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FINAL REPORT: ENHANCED WASTE TANK LEVEL MODEL (U)

Author: M. R. DUIGNAN

March, 1994

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Westinghouse Savannah River Corporation
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FINAL REPORT: ENHANCED WASTE TANK LEVEL MODEL (U)

by

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Executive Summary

Under Technical Task: 93-042-0 (approved, 08/18/93), which is the result of Technical Task Request: HLE-TTR-93053 (issued 05/27/93), a "user-friendly" model was developed to capture environmental effects on the waste level in H-area waste tanks. Before the model was developed a sensitivity study was done to determine the important effects on the waste level changes. For each of the effects a model was developed, but because of either a lack of information or complexity, the models are simple. The models are then used to determine each contribution to the change in level. All the contributions are combined to obtain an overall change in waste level over a fixed period.

As requested, the model was developed to be easy to use and its basic operation can be learned in a short time period. Despite its simplicity, the model is considered more comprehensive then the existing model, which only allows for the thermal expansion and contraction of supernate. However, it is still limited by several simplifying assumptions, listed herein, to make the problem tractable. Improvements can be made as better knowledge is obtained concerning the chemistry of the tank contents, the thermodynamic state of the contents, and local variables, e.g., atmospheric conditions, purge gas condenser condition, amount of salt cake, amount of liquid in the salt cake.

Good agreement was shown to exist between the model's output to one tank's (41) measured level history, during the Spring and Summer seasons for a one year period (92-93), but the agreement diverges during the cooler seasons. The reason for the divergence is not known. While the model indicated that the waste level should have decreased during the colder and drier seasons (because of evaporation, contraction, and precipitation of salts) the measured level remained relatively constant. Some reasons for the divergence may be that evaporation was retarded (e.g., when there is no purge gas flow), an in-leakage of mass to the tank occurred, the model does not properly capture level-changing mechanisms during the cooler seasons, or some type of gas accumulation was occurring within the salt cake. At the end of the one-year period the new model accounted for approximately 2 inches of the measured 4.5-inch change (the divergence during the cooler seasons was approximately 2 inches). In all cases, the new model tracked the measured waste level better than the existing model and therefore its use is recommended.

Finally, no attempt was made to model the presence of gas in the salt cake and makes no assumption about the presence of gas. The high-frequency (daily) fluctuations in waste level (< 0.2") have been shown to correspond to the daily changes in atmospheric pressure, based on an ideal-gas relation. This agreement implies that a fixed amount of gas void may be trapped in the salt cake. However, over longer periods these fluctuations average out and are unimportant. What is not clear, is if gases accumulate in the salt cake, leading to a net effect of increasing the waste level. While this accumulation of gases is not believed to exist (or exists for small amounts of gas and for short periods of time) this fact has yet to be proved.

Acknowledgments

I would like to thank the assistance of all the H-Area Tank Farm personnel who assisted me to understand the problems in waste-tank levels and in amassing the data, so that historical comparisons could be made. Especially, I thank Jeff Pike, Bill Phillips, and John Marra. Special thanks goes to the Co-op student, Nick Walker, who did some necessary literature searches and to the visiting high school mathematics teacher, Cynthia Smith (during her eight-week stay at SRS through The Ruth Patrick Science Foundation), who began the unenviable task of putting the almost 50k-element data base of atmospheric data into a usable form. I would also like to thank the reviewers who input always produce a better product, T. L. Spatz, on the operation of the spreadsheet and J. L. Steimke, on the tasks reports. Finally, the work could not be done without the support and guidance of my management, Al Garrett, Dave Crowley, and Dave Muhlbaier.

Nomenclature*

ρ - Density
H-Area - Location of High-Level Waste Tanks at SRS
i - Electrolyte multiplier
M_{H_2O} - Mass H_2O per mass dry gas
$NaOH$ - Sodium Hydroxide
$NaNO_2$ - Sodium Nitrite
$NaNO_3$ - Sodium Nitrate
$NaAlO_2$ - Sodium Aluminate
Na_2CO_3 - Sodium Carbonate
Na_2SO_4 - Sodium Sulfate
P - Pressure
$P_{mixture}$ - Pressure of the purge-gas/water-vapor mixture
$P_{wv@sat}$ - Saturation pressure of water vapor at the mixture temperature
$P_{reduced}$ - The partial pressure or the water vapor in the tank which is reduced from the vapor pressure that would exit above the liquid in the tank if it were pure water, i.e., containing no electrolytes (Eq. 4).
RH - Relative Humidity
SRTC - Savannah River Technology Center
SRS - Savannah River Site
Tank 41 - One type (type 3A) of waste tank in H-Area
T - Temperature
W_g - Mass flow rate of gas
X_i - Mole fraction of the ith electrolyte

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* Description are only for the body of the report, not Appendix I

Table of Contents

1.0. INTRODUCTION

With the increased sensitivity of waste-level measurements in the H-Area Tanks and with periods of isolation, when no mass transfer occurred for certain tanks, waste-level changes have been recorded which are unexplained. This is especially true for Tank 41, but not limited to that tank. An unexplained change of one (1) inch in the waste level is a reportable event. Qualitative observations indicate that much of the unexplained level change may be explained by environmental effects, i.e., changes in level due to changes in atmospheric pressure, temperature, and relative humidity. Quantitatively, some of the waste-level changes have been explained by using a model that indicates the thermal expansion of the tanks' contents (but the contents are assumed to consist of only supernate). Unfortunately, that model does not work for all tanks, nor at all times for the tanks it gives reasonable level results. That model is limited in scope, but can be enhanced by incorporating other changes which occur because of environmental changes. To this end, a more extensive model was developed to determine the waste-level changes in the H-Area Tanks. In this way, reported unexplained waste-level changes will be more meaningful.

1.1. DATA BASES

The waste tank data base used, to determine how well the current model tracks waste-level changes, is from Tank 41 of H-Area. Any tank could have been used and during any time period, but it was from the large unexplained increases in waste level in Tank 41 which instigated the need for a more comprehensive model. The period selected for Tank 41 is from 05-08-92 to 06-06-93 during which time the waste level increased approximately four (4) inches with no apparent explanation. Also, Tank 41 was chosen because most of the level is of salt cake (≈ 80%), with a shallow pool of supernate lying on its top, and the environmental effects to salt cake had yet to be modeled. This salt cake complicates the situation in that it has a different expansion rate than supernate and the crystallized salts may dissolve into the supernate which affects both the mass contents and the density of the supernate. This data base consisted of daily readings of: a salt cake temperature, a supernate temperature, a steel tank temperature, and the measured waste level.

Another data base was necessary of the outside environment. The Environmental Transport Group of SRTC (1) supplied the necessary information for the year's period already mentioned. That data base consists of hourly readings of atmospheric: temperature, pressure, and humidity. Unfortunately, these data are not from H-Area but from the Central Shops Area at ground level (the nearest meteorological station). While the data base is almost complete several days of information were not available and were filled in with data from Bush field station. On occasion, no data were available at all, and those days were discarded. Finally, for each day the values for hourly air temperature, pressure, and relative humidity were averaged from 07:00 to 11:00 (i.e., the hourly readings taken at 7, 8, 9, 10, and 11 am). These averages were used to determine the daily water content in the air.

1.2. OVERALL ASSUMPTIONS

The accuracy of the model depends on whether all possible mechanisms which respond to environmental effects are captured and on the assumptions imposed on each mechanism, to make the problem tractable. Of course, to incorporate all possible mechanisms is very complex and may not be effective because some effects cause changes that are insignificant when compared to the overall level change, or because the increased amount of the uncertainty, when including an effect, would decrease the certainty in a change of level.

This report is broken up into individual sections, and in each the important assumptions are listed. The assumptions listed below affect the entire model:

1. No gas, or gas generation, is present in the salt cake.
2. Measured temperatures which are generally local, time dependent, values are taken to be representative of the entire body in which they reside, e.g., supernate, salt cake, and to be constant from the previous time they were measured, e.g., the previous day.
2. All changes are determined after thermodynamic equilibrium has been reached.
3. Each effect on level is independent.
4. Uncertainties in known or measured variables are due to independent causes.

1.3. MODEL STEPS

The model has been broken down into six (6) steps, where a step is defined as the process of determining a change in waste level due to a specified mechanism. To facilitate the understanding of what each contribution has on the change in level the result of each step has been listed separately in the model output sheet (Appendix I). Likewise, each step list its uncertainty separately to be able to refine the model more efficiently at the appropriate times. The steps are listed below (see also Fig. 1):

Prestep: Determine the specific gravity of the supernate at current supernate temperature from the specific gravity which was determined through an analytical measurement made at an earlier time, and possibly a different temperature.

[Note about the prestep: Specific gravity is corrected to current temperature of the supernate. This is necessary because the chemistry of each tank is measured less frequently than the daily waste-level monitorings and this analytical measurement may be carried out under different conditions than exist in the tank, i.e., laboratory conditions. Measurements of the supernate chemistry give the three primary salt concentrations, the pH, and the specific gravity of the supernate. The temperature of the analytical test may differ from the tank temperature so the specific gravity is corrected to the current tank temperature. The concentrations are not corrected because the information necessary to make a correction has a high level of uncertainty and any improvement would be questionable.]

Step 1: Determine the change in waste level due to the In-tank condensation/evaporation which occurs because of a water vapor-pressure reduction caused by the supernate salt contents.

Step 2: Determine the change in waste level due to condensation at the purge-gas condenser coil exit.

Step 3: Determine the change in waste level due to the transfer of mass between the salt cake and the supernate. That is, mass which dissolves from the solid into the supernate or precipitates from the supernate to the solid.

[Note about step 3: Two different changes to waste level are obtained from this step because this exchange of mass affects both the supernate and the salt cake. Example, for a temperature increase some of the salt cake dissolves into the supernate and therefore the solid will decrease in height due to the loss of mass. Conversely, the liquid will have an increase in height, due to the gain of mass. This exchange does not address the expansion/contraction due to the temperature, which are Steps 4 and 5.]

Step 4: Determine the change in waste level due to the thermal expansion/ contraction of the salt cake.

Step 5: Determine the change in waste level due to the thermal expansion/ contraction of the supernate.

[Note about step 5: Two different changes in the supernate will occur. That which is within the saturated salt cake, and the rest, which sits on top of the salt cake. Since the salt cake temperature, and its daily temperature changes, usually differ from those of the salt-cake free supernate, then different volumetric changes can be expected.]

Step 6: Determine the change in waste level due to thermal expansion/ contraction carbon steel tank.

[Note about step 6: This effect is generally insignificant to the other effects but is included because of past concerns to its importance.]

2.0. DESCRIPTION OF TASK

This task was broken down into two categories: 1. Determining important environmental effects on waste level, and 2. developing of a model which relates the waste-level changes in a tank to environmental changes. To study the effects, one specific tank was chosen which contains the majority of features of other tanks, so that the model would be general. Tank 41 was selected because: 1. it has had unexplained changes in waste level, 2. of its features: of type 3A design, 3. of using an accurate reel tape to record level, 4. its contents include both liquid and solid mass, etc.

This task was carried out by first proposing to the customer the important environmental effects on the waste level in the task plan (2). Each effect was studied individually and then a model was developed, which then was applied to tank 41 conditions over approximately a year's time. These studies culminated in an overall model which treats each effect independent of the other, assuming the overall change to be the sum of all the changes.

3.0. DETERMINATION OF CHANGE IN WASTE LEVEL

3.1. SPECIFIC GRAVITY CORRECTION

This is considered a prestep of the level determination model

Determine the specific gravity of the supernate at current supernate temperature from the specific gravity which was determined through an analytical measurement made at an earlier time and possibly a different temperature.

3.1.1. Prestep assumptions

1. Liquid is at a uniform temperature.
2. Supernate consists NaOH, $NaNO_3$, $NaNO_2$, and water only.
3. $NaNO_3$ and $NaNO_2$ have the same density-temperature response.
4. Density values listed in Tables 6 & 7 of Appendix I are in error by less than 1%.

3.1.2. Correction

As shown in the prestep of Appendix I, Tables 6 & 7 are used to obtain an interpolated value of the change in supernate density with temperature. Table 6 is for $NaNO_3$ and this table is also assumed to be valid for $NaNO_2$. This correction may or may not be significant depending on the temperature difference between the current supernate in the tank and when the specific gravity was actually measured.

3.1.3. Uncertainties

The true uncertainty cannot be determined because the actual supernate contains other compounds not measured or monitored. Even if the other compounds were known, as well as their concentration, the density information for those species may not be available. For the purpose of this model the uncertainty will be estimated from the uncertainties of the temperature measurements, the tabular values, and chemical concentration measurements of each compound in the supernate.

3.2. CONDENSATION AND EVAPORATION

Under this category, the concern is if there were a net gain or loss to the tank contents which results from a change in the water content of the air, i.e., from that which enters the tank, to that which leaves the tank. There are two primary means of mass transfer between the incoming purge gas and the tank: the first mechanism is, the reduction of the vapor pressure of the water vapor in the incoming purge gas because of the salt content of the supernate. From this process, water will condense out of the purge gas when the vapor pressure reduction causes the incoming purge gas to be super-saturated with water vapor, or water will evaporate from the supernate if the incoming purge gas is below saturation. The second mechanism is, the condensation of water vapor at the purge-gas condenser when the condenser exit temperature is at the dew point. The condensed water then drips into the tank and mixes with the supernate. Each mechanism is outlined below:

3.2.1. Determine the change in waste level due to the in-tank condensation/ evaporation which occurs because of a water vapor-pressure reduction caused by the supernate salt content

This is considered Step 1 of the level determination model

The saline environment in the tank reduces the vapor pressure of the water above the supernate and therefore the purge-gas/water-vapor mixture may be super-saturated upon entering. If so, water vapor will condense until equilibrium is reached, if its in-tank residence time is long enough. It is also possible to have superheated water vapor entering the tank which would cause a net loss of water from the supernate surface to the purge gas. To estimate the mass transfer to or from the surface, some simplifying assumptions were made: 1. the purge-gas/water-vapor mixture, that enters the tank, attains the supernate temperature before it exits (a rough estimate showed that the residence time of an air/water-vapor mixture in the tank is approximately 5 hours, assuming that the flow rate is 320 cfm and the waste level is 356.5", which is on the same order of the time necessary to heat up the air to the supernate temperature, through conduction alone), 2. the diffusion rate of the evaporating water is faster than the gas residence time (3), 3. the mixture reaches thermodynamic equilibrium, and 4. the reduced pressure effect of the supernate on the purge gas is known.

