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Electromagnetic Induction Probe Calibration for Electrical Conductivity Measurements and Moisture Content Determination of Hanford High Level Waste

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Abstract: *Logic of converting EMI measured electrical conductivity to moisture with expected uncertainty. Estimates from present knowledge, assumptions, and measured data. Archie's Law has been used since the 1940's to relate electrical conductivity in porous media to liquid volume fraction. Measured electrical conductivity to moisture content uses: Porosity, Interstitial liquid electrical conductivity, Solid particle density, Interstitial liquid density, and interstitial liquid water content. The uncertainty of assumed values is calculated to determine the final moisture wt.% result uncertainty.*

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Electromagnetic Induction Probe Calibration for Electrical Conductivity Measurements and Moisture Content Determination of Hanford High Level Waste

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**ELECTROMAGNETIC INDUCTION PROBE CALIBRATION FOR ELECTRICAL
CONDUCTIVITY MEASUREMENTS AND MOISTURE CONTENT
DETERMINATION OF HANFORD HIGH LEVEL WASTE
Revision 0**

WHC-SD-WM-ER-531

**Prepared by
Warren D. Wittekind
Ralph D. Crowe**

May 1996

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ABSTRACT

This report demonstrates the logic of converting electromagnetic induction measured electrical conductivity to moisture. The report shows the expected uncertainty in the measurements by using the uncertainty of all the factors in the calculations.

This report is based on best estimates from present knowledge, assumptions (assumptions are checked/validated when possible), and measured data.

The basis for converting measured electrical conductivity to moisture content is known as Archie's Law (Archie 1942). This law has been used by Geophysicists since the 1940's to relate electrical conductivity in porous media to interstitial liquid conductivity, porous volume, and liquid volume fraction.

The conversion of measured electrical conductivity to moisture content uses assumed values for the following:

- Porosity*
- Interstitial liquid electrical conductivity*
- Solid particle density*
- Interstitial liquid density, and interstitial liquid water content.*

The uncertainty of each of these assumed values is calculated to determine the moisture wt%. The results are shown in the following table.

Electromagnetic Induction Inferred Moisture Content with Uncertainties		
Matrix conductivity mS/cm	Moisture content wt% H ₂ O	Uncertainty wt% H ₂ O
80	26.8	± 5.8
60	24.3	± 5.3
40	21.0	± 4.6
20	16.1	± 3.6
10	12.1	± 2.8
5	9.0	± 2.1

Porosity θ = 0.50 uncertainty +0.05

σ_w = 200 mS/cm uncertainty ± 25 mS/cm

ρ_s = 2.20 g/cm³ uncertainty ± 0.10 g/cm³

ρ_L = 1.18 g/cm³ uncertainty ± 0.09 g/cm³

(ρ_{H_2O}/ρ_L) = 0.79 uncertainty ± 0.11 .

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LIST OF TERMS

EMI	electromagnetic induction
HLW	high-level waste
LOW	liquid observation well
WHC	Westinghouse Hanford Company

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ELECTROMAGNETIC INDUCTION PROBE CALIBRATION FOR ELECTRICAL CONDUCTIVITY MEASUREMENTS AND MOISTURE CONTENT DETERMINATION OF HANFORD HIGH LEVEL WASTE

1.0 INTRODUCTION

An electromagnetic induction (EMI) probe is being developed by the Westinghouse Hanford Company (WHC) (Crowe and Wittekind 1995) to measure the amount of water remaining in waste stored in the high-level waste tanks on the Hanford Site. The electromagnetic probe uses a magnetic field to induce electrical current in the surrounding waste proportional to the waste conductivity. The moisture content of the waste is estimated based on the measured waste conductivity. The primary factors that influence the electrical resistance or conductance of the waste are porosity, waste liquid content, waste liquid chemistry, and temperature.

2.0 SUMMARY

This report provides details about EMI work in progress, descriptions of calculations used to convert EMI conductivity measurements into moisture content by weight, and success to date.

The basis for converting EMI measured electrical conductivity to liquid volume content is known as Archie's Law. Since the 1940's this law has been used in geophysics to relate electrical conductivity in porous media with electrolyte conductivity, porous volume, and liquid volume fractions.

To calculate the moisture content by weight fraction from liquid volume fraction requires additional values for salt-saturated interstitial liquid electrical conductivity, solid particle density, interstitial liquid density, and interstitial liquid water fraction. There are uncertainties for each of the physical values used in the weight fraction moisture content calculation.

The EMI method measures average matrix electrical conductivity that can be correlated to moisture content.

The calibration of the measured electrical conductivity to moisture content determination depends on the following physical properties:

- Solid porosity (absolute porosity, not drainable porosity)
- Interstitial liquid electrical conductivity (major dependency on temperature, and lesser dependency on matrix composition)
- Solid (salt grain particle) density

- Interstitial liquid density
- Interstitial liquid water fraction (weight fraction of H_2O in salt-saturated liquid).

Fundamental mathematical equations are explained, numerical values of each parameter and their uncertainties are calculated, and their effects on the moisture content by weight and its total uncertainty is calculated.

The following are unique advantages of an EMI approach to water content measurements:

- Very sensitive to loss of hydraulic conductivity
- Infers free-water content, because electrical conductivity is not affected by chemically bound water.

3.0 THEORY OF ELECTROMAGNETIC INDUCTION MOISTURE MEASUREMENT

Theory of EMI moisture measurement is discussed in Sections 3.2 and 3.3.

3.1 EDDY CURRENTS

When a magnetic field moves through a conductive medium it induces electrical currents in the medium. The inductive method uses a driver coil made of wire with an alternating current flowing through the driver coil to set up an alternating magnetic field that induces eddy current flow in the surrounding material. These induced currents generate a secondary magnetic field that creates an induced current in the pickup coil positioned along the axis of the first coil. The pickup coil has induced currents arising from the eddy currents generated by the original magnetic field and also from the secondary magnetic field from eddy currents in the medium. The secondary magnetic field induced is 180° out-of-phase with the original field. The induced current from the primary magnetic field can be eliminated by designing electronics to produce a signal proportional to the conductivity of the surrounding medium.

The magnitude of the primary magnetic field is proportional to the current in the primary or transmitting coil. The induced eddy currents are proportional to the magnetic field strength of the primary field and the conductivity of the waste. The secondary magnetic field strength from the eddy currents and the induced current in the receiver coil is proportional to the waste conductivity. It is useful to recognize that the electromagnetic energy coupled between the coils is subjected to attenuation and phase-shift as it propagates. We can define a "skin depth" as a measure of the distance that a propagating wave will penetrate.

$$\psi = e^{-\frac{x}{\delta}} e^{i(\frac{x}{\delta} - \omega t)}$$

where

ψ = propagating electromagnetic plane wave
 x = distance
 t = time
 σ = electrical conductivity
 ω = angular frequency
 δ = skin depth $(2/(\mu \omega \sigma))^{1/2}$
 μ = magnetic permeability

Skin depth is a function of frequency and conductivity (or resistance). The propagating wave loses energy to the currents induced in the waste. The more conductive the waste the greater the currents, and the shorter the distance the field travels. For frequencies from 50 to 200 kHz, the skin depth in the waste is about 50 to 100 cm.

The waste conducts an electrical current depending on its electrical resistance. The electrical resistance depends on the geometry of the current flow, and the resistivity of the waste. Resistivity is a fundamental property of the material and has units of ohm-meters. Conductivity is the reciprocal of resistivity and has units of inverse ohm-meters, or equivalent, Siemens per meter. When the liquid and solids in the waste are considered resistors in parallel, most of the current flows through the medium with the lower resistance. Consequently, current flow in the waste is primarily confined to the fluid within the pore spaces. The resistance or conductance of a material is descriptive of the character of the pore space, and of the properties of the interstitial liquid filling the pore space.

3.2 ELECTROMAGNETIC INDUCTION MEASUREMENT OF ELECTRICAL CONDUCTIVITY

The EMI measurement of electrical conductivity depends on the driver coil alternating current and the induced voltage in the pickup coil. Therefore the induced electrical field has a 90° phase lag behind the driver coil electrical field. When a direct induced electrical field in the pickup coils or adjacent conductive medium is created, a direct induced voltage that is 90° out-of-phase with the driving coil is generated. The induced current in the medium induces a secondary voltage in the pickup coil that lags 90° behind the induced electrical current, or 180° phase lag behind the driver coil. These phase lag relationships are illustrated in Figure 1.

There are two pickup coil induced voltages; driver coil direct inductance that lags 90° in phase behind, and an indirect inductance that lags 180° in phase behind the driver coil current and depends on medium electrical conductivity. A phase sensitive impedance meter separates the two phases and determines the medium conductivity signal magnitude.

Figure 1. EMI Probe Driver Pickup Phase Lag Relationships.

EMI Probe Driver Pickup Phase Lag Relationships

There is some phase shift of the electromagnetic field with distance from the driver and pickup coils. Also, there is additional phase shift with increasing electrical conductivity in the adjacent medium. Because of the low electrical conductivity of the waste, these phase shifts are small secondary effects.

The MIZ-40A eddy current tester is the electromagnetic instrumentation for performing the electrical conductivity measurement and is shown in Figure 2. The EMI measurement is recorded on a removable hard disk in the DDR-1 data recorder, also shown in Figure 2.

The electromagnetic measurement of electrical conductivity was calibrated in 46 cm (18 in.) O.D., 50 cm (20 in.) high electrical conductivity test stands. The conductivity test stand is shown in Figure 3. There are four conductivity test stands, 15 mS/cm, 50 mS/cm, 100 mS/cm, and 150 mS/cm. There is also an empty conductivity stand filled with air. There is a 7.62 cm (3 in.) I.D. plastic tube in the center for the EMI probe. The electrically conductive medium is water with potassium chloride for the electrolyte. The electrical conductivity was measured with a temperature compensated electrical conductivity meter. The conductivity meter calibration was verified by measurements on a conductivity standard solution.

3.3 ELECTRICAL CONDUCTIVITY DEPENDENCE ON MOISTURE CONTENT

The EMI technique measures electrical conductivity. It is important to consider the theoretical basis for the electrical conductivity dependence on moisture content in Hanford high-level waste (HLW) tanks. The gross features of electrical conductivity from pure water to fused salt are depicted in Figure 4.

The electrical conductivity of an aqueous solution from pure water to fused salts can be considered between the following phases:

- Pure water
- Chemically saturated electrolytic solution
- Wet solid with all pores volume filled with liquid
- Moist solid dried to the loss of hydraulic conductivity
- Completely dry fused solids.

The electrical conductivity of pure water is very low and increases as electrolytes are added into solution. The electrical conductivity continues to increase as the electrolyte concentration is increased, but the rate of increase of electrical conductivity diminishes as the concentration increases. At electrolyte saturation, the electrical conductivity is at the maximum. As more salts are added, the proportion of solids increases and the liquid solution becomes an interstitial liquid. The electrical conductivity decreases according to an undefined relationship between the solid and liquid solution.

Figure 2. EMI Eddy Current Electronic Components.*

*The MIZ-40A eddy current tester is used to perform the electrical conductivity measurement. The EMI measurement is recorded on a removable hard disk in the DDR-1 data recorder. The position indicator adaptor provides a reference signal when the EMI probe is in motion and scanning up or down in the LOW.

Figure 3. EMI Laboratory Test Stands.*

*The conductivity test stands are 50 cm (18 in.) O.D., and 46 cm (20 in.) high. There are four conductivity test stands, 15 mS/cm, 50 mS/cm, 100 mS/cm, and 150 mS/cm. This conductivity range is appropriate and extends above any conductivity measured in a HLW tank. There is a 7.62 cm (3 in.) I.D. plastic tube in the center for the EMI probe. The electrical conductive medium is water with potassium chloride for the electrolyte.

Figure 4. Electrical Conductivity Between Pure Water and Fused Salt.

Electrical Conductivity between Pure Water and Fused Salt

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As water is removed from the pore space of the solid salt, the electrical conductivity decreases according to Archie's Law. As porous solid salt is dried there is a loss of hydraulic conductivity, and the electrical conductivity becomes very small. Finally, the electrical conductivity of completely dry fused salt is very low.

The two situations of greatest interest to EMI measurements are the electrical conductivity of electrolytic solutions, and electrolytic solutions in a porous solid matrix. The electrolytic solution is discussed in Section 3.3.1.

3.3.1 Electrical Conductivity of Electrolytic Solutions

The electrical conductivity of an electrolytic solution depends on the number of dissociated ions in the solution, their mobility, and the electrical charges of each of the ions. The number of dissociated ions depends on the solubility of various constituent salts. The larger the number of dissociated ions, the higher the absolute electrical conductivity. But, the specific conductance (the electrical conductivity per ion), decreases steadily with the larger number of ions.

The tank waste liquid contains free charged ions from the dissolved salts. When these ions are subjected to an imposed alternating magnetic field, the cations in the solution are accelerated in one direction and the anions in the other. These directions reverse as the field reverses. The movement of the ions is a current. The movement of the ions encounters viscous drag that limits the velocity of the ions, and determines the ions mobility.

The ionic mobility or conductivity per electrical charge in aqueous solutions is remarkably similar for a wide range of different ions within approximately a factor of 2, with two notable exceptions, H^+ and OH^- . The limiting ionic conductivity for H^+ is about seven times greater than most ions, and for OH^- it is about four times greater than most ions (see Table 1). The waste in Hanford HLW tanks is caustic, therefore the H^+ is absent and only the OH^- is significant.

Hanford HLW tanks have dominant constituents $NaNO_3$, $NaNO_2$, $NaOH$, and $NaAlO_2$. The chemical proportion varies between HLW tanks. Supernatant may or may not be saturated with electrolytic salts, but the interstitial liquid in the pore spaces of fused salts is most likely a salt saturated solution.

The electrolyte electrical conductivity depends on the mobile ions. The bound water in $Na_2CO_3 \cdot 7H_2O$ or $Na_2SO_4 \cdot 10H_2O$ does not add to the mobile ions, and is not measured in the EMI determination of moisture content. This salt-saturated solution electrical conductivity is a primary factor used to calculate liquid volume fraction and free-water weight percent.

Table 1. Ionic Conductivity for Relevant Ions (25 °C).

