DST.

Therefore, case A/2/MM1/VPT denotes measurement set A, waste tank levels and diluent flow totalizer; Transfer scenario 2, AN-105 second transfer, 673,000 gallons; flow meter MM1, Micro Motion (R Series); and receiver tank VPT, the vitrification plant tank. Likewise, case A/2/MM1 would denote the same except the receiver tank would now be a DST.

The error results for Transfers 1, 2, and 3 are presented in Table 4.2, 4.3, and 4.4, respectively. The 95% confidence interval and 100% interval (includes all outcomes given all input scenarios) for the largest material balance error are presented in the second and third columns. The percentage error of the 100% interval value compared with the total transfer is given in column 4. Columns 5 and 6 indicate the confidence interval about the mean error.

Table 4.2. Instrumentation Material Balance Error for Transfer 1

Case	Error (gal)		Error (%)	Error (gal)	
	95% CI	100% I	100% I	U 95% Mean CI	L 95% Mean CI
A/1/MM1	-1700	2000	-0.23	22	-22
A/1/MM2	800	1300	0.14	11	-10
A/1/Y1	2500	3300	-0.36	42	-40
A/1/Y2	-1700	2000	-0.23	22	-22
B/1/MM1	4600	5000	-0.54	74	-72
B/1/MM2	1800	2200	-0.24	29	-31
B/1/Y1	8700	9400	-1.05	149	-141
C/1	-600	-1000	-0.11	9	-9

Table 4.3. Instrumentation Material Balance Error for Transfer 2

Case	Error (gal)		Error (%)	Error (gal)	
	95% CI	100% I	100% I	U 95% Mean CI	L 95% Mean CI
A/2	500	800	0.11	7	-8
A/2/VPT	-1300	1900	-0.28	19	-20
B/2/MM1	3500	3600	-0.54	54	-54
B/2/MM2	1300	1600	-0.24	22	-22
B/2/Y1	6400	7000	-1.04	107	-108
B/2/MM2/VPT	1400	1600	-0.24	23	-21
C/2	500	-800	-0.12	8	-7
C/2/VPT	-1300	1900	-0.28	19	-20

Table 4.4. Instrumentation Material Balance Error for Transfer 3

Case	Error (gal)		Error (%)	Error (gal)	
	95% CI	100% I	100% I	U 95% Mean CI	L 95% Mean CI
A/3	500	-800	-0.52	8	-7
A/3/VPT	-900	1100	-0.75	13	-12
B/3/MM1	900	1000	-0.68	12	-13
B/3/MM2	-400	-600	-0.38	6	-7
B/3/Y1	1500	1700	-1.18	25	-23
B/3/MM2/VPT	300	400	-0.24	5	-5
C/3	500	800	0.52	8	-8
C/3/VPT	900	1100	-0.75	13	-12

4.1.3 Evaluation

The material balance errors due to the instrumentation are relatively small, typically accounting for less than 1% of the total transfer. For transfer into another DST, the 100% interval error for Transfer 1 ranged from 1,000 to 2,200 gallons, for Transfer 2 from 800 to 1,600 gallons, and for Transfer 3 from 600 to 800 gallons. The results for transfer to the vitrification plant tanks depended on the diameter of the tank and the number of transfers required to achieve the same total transfer volume. For Transfer 2, the material balance error ranged from 1,600 to 1,900 gallons, and for Transfer 3 from 400 to 1,100 gallons. The upper and lower 95% confidence intervals about the mean show that, for each transfer, the main error was approximately zero. The material balance error due to the instrumentation is small enough that the error due to effects other than actual leakage or mis-routing is identifiable.

In general, height measurements alone produced lower material balance errors. However, as discussed in detail in Section 4.2.1, the variable waste properties and tank conditions that are to be expected during the transfer of saturated wastes make the height measurements subject to significant amounts of error. In instances where the feed or receiver tank has constant waste properties and tank conditions, the instrumentation material balance error would apply. This situation could occur in transfer scenarios 2 and 3 with measurement set B. For these cases, there are variable waste properties and tank conditions in the feed tank and the mass flow meter in the pipeline would provide accurate density measurements of the waste being transferred into the receiver tank. Therefore, the instrumentation material balance error would apply for the receiver tank.

4.2 Variable Waste Properties and Tank Conditions

It has been established in Section 4.1 that the expected transfer instrumentation will provide sufficiently accurate results to be able to assess the material balance error due to variable waste properties and tank conditions. The factors affecting the waste properties, tank conditions, and measurements are considered in detail and are applied to the material balance equations. These results are presented in Sections 4.2.6 through 4.2.8.

4.2.1 Factors Affecting Accurate Measurements of the Waste Height

Height measurements in the feed, receiver, and water tank may be affected by the following factors:

- Density changes due to chemical reactions
- Density changes due to gas generation, retention, and release
- Density changes due to temperature change
- Heterogeneous waste distribution
- Existence of crust and its potential dissolution
- Changes of tank cross-sectional area (e.g., due to crust hanging on the tank wall)
- Waste surface disturbance due to mixer and transfer pump operations and waste distribution.

Density changes have the potential to alter the apparent volume of the waste by as much as 7% (based on numerous dilution studies performed on Hanford waste, documented gas generation, retention and release behaviors, and known chemical solubility data). Factors such as waste surface irregularities can also cause uncertainties in the height measurement of up to 0.2 m (Hedengren et al. 2000). Photographs of the waste surfaces in many of the Hanford tanks show considerable irregularity. Double-shell tank 241-SY-101 (SY-101) has two Enraf devices deployed in it, and, prior to the transfer activities, they differed approximately 0.5 m in waste height indication (about 54,000 gallons of waste) due to their different locations on the waste surface (Kirch et al. 2000).