3.2.1.1. Assumptions to Step 1

1. The purge-gas/water-vapor mixture that enters the tank attains the supernate temperature before it exits (as stated above).
2. The diffusion rate of the evaporating water is faster than the gas residence time.
3. The mixture reaches thermodynamic equilibrium (so that the equilibrium relation, used below, is valid).
4. The reduced pressure effect of the supernate is known.
5. Specific Humidity varies ± 12% of the calculated values over a 24 hour period (see subsection 3.2.1.3.).
6. The supernate is at a uniform and constant temperature.
7. Purge gas is either air or nitrogen.

3.2.1.2. Mass change model from the reduced pressure effect

To determine the change in waste level from the reduced vapor-pressure effect the amount of water vapor which enters and leaves the tank needs to be known.

The mass balance is: Rate of Water Mass Change in Tank =

Rate of Mass of Water Vapor Entering Tank - Rate of Mass of Water Vapor Leaving Tank

or, $$\text{Rate of Water Mass Change in Tank} = W_g * (M_{H_2O, IN} - M_{H_2O, OUT}) \quad (1)$$

where, W_g = Mass Flow Rate of Gas

Both quantities on the RHS of the Eq. 1 need to be determined. Without going into the details of the form of the equation (see for example reference (3)), the water vapor content of the air can be calculated by:

$$M_{H_2O} = \frac{\text{Molecular Weight}_{\text{water vapor}}}{\text{Molecular Weight}_{\text{drygas}}} * \left[\frac{\text{Relative Humidity}_{\text{gas}} * P_{\text{wv@sat}}}{(P_{\text{mixture}} - \text{Relative Humidity}_{\text{gas}} * P_{\text{wv@sat}})}\right]$$

or,

$$M_{H_2O} = (0.622_{\text{air}} \text{ or } 0.643_{N_2}) * \left[\frac{P_{\text{mixture}}}{\text{Relative Humidity}_{\text{air}} * P_{\text{wv@sat}}} - 1\right]^{-1} \tag{2}$$

where, P_{mixture} = pressure of the purge-gas/water-vapor mixture
and $P_{\text{wv@sat}}$ = saturation pressure of water vapor at the mixture temperature

The mass of water vapor entering the tank is determined with Eq. 2 when substituting the appropriate value which represent atmospheric conditions outside the tank. The mass rate of water vapor exiting the tank can be determined using:

$$M_{H_2O} = (0.622_{\text{air}} \text{ or } 0.643_{N_2}) * \left[\frac{P_{\text{mixture}}}{P_{\text{reduced}}} - 1\right]^{-1} \tag{3}$$

P_{reduced} = the partial pressure or the water vapor in the tank which is reduced from the vapor pressure that would exit above the liquid in the tank if it were pure water, i.e., containing no electrolytes.

This reduced pressure is a function of the supernate temperature, the concentration of solute particles, and the nature of those particles. This last dependency makes the reduced vapor pressure non-colligative because the solution is electrolytic. To get a rough estimate of the pressure reduction, results from reference (4) were used. From those results, and along with the following relation (5):

$$P_{\text{reduced}} = [1 - i*(X_1 + X_2 + \ldots)]*(P_{\text{wv@sat}}*\text{Relative Humidity}_{\text{gas at tank exit}}) \tag{4}$$

where, i = electrolyte multiplier
X_i = mole fraction of the ith electrolyte

a multiplier of i = 1.25 was obtained by correlating the available data (4; also see, 6) with Eq. 4, and setting the chemical make-up of the supernate to be 6M-NaOH, 2M-$NaNO_3$, and 1M-$NaNO_2$. The multiplier was assumed to be the same for all three electrolytes. Realistically, i is dependent upon concentration, and to use Eq. 4 accurately, at other concentrations, more information on i is needed. As a first approximation, i may be assumed to be constant, and in practical terms it is probably close to the 1.25 determined. Of course, i is dependent upon concentration and for these electrolytes, which are made up of two ions each, then i should approach a value of 2, as the solution becomes more dilute. A poorer assumption, implicit here, is the chemical make-up of the supernate. There are probably other electrolytes in the supernate, e.g., $NaAlO_2$, which would reduce the solvent (water) mole fraction and make the multiplier less valid, along with the form of Eq. 4. Also, assumed is that the relative humidity of the gas at the tank exit is 100%, because the tank should act similarly to an adiabatic saturator with the long residence time and the considerable distance traveled by the purge gas over the supernate.

Figure 2 depicts the accumulated change in waste level in Tank 41 from the condensation and evaporation of water at the supernate surface due to the effect of water-vapor reduction. The figure shows approximately a one year period of accumulated daily waste-level changes, which were determined by summing the mass changes for each day. That waste-level change is compared to the overall measured waste-level change, Fig. 2. During the first 150 days and the last 50 days (the warmer-wetter seasons) the effect was insignificant. From 150 days to 300 days (the cooler-drier seasons) a significant decrease was experienced, totaling about 1.4" of liquid removed. The pressure reducing effect, for the specific chemical make-up in this tank, was such that the vapor pressure above the supernate was approximately 63% of the vapor pressure if the liquid were pure water. However, since the supernate temperature is usually higher than the outside atmospheric temperature the atmospheric relative humidity needed to be approximately 88% for condensation to occur in the tank (this is explained more in the next section). So on the average, there was a net loss to the atmosphere through evaporation, which explains the accumulated loss in waste level seen in Fig. 2.

3.2.1.3. About condensation/evaporation mass evaluation

As noted in the Introduction, the values used for the atmospheric Temperature (T), Pressure (P), and Relative Humidity (RH) were averaged from hourly values between 07:00 and 11:00, inclusive, to obtain a daily set of readings. There is concern about the accuracy of the data which represent how the tank waste reacts to environmental effects. The more accurate the water content of the incoming purge gas is known, the more accurate will be the result of the level change from condensation and evaporation in the waste tank. That is, when the mass change (defined as: the water-vapor mass entering the tank and the water-vapor mass leaving the tank) is determined on an instantaneous basis; while this is desirable, it is impractical. In reality, readings are obtained once a day of the atmospheric T, P, and RH, and these values fix the water content for that day. The question is: What effect do discrete (daily) readings have on accuracy? To answer this question another question needed to be answered first: Does the use of the 5-hour (i.e., readings at 7, 8, 9, 10, and 11 am) averaged values of T, P, and RH, chosen for this final report presentation, result in a water-vapor content which is representative for an entire day? The results are not shown here, but three one-month periods were checked (May, October, and January) and no significant differences were found in cumulative water-vapor content of the air at the end of each month period by either using an hour-by-hour mass difference or using a daily (five-hour average) mass difference. Now, with the latter question answered, then Fig. 2 can be used to answer the former question, i.e., to determine if an inaccurate change in waste level would be calculated when using only a single measurement per day of the atmospheric T, P, and RH. Result: If the change in waste level were based on the water content of the air determined from a single measurement taken at 06:00 each day, <u>for an entire year</u>, then there would be approximately 1.7 inches of supernate removed from the tank. Figure 2 shows that this amount of water removed is approximately 0.3 inch greater than what was actually removed (i.e., the figure shows that approximately 1.4 inches were removed at the end of the year period). While this extra 0.3 inch is significant over a year's time, it is probably unimportant over shorter periods. The reason why the difference is not larger is that the while the hourly RH varies considerably, the water content is more stable. To illustrate, Fig. 3 shows one day which had large changes in T and RH, but the water content only had a standard deviation of approximately 12%. This amount of fluctuation will cause the 0.3 inch error by using discrete daily readings over a year's time. However, by taking only several hours of readings per day (shown above were five) an accurate value of the day's water content is obtained. For modeling purposes, it is expected that only a daily reading of T, P, and RH will be made so the uncertainty of waste-level change by condensation or evaporation will be at least 12% and corresponding greater if used on a cumulative basis.

3.2.1.4. Uncertainties

Each of the assumptions listed in subsection 3.2.1.1. can cause considerable uncertainties. Besides the uncertainty mentioned in subsection 3.2.1.3. the chemical make-up waste and its vapor pressure-reducing effect may be the largest source of error. Uncertainties that are accounted for in the model are: 1. measured values of pressure, temperature, relative humidity, purge gas flow rate, and concentrations; and 2. correlation uncertainties of water-vapor pressure, liquid-water density, and the electrolytic multiplier.

3.2.2. Determine the change in waste level due to condensation at the purge-gas condenser coil exit

This is considered Step 2 of the level determination model

As shown in Fig. 4, if the conditions of the purge gas at the exit of the condenser are such that the water vapor is at saturation, then condensation will occur and the water will drip back into the tank causing an increase to the tank waste volume. The difficulty here is that the conditions of the purge gas at the exit of the condenser are generally not know because of the lack of instrumentation, i.e., temperature, pressure, and relative humidity. This contribution to the change in waste level may be important depending upon the rate of condensation, when it does exist. In lieu of more quantitative measurements, it is assumed that the purge gas has enough time to attain the exit coolant temperature as it exits the condenser, and it is assumed that the entrance and exit coolant temperatures are measured and readily available. Furthermore, there may not be any condensation if the temperature of the coolant is such that is does not absorb any energy from the purge gas (or if it transfers energy to the purge gas). Therefore, when the inlet coolant temperature is greater than or equal to the outlet temperature then no condensation will occur. When the inlet coolant temperature is less than the outlet temperature then energy has been transferred to the coolant and condensation is possible.

3.2.2.1. Assumptions to Step 2

The most important unknown here is the thermodynamic condition at the exit of the purge-gas condenser. An assumptions about that state, along with the other assumptions are:

1. The actual temperature of the purge gas is not measured, so it will be taken to be the condenser coolant-coil exit temperature.
2. When $T_{coil,inlet} => T_{coil,\ outlet}$ then the purge gas has passed through the condenser without condensing any of the water vapor and therefore, no water is returned to the tank. On the other hand, when $T_{coil,inlet} < T_{coil,\ outlet}$ it will be assumed to have condensed some of the water vapor.
3. The gas pressure at the coil exit is at atmospheric pressure (while the actual pressure will be slightly higher this should be a fair assumption because purge-gas absolute pressure has a secondary effect).
4. The purge gas and water vapor is a non-reacting mixture.
5. That the water vapor acts as an ideal gas.
6. The condenser exit temperature is at the dew-point temperature (this will be true if condensing).
7. The rate of purge-gas flow is of dry gas only (the mass of water vapor is less than 1% of the purge-gas mass and thus cause a insignificant error).
8. That thermal equilibrium exists.

3.2.2.2. Mass accumulation model from condensation at condenser

The mass balance is:

Rate of Water Mass Accumulation in Tank =

Rate of Water Vapor Entering Condenser - Rate of Water Vapor Leaving Condenser (5)

The first term on the RHS of Eq. 5 is the same as the rate of water vapor leaving the tank, which was determined in subsection 3.2.1..2, Eq. 3. The second term on the RHS of Eq. 5 is the amount water vapor at the condenser exit, where the relative humidity is set to 1. Therefore, by setting the relative humidity in Eq. 2 to 100% the concentration of water vapor is:

$$M_{H_2O} = (0.622_{air} \text{ or } 0.643_{N_2}) * \left[\frac{P_{mixture}}{P_{wv@sat}} - 1\right]^{-1} \quad (6)$$

where, $P_{mixture}$ = pressure of the air/water-vapor mixture
$P_{wv@sat}$ = saturation pressure of water vapor at coolant-coil exit temperature

As stated in assumption 3, the absolute pressure of the mixture is assumed the same as atmospheric pressure; in reality $P_{mixture}$ at the condenser exit generally will differ from atmospheric pressure but the difference is only a second order effect, compared to the changing water-vapor pressure. Properties, e.g., vapor pressure of water, densities, were obtained from reference 7.

Hourly data for atmospheric conditions (temperature, pressure, and relative humidity), during the period from 5/8/92 to 6/6/93, were used to determine how much water condensation collected in the waste tanks under varying conditions of the purge-gas condenser. (As stated in the Introduction, these atmospheric data were obtained from the measurement station located at the Central Shops (1).) The purge-gas conditions at the exit of the condenser were set at 100% relative humidity, atmospheric pressure, and at 13°C. This temperature was an arbitrary choice but the parametric study (6: Fig. 2) showed that for an exit temperature above 25°C no significant condensation occurred over the year and for under 5°C most of the level change was accounted for. It is important to have accurate date of the coil exit temperature. The purge-gas flow rate was set to 320 cfm, even though it may have been higher at times.

3.2.2.3. Uncertainties

Since the amount of water that can be condensed from the purge gas depends partially on the amount of water vapor in the gas, which is coming from the waste tank, then most of the uncertainties listed in subsection 3.2.1.4. are appropriate here. They are: 1. measured values of pressure, temperature, relative humidity, purge gas flow rate, and concentrations; and 2. correlation uncertainties of water-vapor pressure, liquid-water density, and the electrolytic multiplier. The assumptions in subsection 3.2.2.1. are a source of larger uncertainties which cannot be readily quantified, but the uncertainties can be reduced substantially for subsection 3.2. by the method mentioned in the next subsection, 3.2.3.

3.2.3. Determining an accurate estimate of the water content of the incoming and exiting purge-gas/water-vapor mixture

For both subsections, 3.2.1 and 3.2.2, it is important to determine the amount of water which enters the control volume (the waste tank) and that which exits the tank/condenser. To avoid the uncertainties, mentioned in the above subsections, measurements should be taken, at periodic intervals (hourly, every six hours, etc.), of the temperature, pressure, and relative humidity at both the tank purge-gas entrance and exit of these three variables. With these measurements then Eqs. 1 and 2 can be used directly to determine the amount of water mass which is either left in the tank or lost to the atmosphere. In this way, the tank is treated like a black box and details about the vapor-reducing effects of the supernate and characteristics of the purge-gas condenser would be irrelevant. Likewise, the uncertainties would be reduced to the measurement uncertainties of the six variables, i.e., T_{in}, P_{in}, RH_{in}, T_{out}, P_{out}, and RH_{out}.