Ion	Molar conductivity ($\text{cm}^2 \text{ S mol}^{-1}$)
H^+	349.65
OH^-	198.00
Na^+	50.08
NO_3^-	71.42
NO_2^-	71.80
AlO_2^-	?

The electrical conductivity of an electrolytic solution depends on the quantity, charge, and mobility of the dissociated ions in the solution. The number of dissociated ions depends on the quantity of dissolved salts in the liquid. The temperature, solubility of salt, and presence of other salts all influence the number of dissolved ions. For dilute solutions, by increasing the number of dissociated ions linearly increases electrical conductivity of the solution. However, as more salt is dissolved with a corresponding increase in the number of dissociated ions, the interactions between the ions increase and the electrical conductivity is difficult to predict theoretically (Harned and Owen 1950). Because of this difficulty, solutions were created with the same range of dissolved salts as in the tank waste liquids, and the conductivities of these solutions were measured. The results of these measurements were used with the actual waste tank sample data to evaluate the variation of electrical conductivity for waste tank liquids.

The dominant constituents in the waste tank liquid samples are NaNO_3 , NaNO_2 , NaOH , and NaAlO_2 . The relative chemical proportions of these salts vary between tanks. Supernatant and liquid in the sludge waste may or may not be saturated with electrolytic salts. The interstitial liquid in the pore spaces of saltcake is considered saturated since it was formed from hot saturated liquid slurries.

Two experimental series of tests were designed. The first series had three levels of four components (NaNO_3 , NaNO_2 , NaOH , and NaAlO_2) with 27 test solutions covering a range from 2M to 6M NaOH . The second series had three levels of three component (NaNO_3 , NaNO_2 , and NaOH), with 15 test solutions over the range of 0M to 2M NaOH . These two series of experimental tests were necessary because NaAlO_2 requires a minimum of 2M NaOH to be dissolved. These two series and the levels of components are believed to cover the major components of expected interstitial liquids and supernatant solutions in Hanford waste tanks. The conductivity of the 42 test solutions was measured at temperatures ranging from 20 °C to 75 °C to establish the temperature dependant electrical conductivity as a function of chemical composition.

The temperature data were used to interpolate the conductivity for the different chemical compositions at regular 5 °C temperature intervals ranging from 20 °C to 75 °C. Regression coefficients, a , b_i and $c_{i,j}$ were calculated for each chemical component in each solution for each 5 °C interval. The electrical conductivity in mS/cm was the dependent variable, and the dependent variables were the molarity of the NaOH, NaNO₃, NaNO₂, and NaAlO₂. Terms to second order were considered for their statistical significance, and the less significant terms were dropped from the model. These fitted parameters were used to predict the electrical conductivity of the analyzed chemical compositions of the single-shell waste tanks by using the following equation.

$$\sigma_w(T, M) = a + \sum_{i=1}^4 b(T)_i M_i + \sum_{i=1}^4 \sum_{j=1}^4 c(T)_{i,j} M_i M_j$$

where

σ_w = Liquid electrical conductivity (mS/cm)

T = Temperature (°C)

M_i = Molarity of i^{th} component, i.e. NaOH, NaAlO₂, NaNO₃, or NaNO₂ (moles/l)

a = Constant regression coefficient (mS/cm)

b_i = Regression coefficient for i^{th} component (mS/cm)/(moles/l)

$c_{i,j}$ = Regression coefficient for i^{th} times j^{th} component (mS/cm)/(moles/l)²

This high electrical conductivity property of the OH⁻ ion explains the relatively large magnitude for the NaOH regression coefficient (shown in Table 2). The diminishing efficiency of additional ions to contribute electrical conductivity explains why the $c_{i,i}$ quadratic terms are all negative. The interference of different ions with the mobility of other ions explains why all the $c_{i,j}$ regression coefficients are negative.

3.3.2 Electrical Conductivity Solution Modeling

A total of 72 drainable liquid or supernatant solution chemical analyses were reported (Van Vleet 1993a and 1993b), these formed the data base of expected compositions for interstitial liquid which are the source of electrical conductivity in Hanford HLW waste tanks. Eighteen of the 72 solutions were listed as drainable liquids and the remaining 54 were listed as supernatant solutions.

Table 2. Electrical Conductivity Regression Coefficients.

M_i or M_i, M_j		Temperature dependence	Constant with temperature		Temperature for regression coefficients		
		m	b		25 °C	50 °C	75 °C
Constant		1.36989	74.0167	a =	108.26	142.51	176.76
NaOH		1.907	35.1738	b_1 =	82.85	130.52	178.20
NaAlO ₂		0.51124	-21.488	b_2 =	-8.71	4.07	16.86
NaNO ₃		0.84134	3.06732	b_3 =	24.10	45.13	66.17
NaNO ₂		1.10913	15.8596	b_4 =	43.59	71.32	99.04
NaOH	NaAlO ₂	-0.163	-1.0865	c_{12} =	-5.16	-9.24	-13.31
NaOH	NaNO ₃	-0.2937	-6.1382	c_{13} =	-13.48	-20.83	-28.17
NaAlO ₂	NaNO ₂	-0.7831	-10.883	c_{24} =	-30.46	-50.04	-69.61
NaOH	NaOH	-0.1382	-5.4911	c_{11} =	-8.95	-12.40	-15.86
NaNO ₃	NaNO ₃	-0.1044	0.73291	c_{33} =	-1.88	-4.49	-7.09
NaNO ₂	NaNO ₂	-0.1857	-4.4752	c_{44} =	-9.12	-13.76	-18.40

The electrical conductivity of the chemical composition of the solutions was calculated at specific temperatures using the regression coefficients previously described. These fitted parameters were used to predict the electrical conductivity of the analyzed chemical compositions of the single-shell waste tanks. The results are listed in Table 3.

Table 3. Predicted Electrical Conductivity of Analyzed Compositions.

	$\sigma_w(T=25\text{ }^{\circ}\text{C}, M)$	$\sigma_w(T=50\text{ }^{\circ}\text{C}, M)$	$\sigma_w(T=75\text{ }^{\circ}\text{C}, M)$
Analyzed liquids (35 samples)	192.30 $\pm$ 26.71	294.48 $\pm$ 49.17	396.65 $\pm$ 72.96

This calculation infers that the EMI data interpretation would benefit from knowing the temperature distribution and the approximate chemical composition of the HLW tank being scanned. The most important of these two quantities is the waste material temperature, which is also the easiest one to measure. A completely unknown chemical composition could introduce an uncertainty on the order of $\pm 26.71/192.30 \times 100\%$, or approximately $\pm 14\%$ relative uncertainty at one standard deviation. Of course, any additional

tank specific facts and information could reduce the effect of this extreme uncertainty of unknown chemical composition. The EMI sensitivity to loss of hydraulic conductivity is not affected by this relative uncertainty of unknown chemical composition or even an unknown temperature.

4.0 WASTE GEOMETRY DESCRIPTION

The measured conductivity of tank waste varies with the following:

- Water content. The amount of water in the waste is limited by the porosity, which is the amount of void space in the waste solid
- Waste liquid salinity. The type and quantity of dissolved salts in the waste liquid
- Waste geometry. The distribution of the water in the waste is determined by the size, shape, and interconnections of the void spaces
- Waste temperature. Increasing temperature increases the waste conductivity.

The moisture content of the waste is calculated from the waste composition using the following equation:

$$MC = \frac{\theta S_w \rho_L \left(\frac{\rho_{H_2O}}{\rho_L} \right)}{(1-\theta)\rho_s + \theta S_w \rho_L}$$

where

MC = moisture content (wt%)

θ = porosity (fraction)

S_w = water saturation (fraction)

ρ_L = waste liquid density (g/cm³)

$\left(\frac{\rho_{H_2O}}{\rho_L} \right)$ = water in waste liquid (fraction)

ρ_s = waste solid density (g/cm³)

The free-water moisture content is the free-water weight divided by the combined liquid and solid weights in the porous medium. The bound water is included in the solid weight.

Based on the evaluation of the geophysics description of different types of rock formations, the tank waste is being regarded as consolidated sediment where the porosity is the space left over between grains of solid matter. Pore spaces must be interconnected and at least partially filled with water in order for the waste to effectively conduct electricity. The pore volumes consist of two parts; larger voids called storage pores, and smaller connecting pores. Most of the resistance to electrical current is provided by the connecting pores. The higher the ratio of the volume of connecting pores to storage pores the greater the relative conductivity of the waste (Wait 1971).

A great deal of research has been done to correlate resistivity directly with water content for petroleum bearing rocks. It has been observed that the resistivity varies as the inverse square of the porosity, when the rock is fully saturated with water. This has led to the wide spread use of an empirical formula relating resistivity and porosity known as Archie's Law. Archie's Law when expressed in terms of conductivity, the inverse of resistivity has the following form:

$$\sigma_t = \sigma_w \frac{\theta^m}{a}$$

where

σ_t = bulk electrical conductivity of waste with pores filled

σ_w = electrical conductivity of liquid contained in pore structure

θ = porosity expressed as a fraction of the volume of the waste

a, m = empirical constants based on experimental observations

This is the basic equation of well-log interpretation. The well-logging industry recognizes and has its origin in this equation (Dewan 1983).

Geologists have made a large number of measurements of both the porosity and resistivity in order to determine values for a and m with a good degree of reliability. Measurements data are typically scattered wide because of the variability of the structure between samples. The sample measurements have been separated into groups based on the porosity. Average values for parameters a and m for three groups of sedimentary rocks (Wait 1971) are listed in Table 4.

Table 4. Forms of Archie's Law for Some Sedimentary Rocks.

Description of rock	Porosity	a	m
Weakly-cemented detrital rocks, such as sand, sandstone, and some limestones	25% to 45%	0.88	1.37
Moderately well-cemented sedimentary rocks, including sandstones and limestones	18% to 35%	0.62	1.72
Firmly-cemented sedimentary rocks	5% to 25%	0.62	1.95

a, m = empirical constants in: $\sigma_t = \sigma_w \theta^m / a$.

The tank waste is assumed to be similar to detrital rocks formed grains accumulated as sediment from suspension. In this type of rock, the a has a value of 0.88 and m has a value of 1.37. This choice of values for both a and m is a best estimate.

The conductance of waste that is partially saturated with liquid is less than the conductance of the same amount of waste that is fully saturated with water. If part of the pore space in the waste is occupied by nonconducting fluid (organic) or gas, the water saturation, S_w , is less than 1 and the waste conductance decreases. Near the surface of the waste, part of the pore space may be filled with air. Studies of the effect of desaturation on the conductance of various types of rock formations have led to an empirical expression resembling Archie's Law.

$$\sigma_t(S_w \leq 1) = \sigma_t(S_w = 1) S_w^{n_1}$$

where

$\sigma_t(S_w \leq 1)$ = conductance of partly dry medium

$\sigma_t(S_w = 1)$ = conductance with all pore spaces filled

S_w = desaturation (pore fraction water filled)

n_1 = 2, a constant (Wait 1971)

There is general acceptance for the value $n_1=2$ (Wait 1971, Dewan 1983, Serra 1984, Hearst and Nelson 1985), it is commonly used throughout the well-logging industry.

5.0 EMI CALCULATED MOISTURE CONTENT

$$MC = \frac{\rho_L}{\rho_b} \left[\frac{\rho_{H_2O}}{\rho_L} \right] \theta S_w^{n_1}$$

where

MC = fraction by mass of water in the waste

ρ_L = density of the interstitial liquid (g/cm³)

ρ_b = bulk density of the waste (g/cm³)

$\left[\frac{\rho_{H_2O}}{\rho_L} \right]$ = water mass fraction in interstitial liquid

θ = porosity, connected pore space to total volume

S_w = fraction total pore space filled with liquid

n_1 = 2, a constant (Wait 1971)

The EMI measurement of electrical conductivity is converted to moisture content by using Archie's Law which has served the well-logging industry since the 1940's. The applicability of Archie's Law depends on the interstitial liquid being electrically conductive and the porous solid that is not being electrically conductive. Archie's Law has been extended to electrically conductive solids (de Witte 1950).

The calibration of the measured electrical conductivity to moisture content determination depends on the following:

- HLW porosity (absolute porosity, not drainable porosity)
- HLW interstitial liquid electrical conductivity
- HLW solid (salt grain particle) density
- HLW interstitial liquid density, and water fraction (fraction of H₂O in salt-saturated liquid).

The calculated effect because of the expected uncertainties for each of these physical properties will be considered in separate sections.

The free-water moisture content is the free-water weight divided by the combined liquid and solid weights in the porous medium. The bound water is included in the solid weight.

$$MC = \frac{\theta S_w \rho_L \left[\frac{\rho_{H_2O}}{\rho_L} \right]}{(1-\theta)\rho_s + \theta S_w \rho_L}$$

where

MC = moisture content mass fraction of free-water in porous medium

θ = absolute porosity volume fraction

S_w = volume fraction of the pore volume occupied by interstitial liquid

ρ_L = interstitial liquid density

$\left[\frac{\rho_{H_2O}}{\rho_L} \right]$ = water mass fraction in interstitial liquid

ρ_s = solid (salt grain particle) density.

The matrix electrical conductivity is described by the following equation:

$$\sigma_t(\sigma_w, \theta, S_w) = \frac{\sigma_w \theta^m}{a} (S_w)^{n_1} \quad (0 \leq S_w \leq 1)$$

where

σ_t = bulk electrical conductivity of the porous solid liquid matrix

θS_w = liquid volume fraction

θ = porosity, volume fraction of solid matrix

σ_w = electrical conductivity of interstitial liquid in porous medium

$a = 0.88$, a constant parameter from Archie's Law

$m = 1.37$, a constant parameter from Archie's Law

$n_1 = 2.0$, a constant parameter from Archie's Law.