The 1999–2000 transfers of SY-101 diluted slurry to DST 241-SY-102 (SY-102) provides an illustrative example of the difficulties encountered using height measurements for a material balance. Prior to the transfer activities, SY-101 had the most concentrated waste of any of the DSTs and had developed a crust layer approximately 3 m thick. Approximately 15,000 scf of gas was retained in the tank (Rassat et al. 2000). SY-102 continues to serve as a receiver tank for process water and salt-well pumped liquid from other 200 West Area tanks. It contained approximately 7.4 m of dilute waste prior to the first transfer from SY-101. Waste height measurements in both SY-101 and SY-102 were recorded during the transfers. A Yokogawa flow meter was installed in the transfer line. An overview of the tank histories and detailed presentation and discussion of the transfer data may be found in Mahoney et al. (2000).

The potential existed for many of the previously listed factors to affect the height measurement in SY-101, but the potential was much less in SY-102. The flow meter total flow is compared in Table 4.5 with that determined from the level measurements in each of the tanks for each of the three transfers conducted. The discrepancy between the level and flow meter measurements for the first transfer is about 23% for SY-101. As the gas inventory in SY-101 was reduced and the subsequent back-dilutions dissolved the crust layer, the apparent error from the level measurement in SY-101 decreased significantly.

Table 4.5. SY-101 Transfer Volume Comparison

Transfer	Transfer Volume: Yokogawa Flow Meter (gal)	Transfer Volume: SY-101 Surface Level[(a)] Enraf 1A (gal)	Transfer Volume: SY-102 Surface Level Enraf (gal)	SY-101 SL % Error (to flow meter)	SY-102 SL % Error (to flow meter)
1	170050	209304	169976	23.08	-0.04
2	432900	483326	418662	11.65	-3.29
3	383240	395606	387432	3.23	1.09
(a) In-line dilution water was added.					

Gas release alone from SY-101 could account for a bulk density change of 5%, amounting to almost 0.5 m of waste height. There is also photographic evidence of the retention of a 1-m-thick crust ring on the tank wall in SY-101 during the first and second transfers. Figure 4.1 shows the waste surface in SY-101 during the first transfer. The center of the waste surface has lowered due to the transfer, but a ledge or shelf of material can be seen close to the tank wall that has retained its original position. During the second transfer and back-dilution, this retention on the wall was even more apparent. Figure 4.2 shows the waste material on the wall during the back-dilution following the second transfer. The waste material covering the wall area on the left side of the picture had recently sloughed off, leaving the waste material seen on the right side. For a 1,000,000-gallon transfer, wall retention of crust material of this magnitude could account for a 0.2 m change in the waste height (~22,000 gallons).

Figure 4.1 Tank Wall Waste Retention During Transfer 1

Figure 4.2 Tank Wall Waste Retention After Transfer 2

The effects of waste surface irregularities on the height measurement were also demonstrated during the SY-101 transfer. During the back-dilution after the second transfer, the bulk of the crust layer was dissolved. The Enraf in riser 1A was observed to be significantly affected by this process. The Enraf displacer can be seen on the solid waste surface in the upper left photo in Figure 4.3. The displacer is approximately 4 in. from top to bottom. As the back-dilution progressed, the solids subsided into the liquid below, burying the displacer (lower left photo). The displacer returned to a level position on the liquid surface approximately 10 hours later. The change in position of the Enraf displacer over the 16 hour period due to changing waste surface can account for approximately 0.4 m of apparent waste height change (~40,000 gallons).

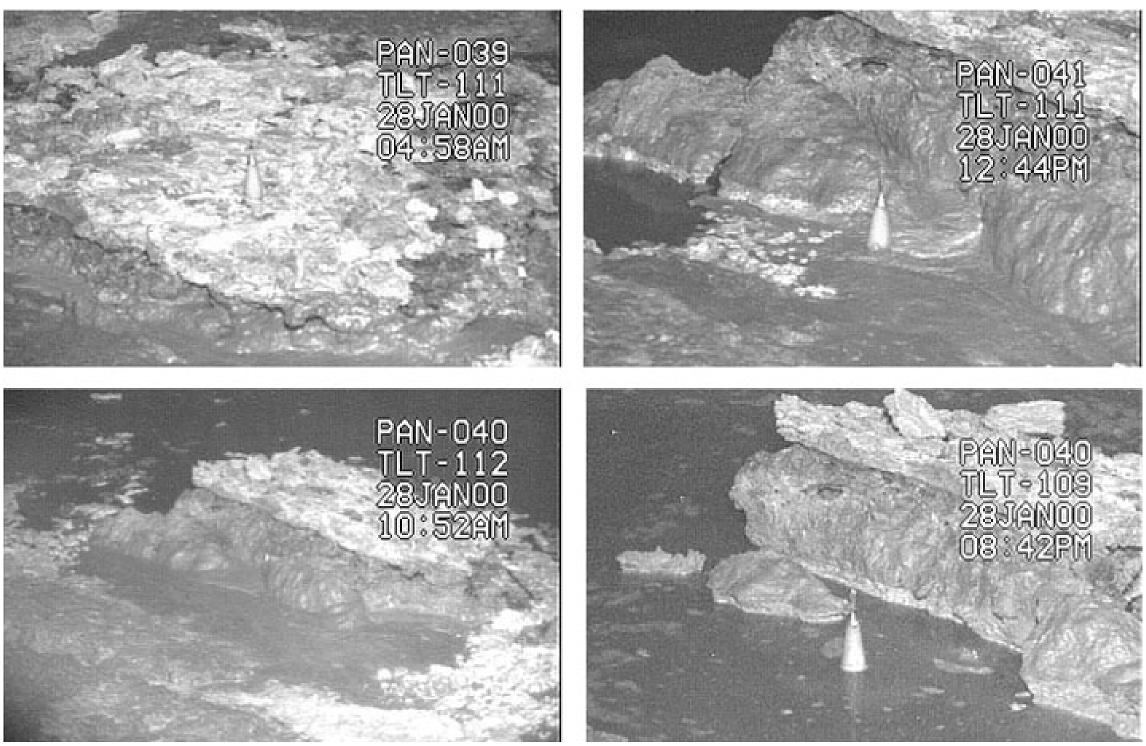

Figure 4.3. Waste Surface Irregularity Effect on Height Measurements

4.2.2 Determination of Height Measurement Accuracy

As discussed in Section 4.2.1, numerous factors can significantly affect the height measurement. In this section, the methods used to determine the accuracy of the waste height for this study are presented.