3.3. MASS EXCHANGE BETWEEN THE SUPERNATE AND THE SALT CAKE

This is considered Step 3 of the level determination model

Determine the change in waste level due to the transfer of mass between the Supernate and the Salt Cake. That is, the mass which dissolves from the solid into the supernate or precipitates from the supernate to the solid. The most important facts, which need to be known to determine the dissolution or precipitation of the waste contents, are: 1. What is the chemical composition of the liquid and the solid, 2. if the compounds in the aqueous solution are at their saturation limit and, 3. what are the solubilities of the various chemical components? Because of the complex make-up of the tank contents only the concentrations of the three main compounds in the tank are known, so several assumptions need to be made:

3.3.1. Assumptions to Step 3

Some of these assumptions are considered poor and can only be improved by obtaining more information concerning the solubility properties of the waste mixture.

1. The liquid is chemically saturated with the measured compounds which are in equilibrium with the solid.
2. Interpolated values of solubility from similar mixtures will give representative values of the true mixture solubility.
3. Average temperatures are uniform and constant throughout the substances, either supernate or salt cake.
4. Average temperature of the supernate within the salt cake is at the salt cake temperature.
5. The supernate within the salt cake has the same chemical make-up as the supernate which sit above the salt cake.
6. The mass transfer occurs much faster than the period over which this step's calculation is carried out (usually a day).
7. The chemical composition is that of NaOH, $NaNO_2$, $NaNO_3$, H_2O alone.

Some of these assumptions may be relaxed since there is some experimental information of the solubilities of actual waste mixtures (8).

3.3.2. Mass exchange model between the supernate and the salt cake

To facilitate the development of this model solubility vs. temperature data for several simulant high-level and low-level wastes were estimated from figures in reference 8. According to that reference, the low-level waste contains principally sodium aluminate and the high-level waste contains principally sodium nitrate with some sulfate and carbonate. Those data were correlated by using least-square fit models and are listed in Tables 5a to 5e of Appendix I. The amount of sodium nitrite in those simulants was insignificant, so a solubility relationship is determined by the use of only the concentrations of NaOH and $NaNO_3$.

First, using the measured concentrations of NaOH and $NaNO_3$ a specific solubility relationship is determined by interpolating among the five different simulant relations. With the estimated mixture solubility relation, the solubility wt% is determined for the supernate, which sit above the salt cake (see Fig. 1), at the previous temperature and the current temperature. The change in mass is then estimated for this portion of the supernate. This same process is repeated for the supernate within the salt cake, by using the previous and current salt-cake temperature. The two values of mass change are added to obtain the total mass change. This mass change is either the amount the supernate picked up from, or released to, the solid. Knowing the densities of the solid and liquid a waste height change for each can be calculated. Figure 5 shows how the mass of both the salt cake and the supernate varied through a year in Tank 41, due to the change of solubility of the supernate. Of a total estimated salt cake height of 190" (less the supernate void) it increased by about 1.5 inches and decreased by about 2 inches. Of the total estimated supernate height of 365" (less the salt cake) it increased to about 3.5 inches and decreased to about 2.5 inches. The overall effect of the mass transfer between the solid and liquid is shown in Fig. 6. There was a maximum net decrease in waste level during the winter (≈ 1"), when the temperature is the coldest, and a maximum net increase in waste level during the summer (≈ 1.5"), when the temperature is the hottest. The purpose here is to determine the change of height because of the exchange of mass and not because of the thermal expansion or contraction of the liquid and solid. Those effects will be addressed in the following sections.

3.3.3. Uncertainties

The largest uncertainties are related to the lack of knowing the chemical make-up of the contents, which compounds are at saturation in the supernate, and what is in the appropriate solubility relationship. At present, these cannot be quantified so only the uncertainty of the available solubility correlations can be used along with the uncertainties in the primary compound concentrations, and the measured temperatures.

3.4. SALT CAKE VOLUME CHANGE DUE TO THERMAL EXPANSION/CONTRACTION

This is considered Step 4 of the level determination model

The main difficulty to determine thermal expansion effects on the salt cake is the lack of knowledge of its chemical make-up and the thermal expansion properties. The thermal expansion model that H-Area currently uses has many assumptions but the primary ones are that the tank contents are solely NaOH, $NaNO_3$, $NaNO_2$, and H_2O and that the waste is totally liquid. The goal here is to relax the latter assumption, but if possibly, the former too.

3.4.1. Assumptions to Step 4

1. Salt Cake is make of NaOH, $NaNO_3$, $NaNO_2$.
2. Temperature is uniform and constant throughout solid.
3. Amount of salt cake is known.
4. If sludge is present, its volume changes, due to temperature, similarly to that of the salt cake.
5. Tank diameter is not affected by temperature change.
6. Salt cake expands and contracts freely.
7. That $(1/\rho)(d\rho/dT)$ is independent of temperature.

3.4.2. Determine the change in waste level due to the thermal expansion/ contraction of the Salt Cake.

Thermal expansion property data were found for solid salts: $NaNO_3$ and $NaNO_2$, but not NaOH. Moreover, the difficulty with these data is that the crystalline structures have differing expansion coefficients along each axis of the crystal. Data for polycrystalline structures for these compound were used and compared to data of simulate solid waste mixtures to determine applicability. Those simulant data were obtained from an experiment (9) to measure the linear coefficient of expansion of two different mock samples of salt-cake material (Purex: 3.40M-$NaNO_3$, 0.35M-Na_2CO_3, 0.08M-Na_2SO_4, 0.55M-$NaAlO_2$, 0.30M-NaOH and HM: 4.60M-$NaNO_3$, 2.20M-$NaNO_2$, 0.11M-Na_2SO_4, 0.84M-$NaAlO_2$, 0.50M-NaOH).

To determine a thermal coefficient of expansion which would be representative of the salt cake in the tanks a comparison was done. Figure 7 shows thermal expansion results, assuming that the entire waste contents were made of the each of the four solid phase salts that were mentioned above. To put these results in perspective they are compare to the expansion of the waste contents, as if they were entirely made of liquid supernate. [Note: For the curves shown in Fig. 7 the expansion coefficients of the pure salts, were obtained as a function of temperature, and were integrated over the pertinent temperature range. The coefficients of thermal expansion for the Purex- and HM-salt combinations were determined by reference (9) to vary insignificantly over the temperature range from 30°C to 200°C, therefore only constant values were stated. Notwithstanding, it seems unlikely that these two compounds have thermal expansion coefficients which vary insignificantly over the 170° temperature range, since all of the other pure compounds do vary significantly over the same temperature range. However, for the small temperature changes of this modeling effort the constant coefficient assumption is sufficient.] It appears that for small waste-temperature differences (generally the waste temperature is kept constant but a fluctuation of a degree or two is not uncommon) the expansion differences among all the solid salts was insignificant, relative to the supernate expansion. Further, the expansion of the solid salts significantly differ from the liquid supernate.

It is suggested, that until better property information is obtained on the thermal expansion of salt cake, the value of the HM-type salt (the lowest curve on Fig. 7) should be used, i.e., 3 x linear coefficient of thermal expansion = 1.02 x 10^{-4} $(\text{length})^3/(\text{length})^3$°C. This compound contains the largest amount of Sodium Nitrate, Sodium Nitrite, and Sodium Hydroxide and gives the smallest expansion rate of the group, dealt with here. This choice would be conservative because the expansion of the salt cake due to temperature should not be over estimated. Figure 8 shows the thermal expansion of both the supernate and salt cake in Tank 41 for a year's period. While the combined effect appears small (≈ 0.5") it does follow the expected seasonal trend of being high during the hot months and low during the cool months. [To see the damping effect on the waste-level changes, due to thermal expansion, when considering the tank contains both solid and liquid salts to a tank that has an equivalent height of waste which is just liquid, compare the bottom curve of Fig. 8 (solid + liquid) to the bottom curve of Fig. 10 (liquid only).]

3.4.3. Uncertainties

The main uncertainties are not knowing the exact make-up of the salt cake, its expansion properties, and temperature gradients. For this model the uncertainties are limited to those of the measured temperatures and to the value of the thermal expansion coefficient, listed above. The uncertainty of the expansion coefficient will be assumed to be 20%, or 0.204 x 10^{-4} $(\text{length})^3/(\text{length})^3$°C, which was estimated from the variation among the different solid salts shown in Fig. 7 along with the variations from the thermal coefficient of expansion because of being functions of temperature.

3.5. SUPERNATE VOLUME CHANGE DUE TO THERMAL EXPANSION/CONTRACTION

This is considered Step 5 of the level determination model

This step was the original model (10) used to determine the change in waste level by temperature. It assumed that the entire contents of a tank consisted solely of three compounds (NaOH, $NaNO_3$, $NaNO_2$) in an aqueous state, i.e., no solid were present. With respect to that model, this section uses the same data base of density vs. temperature data at different concentrations (obtained from reference 11).

3.5.1. Assumptions of Step 5

1. Tank diameter is not affected by the temperature change.
2. Liquid is at a uniform and constant temperature.
3. Waste consists of only NaOH, $NaNO_3$, $NaNO_2$.
4. $NaNO_3$, $NaNO_2$ liquids have the same density-temperature response.
5. Density values in Tables 5 & 6 of the Appendix I are in error by 5%.

3.5.2. Determine the change in waste level due to the thermal expansion/ contraction of the Supernate.

Knowing the concentrations of the three compound, then Tables 5 and 6 of Appendix I are used to obtained interpolated values of the change in density with temperature. With the molar percentage of NaOH and $NaNO_3$ & $NaNO_2$, then one relationship for the supernate is obtained. However, since the temperature of the supernate, which sits on top of the salt cake (see Fig. 1), is usually at a different temperature than the supernate, which saturates the salt cake, a different relationship is obtained for each region. That is, the supernate has a measured temperature and it is assumed uniform and constant throughout the liquid above the salt cake. For the supernate which saturates the salt cake, its temperature, and temperature changes, should be closer to that of the salt cake, which is (generally) higher. More important than the absolute temperature value of the supernate, is the change in temperature. Obtaining the volumetric change of supernate, which is within the salt cake, by using the density vs. temperature relation based on the lower supernate temperature would not cause a large error because the absolute temperature difference between the supernate, above the salt cake, and the salt cake is not large. The fact is, the salt cake temperature changes do not always follow the supernate temperature changes. Many times there is a one or two degree temperature change of the supernate with no temperature change of the salt cake. For this reason, it is important to determine the different volumetric change of the supernate above the salt cake and that of the supernate within the salt cake to obtain a more accurate model. This is especially important for those tank which have a large percentage of salt cake like of Tank 4 where there is approximately the same amount of supernate within the salt cake as there is on top of the supernate. As mentioned above (subsection 3.4.2), Fig. 8 includes the effect of the supernate expansion and contraction with temperature, based on the estimated thermal-expansion data.

3.5.3. Uncertainties

Tabular values and measured temperatures and concentrations make up the calculated uncertainties. As already mentioned, the actual uncertainty is not knowing the correct expansion properties of the supernate.

3.6. CARBON STEEL-TANK VOLUME CHANGE

This is considered Step 6 of the level determination model

The change of waste level from the thermal effects on the steel tank was included for completeness but is not necessary because of it insignificance to the overall change. The model only considers the thermal expansion of carbon steel and does not involve the complex geometry of the tank. The amount of effect this mechanism has on the overall waste-level change did not warrant a more elaborate model.

3.6.1. Assumptions of Step 6

1. The entire tank is made of carbon steel.
2. The thermal coefficient of expansion is constant with temperature.
3. The volumetric thermal coefficient of expansion is 3.3 x 10-5 /°C (valid: 10°C < T < 100°C).
4. The entire tank expands and contracts freely.
5. The measured annular temperatures are constant and uniform throughout the tank wall.

3.6.2. Determine the change in waste level due to thermal expansion/ contraction Carbon Steel Tank.

With the assumptions listed then determined the effect on the contents of the steel tank are straight forward and shown in Appendix I. Figure 9 compare the tank's effect on waste level to the overall measured waste-level change. As stated, the effect was insignificant.

3.6.3. Uncertainties

The main estimated uncertainties are from the measured temperature, the knowledge of the correct thermal coefficient of expansion. Not known is how the tank area actually changes with temperature. Using a more accurate model of the tank geometry which includes the toroidal shape, cooling coils and their support brackets, that the tank top is anchored to the concrete upper surface, etc., would give better results but the magnitude of the calculated level change should still be insignificant.

4.0. CONCLUSIONS

4.1. OVERALL COMPARISON

Figure 10 shows a comparison, over a period of a year, of the measured waste level in tank 41 to the existing model (10) and to the enhanced waste-level model, which is the sum of all the results of each of the effects listed in this report. That is, the summing of the individual contributions shown in Figs. 2, 4, 6, 8, and 9 will result in the middle curve, depicted in Fig. 10. Specifically, the figure shows three curves: the top curve is the measured change of waste level in tank 41 during a year's period (excluding the known changes in level which occurred during planned waste transfers to and from the tank); the middle curve is of the new model which includes environmental effects on the waste tank, salt cake, supernate, and purge gas (but does not account for any gas that may be trapped in the salt cake); the bottom curve is of the existing model which is currently being used by H-area (it only assumes the waste to made of liquid supernate which responds to thermal contraction and expansion). Both the old and the new model are shown to follow the general (seasonal) trend of the measured waste-level changes but the new model appears to follow it closer, in both magnitude and slope. In fact, the main divergence is during a 3 month period, between the 150-day to 250-day marks. During these three month (Fall and Winter) the waste level would be expected to decrease because of the cooler (contraction of contents) and drier (evaporation of supernate) atmosphere, but the measured waste level remained constant.

Some reasons why the model diverges from the measured waste-level change are:

1. In-leakage of mass to the tank occurred.
2. No (or reduced) evaporation occurred (e.g., when there is no purge gas flow).
3. There was more condensation than estimated.
3. The model does not properly capture the level changing mechanisms during the cooler seasons.
4. The measured waste-level change is inaccurate.
5. There was gas generation which accumulated within the salt cake.