The determination of moisture content is based on the best available data, values for σ_w , the interstitial liquid electrical conductivity, θ , the porosity, S_w , and the liquid filled pore space volume fraction. The $\sigma_w(T,M)$ depends on temperature and composition. The temperature is usually already measured, and there has been a lot of work done on temperature distribution in Hanford waste tanks. The porosity θ , can be estimated from previous measurements, or determinations in similar waste tanks. The S_w parameter is believed to be the most likely to vary vertically along a liquid observation well (LOW). For this reason, the S_w parameter is calculated from the EMI electrical conductivity measurement.

$$S_w = \left[\frac{a (\sigma_t / \sigma_w(T,M))^{1/n_1}}{\theta^m} \right]^{1/n_1} \quad (0 \leq S_w \leq 1)$$

Substituting this determined liquid occupied pore volume into the moisture content, the equation shows

$$MC = \frac{\theta \left[\frac{a \sigma_t / \sigma_w(T,M)}{\theta^m} \right]^{1/n_1} \rho_L \left[\frac{\rho_{H_2O}}{\rho_L} \right]}{(1-\theta)\rho_s + \theta \left[\frac{a \sigma_t / \sigma_w(T,M)}{\theta^m} \right]^{1/n_1} \rho_L}$$

where

- MC = moisture content, calculated mass fraction of free-water in porous medium
- θ = porosity, 0.50 with uncertainty of +0.05
- σ_t = EMI measured electrical conductivity of the moist solid matrix, this may be 80, 60, 40, 20, 10, or 5 mS/cm
- a = 0.88, a constant parameter from Archie's Law
- $\sigma_w(T,M)$ = interstitial liquid electrical conductivity, this is a function of T (temperature), and M (chemical composition), and is assumed to be 200 mS/cm with uncertainty of ± 25 mS/cm
- m = 1.37, a constant parameter from Archie's Law
- n_1 = 2.0, a constant parameter from Archie's Law
- ρ_L = interstitial liquid density, a function of M (chemical composition), 1.177432 g/cm³ with an uncertainty of ± 0.094255 g/cm³

ρ_{H_2O}/ρ_L = interstitial liquid water fraction, 0.792408 with an uncertainty of ± 0.109754

ρ_s = solid particle density, this is a function of M (chemical composition), 2.20 g/cm³ with an uncertainty of ± 0.10 g/cm³

This equation is used to determine moisture content from EMI measured electrical conductivity in moist saltcake media.

5.1 POROSITY EFFECT

The porosity involved in the determination of moisture content is the total porosity, not simply the drainable liquid porosity. Porosity in Hanford waste tanks has been a concern. A range of porosities was observed and an average 35% porosity for liquids that could be pumped was declared (DeWeese 1988). The estimated drainable volume for porosity underestimates the absolute porosity that is needed for EMI moisture content calculations. The porosity for drainable liquids represents a definite lower limit for absolute porosity.

Simmons (1995) stated that absolute porosity of 40 vol% to 60 vol% could be accepted for various saltcake profiles. Computer calculations for waste tank vertical moisture profiles (Simmons 1995, Table 1, p. 23) used 0.50 absolute porosity, although in 3 out of 22 cases the absolute porosity had to be increased to 0.55 or 0.60. This is the basis for assuming a 0.50 porosity with an estimated uncertainty of one standard deviation of ± 0.05 . The uncertainty range considered is from 0.50 to 0.55.

This physical property has effect on the calculated moisture content, because of the exponent, $m = 1.37$. The effect of porosity was calculated by assuming a range of porosity values over a wide range of possible values. The moisture weight percent effect of this porosity uncertainty can be determined from Table 5.

Table 5. Porosity Effect on EMI Inferred Moisture Content.

Calculated Moisture Content from EMI Matrix Electrical Conductivity as a Function of Porosity					
Matrix electrical conductivity mS/cm	Porosity				
	0.40	0.45	0.50	0.55	0.60
100					0.3411
80			0.2678	0.2923	0.3196
60	0.2026	0.2218	0.2429	0.2663	0.2926
40	0.1735	0.1909	0.2102	0.2317	0.2562
20	0.1311	0.1453	0.1611	0.1792	0.2001
10	0.0974	0.1085	0.1212	0.1357	0.1528
5	0.0715	0.0800	0.0897	0.1010	0.1145

For 80, 60, 40, 20, 10, and 5 mS/cm, the +0.05 porosity uncertainty on a believed absolute porosity of 0.50 is calculated to be 2.45, 2.34, 2.15, 1.81, 1.45, and 1.13 wt% H₂O content respectively.

5.2 INTERSTITIAL LIQUID CONDUCTIVITY EFFECT

The interstitial liquid electrical conductivity in the determination of moisture content is $\sigma_v(T,M)$ and depends on temperature and composition. The temperature is usually already measured, and there has been a lot of work done on temperature distribution in Hanford waste tanks. This liquid electrical conductivity physical property can be bounded from temperature measurements and HLW chemical analysis values. From the previous section (Section 3.3.2) on electrical conductivity solution modeling, the calculated electrical conductivity of 35 analyzed waste tank solution was 192.30 ± 26.71 mS/cm (25 °C). For this reason, the liquid electrical conductivity was assumed to be 200 mS/cm with an uncertainty of ± 25 mS/cm for the purpose of these calculations. The results of the calculations performed are shown in Table 6.

Table 6. Liquid Electrical Conductivity Effect
on EMI Moisture Content.

Calculated Moisture Content from EMI Matrix Electrical Conductivity as a Function of Liquid Electrical Conductivity					
Matrix electrical conductivity mS/cm	Liquid electrical conductivity mS/cm				
	150	175	200	225	250
100					0.2678
80			0.2678	0.2575	0.2484
60	0.2678	0.2543	0.2429	0.2331	0.2245
40	0.2331	0.2206	0.2102	0.2012	0.1934
20	0.1804	0.1699	0.1611	0.1537	0.1473
10	0.1367	0.1282	0.1212	0.1152	0.1101
5	0.1018	0.0951	0.0897	0.0851	0.0812

For 80, 60, 40, and 20 mS/cm, a ± 25 mS/cm uncertainty on a believed liquid electrical conductivity of 200 mS/cm is calculated to be 2.06, 2.12, 1.94, 1.62, 1.30, and 1.00 wt% H₂O content respectively.

5.3 SOLID PARTICLE DENSITY EFFECT

The solid density ρ_s , can be estimated from single crystal densities of the major constituents of Hanford HLW depicted in Table 7. The major constituents of Hanford's HLW are the four component aqueous mixtures of NaNO_3 , NaNO_2 , NaOH , and NaAlO_2 . These major components indicate that the salt grain particle density can be expected to be close to 2.200 g/cm^3 with an uncertainty of $\pm 0.100 \text{ g/cm}^3$.

Table 7. Solid Density of HLW Components (Weast 1976).

A. Solid Density of Major HLW Components Density in g/cm^3 .	
NaNO_3	2.261
NaNO_2	2.168
NaOH	2.130
NaAlO_2	1.58
Al(OH)_3	2.42
B. Solid Density of Minor HLW Components Density in g/cm^3 .	
$\text{Na}_3\text{C}_6\text{H}_5\text{O}_7 - 5 \text{ H}_2\text{O}$	1.857
Na_2CO_3	2.532
$\text{Na}_2\text{CO}_3 - \text{H}_2\text{O}$	2.25
$\text{Na}_2\text{CO}_3 - 7 \text{ H}_2\text{O}$	1.51
$\text{Na}_2\text{CO}_3 - 10 \text{ H}_2\text{O}$	1.44
$\text{Na}_3\text{PO}_4 - 10 \text{ H}_2\text{O}$	2.536
$\text{Na}_3\text{PO}_4 - 12 \text{ H}_2\text{O}$	1.62
Na_2SO_4	2.68
$\text{Na}_2\text{SO}_4 - 10 \text{ H}_2\text{O}$	1.464

The uncertainty in solid particle density can be converted into uncertainty in calculated moisture weight percent from calculated results contained in Table 8.

For 80, 60, 40, 20, 10, and 5 mS/cm, the $\pm 0.100 \text{ g/cm}^3$ solid particle density uncertainty on a believed solid particle density of 2.20 g/cm^3 is calculated to be 1.61, 1.53, 1.40, 1.17, 0.93, and 0.72 wt% H_2O content respectively.

Table 8. Solid Density Effect on EMI Inferred Moisture Content.

Calculated Moisture Content from EMI Matrix Electrical Conductivity as a Function of Solid Salt Particle Density					
Matrix electrical conductivity mS/cm	Solid density g/cm ³				
	1.90	2.00	2.10	2.20	2.30
100					
80	0.2944	0.2850	0.2761	0.2678	0.2600
60	0.2683	0.2593	0.2508	0.2429	0.2355
40	0.2336	0.2252	0.2174	0.2102	0.2034
20	0.1808	0.1737	0.1672	0.1611	0.1555
10	0.1370	0.1313	0.1260	0.1212	0.1167
5	0.1020	0.0975	0.0934	0.0897	0.0862

5.4 INTERSTITIAL LIQUID DENSITY AND WATER FRACTION EFFECT

Basically, the interstitial liquid density was calculated by averaging 35 measured HLW liquid solutions. The assumed uncertainty was the standard deviation of these 35 measured solutions. Densities may be calculated from the components according to experimental regression coefficients (Reynolds and Herting 1984), or according to a theoretical mixing rule calculation (Patwardhan and Kumar 1986a, 1986b, and 1993, and Sohnel and Novotny 1985). Both approaches give reasonably consistent results, but the theoretical calculation is more accurate and has less scatter in the calculated densities. The four component aqueous mixtures of NaNO_3 , NaNO_2 , NaOH , NaAlO_2 were used, and the mixing rule mathematical relationships were used to calculate the solution density. These density calculations are provided in Appendix C.

Based on solutions analyzed in 35 HLW tanks the average solution density with one standard deviation calculated according to the aqueous solution mixing rule is:

$$\text{Density}_{\text{Analyzed Solutions}} (\rho_L) = 1.177432 \pm 0.094255 \text{ g/cm}^3$$

The water fraction of these analyzed solutions is calculated to be to:

$$\text{H}_2\text{O Fraction } (\rho_{\text{H}_2\text{O}}/\rho_L) = 0.792408 \pm 0.109754$$

The conclusion is that the saturated liquid density for interstitial liquids is $1.177432 \pm 0.094255 \text{ g/cm}^3$. This is the average measured density of HLW tank drainable liquids. The expected water fraction for these measured liquids is 0.792408 ± 0.109754 . The results of the calculations performed are shown in Table 9.

Assuming that the interstitial liquid is a saturated solution, these uncertainties would be reduced.

Table 9. Liquid Density Effects on EMI Inferred Moisture Content.

Calculated Moisture Content from EMI Matrix Electrical Conductivity as a Function of Interstitial Liquid Density and Water Fraction of Interstitial Liquid					
Matrix electrical conductivity mS/cm	Liquid density g/cm ³ , water fraction				
	1.08, 0.902	1.13, 0.847	1.18, 0.792	1.22, 0.738	1.27, 0.682
100					
80	0.2883	0.2787	0.2678	0.2558	0.2426
60	0.2608	0.2525	0.2429	0.2323	0.2206
40	0.2249	0.2180	0.2102	0.2013	0.1915
20	0.1716	0.1668	0.1611	0.1547	0.1475
10	0.1285	0.1251	0.1212	0.1166	0.1114
5	0.0948	0.0925	0.0897	0.0864	0.0827

For 80, 60, 40 and 20 mS/cm, the $\pm 0.094255 \text{ g/cm}^3$ saturated liquid density uncertainty on a liquid density of 1.177432 g/cm^3 and the consequent effect on the liquid water fraction is calculated to be 4.57, 4.02, 3.34, 2.41, 1.71, and 1.21 wt% H₂O content respectively.

5.5 ARCHIE'S LAW PARAMETER VALUES EFFECT

The question of using geological Archie's Law parameters and the introduction of bias is shown to be smaller than other known uncertainties, and need not be considered further at this time.

Besides being the standard correlation used in the search for oil, the Archie's Law relationship has been applied to marine sediments (Tromp et. al. 1995), and ground water reservoirs (Yadav 1995), and provided the best correlation to measured data for the East Antarctic ice sheet (Shabtaie and Bentley 1995). The basic requirements for the valid application of Archie's Law is that the interstitial liquid is electrically conducting and

the porous solid is relatively non electrically conducting. When examining salt cakes in Hanford HLW tanks, both of these requirement are easily fulfilled.

There is scatter in the reported values for constants a , m , and n_1 . The values assumed were selected after consideration of a number of sources. Variation of the Archie's Law parameters does not have as much effect on the calculated moisture content as the other uncertainties. Much effort over a long period of time has been expended to provide a theoretical basis for Archie's Law and the Archie's Law parameters (Wyllie and Gregory 1953).

There is experimental and theoretical data supporting (Wong et. al. 1984) $a=1$ and $m=1.5$ for high porosity, material, $m=2$ for lower porosity material with the transition occurring between 0.2 to 0.4 porosity.

The constants a and m in $\sigma_t = \sigma_w \theta^m / a$ and their effect on the ratio σ_t / σ_w , can be calculated. Between the case $a=0.88$, $m=1.37$ and the case of $a=1.0$, $m=1.5$. There is a proportionality when $\theta = 0.5$, of $(0.5^{1.37} / 0.88) / (0.5^{1.5} / 1) = 1.2435$. This looks like a big discrepancy, but consider the final effect on calculated wt% moisture based on an EMI measurement. The equation used is

$$\sigma_t(\sigma_w, \theta, S_w) = \frac{\sigma_w \theta^m}{a} (S_w)^{n_1} \quad (0 \leq S_w \leq 1)$$

where

σ_t = bulk electrical conductivity of the porous solid liquid matrix

σ_w = conductivity of the electrolytic liquid in the porous volume

θ = porosity expressed as a fraction per unit volume of the solid matrix

S_w = fraction of pore space filled with water

$n_1 = 2$, a constant (Wait 1971)

a , m = empirical constants based on experimental observations.

The constant n_1 has been reported as having a value close to 2, therefore, $n_1=2$ was used. As shown in Table 10, the effect on calculated moisture content is calculated using the same formula that was used to propagate the uncertainties in the final result.

For 60, 40 and 20, 10 and 5 mS/cm, the change from $a=0.88$, $m=1.37$ to $a=1$, $m=1.5$, has the effect on water fraction is calculated to be 1.88, 1.72, 1.45, 1.16, and 0.90 wt% H₂O content respectively.

Table 10. Archie's Law Parameters Effect on EMI Inferred Moisture Content.