The most significant factor affecting waste height measurement, as was demonstrated in SY-101, is the existence of a crust layer. Surface irregularities and apparent change of the tank cross-sectional area due to retention of waste material on the walls were visually observed during the transfers.

For the three transfer scenarios we considered, only AN-105 during the first transfer is expected to have a crust layer. The uncertainty in the height measurement of the feed tank for this transfer is therefore taken to be 0.2 m (Hedengren et al. 2000). The effect of possible material retention on the walls is applied by comparison to that seen in SY-101. The expected material retention is distributed over the tank wall exposed by the transfer, and the resulting difference in the cross-sectional area is applied as the uncertainty to the area. For those transfers with no crust layer in the feed tank, or a liquid surface or empty receiver tank, the uncertainty of the waste height is taken to be that of the Enraf instrument, or 0.00254 m.

The effect of possible mixer pump operation during the transfer is also considered. During the transfer from AZ-102, a mixer pump is expected to be employed. There is some evidence from the recent mixing operations in AZ-101 that the action of the mixer pump can disturb the waste surface. Additionally, numerical simulations of tank-mixing processes have been conducted which provide detailed shear and velocity measurements at the waste surface. It is estimated that these effects can introduce an uncertainty of about 2 cm into the waste height measurement.

4.2.3 Factors Affecting Accurate Measurements of the Waste Flow Rate

Waste flow rates are also subject to uncertainty. Factors that may affect measurement of the flow rate include

- Flow rate out of optimum range of instrument
- Gas accumulation in pipeline due to pipe routing or component configurations
- Deviation from vendor-specified pipe configurations (volumetric flow meter)
- Installation in proximity to power sources
- Orientation of meter relative to phase/s (gas, liquid, and solid) of material flow
- Excessive vibration from external sources (mass flow meter)
- High concentrations of metallic particulate (mass flow meter)
- Heterogeneous waste stream (high-frequency transients in density, mass flow meter)
- Heterogeneous waste stream (vertical distribution, volumetric flow meter)
- Density changes due to temperature changes (volumetric flow meter).

The majority of these factors can be controlled by choosing the correct instrument for the task and installing it correctly. Therefore, measurement of the flow rate will provide better data for a material balance than the waste height measurements. As with the height measurements however, accurate data for the density of the waste is a critical parameter.

4.2.4 Methods to Determine Waste Density

To achieve accuracy in a waste transfer material balance, the waste must be well classified. As discussed in the previous sections, the waste density is a crucial parameter. In this section, methods that may be used to determine the waste density due to chemical reactions and gas content are discussed.

4.2.4.1 Chemical Reaction Effects on Waste Density

Waste density in the Hanford tanks is affected by

- Dissolution of solids
- Precipitation of solids
- Mixture of a waste solution with water
- Mixture of different waste solutions

Five methods have been identified to determine waste density under these conditions. They are presented in order from the most preferable to the least accurate.

1. **Densitometer**: A mass flow meter provides density information. In-process density measurements are inherently the most accurate.
2. **Laboratory Experiments**: Although laboratory experiments cannot duplicate in-tank processes exactly, they can provide quantitative data for chemical reactions, solid and liquid phase concentrations, and the solution density from tank waste or simulants (e.g., Herting 1997, 1998). These data can be extrapolated to tank or transfer conditions.
3. **Chemical Modeling**: The computer modeling can be coupled with the first two methods to provide a means of checking, adding additional information, or, in instances of no actual tank data, used alone to provide detailed information on the waste chemistry under varying conditions (Onishi et al. 2000).
4. **Empirical Formula from Hanford Wastes**: Extrapolates solution density under varying conditions based on empirical relations from data encompassing all or some of the Hanford tanks. This can be coupled with methods 2 and 3 to complete data sets.
5. **Assign a Value by Comparison**: Using the known data of a particular waste, the solution density is assigned based on comparisons of that data to other Hanford waste or solution chemistry data. This is a judgment-based method, so it is therefore subject to large uncertainties.

4.2.4.2 Gas Content Affects Waste Density

Gas is generated, retained, and released in varying quantities by the waste in the Hanford tanks. Extensive studies have been conducted to explain and quantify the gas content (e.g., Mahoney et al. 1999). The effect of this gas content on the waste density (and therefore waste volume) during a transfer scenario can be determined by:

1. Determining the gas content of the transferred waste. This may be achieved by direct in situ measurements, tank dome space gas specie concentrations, laboratory experiments with tank waste or simulants, or comparison with similar wastes.
2. Determining the effect of transfer activities on gas content. Again, in-tank data from prior transfers or laboratory experiments can be used. The effect may also be bounded by assuming that all the gas is either retained or released by the transfer.

The preparation of the tank for the transfer must be considered as well. A well-mixed tank will have released most of its retained gas; supernatant liquid with no solids content will only have transient gas in it.

4.2.5 Determination of Waste Density

Methods discussed in Subsections 4.2.4.1 and 4.2.4.2 were used in this study to determine the waste density. The methods employed for each transfer are discussed here.