To better see when the model followed the measured accumulated waste-level change and when it did not, both sets of data were fitted to a least-square fit, and from those fits the slope of each curve was obtained. These curve fits are an average representation of the change in waste level, i.e., they smooth out the daily fluctuations to give the global temporal movement of waste level. Figure 11 shows the absolute difference between those slopes. During the first 150 days the difference in the rate of change remained within 0.005 inches/day (about 18 gallons/day), but then there was a steady increase in the difference to 0.015 inches/day (about 50 gallons/day). Finally, after 300 days the slopes began to converge again. Notwithstanding, at the end of the year's period the new model accounted for nearly 50% for the waste-level increase, a considerable improvement.

4.2. UNCERTAINTIES

In each of the different steps that comprise the model, an attempt has been made to address the underlying uncertainties. Even so, the true level of uncertainty is not known because of the many reasons, aforementioned. To obtain a feel for the overall uncertainty it has been estimated to be on the order of 50% of any particular day's level change. This is approximately the uncertainty estimated by the spreadsheet model, when including all the uncertainties for each step. Of course, rough estimates were made of measurement uncertainties of transducers (temperature, pressure, relative humidity, levels, flow rates), of analytical measurements of chemical properties, and of estimates like salt cake height and percent liquid void. Also, estimate were made for the uncertainties on chemical and thermal property information, and on the many curve-fitted data bases. The actual uncertainties may be greater, but are probably smaller, even so, the largest uncertainties will come from the modeling assumptions which are not readily determinable. Therefore, with a 50% uncertainty chosen for one day's level change, the overall cumulative uncertainty is shown in Fig. 12. The darkest line represents a curve fit of the model's calculated level change, for the year. The two lighter curves is the estimated cumulative error. Since each days measurement and its uncertainty depends on the preceding day's results, the daily errors are not independent and therefore directly additive. Note, almost the entire divergence region, between the measured waste-level change and that determined by the model (150 days to 300 days), is bounded by the cumulative uncertainty.

4.3. SUGGESTIONS FOR IMPROVEMENT

Determining the change to waste level by each of the separate effects mentioned in this report would improve substantially by increasing the knowledge of the exact make-up of the waste composition (on a frequent basis) and of the thermal and chemical properties. Useful information would be details of the following:

1. Current chemical make-up of the supernate as well as its thermal and chemical properties. This is especially true when additions are made to the tank which can change the chemistry.
2. Make-up of the salt cake, as well as its thermal and chemical properties.
3. The chemical equilibrium of the solids with the liquids.
4. Specifics of the purge-gas condenser, especially the thermodynamic conditions of the purge gas at the condenser exit.
5. Purge-gas thermodynamic conditions and flow rates in the tank.
6. How the tank area changes with tank level.

All of the above information will lead to a better understanding on how the environment affects the waste level and thereby improving the model, so that changes in waste level can be better predicted. Of all the effects on changing waste level, those of most importance are the ones that cause irreversible changes because it is those types of changes which lead to net accumulated increases or decreases in level. Eventually, the net accumulation result in changes which need to be explained. Possible effects that lead to irreversible waste-level changes are: condensation from the purge-gas condenser, condensation/evaporation from the pressure reducing effect of the electrolytic liquid (irreversible if dissolution/precipitation, condensation/evaporation, or mass addition to the tank change the chemical make-up of the supernate), gas accumulation within the salt cake, or dissolution of salt cake with temperature increases but no precipitation with a temperature decrease (will occurs when the liquid is not saturated with one or all of the salt cake compounds). These four irreversible effects are addressed below in the follow three subsections: 4.3.1., 4.3.2., and 4.3.3.

4.3.1. Increase Instrumentation

Of all the effects addressed by this report, those in steps 1 and 2 have the largest non-reversible effects, that is, condensation/evaporation at the supernate/purge-gas interface and condensation from the purge-gas condenser. Better information on the vapor pressure reducing effect, of the supernate, and condenser conditions will elicit a more accurate picture of the waste-level changes. However, as mentioned in subsection 3.2.3., by using transducers to measure the purge-gas temperature, pressure, and relative humidity at the tank entrance and exit then the exact change of water content in the purge gas is obtained and therefore the water which remained or escaped from the tank is accurately determined. This method treats the tank as black box and avoids the need to know the complex working inside the tank.

4.3.2. Determine Gas Accumulations in Salt Cake

An effect not addressed by this report, is the gas content and its generation is the salt cake. On 06-04-93 J. P. Morin demonstrated that if the salt cake in tank 41 had a fixed gas void of 10%, then the daily-measured waste-level fluctuations closely followed the daily atmospheric pressure changes, by using an ideal-gas law relation. Specifically, during a the "stable" tank-41 waste-level period, from 12-01-92 to 01-24-93, the level was measured to be 359.0" and fluctuated ± 0.3", while the ideal-gas model determined a fluctuation of approximately ± 0.2". Unfortunately, when the tank level was not stable and began to increase the model diverges, while still picking up the day-to-day fluctuations well. The only way to account for the level increases would be to assume that there was gas evolution and retention within the salt cake. From this gas void study, it appeared that there may well be a gaseous void within the salt cake from the good correlation between the measured high-frequency daily fluctuations (< 0.2") to daily waste-level change, determined from atmospheric pressure changes. The addition of a gas-void model to this report's model may improve the tracking of the daily ups and down in waste level, but that was not seen to be the focus of this effort: To determine if significant waste-level changes (one inch or greater) were due to environmental effects. The longer term (lower frequency) changes in waste level appear to be responsive to atmospheric temperature and water-content changes. Example: The first 150 days of Fig. 10 indicates a measured level change of approximately 2 inches and this report's model account for approximately 1.8 inches of that change. Even the supernate-only model accounted for 1 inch of the change. What is not known and would be important, is if there were an accumulation of gas within the salt cake. However, any gas accumulation would eventually have to escape and would probably escape in a sudden fashion which would be immediately noticeable through level detection and gas samplings. That occurrences have not been observed.

4.3.3. Experimental Testing for Dissolution/Precipitation

Figures 5 and 6 show the importance of understanding the dissolution/ precipitation process to waste-level. Unfortunately, this knowledge is very difficult to obtain because of the need to know the current chemical make-up of the supernate and the salt cake, the solubility of each of the compounds in the supernate that make-up the salt cake, the homogeneity of the salt cake and the homogeneity of the dissolved compounds, when this occurs. The logical step, to a better understanding, is to carry out an experiment of different salt-cake/supernate combinations which are likely to exist in the waste tanks. These experiments can measure the true waste-level changes with temperature. These waste-level changes will include not only the changes to waste level due to dissolution and precipitation but also due to the thermal expansion and contraction of the tank's constituents.

5.0 MODEL SOFTWARE

As requested, this model has been made such that it is "user-friendly," i.e., in a platform easy to access and learn. The first waste-level model (10) was developed in an Excel spreadsheet format and is readily accessible, and currently used, by the H-Area personnel. To minimize the amount of time that the personnel would need to learn how to operate the new model, the same spreadsheet format was followed. Figure 13 is a flowchart of how the software carries out the enhanced waste-level model. The sequence of the flow chart is the same as is listed in this report to aid understanding. When implementing the program the actual step-by-step process is hidden from the user. After the pertinent tank data are entered into the data sheet, the result is immediately available and shown in the input/output sheet of the program, Fig. 14. Along with the overall change in waste-level, the contribution of each step to the total waste-level change is listed for reference. Appendix I contains twenty-two pages that comprise the entire spreadsheet model. Not shown are the equations for each spreadsheet cell. The display of all the equations that go into the spreadsheet were not included in this report because they are readily available to anyone, by perusing the spreadsheet model, and their addition here would probably double the size of this report.

6.0. REFERENCES

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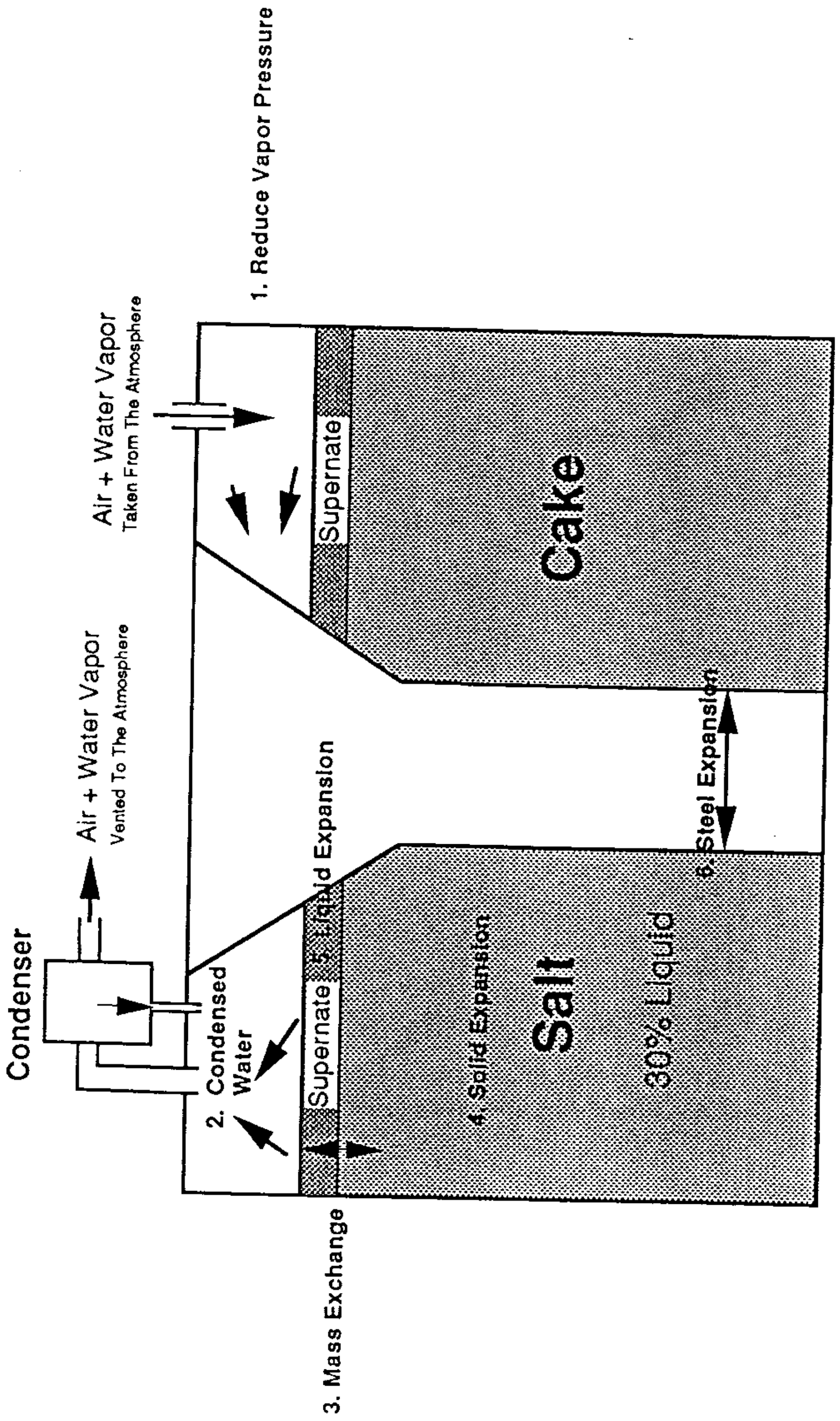

1. Reduce Vapor Pressure
Air + Water Vapor
Taken From The Atmosphere
Air + Water Vapor
Vented To The Atmosphere
Condenser
2. Condensed Water
3. Mass Exchange
4. Solid Expansion
5. Liquid Expansion
6. Steel Expansion
Supernate
Cake
Supernate
Salt
30% Liquid