Calculated Moisture Content from EMI Matrix Electrical Conductivity as a Function of Archie's Law Parameters					
Matrix electrical conductivity mS/cm	Archie's Law parameters				
	a= 0.88 m= 1.37	a= 0.91 m= 1.4025	a= 0.94 m= 1.4350	a= 0.97 m= 1.4675	a= 1.0 m= 1.50
100					
80	0.2678	0.2728			
60	0.2429	0.2477	0.2524	0.2570	0.2617
40	0.2102	0.2145	0.2189	0.2232	0.2274
20	0.1611	0.1648	0.1684	0.1720	0.1756
10	0.1212	0.1241	0.1270	0.1299	0.1328
5	0.0897	0.0919	0.0942	0.0965	0.0987

a, m = empirical constants in: $\sigma_t = \sigma_w \theta^m / a$.

This expected bias because of accepted Archie's Law parameters, a and m, is less than the uncertainties due to different effects on the final calculated wt% moisture identified earlier in this chapter.

6.0 EVALUATION AND RESULTS

The uncorrelated (liquid density and water fraction properties are correlated, so they are combined into a single term) uncertainty equation can be stated mathematically as:

$$\Delta MC = \sqrt{\left(\frac{\partial MC}{\partial \theta} \delta \theta\right)^2 + \left(\frac{\partial MC}{\partial \sigma_w} \delta \sigma_w\right)^2 + \left(\frac{\partial MC}{\partial \rho_s} \delta \rho_s\right)^2 + \left(\frac{\partial MC}{\partial \rho_L} \delta \rho_L + \frac{\partial MC}{\partial (\rho_{H_2O}/\rho_L)} \delta \left(\frac{\rho_{H_2O}}{\rho_L}\right)\right)^2}$$

The uncertainty in the moisture content will be calculated for each of the measured conductivity ranges, 80, 60, 40, 20, 10, and 5 mS/cm. The analytic derivatives are not taken since numerical values were calculated previously. The final results are shown in Table 11.

Table 11. EMI Inferred Moisture Content with Uncertainties.

Matrix conductivity mS/cm	Moisture content wt% H ₂ O	Uncertainty wt% H ₂ O
80	26.8	± 5.8
60	24.3	± 5.3
40	21.0	± 4.6
20	16.1	± 3.6
10	12.1	± 2.8
5	9.0	± 2.1

$$\Delta MC(80 \frac{mS}{cm}) = \sqrt{2.45^2 + 2.06^2 + 1.61^2 + 4.57^2} \approx \pm 5.8 \text{ wt\% H}_2\text{O}$$

$$\Delta MC(60 \frac{mS}{cm}) = \sqrt{2.34^2 + 2.12^2 + 1.53^2 + 4.02^2} \approx \pm 5.3 \text{ wt\% H}_2\text{O}$$

$$\Delta MC(40 \frac{mS}{cm}) = \sqrt{2.15^2 + 1.94^2 + 1.40^2 + 3.34^2} \approx \pm 4.6 \text{ wt\% H}_2\text{O}$$

$$\Delta MC(20 \frac{mS}{cm}) = \sqrt{1.81^2 + 1.62^2 + 1.17^2 + 2.41^2} \approx \pm 3.6 \text{ wt\% H}_2\text{O}$$

$$\Delta MC(10 \frac{mS}{cm}) = \sqrt{1.45^2 + 1.30^2 + 0.93^2 + 1.71^2} \approx \pm 2.8 \text{ wt\% H}_2\text{O}$$

$$\Delta MC(5 \frac{mS}{cm}) = \sqrt{1.13^2 + 1.00^2 + 0.72^2 + 1.21^2} \approx \pm 2.1 \text{ wt\% H}_2\text{O}$$

7.0 CONCLUSIONS

The measurement of electrical conductivity by the EMI technique is an established method used for well-logging by Geophysicists since the 1940's. There are standard relationships used, such as Archie's Law which relate moist solid electrical conductivity to conductivity of the interstitial liquids, and other medium properties.

The electrical conductivity of typical Hanford HLW tank interstitial liquids was defined in experiments with different mixtures of chemicals to determine the electrical conductivity contribution from NaNO_3 , NaNO_2 , NaOH , and NaAlO_2 .

EMI hardware has been acquired. Laboratory tests demonstrate the increase in EMI response with electrical conductivity in the test stand medium. The EMI technique has been used in the tank farms to scan 10 HLW tanks, and results were compared to the neutron probe, gamma probe, and other EMI scans performed at different frequencies or different coil spacings.

This technology has been transferred from Pacific Northwest Laboratory to WHC and is available to measure moisture content or interstitial liquid level.

The advantages of the EMI probe are as follows:

- Very sensitive to loss of hydraulic conductivity
- Infers free-water content, since electrical conductivity is not affected by bound water
- High vertical spatial resolution dependent on EMI coil spacing
- High radial spatial resolution dependent on EMI coil spacing with multiple depth interrogations possible in a single scan
- Ability to look through adjacent regions to deeper regions
- Sensitive to small changes in material properties
- Light in weight and has low power requirements.

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D. L. Lessor and D. R. Rector, the independent reviewers from Pacific Northwest National Laboratory, are responsible for contributing the mixing rule calculation for solution density and water fraction documented in Appendix C. Also, D. L. Lessor also contributed discussions on EMI technology, Archie's Law, sampling, and modeling.

K. D. Lambert worked to constructed the spreadsheet files to propagate individual parameter uncertainties into the calculated moisture content.

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APPENDIX A
TEMPERATURE DISTRIBUTION CALCULATION FOR
A LIQUID OBSERVATION WELL

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The problem is to estimate the steady state temperature distribution in a waste tank with uniform thermal properties and uniform heat generation. The problem is to find the solution for the steady-state temperature distribution $T(r,z)$ in a solid cylinder where $a, 0 \leq r \leq b, 0 \leq z \leq a$, with heat generation at a constant rate of g_0 per unit volume and constant thermal conductivity k_w , while all boundaries are subject to convective heat transfer boundary conditions.

The mathematical formulation of the problem is as follows:

$$\begin{aligned} \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} &= -\frac{g_0}{k_w} & \text{in } 0 \leq r \leq b, 0 \leq z \leq a \\ k_w \left. \frac{\partial T}{\partial r} \right|_{r=b} + h_0 T(r=b) &= 0 & \text{at } r = b \\ -k_w \left. \frac{\partial T}{\partial z} \right|_{z=0} + h_1 T(z=0) &= 0 & \text{at } z = 0 \\ k_w \left. \frac{\partial T}{\partial z} \right|_{z=a} + h_2 T(z=a) &= 0 & \text{at } z = a \end{aligned} \quad (1)$$

A new variable $\theta(r,z)$ is defined to remove the inhomogeneous term in Equation (1).

$$\begin{aligned} T(r,z) &= \theta(r,z) + \frac{g_0}{k_w} \left(-\frac{z^2}{2} + c_1 z + c_2 \right) \\ &= \theta(r,z) + f(z) \end{aligned} \quad (2)$$

The function $f(z)$ is comparable to a temperature profile in a one dimensional slab and must satisfy the following boundary conditions.

$$\begin{aligned} -k_w \left. \frac{\partial f}{\partial z} \right|_{z=0} + h_1 f(z=0) &= 0 & \text{at } z = 0 \\ k_w \left. \frac{\partial f}{\partial z} \right|_{z=a} + h_2 f(z=a) &= 0 & \text{at } z = a \end{aligned} \quad (3)$$

As long as there is heat generation (e.g. $g_0 > 0$), $f(z)$ there will be a maximum value within the allowable range of z . The temperature profile in the waste tanks typically exhibit a maximum value near the bottom of the tank. It can be shown by setting the derivative of $f(z)$ equal to zero, the constant c_1 is the axial location of the maximum temperature, z_m .

$$\frac{df}{dz} = \frac{g_0}{k_w} (-z_m + c_1) = 0 \quad (4)$$

$$\Rightarrow c_1 = z_m$$

The constant c_2 is found from the boundary condition for $f(z)$ at $z = 0$.

$$-k_w \left. \frac{df}{dz} \right|_{z=0} + h_0 f(z=0) = -k_w \frac{g_0}{k_w} (z_m) + h_1 \frac{g_0}{k_w} (c_2) = 0 \quad (5)$$

$$\Rightarrow c_2 = \frac{k_w z_m}{h_1}$$

Using the boundary condition for $f(z)$ at $z = a$, h_1 can be expressed in terms of c_1 and c_2 .

$$k_w \left. \frac{df}{dz} \right|_{z=a} + h_2 f(a) = k_w \frac{g_0}{k_w} (-a + z_m) + h_2 \frac{g_0}{k_w} \left(-\frac{a^2}{2} + z_m a + \frac{k_w}{h_1} z_m \right) = 0$$

$$\Rightarrow h_2 = \frac{k_w (a - z_m)}{-\frac{a^2}{2} + z_m \left(a + \frac{k_w}{h_1} \right)} \quad (6)$$

The arbitrary constants c_1 and c_2 , are chosen in this way to simplify the problem to Equation (7) as follows.

$$\begin{aligned}
\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r} \frac{\partial \theta}{\partial r} + \frac{\partial^2 \theta}{\partial z^2} &= 0 \quad \text{in } 0 \leq r \leq b, 0 \leq z \leq a \\
k_w \left. \frac{\partial \theta}{\partial r} \right|_{r=b} + h_0 \theta(r=b) &= -h_0 f(z) \quad \text{at } r = b \\
-k_w \left. \frac{\partial \theta}{\partial z} \right|_{z=0} + h_1 \theta(z=0) &= 0 \quad \text{at } z = 0 \\
k_w \left. \frac{\partial \theta}{\partial z} \right|_{z=a} + h_2 \theta(z=a) &= 0 \quad \text{at } z = a
\end{aligned} \tag{7}$$

The solution to Equation (7) can be written as a product of two functions, $\theta = \sum_m \theta_m$, and $\theta_m(r, z) = R_m(r) Z_m(z)$.

$$\begin{aligned}
R_m(r) &= I_0(\eta_m r) \\
Z_m(z) &= \eta_m \cos(\eta_m z) + \frac{h_1}{k_w} \sin(\eta_m z)
\end{aligned} \tag{8}$$

and

$$\begin{aligned}
\eta_m &= m^{\text{th}} \text{ root of } g(\eta) \\
g(\eta) &= \eta \left(\frac{h_1}{k_w} + \frac{h_2}{k_w} \right) \cos(\eta a) + \left(\eta^2 + \frac{h_1}{k_w} \frac{h_2}{k_w} \right) \sin(\eta a)
\end{aligned} \tag{9}$$

A solution for $\theta(r, z)$ can be written and is constructed using these functions.

$$\theta(r, z) = \sum_{m=1}^{\infty} \frac{-h_0 I_0(\eta_m r)}{h_0 I_0(\eta_m b) + k_w \eta_m I_1(\eta_m b)} A_m Z(\eta_m, z) \tag{10}$$

The application of the boundary condition at $r = b$ is used to determine the coefficients A_m .

$$A_m = \frac{\int_0^a f(z') Z(\eta_m, z') dz'}{\int_0^a Z(\eta_m, z')^2 dz'} \quad (11)$$

Equations (8), (9), (10), and (11) form a complete solution for describing problems in terms of an infinite series. Table A-1 gives some representative values for the A_m coefficients for conditions characteristic of waste Tank 241-BY-104.

Table A-1. Typical Values for Expansion Coefficients and Eigenvalues.

m	η_m (ft ⁻¹)	A_m (ft F)
1	0.136	20.1
2	0.361	0.85
3	0.594	0.22
4	0.829	0.07
5	1.065	0.03

Since the first expansion coefficient A_1 is much larger than the rest of the coefficients, $f(z)$ can be approximated with a single term.

$$f(z) \approx A_1 Z(\eta_1, z) \quad (12)$$

This allows the spatial temperature in the waste tank to be expressed in the following simplified form.

$$\begin{aligned} \theta(r, z) &= \frac{-h_0 I_0(\eta_1 r)}{h_0 I_0(\eta_1 b) + k_w \eta_1 I_1(\eta_1 b)} A_1 Z(\eta_1, z) \\ &= -f(z) \left[\frac{h_0 I_0(\eta_1 r)}{h_0 I_0(\eta_1 b) + k_w \eta_1 I_1(\eta_1 b)} \right] \end{aligned} \quad (13)$$

Finally, by combining this Equation (13) with Equation (2) and expressing $f(z)$ in terms of the known parameters, the desired result is obtained.

$$T(r, z) = f(z) + \theta(r, z)$$

$$= T_{vp} + \frac{g_0}{k_w} \left[\frac{-z^2}{2} + z_m \left(z + \frac{k_w}{h_1} \right) \right] \left[1 - \frac{h_0 I_0(\eta_1 r_{low})}{h_0 I_0(\eta_1 b) + k_w \eta_1 I_1(\eta_1 b)} \right] \quad (14)$$

The following specific information is needed to apply Equation (14) to a specific tank.

- Waste volume or waste height.
- Heat load.
- Radial location of thermocouple tree.
- Radial location of liquid observation well.
- Vapor space temperature.
- Maximum waste temperature.
- Axial location of maximum temperature.
- Heat transfer coefficient at the surface of waste.

The waste volume and heat load are used to determine the average volumetric heat generation rate, g_0 . The measured vapor space and peak temperatures used together with the axial location of the peak temperature, z_m , determine the average thermal conductivity, k_w . The radial position of the liquid observation well, r_{low} , is used to correct for the radial temperature gradient.

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APPENDIX B

**ARCHIE'S LAW STATUS AND
CHOICE OF CONSTANTS**

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Appendix B discusses Archie's law status, applicability, and the logic for choice of constants.

Archie's law was first proposed (Archie 1942) to correlate electrical conductivity of an electrically conductive solution in an electrically conductive porous solid matrix. There has been a great deal of research in correlating resistivity of a rock with the water content (Carmichael 1989). These studies have led to the widespread use of Archie's law, which is an empirical formula relating resistivity and porosity as shown.

$$\rho_t = a \rho_w \theta^{-m} \quad (S_w = 1) \quad (1)$$

where

ρ_t = the bulk resistivity of the rock liquid matrix

ρ_w = the resistivity of the electrolytic liquid that is in the porous volume

θ = the porosity expressed as a fraction per unit volume of the solid matrix

a, m = parameters whose values are assigned arbitrarily to make the equation fit a particular group of measurements.

Table B-1 shows an example of the a and m values referenced from Carmichael (1989), Table 14, p. 387.

Calculated magnitudes of the formation factor (ρ_t/ρ_w), using the values of a and m are shown in Table B-2.