Density data have been documented from core and grab samples describing the current waste properties in AN-105 and AZ-102. These data sources include Hedengren et al. (2000), Bingham et al. (1999), Herting (1997), and Schreiber (1995). The supernatant removed from AN-105 during the first transfer is diluted at 56% by volume with water in-line. No dilution data exist for AN-105 supernatant liquid and water. The resultant mixture density is therefore determined based on a volumetric approach. Comparison of supernatant dilution data from DST 241-AN-104 (AN-104; waste similar to AN-105), however, shows that volume is not conserved. The uncertainty of the result of the volumetric average density in AN-105 is therefore taken to be that shown in the AN-104 studies (Herting 1998).

This dilution process is also considered with the chemical model GMIN (Felmy 1995). The initial aqueous species in the supernatant liquid in AN-105 are presented in Figure 4.4. Note that the measurement accounted for total sodium, total nitrate, etc., while the chemical model accounted for sodium, sodium nitrate, etc. The summations show good agreement.

Upon dilution with water at 56% by volume, there is indication that gibbsite may precipitate (see Figure 4.5). However, the quantity (0.6% by volume) is minimal and has minimal effect on the waste density. The effect is less than that seen in AN-104 (Herting 1998) or, in regard to its effect on the apparent volume of waste in the tank, less than the 0.00254 m of uncertainty in the Enraf. Furthermore, the kinetic rate to form gibbsite is expected to be much greater than the duration of the waste transfer. The possible effect is therefore ignored in this case. This example does, however, serve as a poignant illustration of the value of considering chemical modeling to identify and avoid potential complications.

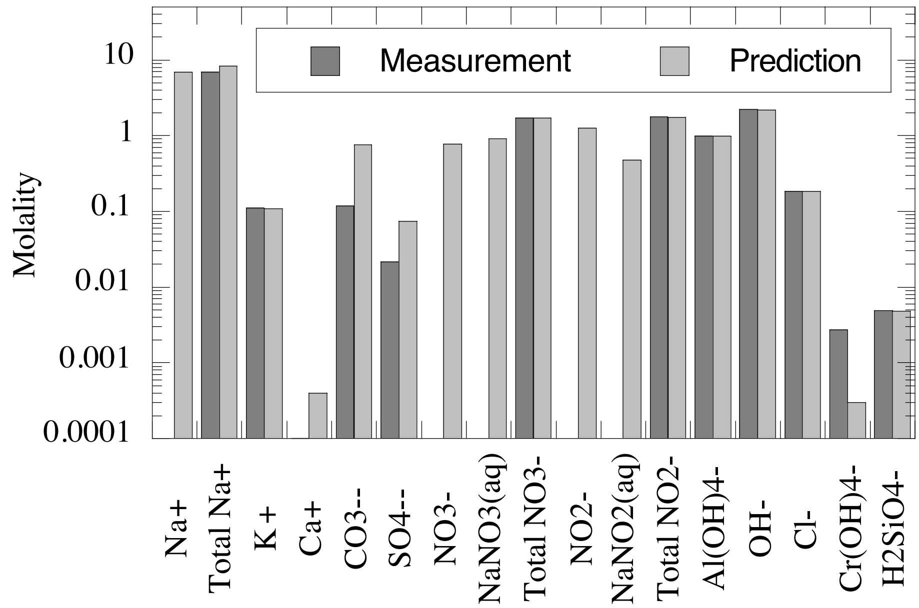

Figure 4.4. Measured and Predicted Supernatant Liquid Chemical Concentrations for AN-105

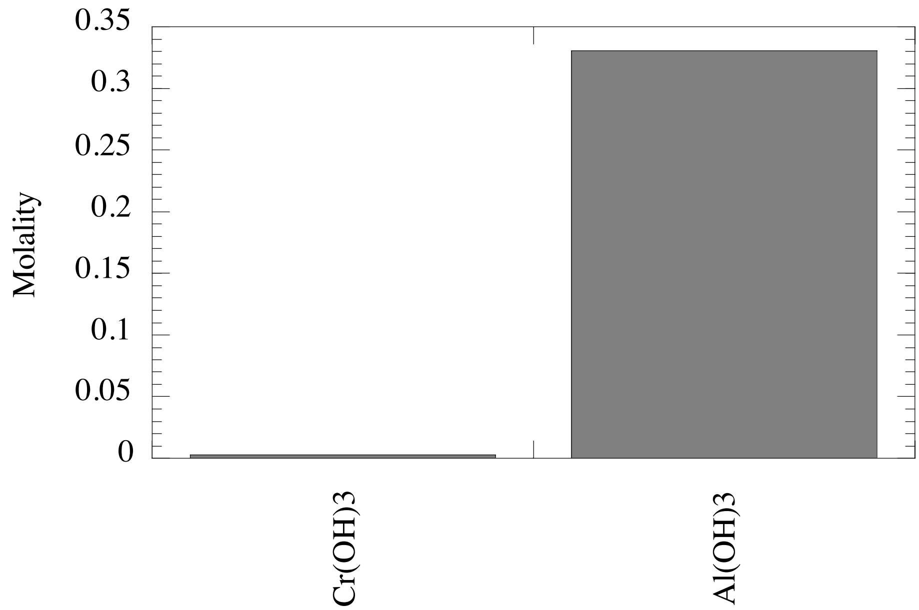

Figure 4.5. Predicted Dry Solid Concentration for AN-105 Supernatant Liquid Diluted at 56% by Volume with Water

The supernatant liquid in AN-105 also contains gas at $2x10^{-5}$% ($\pm 1x10^{-5}$%) by volume (Mahoney et al. 1999). It was assumed that this gas is all released, partially released, or completely retained after the transfer. This effect is included in the uncertainty of the density of the mixture.