FIGURE 1

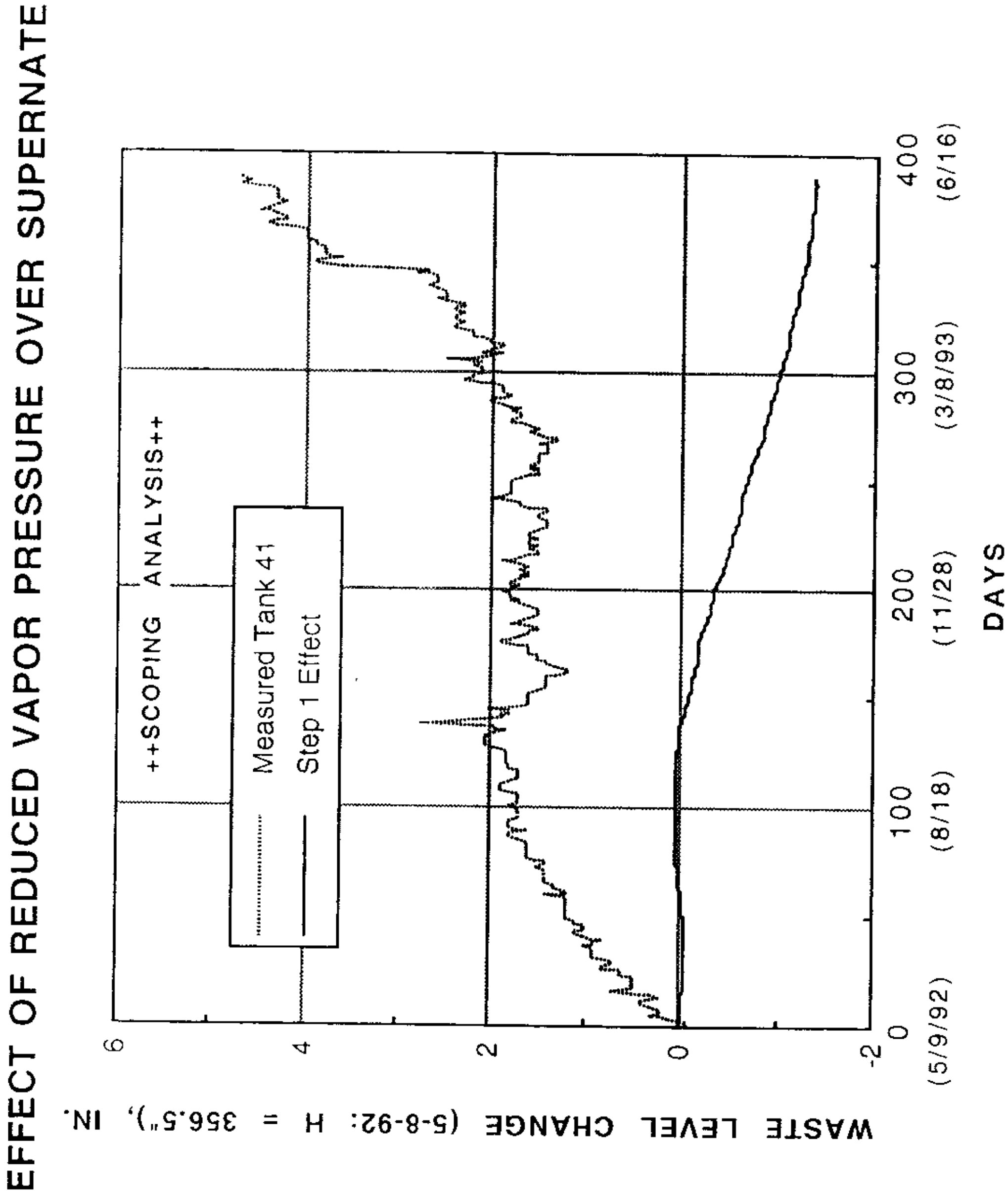


FIGURE 2

++ SCOPING ANALYSIS ++

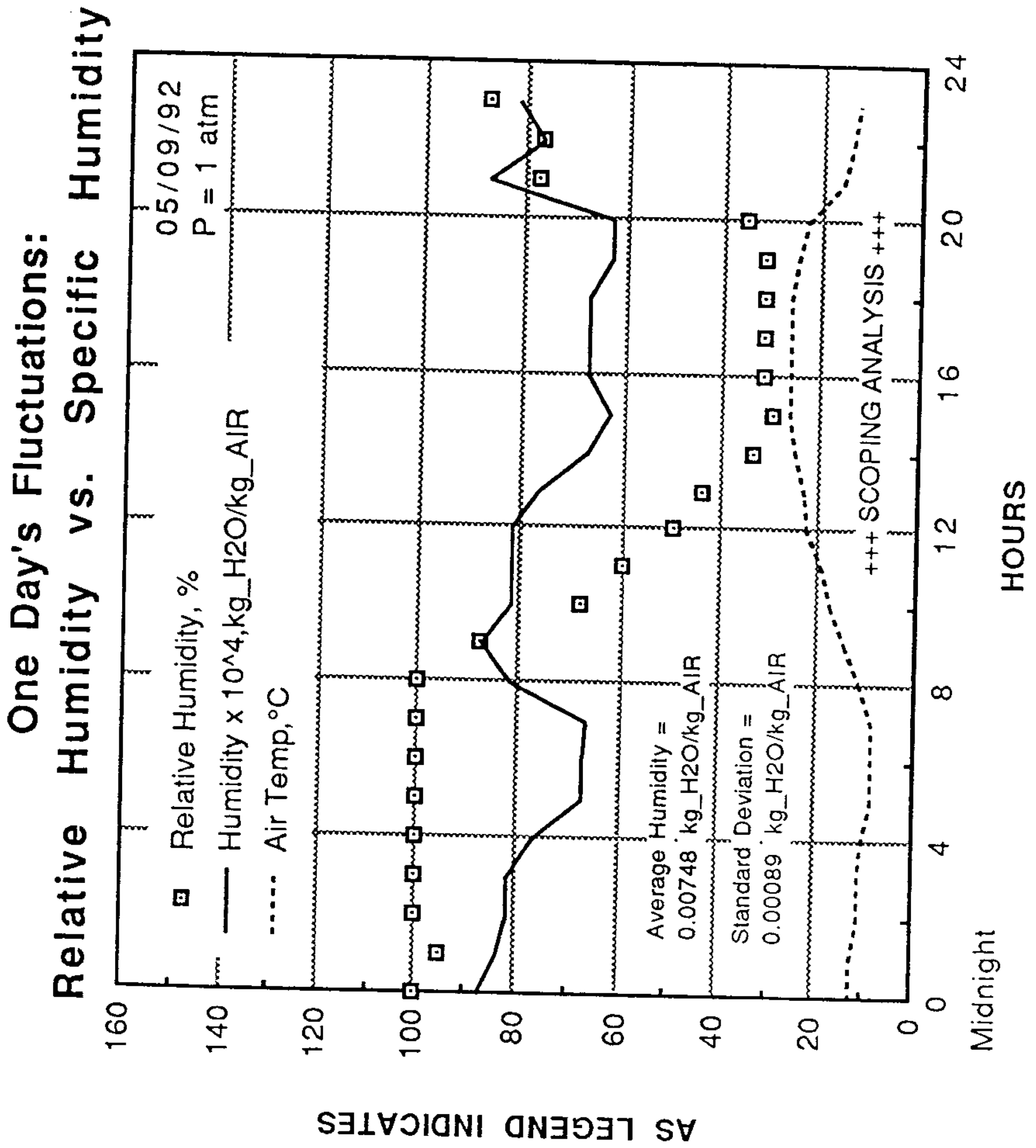


FIGURE 3

++ SCOPING ANALYSIS ++

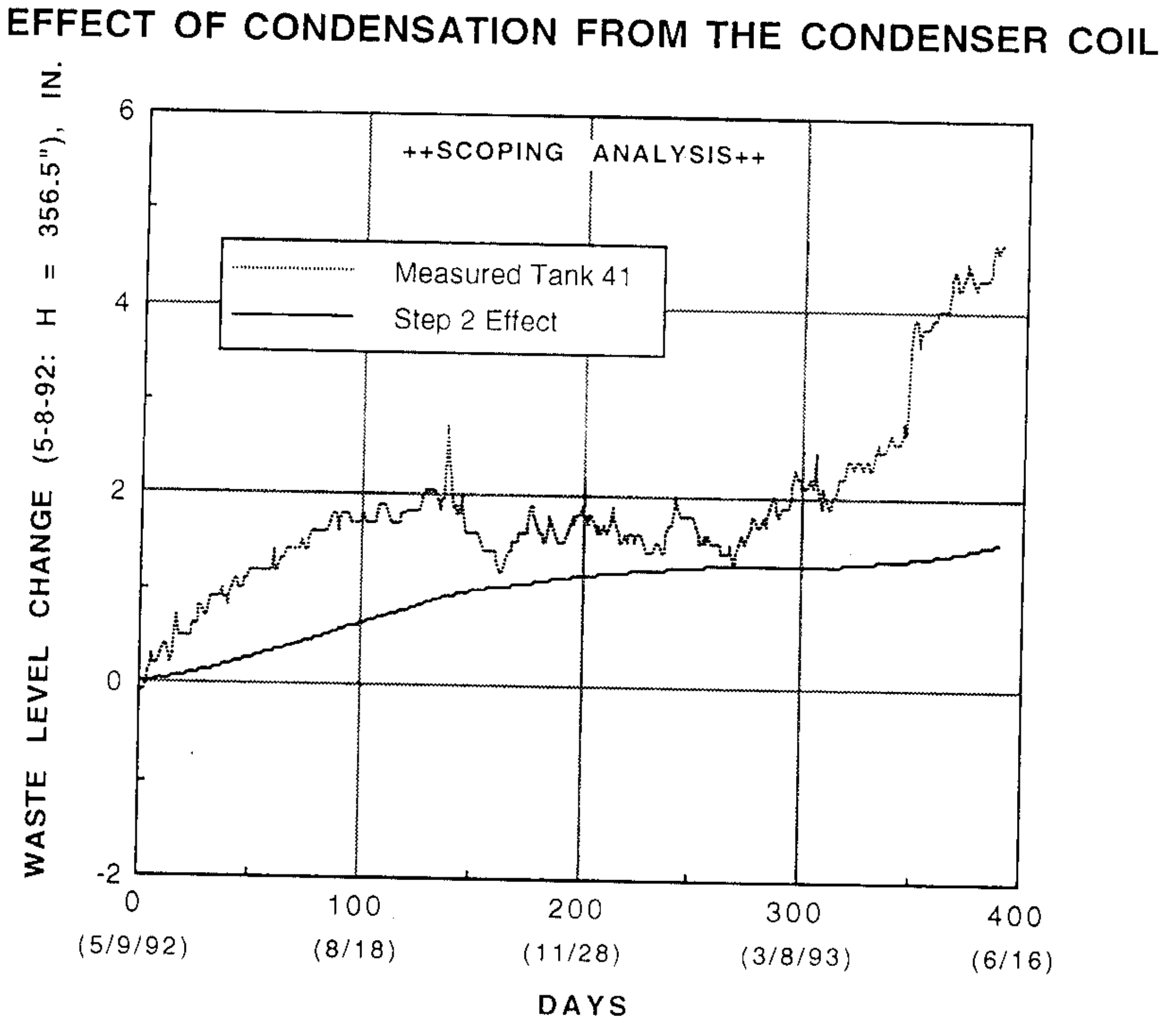