The key points to be noted from the data presented in this table is the magnitude of the formation factors in the first two columns. Those formulation factors expected to be most similar to Hanford HLW tank contents are not that much different in magnitude at porosity $\theta = 0.35$.

Shown in Figure B-1 is a graph for these different rock types with $1/\rho_w = \sigma_w = 200$ mS/cm. Four types are fairly similar but lava, which was suddenly solidified, is different. Hanford HLW salt cake is expected to follow the crystalline, sedimentary, detrital rock curves.

Table B-1. Forms of Archie's Law.

FORMS OF ARCHIE'S LAW THAT MAY BE USED WHEN LITHOLOGY OF A ROCK IS KNOWN			
	Description of Rock	a	m
1	Weakly-cemented detrital rocks, such as sand, sandstone and some limestones, with a porosity range from 0.25 to 0.45, usually Tertiary in age.	0.88	1.37
2	Moderately-cemented sedimentary rocks, including sandstones and limestones, with a porosity range from 0.18 to 0.35, usually Mesozoic in age.	0.62	1.72
3	Firmly-cemented sedimentary rocks with a porosity range from 0.05 to 0.25, usually Paleozoic in age.	0.62	1.95
4	Highly porous volcanic rocks, such as tuff, aa and pahoehoe, with porosity in the range 0.20 to 0.80.	3.5	1.44
5	Rocks with less than 0.04 porosity, including dense igneous rocks and metamorphosed sedimentary rocks.	1.4	1.58

a = Archie's Law constant of proportionality

m = Archie's Law constant porosity exponent in $\rho_t = a \rho_w \theta^{-m}$.

Table B-2. Formation Factor Calculation.

Porosity	$0.88 \theta^{-1.37}$	$0.62 \theta^{-1.72}$	$0.62 \theta^{-1.95}$	$3.50 \theta^{-1.44}$	$1.40 \theta^{-1.58}$
0.60				7.30	
0.55				8.28	
0.50				9.50	
0.45	2.63			11.05	
0.40	3.09			13.09	
0.35	3.71	3.77		15.87	
0.30	4.58	4.92		19.82	
0.25	5.88	6.73	9.26	25.77	
0.20		9.88	14.30	35.53	
0.15			25.06		
0.10			55.26		
0.05			213.50		159.13
0					

Figure B-1. Archie's Law Comparison.

REFERENCES

- Archie, G. E., 1942, *The Electrical Resistivity Log as an Aid in Determining Some Reservoirs Characteristics*, Transactions of the American Institute of Mining Engineering, 146, 54, 1942.
- Carmichael, R. S., 1989, *CRC Practical Handbook of Physical Properties of Rock and Minerals*, "Electrical Properties" by George V. Keller, p. 359, 1989.

APPENDIX C
LIQUID DENSITY AND WATER
FRACTION CALCULATION

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Introduction for Laboratory Solution Data

This is the mathematical calculation of HLW tank liquid density and water fraction. The liquid density and water fraction are used to convert from liquid volume to weight percent water. The liquid density is calculated by two different methods and compared to laboratory measured densities of a H_2O , NaNO_3 , NaNO_2 , NaOH , and NaAlO_2 mixed solution. The first density calculation method is by a least squares fit to specific gravity data. The second density calculation method is by a mixing rule.

Assumptions

The HLW tank liquid is predominantly a mixture of H_2O , NaNO_3 , NaNO_2 , NaOH , and NaAlO_2 , with other, minor, constituents.

Discussion - Least Squares Fit to Specific Gravity Data

253 specific gravities were measured (Reynolds and Herting 1984) and a least squares fit was accomplished to this data. A correlation for density was calculated in terms of temperature and either molality or molarity for the NaNO_3 , NaNO_2 , NaOH , and NaAlO_2 in solution.

The correlation was compared to 45 densities measured as part of the electrical conductivity as a function of composition and temperature measurements. The Reynolds and Herting correlation compared reasonably with the experimental measurements:

$$\text{Density}_{\text{R\&H}} - \text{Density}_{\text{Expt.}} = +0.018651 \pm 0.034428 \text{ g/cm}^3$$

This is considered to be acceptable agreement with the $\text{Density}_{\text{Expt.}}$ for laboratory solution data.

Discussion - Mixing Rule Calculation for Specific Gravity

This specific gravity averaging theory (Patwardhan and Kumar, 1993) was applied to a mixture of NaNO_3 , NaNO_2 , NaOH and NaAlO_2 . A numerical relationship for NaNO_3 , NaNO_2 , and NaOH densities (Söhnel and Novotný, 1985) was calculated in terms of temperature and molarity. The NaAlO_2 density was approximated by assuming the same density relationship as NaNO_3 in aqueous solution.

The theoretical mixing rule calculation was compared to 45 densities measured as part of the electrical conductivity as a function of composition and temperature measurements. The theoretical relation compared excellently with the experimental measurements:

$$\text{Density}_{\text{mr}} - \text{Density}_{\text{Expt.}} = +0.001776 \pm 0.010857 \text{ g/cm}^3$$

This is considered to be excellent agreement with the $\text{Density}_{\text{Expt.}}$ for laboratory solution data.

Introduction for 35 Analyzed HLW Tank Liquid Samples

A number of HLW tank liquids have been analyzed. Some did not have a sufficient proportion of the salts in solution measured in order to predict the liquid density, but 35 analyzed HLW tank solutions did have the molarity for NaNO_3 , NaNO_2 , NaOH , and NaAlO_2 in solution. These solutions were not saturated solutions, and there was a wide range of densities and water fractions.

These HLW tank solution densities were calculated by the least squares method and by the mixing rule method. The water proportion of the tank solution was calculated for these analyzed tank solutions.

Discussion - Least Squares Fit for Water Fraction

These solution densities were calculated by the least squares method. The analyzed HLW tank solution density was subtracted from the least squares fit to these analyzed liquids.

$$\text{Density}_{\text{R\&H}} - \text{Density}_{\text{Expt.}} = -0.102211 \pm 0.196342 \text{ g/cm}^3$$

These results indicate that some solid particles drained into the liquid, raising the liquid density above the calculated aqueous solution density.

Discussion - Mixing Rule Calculation for Water Fraction

These solution densities were calculated by the mixing rule method. The analyzed HLW tank solution density was subtracted from the mixing rule calculation for these analyzed liquids.

$$\text{Density}_{\text{mr}} - \text{Density}_{\text{Expt.}} = -0.129426 \pm 0.185865 \text{ g/cm}^3$$

These results indicate that some solid particles drained into the liquid, raising the liquid density above the calculated aqueous solution density.

Calculations continue considering the calculated solution density and water fraction by the mixing rule method only.

$$\text{Density}_{\text{Analyzed Solutions}} (\rho_L) = 1.177432 \pm 0.094255 \text{ g/cm}^3$$

$$\text{H}_2\text{O Fraction } (\rho_{\text{H}_2\text{O}}/\rho_L) = 0.792408 \pm 0.109754$$

The solution density and the water fraction of the solution are correlated, the higher the solution density, the lower the H_2O fraction. The uncertainty in EMI moisture content calculation takes into account that these uncertainties are correlated.

Figure C-1 shows the mixing rule calculation for density of the analyzed waste tank solutions versus water fraction.

Figure C-1. Analyzed Waste Tank Solution Calculations.
Composition Density and Water Fraction Using Mixing Rule Method.

FORTRAN Computer Coding for Comparison to 45 Test Mixture Densities

```

C   FORTRAN COMPUTER PROGRAM TO CALCULATE HLW TANK
C   INTERSTITIAL LIQUID DENSITY AND WATER FRACTION.
C
C   A FOUR COMPONENT SYSTEM IS CONSIDERED: SODIUM HYDROXIDE,
C   SODIUM NITRATE, SODIUM NITRITE, AND SODIUM ALUMINATE.
C
C   REF: THERMODYNAMIC PROPERTIES OF AQUEOUS SOLUTIONS OF MIXED
C   ELECTROLYTES: A NEW MIXING RULE, PATWARDHAN & KUMAR IN
C   AIChE JOURNAL, APRIL 1993, VOL. 39, NO.4, P.711-714.
C
C   REF: DENSITIES OF AQUEOUS SOLUTIONS OF INORGANIC SUBSTANCES
C   BY OTAKAR SOHNEL AND PETR NOVOTNY, 1985.
C
C   REF: SOLUBILITIES OF SODIUM NITRATE, SODIUM NITRITE, AND
C   SODIUM ALUMINATE IN SIMULATED NUCLEAR WASTE
C   BY DANIEL A. REYNOLDS AND DANIEL L. HERTING, RHO-RE-ST-14 P
C
C   DIMENSION TMOH(50), TMNO3(50), TMNO2(50), TMALO2(50)
C   DIMENSION TMOLWT(4), PSI(4), RHO(25)
C   DIMENSION TMOLAL(4), DENFIT(50), DENEXP(50)
C
C   DATA TMOLWT /40.00, 84.99, 69.00, 81.97/
C
C   K=1
C   TEST MATRIX PROGRAM
C   1 READ (5, 100, END=2) ICASE, TMOH(K), TMALO2(K),
C   & TMNO3(K), TMNO2(K), DENFIT(K), DENEXP(K)
C   100 FORMAT (I12, 4F9.0, 8X, 2F10.0)
C   WRITE (6,99) ICASE, TMNO3(K), TMNO2(K), TMOH(K),
C   & TMALO2(K), DENFIT(K), DENEXP(K)
C   99 FORMAT (I4,4F9.3,8X,2F10.3,3X,'ECHO INPUT')
C   K=K+1
C   GOTO 1
C
C   2 KK=K-1
C   K=1
C   T=25.0
C   CALCULATED WATER DENSITY AT TEMPERATURE = 25 C
C   USING QUADRATIC LAGRANGIAN INTERPOLATING POLYNOMIAL.
C   RHOWAT=(T-25.)*(T-60.)*1./((3.98-25.)*(3.98-60.))+
C   & (T-3.98)*(T-60.)*0.99707/((25.-3.98)*(25.-60.))+
C   & (T-3.98)*(T-25.)*0.98324/((60.-3.98)*(60.-25.))
C   T2=T**2
C   SUM1A=0.0
C   SUM1B=0.0
C   SUM2A=0.0
C   SUM2B=0.0
C
C   THESE CORRELATIONS ARE FROM SOHNEL AND NOVOTNY REFERENCE
C   3 C=TMNO3(K)+TMNO2(K)+TMOH(K)+TMALO2(K)
C   NaOH DENSITY AT SAME STRENGTH AS MIXED SOLUTION
C   RHONOH=(4.916E1-9.064E-2*T+6.308E-4*T2)*C

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& +(-4.907+1.633E-2*T-1.041E-4*T2)*(C**1.5)
  RHONOH=RHOWAT+RHONOH*1.E-3
C   NaNO3 DENSITY AT SAME STRENGTH AS MIXED SOLUTION
  RHONO3=(6.298E1-2.382E-1*T+1.520E-3*T2)*C
& +(-4.138+6.626E-2*T-4.208E-4*T2)*(C**1.5)
  RHONO3=RHOWAT+RHONO3*1.E-3
C   NaNO2 DENSITY AT SAME STRENGTH AS MIXED SOLUTION
  RHONO2=(5.142E1-3.362E-1*T+4.079E-3*T2)*C
& +(-3.242+7.155E-2*T-9.671E-4*T2)*(C**1.5)
  RHONO2=RHOWAT+RHONO2*1.E-3
C
  I=1
  RHO(I)=1.450
  SALTWT=TMOH(K)*TMOLWT(1)+TMNO3(K)*TMOLWT(2)+TMNO2(K)
& *TMOLWT(3)+TMAL02(K)*TMOLWT(4)
C
C   CALCULATE MOLALITY FROM MOLARITY USING ASSUMED, ITERATED DENSITY
4  TMOLAL(1)=TMOH(K)/(RHO(I)*1.E3-SALTWT)*1.E3
  TMOLAL(2)=TMNO3(K)/(RHO(I)*1.E3-SALTWT)*1.E3
  TMOLAL(3)=TMNO2(K)/(RHO(I)*1.E3-SALTWT)*1.E3
  TMOLAL(4)=TMAL02(K)/(RHO(I)*1.E3-SALTWT)*1.E3
  TMOLSM=TMOLAL(1)+TMOLAL(2)+TMOLAL(3)+TMOLAL(4)
  IF (K-10*(K/10).EQ.1) WRITE (6,98) K, I, RHOWAT,
& RHO(I), SALTWT, (TMOLAL(J),J=1,4), TMOLSM
98 FORMAT (2I6,3F9.3,3X,5F9.3,3X,'TMOLAL S')
C
C   THE PSISUM/PSIRHO IS THE MIXING RULE FROM PATWARDIAN AND KUMAR
PSI(1) = 1.E3*TMOLAL(1)/TMOLSM + TMOLAL(1)*TMOLWT(1)
PSI(2) = 1.E3*TMOLAL(2)/TMOLSM + TMOLAL(2)*TMOLWT(2)
PSI(3) = 1.E3*TMOLAL(3)/TMOLSM + TMOLAL(3)*TMOLWT(3)
PSI(4) = 1.E3*TMOLAL(4)/TMOLSM + TMOLAL(4)*TMOLWT(4)
PSISUM=PSI(1)+PSI(2)+PSI(3)+PSI(4)
C   APPROXIMATION: NaAlO2 DENSITY ASSUMED TO BE NaNO3 DENSITY
PSIRHO=PSI(1)/RHONOH+PSI(2)/RHONO3+
& PSI(3)/RHONO2+PSI(4)/RHONO3
  I=I+1
  RHO(I)=PSISUM/PSIRHO
  IF (K-10*(K/10).EQ.1) WRITE (6,97) K, I, (PSI(J),J=1,4),
& RHONOH, RHONO3, RHONO2, RHO(I-1), RHO(I)
97 FORMAT (2I6,4F9.3,3X,5F9.3,3X,'PSI RHOS RHO')
C
C   DENSITY NOT CONVERGED? RECALCULATE MOLALITY FROM ITERATED DENSITY
IF (ABS(RHO(I)-RHO(I-1)).GT.1.E-4.AND.I.LT.25) GOTO 4
WATPRT=(RHO(I)*1000.-SALTWT)*1.E-3
WTRFRC=WATPRT/RHO(I)
C
C   DENFIT IS CORRELATION FROM REYNOLDS AND HERTING
DENFIT(K)=1.017+5.87E-2*TMAL02(K)-1.943E-2*TMOH(K)-5.05E-4*(25.0)
& +4.59E-2*(TMAL02(K)+TMOH(K)+TMNO3(K)+TMNO2(K))
& -8.83E-4*(TMNO3(K)*TMNO2(K))
  IF (K-10*(K/10).EQ.1) WRITE (6,96) K, I,
& PSISUM, PSIRHO, RHO(I), WATPRT, WTRFRC
96 FORMAT (2I6,5F9.3,3X,'PSISUM WTRFRC')
H2OPRT=(DENFIT(K)*1.E3-TMOH(K)*TMOLWT(1)-TMNO3(K)*TMOLWT(2)

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& -TMNO2(K)*TMOLWT(3)-TMAL02(K)*TMOLWT(4))*1.E-3
H2OFRC=H2OPRT/DENFIT(K)
WRITE (6,101) K, RHO(I), WATPRT, WTRFRC,
& DENFIT(K), H2OPRT, H2OFRC, DENEXP(K)
101 FORMAT (I4,3F10.6,3X,3F12.6,3X,F12.6,' DATA KUMAR.OUT')
SUM1A=SUM1A+RHO(I)-DENEXP(K)
SUM2A=SUM2A+((RHO(I)-DENEXP(K))**2)
SUM1B=SUM1B+DENFIT(K)-DENEXP(K)
SUM2B=SUM2B+((DENFIT(K)-DENEXP(K))**2)
K=K+1
IF (K.LE.KK) GOTO 3

C
AVGA=SUM1A/FLOAT(KK)
SDEVA=SQRT((SUM2A-FLOAT(KK)*AVGA**2)/FLOAT(KK-1))
AVGB=SUM1B/FLOAT(KK)
SDEVB=SQRT((SUM2B-FLOAT(KK)*AVGB**2)/FLOAT(KK-1))
WRITE (6,102) KK, AVGA, SDEVA, AVGB, SDEVB
102 FORMAT (I4,2F12.6,3X,2F12.6,' DIFF, SDEV (MIX, FIT)')
END