Herting (1997) diluted AN-105 settled solids at 80% by volume with water. We therefore have the necessary data point to describe the density of the supernatant liquid in AN-105 prior to the second transfer. Unfortunately, only a single liquid density measurement is reported. Herting's dilution study in AN-104 (Herting 1998) was again used to supplement the available data. As the liquid density measurement techniques can be assumed to be the same in each study, the standard deviation of the measurements in AN-104 (settled solids diluted at 80% by volume with water) were used as the expected uncertainty in the reported AN-105 density.

For transfer of slurry from AZ-102, the density and solids content were determined by volumetrically mixing the supernatant and settled solids. Initial waste properties were taken from Bingham et al. (1999) and Schreiber (1995). The uncertainty of the slurry density was computed by propagation of the initial condition uncertainties.

4.2.6 Summary of Input Data

The variable waste properties and tank conditions for the three transfers are given in Tables 4.6, 4.7 and 4.8. The waste data are taken or determined from Hedengren et al. (2000),

Table 4.6. AN-105 first Transfer Parameters

Parameter (units)	AN-105 First Transfer	Uncertainty	Distribution
Water Mass Flow Rate (kg/min)	188.48	± 0.25%	normal
Dilution Water Density (kg/m^3)	992	± 0.02%	uniform
Water Flow Rate (m^3/min)	0.19	± 0.5%	uniform
Water Tank Initial Height (m)	7	± 0.00254	uniform
Water Tank Final Height (m)	0.213	± 0.00254	uniform
Water Tank Area (m^2)	182.4	NA[(a)]	NA
Feed Tank Area (m^2)	410.433	min–0.79 max at value[(b)]	triangular max at value[(b)]
Feed Waste Density (kg/m^3)	1430	± 30	normal
Feed Tank Initial Height (m)	10.41	± 0.2	uniform
Feed Tank Final Height (m)	5.02	± 0.2	uniform
Feed and Water Mass Flow Rate (kg/min)	669.39	± 0.2%	uniform
Transfer Time (min)	6509	± 1	uniform
Receiver Tank Area (m^2)	410.433	NA	NA
Receiver Tank Initial Height (m)	0.305	± 0.00254	uniform
Receiver Tank Initial Density (kg/m^3)	1,000	± 0.09%	uniform
Receiver Tank Final Height (m)	8.711	± 0.00254	uniform
Receiver Tank Final Density (kg/m^3)	1269	min – 1.21% mean – 0.54% max at value[(b)]	skewed normal

(a) NA denotes not applicable.
(b) Distribution maximum % at given parameter value.

Table 4.7. AN-105 Second Transfer Parameters

Parameter (units)	AN-105 Second Transfer	Uncertainty	Distribution
Feed Tank Area (m^2)	410.433	NA[a]	NA
Feed Waste Density (kg/m^3)	1280	SD = 14.14	normal
Feed Tank Initial Height (m)	7.58	± 0.00254	uniform
Feed Tank Final Height (m)	1.37	± 0.00254	uniform
Feed Mass Flow Rate (kg/min)	678.4	± 0.2 %	uniform
Transfer Time (min)	4809	± 1	uniform
Receiver Tank Area (m^2)	410.433	NA	NA
Receiver Tank Initial Height (m)	0.0	NA	NA
Receiver Tank Initial Density (kg/m^3)	0.0	NA	NA
Receiver Tank Final Height (m)	6.21	± 0.00254	uniform
Receiver Tank Final Density (kg/m^3)	1280	SD = 14.14	normal
(a) NA denotes not applicable.			

Table 4.8. AZ-102 Transfer Parameters

Parameter (units)	AZ-102	Uncertainty	Distribution
Feed Tank Area (m^2)	410.433	NA[a]	NA
Feed Waste Density (kg/m^3)	1147	± 47	normal
Feed Tank Initial Height (m)	7.92	± 0.00254 ± 0.02[b]	uniform
Feed Tank Final Height (m)	6.54	± 0.00254 ± 0.02[b]	uniform
Feed Mass Flow Rate (kg/min)	607.91	± 0.2%	uniform
Transfer Time (min)	1069	± 1	uniform
Receiver Tank Area (m^2)	410.433	NA	NA
Receiver Tank Initial Height (m)	0.0	NA	NA
Receiver Tank Initial Density (kg/m^3)	0.0	NA	NA
Receiver Tank Final Height (m)	1.38	± 0.00254	uniform
Receiver Tank Final Density (kg/m^3)	1147	± 47	normal
(a) NA denotes not applicable. (b) Includes effect of mixer pump operation.			

Herting (1997), Schreiber (1995), and Bingham et al. (1999). The uncertainties in the data, as well as their distributions, are also included. Depending on the instrumentation setup, different parameters will be measured. Where no data or uncertainties were available, the methods and effects discussed in Sections 4.2.2 and 4.2.5 were used. Instrumentation uncertainties for the different setups are included in the respective tables.

4.2.7 Waste Material Balance Results

The material balance errors due with variable waste properties and tank conditions were evaluated using Equations (2.22), (2.23), and (2.24). The Monte Carlo simulation approach was again used for error propagation.

As discussed, three sets of measurements and three different transfer scenarios were considered. To facilitate the presentation and discussion of the results, these different cases are denoted in the manner outlined in Section 4.1.2, with an additional identifier of D to indicate a disturbed waste surface due to action of a mixer pump (applicable to transfer 3).

The variable waste properties and tank conditions error results for Transfers 1, 2, and 3 are presented in Table 4.9, 4.10, and 4.11, respectively. The 95% confidence interval and 100% interval (includes all outcomes given all input scenarios) for the largest material balance error are presented in the second and third columns. The percentage error of the 100% interval value compared to the total transfer is given in column 4. Columns 5 and 6 indicate the 95% confidence interval about the mean error.