FIGURE 4

++ SCOPING ANALYSIS ++

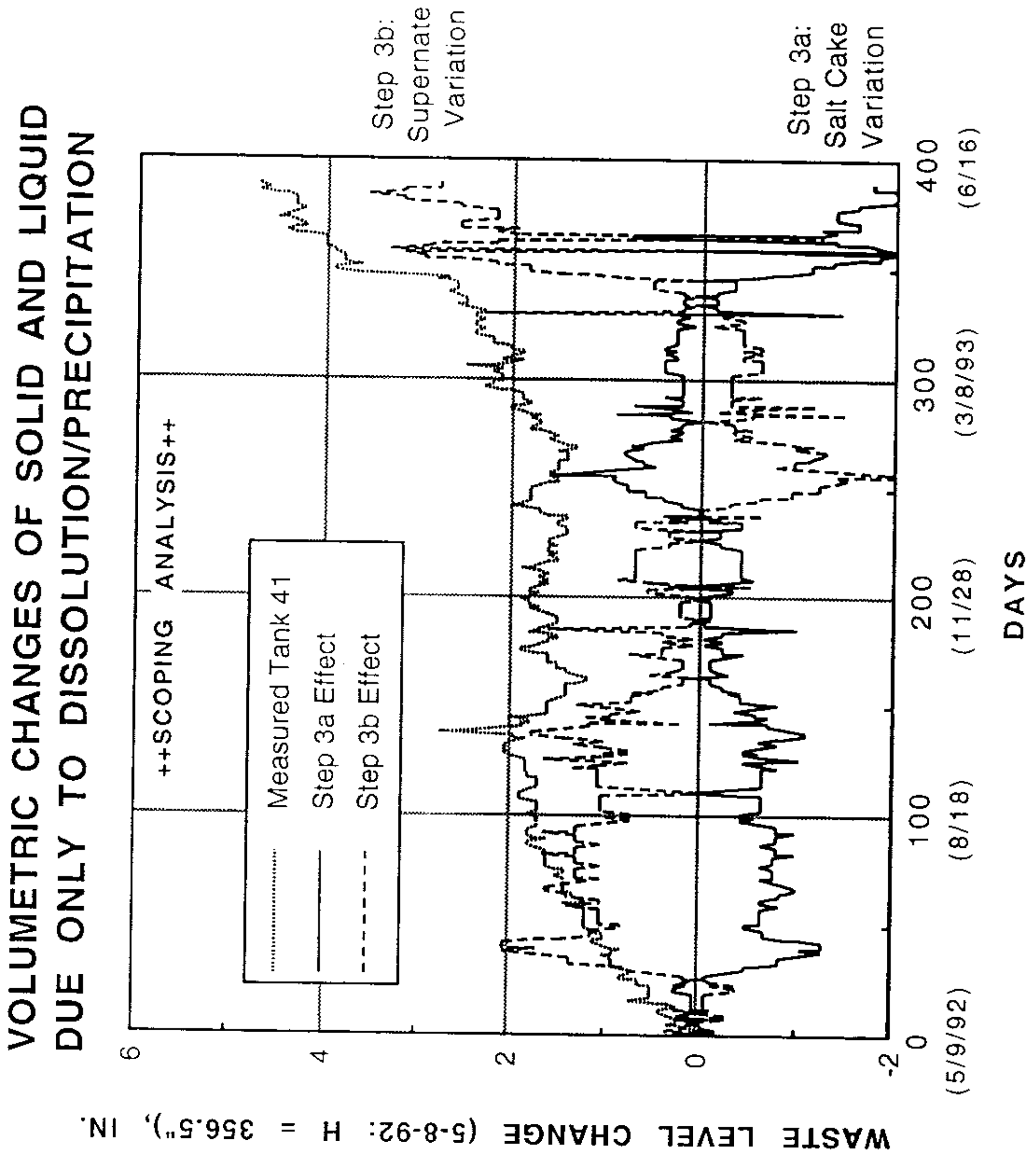


FIGURE 5

++ SCOPING ANALYSIS ++

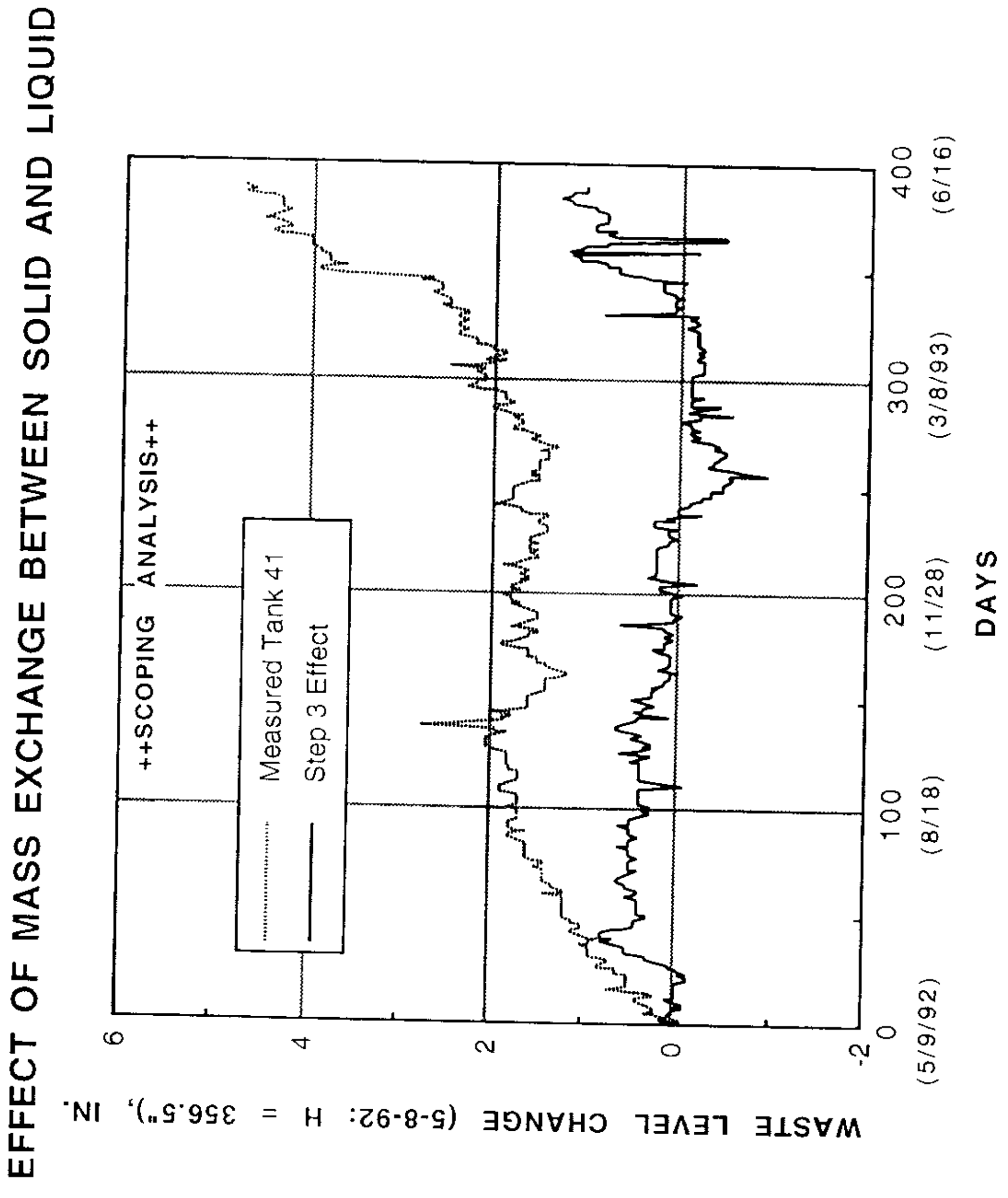
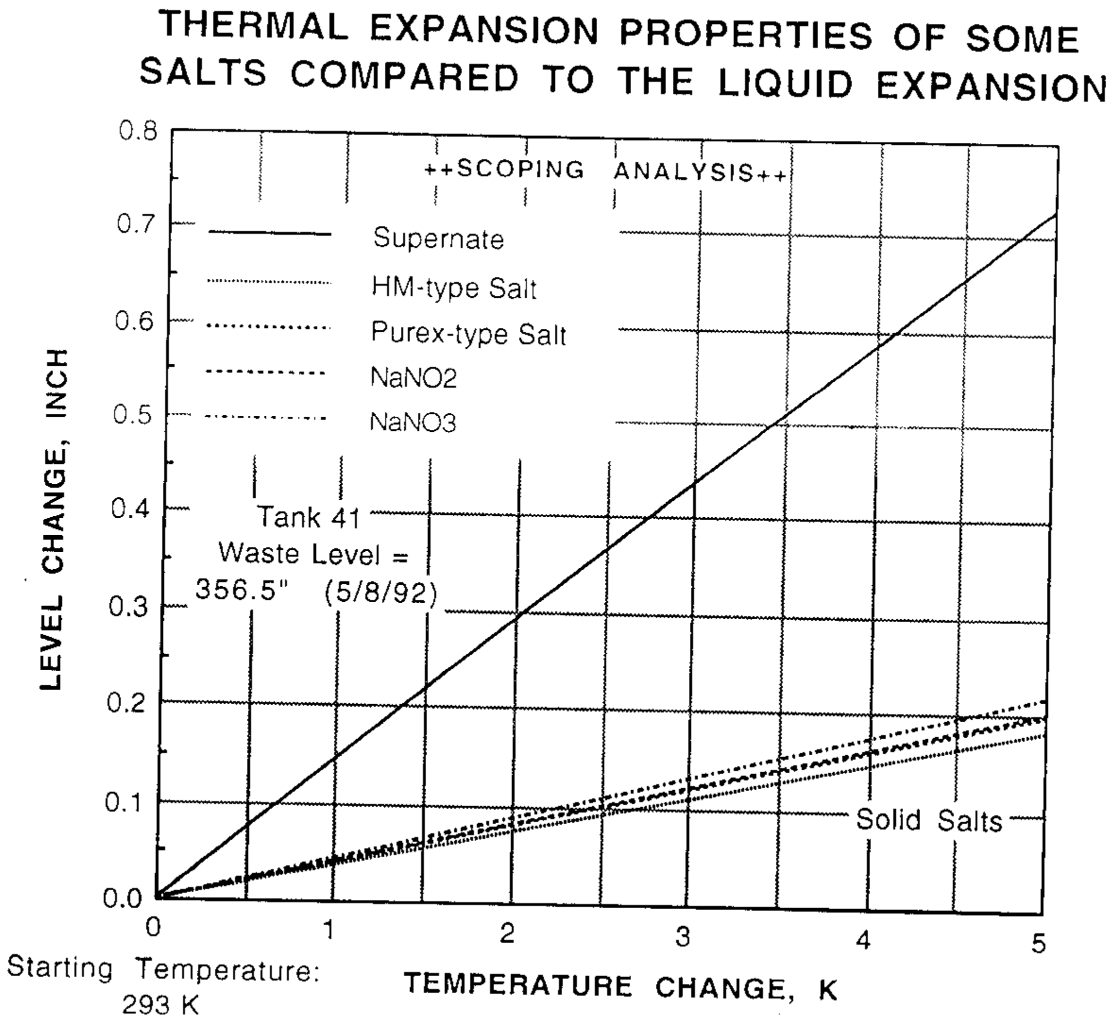