```

FORTRAN Computer Output for Comparison to 45 Test Mixture Densities

1	1.000	1.500	4.000	1.000	1.329	1.300	ECHO INPUT												
2	2.000	1.500	4.000	2.000	1.478	1.400	ECHO INPUT												
3	1.000	3.000	4.000	2.000	1.501	1.410	ECHO INPUT												
4	2.000	1.500	6.000	1.000	1.427	1.400	ECHO INPUT												
5	2.000	1.500	4.000	0.000	1.269	1.290	ECHO INPUT												
6	0.000	1.500	6.000	1.000	1.338	1.310	ECHO INPUT												
7	1.000	3.000	6.000	1.000	1.450	1.400	ECHO INPUT												
8	1.000	0.000	4.000	0.000	1.157	1.190	ECHO INPUT												
9	2.000	0.000	4.000	1.000	1.308	1.300	ECHO INPUT												
10	1.000	1.500	2.000	2.000	1.381	1.300	ECHO INPUT												
11	0.000	1.500	4.000	0.000	1.180	1.200	ECHO INPUT												
12	0.000	1.500	2.000	1.000	1.232	1.190	ECHO INPUT												
13	1.000	1.500	2.000	0.000	1.172	1.180	ECHO INPUT												
14	1.000	1.500	4.000	1.000	1.329	1.300	ECHO INPUT												
15	1.000	0.000	2.000	1.000	1.209	1.190	ECHO INPUT												
16	1.000	0.000	4.000	2.000	1.366	1.300	ECHO INPUT												
17	1.000	3.000	2.000	1.000	1.344	1.290	ECHO INPUT												
18	2.000	3.000	4.000	1.000	1.440	1.400	ECHO INPUT												
19	1.000	1.500	6.000	0.000	1.278	1.300	ECHO INPUT												
20	0.000	0.000	4.000	1.000	1.216	1.200	ECHO INPUT												
21	2.000	1.500	2.000	1.000	1.321	1.290	ECHO INPUT												
22	1.000	3.000	4.000	0.000	1.292	1.250	ECHO INPUT												
23	1.000	0.000	6.000	1.000	1.315	1.310	ECHO INPUT												
24	0.000	3.000	4.000	1.000	1.354	1.310	ECHO INPUT												
25	1.000	1.500	6.000	2.000	1.487	1.410	ECHO INPUT												
26	0.000	1.500	4.000	2.000	1.389	1.310	ECHO INPUT												
27	1.000	1.500	4.000	1.000	1.329	1.300	ECHO INPUT												
1	1.500	1.500	1.000	0.000	1.168	1.194	ECHO INPUT												
2	0.000	1.500	0.000	0.000	1.074	1.061	ECHO INPUT												
3	0.000	1.500	2.000	0.000	1.127	1.128	ECHO INPUT												
4	3.000	1.500	0.000	0.000	1.208	1.213	ECHO INPUT												
5	3.000	1.500	2.000	0.000	1.261	1.279	ECHO INPUT												
6	1.500	0.000	0.000	0.000	1.074	1.078	ECHO INPUT												
7	1.500	0.000	2.000	0.000	1.127	1.151	ECHO INPUT												
8	1.500	1.500	1.000	0.000	1.168	1.173	ECHO INPUT												
9	1.500	3.000	0.000	0.000	1.208	1.193	ECHO INPUT												
10	1.500	3.000	2.000	0.000	1.261	1.257	ECHO INPUT												
11	0.000	0.000	1.000	0.000	1.032	1.037	ECHO INPUT												
12	3.000	0.000	1.000	0.000	1.170	1.191	ECHO INPUT												
13	0.000	3.000	1.000	0.000	1.170	1.157	ECHO INPUT												
14	3.000	3.000	1.000	0.000	1.299	1.299	ECHO INPUT												
15	1.500	1.500	1.000	0.000	1.168	1.173	ECHO INPUT												
1	1.630	1.300	6.350	2.160	1.532	1.445	ECHO INPUT												
2	4.500	1.000	1.000	0.000	1.280	1.301	ECHO INPUT												
3	6.000	1.000	2.000	1.000	1.479	1.454	ECHO INPUT												
1	1	0.997	1.450	430.460	3.923	0.981	1.471	0.981	7.356	TMOLAL S									
1	2	690.267	216.694	301.516	213.732	1.258	1.376	1.297	1.450	1.300	PSI RHOS RHO								
1	2	0.997	1.300	430.460	4.601	1.150	1.725	1.150	8.627	TMOLAL S									
1	3	717.382	231.098	319.057	227.624	1.258	1.376	1.297	1.300	1.300	PSI RHOS RHO								
1	3	0.997	1.300	430.460	4.598	1.150	1.724	1.150	8.622	TMOLAL S									
1	4	717.269	231.038	318.984	227.566	1.258	1.376	1.297	1.300	1.300	PSI RHOS RHO								
1	4	1494.857	1149.603	1.300	0.870	0.669	PSISUM WTRFR												
1	1.300325	0.869865	0.668960	1.328280	0.897820	0.675927	1.300000	DATA KUMAR.OUT											
2	1.392758	0.795338	0.571052	1.477456	0.880036	0.595643	1.400000	DATA KUMAR.OUT											
3	1.398754	0.782824	0.559658	1.500406	0.884476	0.589491	1.410000	DATA KUMAR.OUT											
4	1.404399	0.808949	0.576011	1.425796	0.830346	0.582374	1.400000	DATA KUMAR.OUT											
5	1.300501	0.867021	0.666682	1.268256	0.834776	0.658208	1.290000	DATA KUMAR.OUT											
6	1.312997	0.887527	0.675955	1.336645	0.911175	0.681688	1.310000	DATA KUMAR.OUT											
7	1.409679	0.795719	0.564468	1.448746	0.834786	0.576213	1.400000	DATA KUMAR.OUT											
8	1.198678	0.953688	0.795617	1.154155	0.911165	0.788099	1.190000	DATA KUMAR.OUT											
9	1.294123	0.882173	0.681676	1.306655	0.894705	0.684729	1.300000	DATA KUMAR.OUT											
10	1.284184	0.851754	0.663265	1.379941	0.947511	0.686632	1.300000	DATA KUMAR.OUT											
11	1	0.997	1.450	263.500	3.371	0.000	1.264	0.000	4.635	TMOLAL S									
11	2	862.123	0.000	359.959	0.000	1.198	1.281	1.221	1.450	1.205	PSI RHOS RHO								
11	2	0.997	1.205	263.500	4.249	0.000	1.593	0.000	5.842	TMOLAL S									
11	3	897.227	0.000	382.667	0.000	1.198	1.281	1.221	1.205	1.205	PSI RHOS RHO								
11	3	0.997	1.205	263.500	4.248	0.000	1.593	0.000	5.842	TMOLAL S									
11	4	897.209	0.000	382.655	0.000	1.198	1.281	1.221	1.205	1.205	PSI RHOS RHO								
11	4	1279.864	1062.103	1.205	0.942	0.781	PSISUM WTRFR												
11	1.205028	0.941528	0.781333	1.179105	0.915605	0.776525	1.200000	DATA KUMAR.OUT											
12	1.187157	0.921687	0.776382	1.230765	0.965295	0.784305	1.190000	DATA KUMAR.OUT											
13	1.187270	0.918780	0.773859	1.170740	0.902250	0.770667	1.180000	DATA KUMAR.OUT											
14	1.300325	0.869865	0.668960	1.328280	0.897820	0.675927	1.300000	DATA KUMAR.OUT											

16	1.179781	0.932821	0.790673	1.207815	0.960855	0.795532	1.190000	DATA	KUMAR. OUT		
16	1.293980	0.885050	0.683975	1.365355	0.956425	0.700495	1.300000	DATA	KUMAR. OUT		
17	1.291373	0.837413	0.648467	1.342866	0.888906	0.661947	1.290000	DATA	KUMAR. OUT		
18	1.398956	0.780006	0.557563	1.439057	0.820107	0.569892	1.400000	DATA	KUMAR. OUT		
19	1.313237	0.884747	0.673715	1.276620	0.848130	0.664356	1.300000	DATA	KUMAR. OUT		
20	1.198535	0.956565	0.798112	1.214855	0.972885	0.800824	1.200000	DATA	KUMAR. OUT		
21	1	0.997	1.450	435.450	1.971	1.478	0.986	6.407	TMOLAL S		
21	2	386.545	475.235	332.785	234.641	1.229	1.328	1.259	1.450	1.284	PSI RHOS RHO
21	2	0.997	1.284	435.450	2.357	1.768	1.179	7.662	TMOLAL S		
21	3	401.990	508.051	352.767	250.466	1.229	1.328	1.259	1.284	1.284	PSI RHOS RHO
21	3	0.997	1.284	435.450	2.356	1.767	1.178	7.657	TMOLAL S		
21	4	401.938	507.941	352.700	250.413	1.229	1.328	1.259	1.284	1.284	PSI RHOS RHO
21	4	1512.991	1178.072	1.284	0.849	0.661	PSISUM	UTRFRFC			
21	1.284294	0.848844	0.660942	1.319916	0.884466	0.670093	1.290000	DATA	KUMAR. OUT		
22	1.306695	0.854705	0.654097	1.291206	0.839216	0.649948	1.250000	DATA	KUMAR. OUT		
23	1.307616	0.900656	0.688777	1.313695	0.906735	0.690217	1.310000	DATA	KUMAR. OUT		
24	1.306487	0.857517	0.656353	1.352555	0.903585	0.668085	1.310000	DATA	KUMAR. OUT		
25	1.404162	0.811732	0.578090	1.485820	0.893390	0.601278	1.410000	DATA	KUMAR. OUT		
26	1.300148	0.872708	0.671238	1.388305	0.960865	0.692114	1.310000	DATA	KUMAR. OUT		
27	1.300325	0.869865	0.668960	1.328280	0.897820	0.675927	1.300000	DATA	KUMAR. OUT		
28	1.176906	0.905921	0.769748	1.166558	0.895573	0.767706	1.194100	DATA	KUMAR. OUT		
29	1.061636	0.958136	0.902509	1.073225	0.969725	0.903562	1.060800	DATA	KUMAR. OUT		
30	1.137346	0.953846	0.838660	1.126165	0.942665	0.837058	1.127500	DATA	KUMAR. OUT		
31	1	0.997	1.450	358.470	0.000	2.748	1.374	0.000	4.123	TMOLAL S	
31	2	0.000	900.256	428.154	0.000	1.166	1.232	1.182	1.450	1.215	PSI RHOS RHO
31	2	0.997	1.215	358.470	0.000	3.501	1.750	0.000	5.251	TMOLAL S	
31	3	0.000	964.196	454.109	0.000	1.166	1.232	1.182	1.215	1.216	PSI RHOS RHO
31	3	0.997	1.216	358.470	0.000	3.500	1.750	0.000	5.250	TMOLAL S	
31	4	0.000	964.159	454.094	0.000	1.166	1.232	1.182	1.216	1.216	PSI RHOS RHO
31	4	1418.253	1166.772	1.216	0.857	0.705	PSISUM	UTRFRFC			
31	1.215535	0.857065	0.705093	1.206951	0.848482	0.702996	1.212800	DATA	KUMAR. OUT		
32	1.284403	0.845933	0.658620	1.259892	0.821422	0.651978	1.278900	DATA	KUMAR. OUT		
33	1.078991	0.951506	0.881848	1.073225	0.945740	0.881213	1.077600	DATA	KUMAR. OUT		
34	1.154956	0.947471	0.820353	1.126165	0.918680	0.815760	1.151000	DATA	KUMAR. OUT		
35	1.176906	0.905921	0.769748	1.166558	0.895573	0.767706	1.172700	DATA	KUMAR. OUT		
36	1.199102	0.864617	0.721054	1.206951	0.872467	0.722868	1.192700	DATA	KUMAR. OUT		
37	1.267604	0.853119	0.673017	1.259892	0.845407	0.671015	1.256500	DATA	KUMAR. OUT		
38	1.039794	0.999794	0.961531	1.030845	0.990845	0.961197	1.036800	DATA	KUMAR. OUT		
39	1.193821	0.898851	0.752919	1.168545	0.873575	0.747575	1.190700	DATA	KUMAR. OUT		
40	1.159798	0.912798	0.787032	1.168545	0.921545	0.788626	1.157300	DATA	KUMAR. OUT		
41	1	0.997	1.450	501.970	1.055	3.164	3.164	0.000	7.384	TMOLAL S	
41	2	185.050	697.519	646.919	0.000	1.244	1.352	1.278	1.450	1.306	PSI RHOS RHO
41	2	0.997	1.306	501.970	1.243	3.730	3.730	0.000	8.704	TMOLAL S	
41	3	192.593	745.600	685.955	0.000	1.244	1.352	1.278	1.306	1.307	PSI RHOS RHO
41	3	0.997	1.307	501.970	1.243	3.729	3.729	0.000	8.700	TMOLAL S	
41	4	192.574	745.478	685.855	0.000	1.244	1.352	1.278	1.307	1.307	PSI RHOS RHO
41	4	1623.908	1242.919	1.307	0.805	0.616	PSISUM	UTRFRFC			
42	1.306528	0.804558	0.615798	1.298298	0.796328	0.613363	1.299100	DATA	KUMAR. OUT		
42	1.176906	0.905921	0.769748	1.166558	0.895573	0.767706	1.172600	DATA	KUMAR. OUT		
43	1.442332	0.783043	0.542901	1.531011	0.871723	0.569377	1.445400	DATA	KUMAR. OUT		
44	1.304367	0.812912	0.632323	1.279321	0.787866	0.615847	1.300800	DATA	KUMAR. OUT		
45	1.452131	0.711221	0.489777	1.477917	0.737007	0.498680	1.453600	DATA	KUMAR. OUT		
45	0.001776	0.010857	0.018651	0.034428	DIFF, SDEV (MIX, FIT)						