Table 4.9. Material Balance Error for Transfer 1

Case	Error (gal)		Error (%)	Error (gal)	
	95% CI	**100% I**	**100% I**	**U 95% Mean CI**	**L 95% Mean CI**
A/1/MM2	44900	68400	7.2	5117	3932
A/1/Y2	45000	68500	7.2	5137	3953
B/1/MM2	9700	13600	1.5	5156	5029
C/1	44900	67200	7.0	5255	4074

Table 4.10. Material Balance Error for Transfer 2

Case	Error (gal)		Error (%)	Error (gal)	
	95% CI	**100% I**	**100% I**	**U 95% Mean CI**	**L 95% Mean CI**
A/2	22400	55100	8.2	405.7	-213.3
B/2/MM2	15000	30800	4.6	302.9	-120.8
C/2	22200	55300	8.2	406.6	-214.1

Table 4.11. Material Balance Error for Transfer 3

Case	Error (gal)		Error (%)	Error (gal)	
	95% CI	**100% I**	**100% I**	**U 95% Mean CI**	**L 95% Mean CI**
A/3	6100	12500	8.3	108.9	-59.6
A/3/D	7000	15600	10.2	127.6	-66.9
B/3/MM2	4300	7000	4.6	92.5	-26
C/3	6100	12500	8.4	115.8	-51.4
C/3/D	7200	15800	10.3	138.2	-58.8

4.2.8 Evaluation

Material balance errors on the order of 8% of the total transfer are expected with variable waste properties and tank conditions. The 100% interval error for Transfer 1 ranged from 13,600 to 68,500 gallons, for Transfer 2 from 30,800 to 55,700 gallons, and for Transfer 3 from 7,000 to 15,800 gallons. Notice that, for each transfer, the upper and lower 95% confidence intervals about the mean show that the mean error is skewed to the positive side. For Transfer 1, the mean is always positive. A positive error indicates a gain in mass. The variable waste properties and tank conditions can therefore potentially mask a leak or mis-routing. For each transfer, measurement set B, which had less reliance on height measurements, produced the lowest errors.

4.3 Alternative Instrumentation Setup

It was shown in the previous section that the introduction of additional uncertainty into the height measurements, be it from density changes, surface irregularities, disturbance of the waste surface, or retention of waste material on the tanks walls, significantly and adversely affects the material balance errors. For each transfer considered, decreased reliance on level measurements produced smaller errors. An alternative instrumentation setup with mass flow meters at the beginning and end of the transfer line is therefore considered. The best results will be achieved with either the Micro Motion Elite CMF 200 or T150.

Installation of a mass flow meter at the end of the transfer line will accomplish the following:

- Eliminate need for reliance on in-tank height measurements
- Allow waste density to be monitored
- Provide redundancy on the material balance
- Allow uncertainty to be determined more precisely.

4.3.1 Material Balance Equations

Mass flow meters at the beginning and end of the transfer line are expected to improve the material balance error. A schematic of the alternative instrumentation setup is shown in Figure 4.6.

In addition to significantly improving the material balance accuracy, including the mass flow meter at the end of the transfer line provides redundancy on the material balance. A material balance can be conducted between the two mass flow measurements in the pipe. Additionally, material flow measurements of the water and feed waste can be balanced against the flow meter at the beginning of the pipe, and material flow measurements from the receiver tank can be balanced against the flow meter at the end of the pipe.

The applicable material balance equations the alternative instrumentation setup are presented below. All variables are as denoted in Section 2. The material balance error for the pipeline is

$$E = \int_{t=t_0}^{t=t_1} \rho_{FW} Q_{FW} dt - \int_{t=t_0}^{t=t_1} \rho_{PD} Q_{PD} dt \tag{4.1}$$

which simplifies to

$$E = \rho_{FW} Q_{FW} t_1 - \rho_{PD} Q_{PD} t_1 \tag{4.2}$$

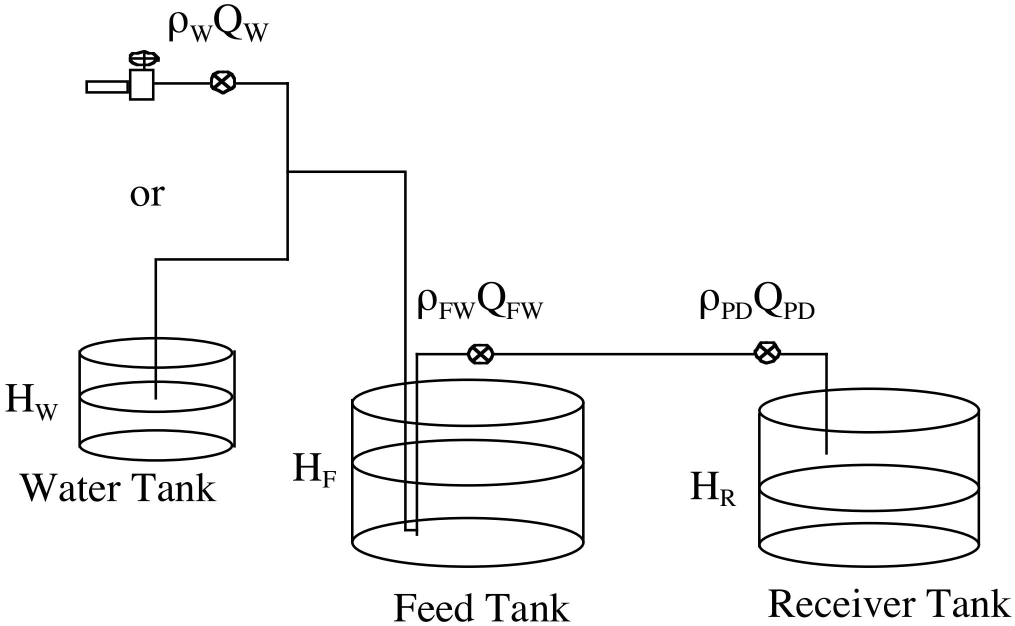

Figure 4.6. Alternative Instrumentation Setup

The material balance error for the material flow of the water and feed waste and the flow meter at the beginning of the pipe is