FIGURE 6

++ SCOPING ANALYSIS ++

++ SCOPING ANALYSIS ++

FIGURE 7



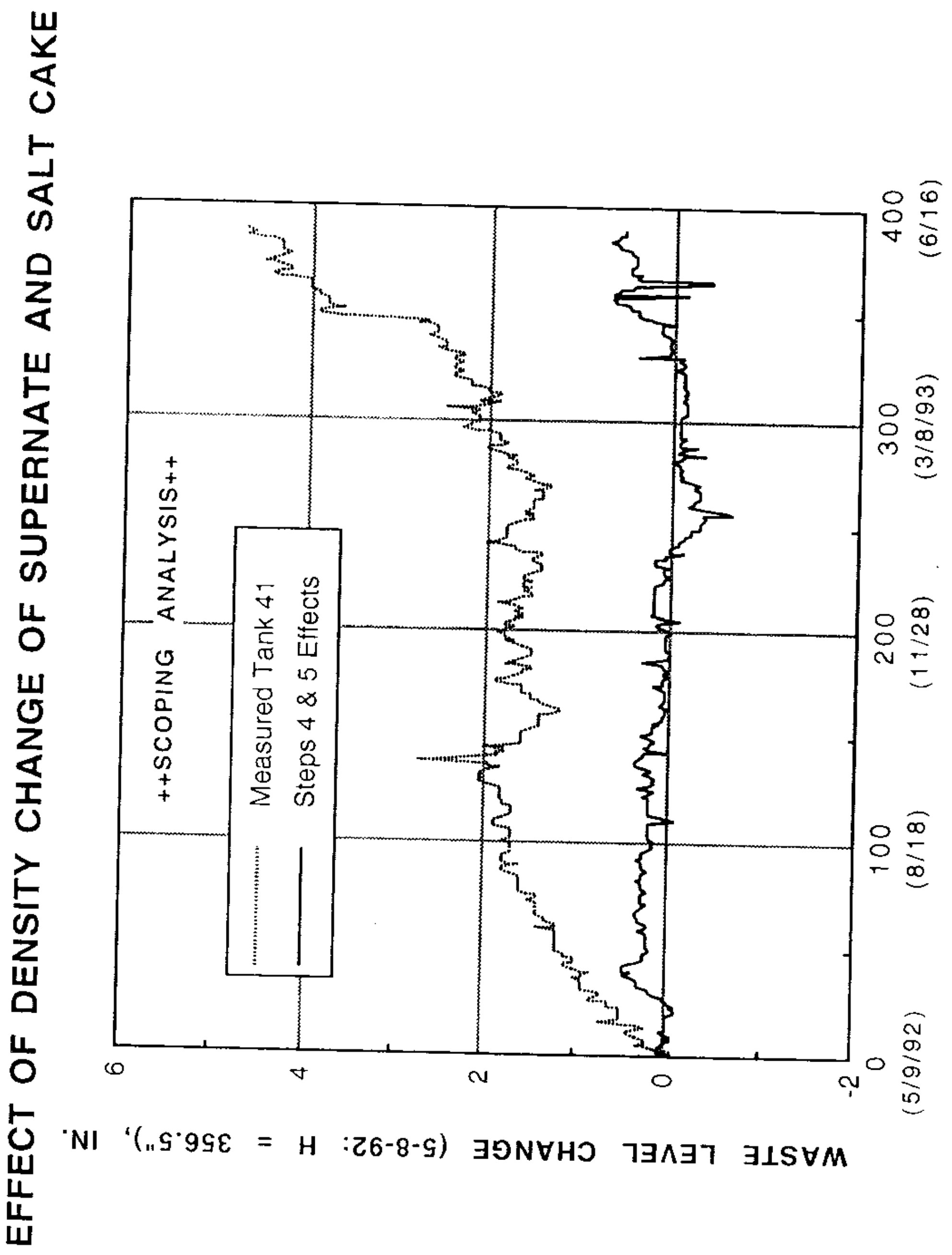


FIGURE 8

++ SCOPING ANALYSIS ++

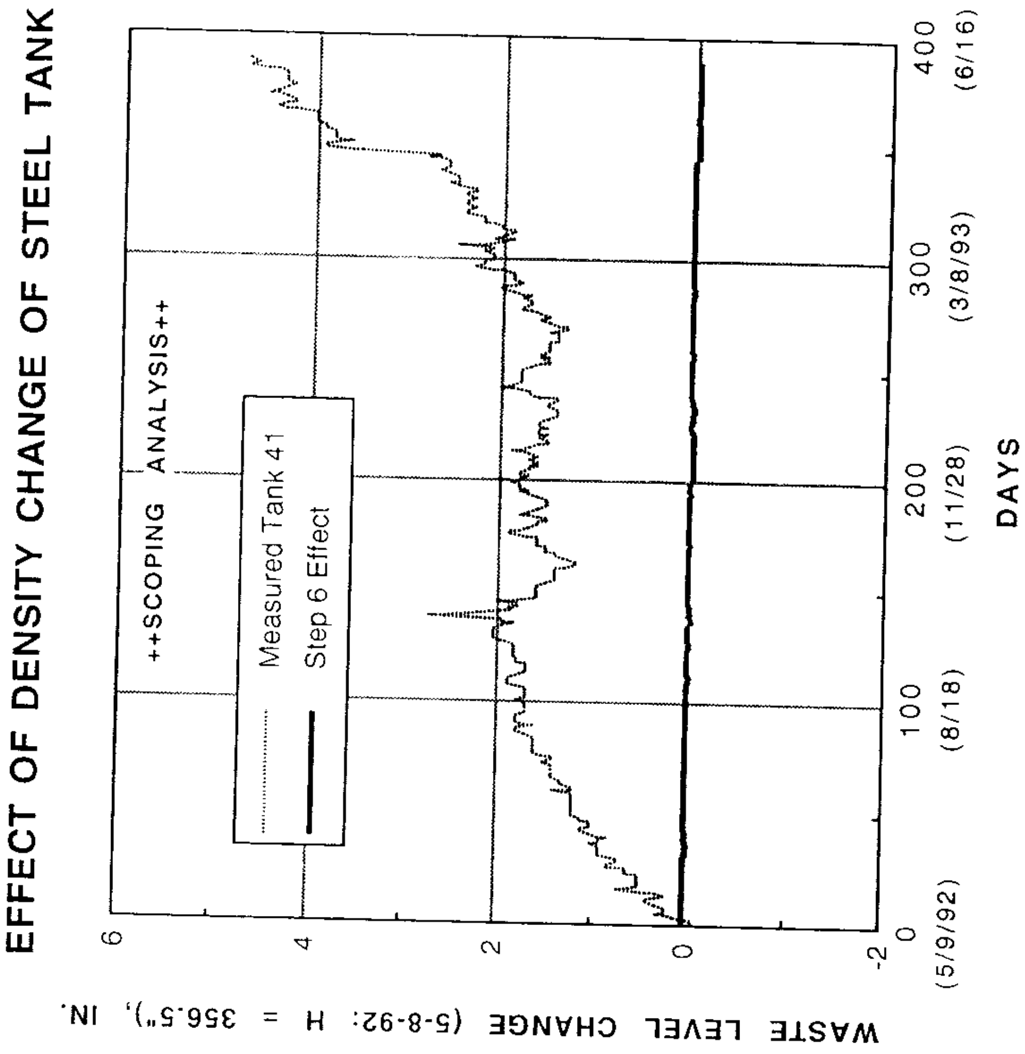


FIGURE 9

++ SCOPING ANALYSIS ++

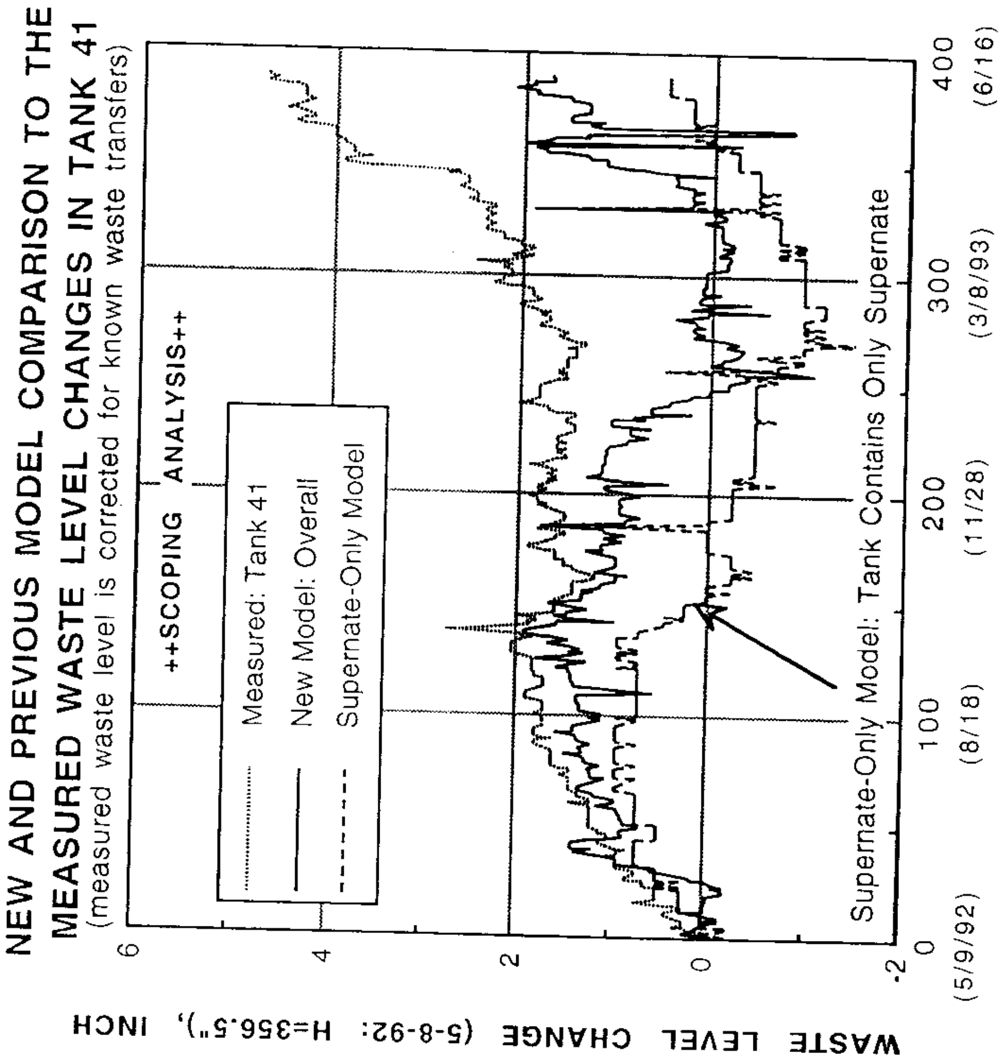


FIGURE 10

++ SCOPING ANALYSIS ++

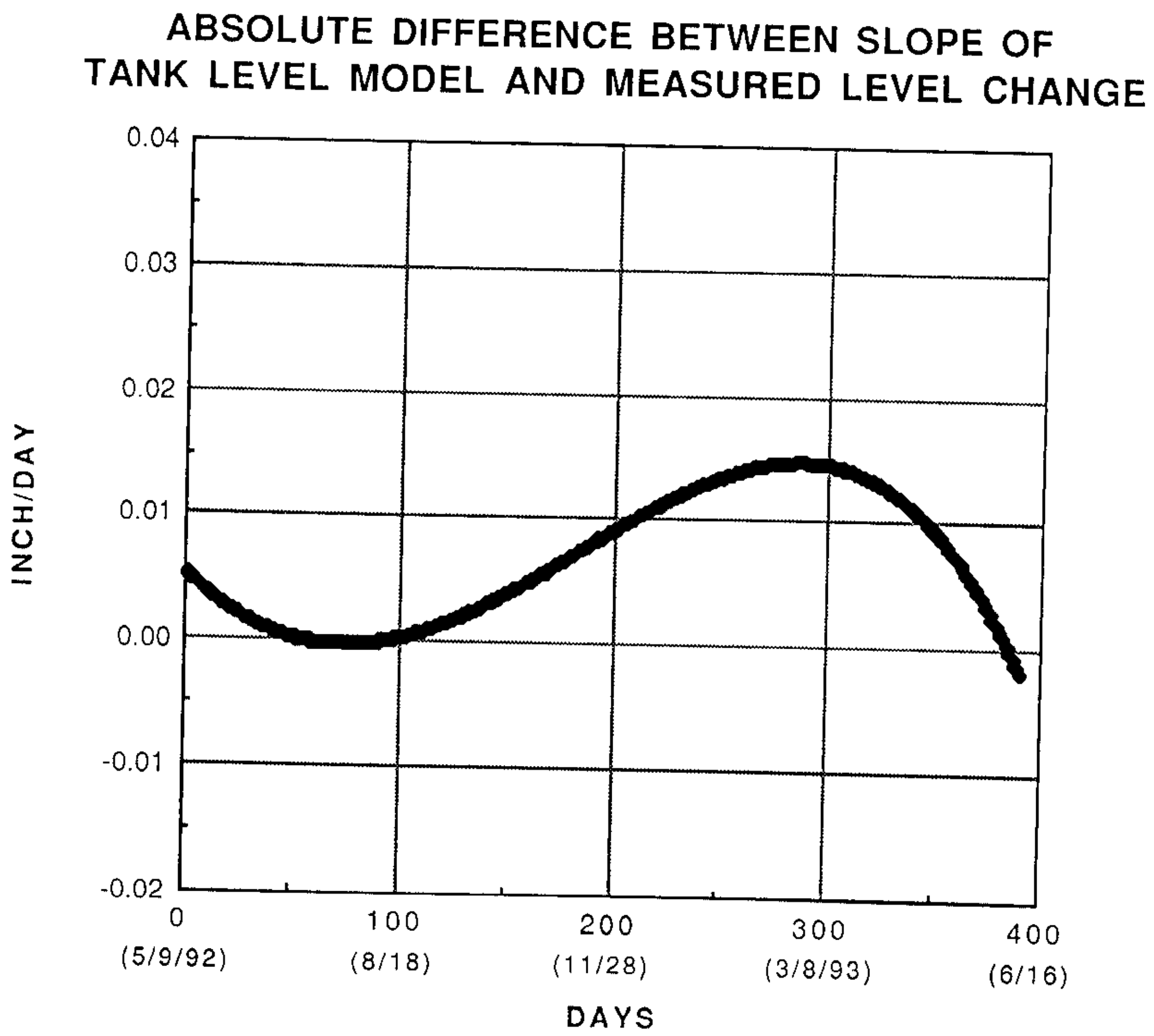


FIGURE 11

++ SCOPING ANALYSIS ++

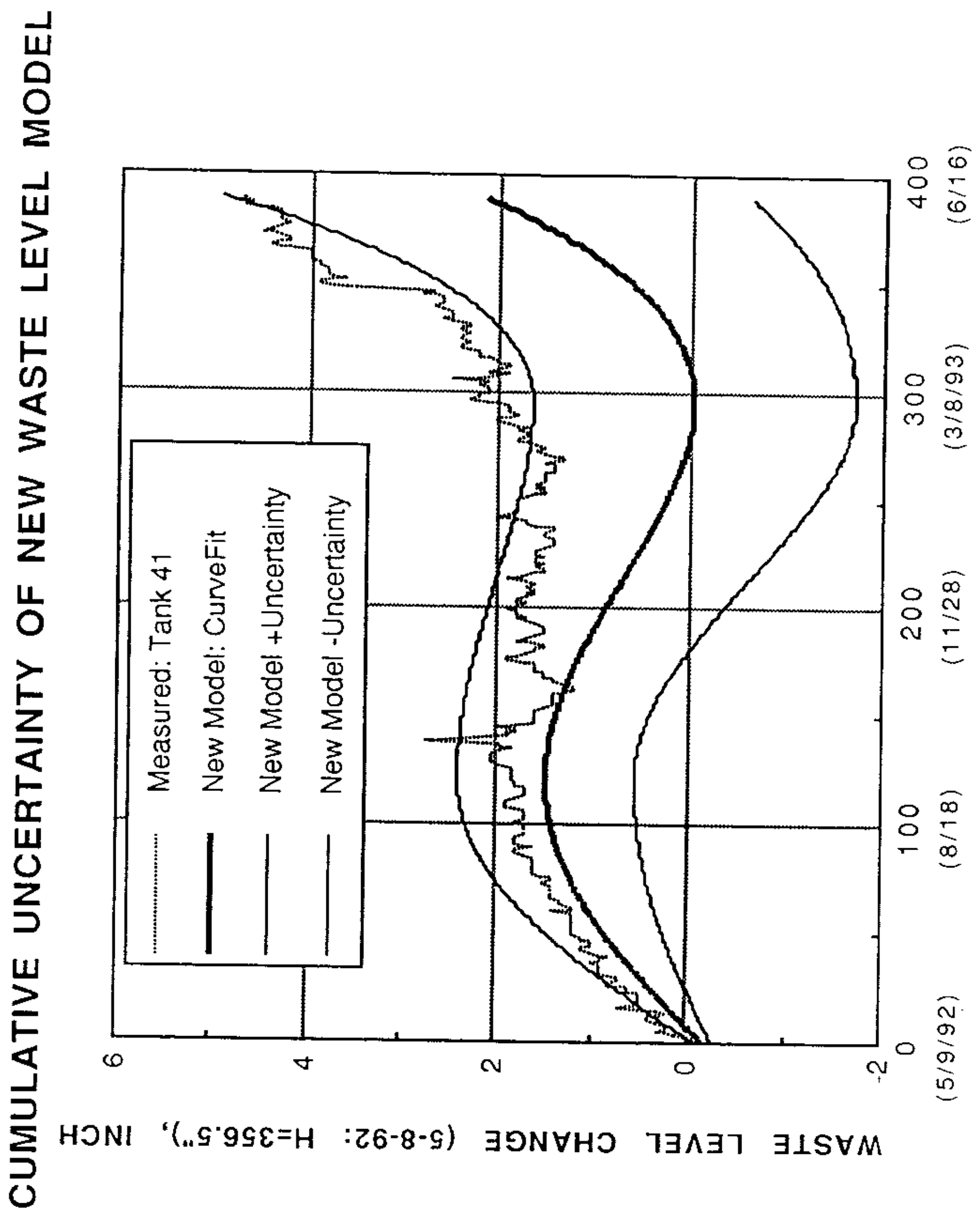


FIGURE 12

++ SCOPING ANALYSIS ++

Calculation Flow Chart

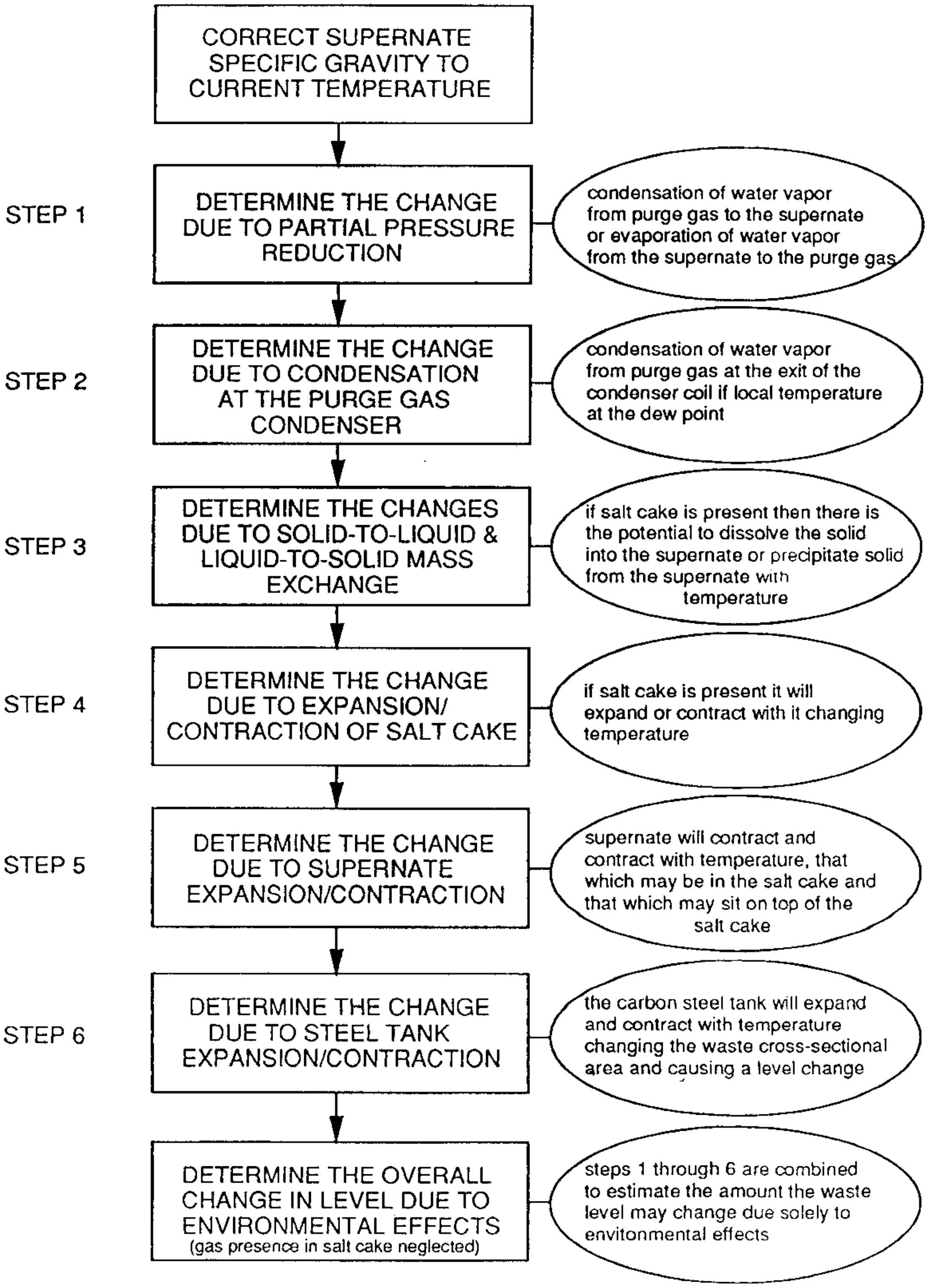


FIGURE 13

Input Data for Waste Tank No.: 41

	MEAS. DATE:	MEAS. HOUR:	MEASURER'S LAST NAME:
Previous:	5/10/94	6	
Current:	5/11/94	6	DUIGNAN