FORTRAN Computer Coding for Calculating 35 HLW Tank Analyzed Liquids

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C   FORTRAN COMPUTER PROGRAM TO CALCULATE HLW TANK
C   INTERSTITIAL LIQUID DENSITY AND WATER FRACTION.
C
C   A FOUR COMPONENT SYSTEM IS CONSIDERED: SODIUM HYDROXIDE,
C   SODIUM NITRATE, SODIUM NITRITE, AND SODIUM ALUMINATE.
C
C   REF: THERMODYNAMIC PROPERTIES OF AQUEOUS SOLUTIONS OF MIXED
C   ELECTROLYTES: A NEW MIXING RULE, PATWARDHAN & KUMAR IN
C   AIChE JOURNAL, APRIL 1993, VOL. 39, NO.4, P.711-714.
C
C   REF: DENSITIES OF AQUEOUS SOLUTIONS OF INORGANIC SUBSTANCES
C   BY OTAKAR SOHNEL AND PETR NOVOTNY, 1985.
C
C   REF: SOLUBILITIES OF SODIUM NITRATE, SODIUM NITRITE, AND
C   SODIUM ALUMINATE IN SIMULATED NUCLEAR WASTE
C   BY DANIEL A. REYNOLDS AND DANIEL L. HERTING, RHO-RE-ST-14 P
C
C   DIMENSION TMOH(50), TMNO3(50), TMNO2(50), TMALO2(50)
C   DIMENSION TMOLAL(4), TMOLWT(4), PSI(4), RHO(25)
C   DIMENSION DENFIT(50), DENEXP(50), DENMR(50)
C
C   DATA TMOLWT /40.00, 84.99, 69.00, 81.97/
C
C   K=1
C   MEASURED HLW TANK SAMPLES PROGRAM
C   1 READ (5, 100, END=2) ICASE, TMNO3(K), TMNO2(K), TMOH(K),
C   & TMALO2(K), DENEXP(K)
C   100 FORMAT (I7, 3X, 5F10.0)
C   WRITE (6,99) ICASE, TMNO3(K), TMNO2(K), TMOH(K),
C   & TMALO2(K), DENEXP(K)
C   99 FORMAT (I4,4F9.3,3X,F10.3,3X,'ECHO INPUT')
C   K=K+1
C   GOTO 1
C
C   2 KK=K-1
C   K=1
C   T=25.0
C   CALCULATED WATER DENSITY AT TEMPERATURE = 25 C
C   USING QUADRATIC LAGRANGIAN INTERPOLATING POLYNOMIAL.
C   RHOWAT=(T-25.)*(T-60.)*1./((3.98-25.)*(3.98-60.))+
C   & (T-3.98)*(T-60.)*0.99707/((25.-3.98)*(25.-60.))+
C   & (T-3.98)*(T-25.)*0.98324/((60.-3.98)*(60.-25.))
C   T2=T**2
C   SUM1A=0.0
C   SUM1B=0.0
C   SUM2A=0.0
C   SUM2B=0.0
C
C   THESE CORRELATIONS ARE FROM SOHNEL AND NOVOTNY REFERENCE
C   3 C=TMNO3(K)+TMNO2(K)+TMOH(K)+TMALO2(K)
C   NaOH DENSITY AT SAME STRENGTH AS MIXED SOLUTION
C   RHONOH=(4.916E1-9.064E-2*T+6.308E-4*T2)*C

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& +(-4.907+1.633E-2*T-1.041E-4*T2)*(C**1.5)
  RHONOH=RHOWAT+RHONOH*1.E-3
C  NaNO3 DENSITY AT SAME STRENGTH AS MIXED SOLUTION
  RHON03=(6.298E1-2.382E-1*T+1.520E-3*T2)*C
& +(-4.138+6.626E-2*T-4.208E-4*T2)*(C**1.5)
  RHON03=RHOWAT+RHON03*1.E-3
C  NaNO2 DENSITY AT SAME STRENGTH AS MIXED SOLUTION
  RHON02=(5.142E1-3.362E-1*T+4.079E-3*T2)*C
& +(-3.242+7.155E-2*T-9.671E-4*T2)*(C**1.5)
  RHON02=RHOWAT+RHON02*1.E-3
C
  I=1
  RHO(I)=1.450
  SALTWT=TMOH(K)*TMOLWT(1)+TMNO3(K)*TMOLWT(2)+TMNO2(K)
& *TMOLWT(3)+TMAL02(K)*TMOLWT(4)
C
C  CALCULATE MOLALITY FROM MOLARITY USING ASSUMED, ITERATED DENSITY
4  TMOLAL(1)=TMOH(K)/(RHO(I)*1.E3-SALTWT)*1.E3
  TMOLAL(2)=TMNO3(K)/(RHO(I)*1.E3-SALTWT)*1.E3
  TMOLAL(3)=TMNO2(K)/(RHO(I)*1.E3-SALTWT)*1.E3
  TMOLAL(4)=TMAL02(K)/(RHO(I)*1.E3-SALTWT)*1.E3
  TMOLSM=TMOLAL(1)+TMOLAL(2)+TMOLAL(3)+TMOLAL(4)
  IF (K-10*(K/10).EQ.1) WRITE (6,98) K, I, RHOWAT,
& RHO(I), SALTWT, (TMOLAL(J),J=1,4), TMOLSM
98  FORMAT (2I6,3F9.3,3X,5F9.3,3X,'TMOLAL S')
C
C  THE PSISUM/PSIRHO IS THE MIXING RULE FROM PATWARDIAN AND KUMAR
  PSI(1) = 1.E3*TMOLAL(1)/TMOLSM + TMOLAL(1)*TMOLWT(1)
  PSI(2) = 1.E3*TMOLAL(2)/TMOLSM + TMOLAL(2)*TMOLWT(2)
  PSI(3) = 1.E3*TMOLAL(3)/TMOLSM + TMOLAL(3)*TMOLWT(3)
  PSI(4) = 1.E3*TMOLAL(4)/TMOLSM + TMOLAL(4)*TMOLWT(4)
  PSISUM=PSI(1)+PSI(2)+PSI(3)+PSI(4)
C  APPROXIMATION: NaAlO2 DENSITY ASSUMED TO BE NaNO3 DENSITY
  PSIRHO=PSI(1)/RHONOH+PSI(2)/RHON03+
& PSI(3)/RHON02+PSI(4)/RHON03
  I=I+1
  RHO(I)=PSISUM/PSIRHO
  IF (K-10*(K/10).EQ.1) WRITE (6,97) K, I, (PSI(J),J=1,4),
& RHONOH, RHON03, RHON02, RHO(I-1), RHO(I)
97  FORMAT (2I6,4F9.3,3X,5F9.3,3X,'PSI RHOS RHO')
C
C  DENSITY NOT CONVERGED? RECALCULATE MOLALITY FROM ITERATED DENSITY
  IF (ABS(RHO(I)-RHO(I-1)).GT.1.E-4.AND.I.LT.25) GOTO 4
  DENMR(K)=RHO(I)
  WATPRT=(RHO(I)*1000.-SALTWT)*1.E-3
  WTRFRC=WATPRT/RHO(I)
C
C  DENFIT IS CORRELATION FROM REYNOLDS AND HERTING
  DENFIT(K)=1.017+5.87E-2*TMAL02(K)-1.943E-2*TMOH(K)-5.05E-4*(25.0)
& +4.59E-2*(TMAL02(K)+TMOH(K)+TMNO3(K)+TMNO2(K))
& -8.83E-4*(TMNO3(K)*TMNO2(K))
  IF (K-10*(K/10).EQ.1) WRITE (6,96) K, I,
& PSISUM, PSIRHO, RHO(I), WATPRT, WTRFRC
96  FORMAT (2I6,5F9.3,3X,'PSISUM WTRFRC')

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H2OPRT=(DENFIT(K)*1.E-3-TMOH(K)*TMOLWT(1)-TMNO3(K)*TMOLWT(2)
& -TMNO2(K)*TMOLWT(3)-TMAL02(K)*TMOLWT(4))*1.E-3
H2OFRC=H2OPRT/DENFIT(K)
WRITE (6,101) K, RHO(I), WATPRT, WTRFRC,
& DENFIT(K), H2OPRT, H2OFRC, DENEXP(K)
101 FORMAT (I4,3F10.6,3X,3F12.6,3X,F12.6,' DATA KUMAR1.OUT')
SUM1A=SUM1A+RHO(I)-DENEXP(K)
SUM2A=SUM2A+((RHO(I)-DENEXP(K))**2)
SUM1B=SUM1B+DENFIT(K)-DENEXP(K)
SUM2B=SUM2B+((DENFIT(K)-DENEXP(K))**2)
K=K+1
IF (K.LE.KK) GOTO 3

C
AVGA=SUM1A/FLOAT(KK)
SDEVA=SQRT((SUM2A-FLOAT(KK)*AVGA**2)/FLOAT(KK-1))
AVGB=SUM1B/FLOAT(KK)
SDEVB=SQRT((SUM2B-FLOAT(KK)*AVGB**2)/FLOAT(KK-1))
WRITE (6,102) KK, AVGA, SDEVA, AVGB, SDEVB
102 FORMAT (I4,2F12.6,3X,2F12.6,' AVG, SDEV (MIX, FIT)')

C
SUM1A=0.0
SUM1B=0.0
SUM2A=0.0
SUM2B=0.0
DO 5 K=1,KK
SUM1A=SUM1A+DENMR(K)
SUM2A=SUM2A+(DENMR(K)**2)
SALTWT=TMOH(K)*TMOLWT(1)+TMNO3(K)*TMOLWT(2)
& +TMNO2(K)*TMOLWT(3)+TMAL02(K)*TMOLWT(4)
WTRFRC=((DENMR(K)*1000.-SALTWT)*1.E-3)/DENMR(K)
SUM1B=SUM1B+WTRFRC
SUM2B=SUM2B+(WTRFRC**2)
5 CONTINUE
AVGA=SUM1A/FLOAT(KK)
SDEVA=SQRT((SUM2A-FLOAT(KK)*AVGA**2)/FLOAT(KK-1))
AVGB=SUM1B/FLOAT(KK)
SDEVB=SQRT((SUM2B-FLOAT(KK)*AVGB**2)/FLOAT(KK-1))
WRITE (6,103) KK, AVGA, SDEVA, AVGB, SDEVB
103 FORMAT (I4,2F12.6,3X,2F12.6,' AVG, SDEV (RHO-L, RHOH20/RHO-L)')