$$E = \int_{t=t_0}^{t=t_1} \rho_w Q_w dt - \int_{H_F=H_{F0}}^{H_F=H_{F1}} A_F \rho_F dH_F - \int_{t=t_0}^{t=t_1} \rho_{FW} Q_{FW} dt \tag{4.3}$$

or

$$E = -\int_{H_W=H_{W0}}^{H_W=H_{W1}} A_W \rho_W dH_W - \int_{H_F=H_{F0}}^{H_F=H_{F1}} A_F \rho_F dH_F - \int_{t=t_0}^{t=t_1} \rho_{FW} Q_{FW} dt \tag{4.4}$$

Equations (4.3) and (4.4) simplify to

$$E = \rho_W Q_W t_1 + A_F \rho_F (H_{F0} - H_{F1}) - \rho_{FW} Q_{FW} t_1 \tag{4.5}$$

and

$$E = A_W \rho_W (H_{W0} - H_{W1}) + A_F \rho_F (H_{F0} - H_{F1}) - \rho_{FW} Q_{FW} t_1 \tag{4.6}$$

respectively. Likewise, the material balance error for the material flow of the receiver tank and the flow meter at the end of the pipe is

$$E = \int_{H_R=H_{R0}}^{H_R=H_{R1}} A_R \rho_R dH_R - A_R \rho_{R0} H_{R0} - \int_{t=t_0}^{t=t_1} \rho_{PD} Q_{PD} dt \tag{4.7}$$

which simplifies to

$$E = A_R(\rho_{R1}H_{R1} - \rho_{R0}H_{R0}) - \rho_{PD}Q_{PD}t_1 \quad (4.8)$$

4.3.2 Results and Evaluation

The material balance errors for the alternative instrumentation setup were determined under the variable waste properties and tank conditions presented in Section 4.2.6. Three error calculations for each transfer were conducted as follows:

P. Error between the two mass flow meters [Equation (4.2)]
F. Error between material flow measurements of the water and feed waste and the flow meter at the beginning of the pipe [Equation (4.5) or (4.6)]
R. Error between material flow measurements of the receiver tank and the flow meter at the end of the pipe [Equation (4.8)]

The different cases are again denoted in the manner outlined in Section 4.1.2. The results for the pipeline are presented in Table 4.12, and the results for all three error calculations are presented in Table 4.13.

Table 4.12. Pipeline Material Balance Error, All Transfers

Case	Error (gal)		Error (%)	Error (gal)	
	95% CI	100% I	100% I	U 95% Mean CI	L 95% Mean CI
P/1/MM2	2900	3900	0.4	42	-41.9
P/2/MM2	2100	2900	0.4	30.9	-30.7
P/3/MM2	500	900	0.6	7.6	-7.6

The error in the pipeline ranges from 3,900 gallons for Transfer 1 to 2,900 gallons for Transfer 2 and to 900 gallons for Transfer 3. These errors represent less than 1% of the total transfer volumes.

Table 4.13. Alternative Instrumentation Setup Material Balance Error, All Transfers

Case	Error (gal)		Error (%)	Error (gal)	
	95% CI	100% I	100% I	U 95% Mean CI	L 95% Mean CI
P/1/MM2	2900	3900	0.4	42	-41.9
F/1/MM2	38300	61800	6.5	118.3	-1021.2
R/1/MM2	9900	13500	1.5	5216.9	5089.3
P/2/MM2	2100	2900	0.4	30.9	-30.7
F/2/MM2	15600	29700	4.4	205.9	-225.6
R/2/MM2	15900	30800	4.6	307.6	-124.4
P/3/MM2	500	900	0.6	7.6	-7.6
F/3/MM2	4000	6900	4.6	57.3	-57.2
F/3/MM2/D	5600	10600	6.9	73.6	-79
R/3/MM2	4300	7000	4.7	85	-31.9

The material balance errors in the pipe are much less than the feed and receiver tank errors for each of the transfer scenarios. Comparison of the material balance errors in Table 4.13 to those in Tables 4.9, 4.10, and 4.11 clearly demonstrates the significant improvement in the achievable material balance accuracy for the alternative instrumentation setup. The apparent material balance error in the feed and receiver tanks is also reduced by the direct comparison of the tank material to a flow meter. Again, the positive mean errors indicated by the 95% confidence interval about the mean can potentially mask leaks or mis-routings.

The redundancy in the material balance calculations for the alternative instrumentation setup also provides the ability to check and maintain instrumentation accuracy. For example, if the material balances for the feed and receiver tanks and the flow meter at the beginning of the pipe indicate no error, but the flow meter at the end of the pipe indicates error, that is a strong indication that the flow meter at the end of the pipe is not operating correctly. Likewise, if a tank measurement is not in agreement with combinations of the other measurements, instrumentation inaccuracy or in-tank effects are indicated.

4.3.3 Transfer System Implications of Alternative Instrumentation Setup

Implementation of the alternative instrumentation setup requires additional mass flow meters to be installed at the receiver tank end of the transfer line. It is planned to have flow meters for the outflow of each tank; therefore, modification of the waste flow path would be required. The Micro Motion meters allow the flow rate to be measured for flow in either direction through the meter with no loss in accuracy.