C
AT RHO-L = 0.997070, THE RHOH20/RHO-L IS 1.000000 (CASE 0)
C
AT RHO-L = 1.386575, THE RHOH20/RHO-L IS 0.560727 (CASE 9)
C
SO (DELTA RHOH20/RHO-L)/(DELTA RHO-L) IS
C
(1.000000-0.560727)/(0.997070-1.386575)
DEL=(1.000000-0.560727)/(0.997070-1.386575)
WRITE (6,104) DEL
104 FORMAT (3X,'SLOPE OF (DEL RHOH20/RHO-L)/(DEL RHO)',F12.6)
SALTWT=TMOH(9)*TMOLWT(1)+TMNO3(9)*TMOLWT(2)
& +TMNO2(9)*TMOLWT(3)+TMAL02(9)*TMOLWT(4)
WTRFRC=((DENMR(9)*1000.-SALTWT)*1.E-3)/DENMR(9)
DEL=(1.0-WTRFRC)/(RHOWAT-DENMR(9))
WRITE (6,104) DEL
END

```

FORTRAN Computer Coding for Calculating 35 HLW Tank Analyzed Liquids

1	1.020	1.520	2.080	0.040	1.680	ECHO INPUT					
2	0.050	0.000	1.840	0.360	1.570	ECHO INPUT					
3	0.130	0.050	1.060	0.330	1.510	ECHO INPUT					
4	0.030	0.000	3.000	0.190	1.140	ECHO INPUT					
5	1.290	0.670	2.480	1.140	1.120	ECHO INPUT					
6	0.050	0.000	0.340	0.430	1.230	ECHO INPUT					
7	2.070	0.280	2.610	1.690	1.280	ECHO INPUT					
8	0.110	0.000	2.650	0.740	1.470	ECHO INPUT					
9	3.430	1.450	2.610	1.380	1.100	ECHO INPUT					
10	0.070	0.000	2.000	0.650	1.330	ECHO INPUT					
11	2.700	0.690	2.050	1.160	1.220	ECHO INPUT					
12	2.600	0.980	2.110	0.940	1.340	ECHO INPUT					
13	2.900	1.090	1.900	1.440	1.370	ECHO INPUT					
14	2.500	0.760	1.630	0.880	1.440	ECHO INPUT					
15	0.870	0.120	0.580	0.400	1.200	ECHO INPUT					
16	0.170	0.000	0.590	1.160	1.420	ECHO INPUT					
17	0.480	0.070	1.100	0.490	1.450	ECHO INPUT					
18	0.770	0.060	0.790	3.070	1.400	ECHO INPUT					
19	4.890	0.000	1.820	0.410	1.460	ECHO INPUT					
20	0.810	0.150	1.540	0.590	1.400	ECHO INPUT					
21	0.490	0.000	1.810	1.400	1.420	ECHO INPUT					
22	1.180	0.470	1.430	0.580	1.150	ECHO INPUT					
23	0.160	0.050	1.450	0.110	1.140	ECHO INPUT					
24	0.180	0.190	0.720	0.400	1.130	ECHO INPUT					
25	0.950	0.620	1.810	0.950	1.210	ECHO INPUT					
26	0.700	0.200	2.690	0.300	1.200	ECHO INPUT					
27	0.470	0.210	2.180	0.720	1.300	ECHO INPUT					
28	0.460	0.160	1.310	1.090	1.220	ECHO INPUT					
29	0.020	0.000	2.190	0.580	1.240	ECHO INPUT					
30	0.920	0.000	0.800	1.060	1.430	ECHO INPUT					
31	0.380	0.000	0.980	1.020	1.110	ECHO INPUT					
32	0.490	0.000	0.390	0.970	1.500	ECHO INPUT					
33	1.390	0.640	2.000	1.060	1.110	ECHO INPUT					
34	0.230	0.000	2.840	0.550	1.240	ECHO INPUT					
35	2.910	1.370	2.290	2.040	1.210	ECHO INPUT					
1	1	0.997	1.450	278.049	1.775	0.870	1.297	0.034	3.976	TMOLAL S	
1	2	517.345	292.855	415.672	11.381	1.172	1.240	1.189	1.450	1.193	PSI RHOS RHO
1	2	0.997	1.193	278.049	2.272	1.114	1.660	0.044	5.091	TMOLAL S	
1	3	537.242	313.587	440.754	12.166	1.172	1.240	1.189	1.193	1.194	PSI RHOS RHO
1	3	0.997	1.194	278.047	2.272	1.114	1.660	0.044	5.089	TMOLAL S	
1	4	537.212	313.555	440.717	12.164	1.172	1.240	1.189	1.194	1.194	PSI RHOS RHO
1	4	1303.649	1092.107	1.194	0.916	0.767	PSISUM MTRFRC				
1	1.193740	0.915692	0.767078	1.178833	0.900785	0.764132	1.680000	DATA	KUMAR1.0UT		
2	1.093829	0.986471	0.901851	1.093031	0.985672	0.901779	1.570000	DATA	KUMAR1.0UT		
3	1.068548	0.984599	0.921437	1.075207	0.991259	0.921923	1.510000	DATA	KUMAR1.0UT		
4	1.126262	0.988138	0.877361	1.105036	0.966912	0.875005	1.140000	DATA	KUMAR1.0UT		
5	1.242277	0.893764	0.719456	1.278465	0.929953	0.727398	1.120000	DATA	KUMAR1.0UT		
6	1.038436	0.985340	0.948869	1.060648	1.007551	0.949940	1.230000	DATA	KUMAR1.0UT		
7	1.295867	0.857689	0.661865	1.357589	0.919410	0.677238	1.280000	DATA	KUMAR1.0UT		
8	1.145439	0.969433	0.846341	1.156973	0.980967	0.847873	1.470000	DATA	KUMAR1.0UT		
9	1.386575	0.777491	0.560727	1.437410	0.828326	0.576263	1.100000	DATA	KUMAR1.0UT		
10	1.115573	0.976343	0.875194	1.128518	0.989288	0.876626	1.330000	DATA	KUMAR1.0UT		
11	1	0.997	1.450	454.168	2.059	2.711	0.693	1.165	6.628	TMOLAL S	
11	2	392.949	639.524	152.355	271.241	1.232	1.333	1.263	1.450	1.297	PSI RHOS RHO
11	2	0.997	1.297	454.168	2.433	3.204	0.819	1.377	7.832	TMOLAL S	
11	3	407.918	681.414	161.046	288.598	1.232	1.333	1.263	1.297	1.297	PSI RHOS RHO
11	3	0.997	1.297	454.168	2.431	3.202	0.818	1.376	7.828	TMOLAL S	
11	4	407.861	681.233	161.012	288.532	1.232	1.333	1.263	1.297	1.297	PSI RHOS RHO
11	4	1538.658	1186.036	1.297	0.843	0.650	PSISUM MTRFRC				
11	1.297314	0.843146	0.649917	1.333930	0.879762	0.659526	1.220000	DATA	KUMAR1.0UT		
12	1.294648	0.844603	0.652380	1.320623	0.870577	0.659217	1.340000	DATA	KUMAR1.0UT		
13	1.329592	0.813875	0.612123	1.385642	0.869924	0.627813	1.370000	DATA	KUMAR1.0UT		
14	1.262986	0.860737	0.681510	1.287525	0.885277	0.687580	1.440000	DATA	KUMAR1.0UT		
15	1.094925	0.956715	0.873773	1.106916	0.968707	0.871405	1.200000	DATA	KUMAR1.0UT		
16	1.093567	0.960433	0.878258	1.149131	1.015998	0.884144	1.420000	DATA	KUMAR1.0UT		
17	1.097459	0.967669	0.881736	1.109961	0.980171	0.883068	1.450000	DATA	KUMAR1.0UT		
18	1.229943	0.877113	0.713133	1.384465	1.031634	0.745150	1.400000	DATA	KUMAR1.0UT		
19	1.332860	0.810851	0.608354	1.319887	0.797879	0.604505	1.460000	DATA	KUMAR1.0UT		
20	1.139047	0.949893	0.833936	1.150810	0.961655	0.835634	1.400000	DATA	KUMAR1.0UT		
21	1	0.997	1.450	228.803	1.482	0.401	0.000	1.146	3.030	TMOLAL S	
21	2	548.475	166.534	0.000	472.350	1.140	1.192	1.151	1.450	1.167	PSI RHOS RHO
21	2	0.997	1.167	228.803	1.929	0.522	0.000	1.492	3.943	TMOLAL S	
21	3	566.341	176.811	0.000	500.669	1.140	1.192	1.151	1.167	1.168	PSI RHOS RHO

21	3	0.997	1.168	228.803	1.928	0.522	0.000	1.491	3.941	TMOLAL S
21	4	566.313	176.794	0.000	500.623	1.140	1.192	1.151	1.168	PSI RHOS RHO
21	4	1243.730	1065.241	1.168	0.939	0.804	PSISUM	WTRFRC		
21	1.167557	0.938754	0.804033	1.221217	0.992414	0.812643	1.420000	DATA	KUMAR1.OUT	
22	1.165559	0.928098	0.796269	1.178140	0.940680	0.798444	1.150000	DATA	KUMAR1.OUT	
23	1.073791	0.989726	0.921712	1.063894	0.979829	0.920984	1.140000	DATA	KUMAR1.OUT	
24	1.067128	0.977131	0.915665	1.082226	0.992230	0.916842	1.130000	DATA	KUMAR1.OUT	
25	1.191704	0.917912	0.770252	1.223199	0.949407	0.776167	1.210000	DATA	KUMAR1.OUT	
26	1.161936	0.956452	0.823154	1.148146	0.942662	0.821030	1.200000	DATA	KUMAR1.OUT	
27	1.153845	0.953191	0.826100	1.168516	0.967863	0.828283	1.300000	DATA	KUMAR1.OUT	
28	1.138553	0.946670	0.831468	1.181458	0.989575	0.837588	1.220000	DATA	KUMAR1.OUT	
29	1.116421	0.979578	0.877428	1.123930	0.987088	0.878246	1.240000	DATA	KUMAR1.OUT	
30	1.135119	0.938040	0.826380	1.178655	0.981576	0.832793	1.430000	DATA	KUMAR1.OUT	
31	1	0.997	1.450	155.106	0.757	0.293	0.000	0.788	1.838	TMOLAL S
31	2	442.037	184.605	0.000	493.140	1.093	1.125	1.098	1.450	1.112 PSI RHOS RHO
31	2	0.997	1.112	155.106	1.024	0.397	0.000	1.066	2.487	TMOLAL S
31	3	452.727	193.412	0.000	515.940	1.093	1.125	1.098	1.112	1.112 PSI RHOS RHO
31	3	0.997	1.112	155.106	1.024	0.397	0.000	1.066	2.487	TMOLAL S
31	4	452.720	193.406	0.000	515.925	1.093	1.125	1.098	1.112	1.112 PSI RHOS RHO
31	4	1162.052	1044.785	1.112	0.957	0.861	PSISUM	WTRFRC		
31	1.112240	0.957135	0.860547	1.154450	0.999344	0.865646	1.110000	DATA	KUMAR1.OUT	
32	1.092492	0.955736	0.874822	1.138651	1.001895	0.879897	1.500000	DATA	KUMAR1.OUT	
33	1.225987	0.896802	0.731494	1.260583	0.931398	0.738863	1.110000	DATA	KUMAR1.OUT	
34	1.148620	0.970389	0.844830	1.147637	0.969406	0.844697	1.240000	DATA	KUMAR1.OUT	
35	1.380267	0.779598	0.564816	1.471307	0.870637	0.591744	1.210000	DATA	KUMAR1.OUT	
35	-0.129426	0.185865	-0.102211	0.196342	AVG, SDEV (MIX, FIT)					
35	1.177432	0.094255	0.792408	0.109754	AVG, SDEV (RHO-L, RHOM20/RHO-L)					
SLOPE OF (DEL RHOM20/RHO-L)/(DEL RHO)				-1.127773						
SLOPE OF (DEL RHOM20/RHO-L)/(DEL RHO)				-1.127771						

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APPENDIX D
REVIEW COMMENT RECORD FOR
INDEPENDENT REVIEW

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REVIEW COMMENT RECORD (RCR)	1. Date May 6, 1996	2. Review No. EMI - PNL
	3. Project No.	4. Page 1 of 2

5. Document Number(s)/Title(s) WHC-SD-WM-ER-531 REV 0 Electromagnetic Induction Probe Calibration for Electrical Conductivity Measurements and Moisture Content Determination of Hanford High Level Waste	6. Program/Project/ Building Number EMI Moisture Monitor	7. Reviewer Dave Rector Del Lessor	8. Organization/Group PNNL/Fluid Dynamics PNNL/Fluid Dynamics	9. Location/Phone ISBL/240/RCHN 372-4530 ISBL/243/RCHN 375-2382
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17. Comment Submittal Approval:

10. Agreement with indicated comment disposition(s)

11. CLOSED

Organization Manager (Optional)

May 7, 1996
DateDelbert P. Lessor
Reviewer/Point of ContactWarren D. Wittke
Author/OriginatorMay 7, 1996
DateDelbert P. Lessor
Reviewer/Point of ContactWarren D. Wittke
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.	While Archie's Law probably provides a useful functional form for the moisture-vs-conductivity relation, the highly ionic and highly soluble saltcake may require different parameters than the only slightly soluble geologic materials for which parameters have been determined. We think that the report should include a recommendation for an experimental determination of Archie's Law parameters for a highly ionic, highly soluble porous material, unless conductivity-vs-moisture information can be found for such material. Parameters determined for geologic salt formations might be satisfactory.		Yes. The suggestion for a demonstration test, along with laboratory determination of porosity, interstitial liquid electrical conductivity, and free water mass fraction as a proof-of-principal is accepted. This will be worked on as time, schedule and project resources permit.	Closed, DRL

WHC-SD-WM-ER-531 REV 0

REVIEW COMMENT RECORD (RCR)				1. Date May 6, 1996	2. Review No. EMI - PNL
				3. Project No.	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	
2.	If Archie's Law parameters are determined by new experiments or from literature sources for soluble ionic salts, the authors should recommend that the conductivity of the interstitial liquid, used in Archie's Law, be calculated from their thorough work determining that conductivity for a given composition and temperature.		Yes. When tank data exists, i.e. composition and temperature, for prediction of interstitial liquid conductivity, the data base for electrical conductivity as a function of composition and temperature will be used to improve the calculated moisture measurement.	Closed. DLK	
3.	The authors should emphasize that a modest amount of experimentation and application of theory will probably allow the determination of some information about the moisture depth profile, going beyond a single weighted average moisture value.		Yes. Planned lab tests for lift-off and depth of penetration can support moisture depth profile interpretation. If moisture is higher or lower at surface compared to below surface may reveal whether moisture is increasing or decreasing with time.	Closed. DLK	
4.	A potential difficulty in EMI moisture sensing in saltcake comes from fractures, fissures, and uneven surfaces which can alter the EMI signal. We believe that potential problems from such discontinuities are not prohibitive to EMI moisture sensing, but may require some action, such as watching for evidence of fissures from the video camera, or applying statistical tests to the data.		Yes. At a first approximation, the presence of fractures, fissures, etc. or subsurface voids will be similar to the effect of EMI probe lift-off, which is the highest priority for EMI lab tests. The EMI trace in angle and magnitude as the surface is approached will be important in interpreting the moisture content.	Closed. DLK	
5.	A merit of the EMI moisture probe that should be pointed out is that it could provide information on ferromagnetic degradation products of ferrocyanide, without compromising the detection of moisture. This can be done if the sensing operation makes adequate use of the available signals, such as using both the amplitude and phase of the material-induced voltage change, or both the resistive and reactive parts of the material-induced impedance change.		Yes. It is true that the magnetic susceptibility for iron compounds is comparatively high (≈ 10 or 15×10^{-3}), the interpretation is not unambiguous. Cerium, chromium, cobalt, rare earth elements, manganese have similarly high magnetic susceptibilities. Wires from another instrument may also mimic the high magnetic susceptibility of chemical compounds.	Closed. DLK	

MHC-SD-MM-ER-531 REV 0

Electromagnetic Induction Probe Calibration for Electrical Conductivity Measurements and Moisture Content Determination of Hanford High Level Waste

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

Westinghouse
Hanford Company Richland, Washington

Management and Operations Contractor for the
U.S. Department of Energy under Contract DE-AC06-87RL10930

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