Some engineering aspects of implementing an additional mass flow meter are discussed below. The process flow specifications are 100 to 164 gpm with a specific gravity of 1.1 to 1.4, which yields a flow rate range of approximately 1000 to 2000 lb/min. The head loss through the flow meters has been estimated for the higher flow rate of 164 gpm, which equates to 7.2 ft/sec in a Sch-40 3-in. pipe. The head losses are listed in Table 4.14**.** The space requirement for the Micro Motion CMF200 and CMF300 are approximately 7 in. x 29 in x 23 in. and 10 in. x 39 in. x 36 in., respectively. The Micro Motion T150 housing is approximately 32 in. long and 7.2 in. in diameter.

Table 4.14. Mass Flow Meter Head Loss

Meter	Mass Flow Rate Range (lb/min)	Head Loss Across Unit at 164 gpm (ft)
CMF200 U-tube	0 to 3,200	24[(a)]
CMF300 U-tube	0 to 10,000	3
T150 Straight tube	0 to 3,200	10[(a)]
(a) Does not account for contraction and expansion from 3-in. pipe.		

5.0 Summary and Conclusions

We developed a material balance assessment methodology based on conservation of mass to address the pipeline transfer of DST tank waste with variable waste properties and tank conditions. The methodology consists of a set of material balance equations and general approaches to solve them, including how to determine waste density changes due to chemical reactions and gas generation/retention/release. It is intended to be a backup to pit leak detectors to detect waste leaking and mis-routings during waste transfer between and within the 200 East and 200 West Areas, including the planned vitrification plant.

The main factors causing variable waste properties and tank conditions are waste density changes caused by chemical reactions and gas generation/retention/release, the existence of a crust layer and its potential effects on density, waste height and tank cross-sectional area, and waste surface disturbance due to mixer pump operation during the waste transfer. Without these effects, this mass-based material balance methodology is simplified to the traditional volume-based material balance approach for constant waste properties and tank conditions. Thus, the latter is applicable to tanks without these complex factors such as AP Tank Farm waste transfers.

The material balance assessment methodology was applied to three waste transfers: AN-105 first transfer of 911,400 gallons of in-line diluted supernatant liquid, AN-105 second transfer of 673,000 gallons of liquid waste, and AZ-102 transfer of 150,000 gallons of slurry. Three instrumentation setups were considered: (A) feed and receiver tank levels and diluent flow meter, (B) flow meter at the beginning of the transfer pipeline and receiver tank level, and (C) diluent, feed, and receiver tank levels.

Monte Carlo simulations to determine the potential waste transfer material balance errors due to the instrumentation indicate that the errors are relatively small (up to 2,200 gallons for AN-105 first transfer with instrumentation setup B, having a Micro Motion Elite CMF 200 or T150 mass flow meter), typically accounting for less than 1% of the total transfer. This error is small enough to be able to identify the error due to effects other than actual leakage or mis-routing. Specific amounts of material balance error for the instrumentation in each waste transfer case are summarized below:

- For the AN-105 first liquid waste transfer, errors range from 1,000 gal (0.11% error) with Enraf surface measurements in feed, water, and receiver tanks (instrumentation setup C) to 2,200 gal with the Micro Motion mass flow meter (Elite CMF 200 or T150) and Enraf surface measurement in the receiver tank (instrumentation setup B).
- For the AN-105 second liquid transfer to DSTs, errors range from to 800 gal (0.12%) with all Enraf measurements (instrumentation setup C) to 1,600 gal (0.11%) with the Micro Motion mass flow meter (instrumentation setup B). For transfer to the vitrification plant storage tanks, these errors ranges from 1,600 gal (0.24%) with instrumentation setup B to 1,900 gal (0.28%) with instrumentation setups A and C.
- For the AZ-102 slurry transfer, errors vary from 600 gal (0.38%) with the Micro Motion mass flow meter (instrumentation setup B) to 800 gal (0.52%) with all Enraf measurements (instrumentation setups A and C). For the vitrification plant storage tanks, these errors range

from 400 gal (0.24%) with instrumentation setup B to 1,100 gal (0.75%) with instrumentation setups A and C.

Height measurements alone generally produced lower material balance errors. However, the variable waste properties and tank conditions that are to be expected during the transfer of saturated wastes make the height measurements subject to a significant error. When uncertainties due to variable waste properties and tank conditions were included in the analysis, the material balance errors became much larger, as summarized below.

- For the AN-105 first liquid waste transfer, errors range from 13,600 gal (1.5%) with instrumentation setup B to 68,400 gal (7.2%) with instrumentation setup C.
- For the AN-105 second liquid transfer, errors range from 30,800 gal (4.6%) with instrumentation setup B to 55,300 gal (8.2%) with instrumentation setup C.
- For the AZ-102 slurry transfer, errors vary from 7,000 gal (4.6%) with instrumentation setup B to 15,800 gal (10.3%) with instrumentation setup C.

An alternative instrumentation setup to reduce these errors is to have a Micro Motion Elite CMF 200 or T150 mass flow meter at the both ends of the transfer pipeline. Installation of these mass flow meters at the both end of the transfer line will serve to

- eliminate reliance on in-tank height measurements
- allow waste density to be monitored
- provide redundancy on the material balance
- allow uncertainty to be determined more precisely.

Under this alternative instrumentation setup, the material balance error in the transfer pipeline is

- for the AN-105 first liquid transfer, 3,900 gallons (0.4%).
- for the AN-105 second liquid transfer, 2900 gallons (0.4%).
- for the AZ-102 slurry transfer, 900 gallons (0.6%).

Thus, depending on the operational needs, one can select

- volume-based material balance equations for constant waste properties and tank conditions
- mass-based material balance equations for variable waste properties and tank conditions with one or more combinations of the three instrumentation setups (A, B, and C)
- mass-based material balance equations for variable waste properties and tank conditions with the alternative instrumentation setup having Micro Motion mass flow meters at both ends of the transfer pipeline.

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