	Previous	Current	Measuremt Uncertainty Orig.Units
# Hours between measurements =		24.00	
Atmospheric Temperature (°C)		16.6	2
Atmospheric Pressure (millibar)		1021.2	10
Atmospheric Relative Humidity (%)		75.1	5
Average Annulus Temperature (°C)	27	28	2
Average Salt Cake Temperature (°C)	29	30	2
Average Supernate Temperature (°C)	24	25	2
Condenser Coolant Inlet Temperature (°C)		12	2
Condenser Coolant Oulet Temperature (CCOT) (°C)		13	2
Condenser Gas Oulet Temperature = CCOT (°C)		13	2
#Specific Gravity of Supernate ((g/cm3)/(g/cm3_H2O@4°C))		1.36	0.1
#Concentration of NaOH (M) (40 g/gmole)		5.33	0.05
#Concentration of NaNO2 (M) (69 g/gmole)		0.9	0.05
#Concentration of NaNO3 (M) (85 g/gmole)		1.56	0.05
#Measurements of four items above were at temperature of (°C)		24	2
The Specific Gravity of Supernate at Current Temperature		1.4	0.16
Total Waste Height (in.)	356.4	?	0.2
Salt Cake Height (in.)	290	?	1
Assumed Liquid Void of Salt Cake (%)	30	?	5
Flow Rate of Purge Gas (cfm)		320	3
Approximate Volume-to-Height Value (gallons per inch)		3510	35
Type of Purge Gas [Air (A) or Nitrogen (N)]		A	N/A

#Information from analytical laboratory measurements

Changes In Waste Level Due To Effects Listed Below:

Results

Waste Level Change From	inches	% of total	Uncertainty* inches	Uncertainty* %
Partial Pressure Reduction:	-0.004	1.4%	0.002	39%
Condenser Condensate:	0.004	1.2%	0.001	38%
Solid/Liquid Mass Exch.:	0.203	66.7%	0.123	61%
Solid Density Change:	0.021	6.8%	0.005	26%
Liquid Density Change:	0.065	21.4%	0.010	15%
Tank Volume Change:	-0.008	2.6%	0.002	20%
Total Level Change:	0.28	100%	0.12	44%

New Waste Level: 356.68 inches ± 0.24 inches

*Uncertainty is based ONLY on thermodynamic property information, curve fitting, inputted measurement uncertainties, and from the models used to obtain the level changes. From the uncertainty in the assumptions listed in each Step, the actual uncertainty will be greater, i. e., the listed uncertainty should be considered a minimum. Uncertainties are assumed independent.

FIGURE 14

APPENDIX I: EXCEL SPREADSHEET MODEL

	A	B	C	D	E	F	G
1	**Input Data for Waste Tank No.:**			41			
2		MEAS. DATE:	MEAS. HOUR:	MEASURER'S	**Previous**	**Current**	**Measuremt**
3	***Previous:***	5/10/92	6	LAST NAME:	# Hours between measure-		**Uncertainty**
4	***Current:***	5/11/92	6	DUIGNAN	ments =	**24.00**	**Orig.Units**
5	Atmospheric Temperature (°C)					16.6	2
6	Atmospheric Pressure (millibar)					1021.2	10
7	Atmospheric Relative Humidity (%)					75.1	5
8	Average Annulus Temperature (°C)				27	28	2
9	Average Salt Cake Temperature (°C)				29	30	2
10	Average Supernate Temperature (°C)				24	25	2
11	Condenser Coolant Inlet Temperature (°C)					12	2
12	Condenser Coolant Oulet Temperature (CCOT) (°C)					13	2
13	Condenser Gas Oulet Temperature = CCOT (°C)					13	2
14	#Specific Gravity of Supernate ((g/cm3)/(g/cm3_H2O@4°C))					1.36	0.1
15	#Concentration of NaOH (M)			(40 g/gmole)		6.33	0.05
16	#Concentration of NaNO2 (M)			(69 g/gmole)		0.9	0.05
17	#Concentration of NaNO3 (M)			(85 g/gmole)		1.56	0.05
18	#Measurements of four items above were at temperature of (°C)					24	2
19	The Specific Gravity of Supernate at Current Temperature					1.4	0.16
20	Total Waste Height (in.)				356.4	?	0.2
21	Salt Cake Height (in.)				290	?	1
22	Assumed Liquid Void of Salt Cake (%)				30	?	5
23	Flow Rate of Purge Gas (cfm)					320	3
24	Approximate Volume-to-Height Value (gallons per inch)					3510	35
25	Type of Purge Gas [Air (A) or Nitrogen (N)]					A	N/A
26	#Information from analytical laboratory measurements						
27	***Changes In Waste Level Due To Effects Listed Below:***						
28							
29	**Results**					**Uncertainty***	
30	*Waste Level Change From*		inches	% of total		inches	%
31	Partial Pressure Reduction:		-0.004	1.4%		0.002	39%
32	Condenser Condensate:		0.004	1.2%		0.001	38%
33	Solid/Liquid Mass Exch.:		0.203	66.7%		0.123	61%
34	Solid Density Change:		0.021	6.8%		0.005	26%
35	Liquid Density Change:		0.065	21.4%		0.010	15%
36	Tank Volume Change:		-0.008	2.6%		0.002	20%
37							
38	**Total Level Change:**		0.28	100%		0.12	44%
39	**New Waste Level:**		356.68	inches ±	0.24	inches	
40	*Uncertainty is based ONLY on thermodynamic property information, curve fitting, inputted						
41	measurement uncertainties, and from the models used to obtain the level changes. From the						
42	uncertainty in the assumptions listed in each Step, the actual uncertainty will be greater, i. e.,						
43	the listed uncertainty should be considered a minimum. Uncertainties are assumed independent.						
44							
45							
46							
47							

	H	I	J	K	L	M	N
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2	**Calculation Appendix: Correction to the supernate Specific Gravity**						
3	Specific Gravity from the Analytical Laboratory Measurement may have been						
4	obtained at a temperature different than the current temperature of the super-						
5	nate therefore it is corrected here by carrying out a similar calculation as given in						
6	Step 5 of this spreadsheet. Of course, the limitations pointed out in Step 5 must						
7	also hold true for this calculation.						
8	Assumptions:						
9	1. Liquid is at a uniform temperature.						
10	2. Waste consists of NaNO3, NaNO2, and NaOH only.						
11	2. NaNO3 and NaNO2 liquids have the same density-temperature response.						
12							
13	Supernate temperature during measurement =				24		
14	Current supernate temperature =				25		
15	Avg. temperature to determine thermal expansion =				24.5		
16							
17		***Based on original Specific Gravity***					
18	The combined weight percentage of NaNO3 and NaNO2 =					14.32 wt %	
19	The weight percentage of NaOH =					15.68 wt %	
20	Interpolation Work Box to determine			Interpolation Work Box to determine			
21	d(density)/dT for NaNO3 and NaNO2			d(density)/dT for NaOH			
22	at the variable given above from Table 6			at the variable given above from Table 7			
23	beginning row in Table 6 is:		6	beginning row in Table 7 is:		6	
24	beginning col in Table 6 is:		2	beginning col in Table 7 is:		3	
25	(unc. of tabular values assumed: 1%)			(unc. of tabular values assumed: 1%)			
26		Temperature, °C			Temperature, °C		
27	wt%	20	40	wt%	20	40	
28	12.00 wt %	1.0819	1.0724	12.00 wt %	1.1309	1.121	
29	16.00 wt %	1.1118	1.1013	16.00 wt %	1.1751	1.1645	
30							
31	14.32 wt %	1.06458658	1.055666	15.68 wt %	1.090275	1.081018	
32	therefore at T= and wt% =			therefore at T= and wt% =			
33		24.5	14.32		24.5	15.68	
34	density =	1.0626	g/cm3	density =	1.0882	g/cm3	
35	and (1/density)*(ddensity/dT) =			and (1/density)*(ddensity/dT) =			
36	4.1978E-04	/°C unc =	2.8172E-05	4.2532E-04	/°C unc =	9.3027E-06	
37							
38	Based on the molar percentage then:			NaOH =		52.3%	
39				NaNO3 & NaNO2 =		47.7%	
40	therefore (1/density)*(ddensity/dT) =			4.2268E-04	/°C unc =	4.0507E-05	
41	and for dT =	1	°C then dSpGr/SpGr =		4.2268E-04		
42	**Corrected SpGr =**					uncertainty	
43	**1.36**	**+**	**0.00057484**	**=**	**1.4**	0.2	
44							
45							
46							
47							

	O	P	Q	R	S	T	U
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 1: Determine the change in height from condensation/evaporation						
4	In-Tank from the purge gas stream						
5							
6		IS THERE SUPERNATE IN TANK:			YES		
7	*THEREFORE: CONDENSATION AND EVAPORATION CAN OCCUR*						
8							
9	Assumptions:						
10	1. The purge-gas / water-vapor mixture that enters the tank attains						
11	the supernate temperature before it exits (a rough estimate showed that the						
12	residence time of the mixture in the tank is approximately 5 hours assuming that						
13	the flow rate is 320 cfm an the waste level is approximately 355" which is on the						
14	order of the time necessary to heat up the air to the supernate temperature						
15	through conduction alone).						
16	2. the diffusion rate of the evaporating water is faster than the gas residence						
17	time (5 hours).						
18	3. The mixture reaches thermodynamic equilibrium (so that the equilibrium						
19	relation -used below- is valid).						
20	4. The reduced pressure effect of the supernate is known.						
21	5. Specific Humidity varies ±12% of calculated values over a 24 hour period.						
22							
23	Water vapor pressure at saturation from Table 1 for atmospheric conditions						
24							
25	Pwatervapor@sat =		18.91	millibars @ T=	16.6	°C	
26			(Uncertainty:	2.5	millibars)		
27							
28	Mass of water which ENTERS the tank with the purge gas =						
29	Mass of Water Vapor / Mass of Dry Purge Gas =						
30	[Mol.Wt.H2O/Mol.Wt.Purge Gas] / [P(atmosphere)/P(vapor press of water) - 1] =						
31							
32	**0.0088**	**kg-H2O/kg-Gas**					
33	(Uncertainty:	0.0017	kg-H2O/kg-Gas)				
34							
35	Mass of water which LEAVES the tank with the purge gas =						
36	Mass of Water Vapor/Mass of Purge Gas =						
37	[Mol.Wt.H2O/Mol.Wt.Purge Gas] / [P(atmosphere)/P(reduced) - 1]						
38							
39	P(reduced) = [1 - 1.25*(X:NaOH + X:NaNO3 + X:NaNO2)]*(Pwatervapor@sat)						
40							
41	X:NaOH =	0.157	X:NaNO3 =	0.097	X:NaNO2 =	0.046	
42	uncertainty:	0.019	uncertainty:	0.012	uncertainty:	0.006	
43							
44							
45							
46							
47							

	V	W	X	Y	Z	AA	AB
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2	Step 1: Continued						
3							
4	Water vapor pressure at saturation from Table 1 for supernate conditions						
5							
6		Pwatervapor@sat =	31.69	millibars @ T=	25	°C	
7			(Uncertainty:	2.5	millibars)		
8							
9	therefore,	Preduced =	19.81	millibars			
10			(Uncertainty:	6.1	millibars)		
11							
12	and then [Mol.Wt.H2O/Mol.Wt.Purge Gas] / [P(atmosphere)/P(reduced) - 1] =						
13							
14	**0.0123**	**kg-H2O/kg-Gas**					
15	(Uncertainty:	0.0041	kg-H2O/kg-Gas)				
16							
17	The Mass of water which stays (+) in the tank, or is removed (-) from the tank:						
18							
19	0.0088	-	0.0123	=	-3.5364E-03	kg-H2O/kg-Gas	
20				(Uncertainty:	1.37E-03	kg-H2O/kg-Gas)	
21							
22	Assuming the flow rate of purge gas is that of dry				AIR	then:	
23							
24	Mass Flow Rate of Gas =		320	x density (Table 3)			
25		=	668	kg-Gas / hour			
26	(A 1% uncertainty of density excluding the uncertainty of pressure and temperature values)						
27	(therefore, uncertainty of flow rate due to density is:				9.2	kg-Gas/hour)	
28							
29	Rate of change of water in the tank is:						
30							
31	-3.5364E-03	x	668	=	-2361.10	g-H2O / hour	
32				=	-56.67	kg-H2O/period	
33				(period =	24	hours)	
34							
35	Vol-to-hght =	3510	gal./inch =	13286795	cm3/inch then:		
36							
37	and using a Water Density of		0.9970	g/cm3 at T =	25	°C	
38			(uncertainty:	0.0067	g/cm3)		
39	(Uncertainty of water density due to uncertainty in Temperature only, see Table 2)						
40	**Waste height change=**		**-0.004**	**inch,**	**uncertainty =**	0.002	
41							
42							
43							
44							
45							
46							
47							

	AC	AD	AE	AF	AG	AH	AI
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 2: Determine change in height from condensation at the condenser coil exit						
4							
5	Assumptions:						
6	1. The actual temperature of the purge gas is not measured so it will be taken to						
7	the condenser coil exit temperature.						
8	2. When Tcoil,inlet => Tcoil,oulet then the purge gas has passed through the						
9	condenser without condensing any of the water vapor and therefore no water is						
10	returned to the tank. On the other hand, when Tcoil, inlet < Tcoil, outlet it						
11	will be assumed to have condensed some of the water vapor						
12	3. The gas pressure at the coil exit is at atmospheric pressure (this should be a						
13	fair assumption because pressure has a secondary effect).						
14	4. The purge gas and water vapor is a non-reacting mixture.						
15	5. That the water vapor acts as an ideal gas.						
16	6. The condenser exit temperature is at the dew point temperature (will be true						
17	if condensing).						
18	7. The rate of purge-gas flow is of dry gas only (the mass of water vapor is less						
19	than 1% of the purge-gas mass).						
20	8. That thermal equilibrium exists.						
21							
22	If Tcoil, outlet = T(purge gas) = T(dew point) then,						
23							
24	Pwatervapor@sat =		14.98	millibars @ T=	13	℃	
25			(Uncertainty:	2.50	millibars)		
26							
27	Mass of water which LEAVES the condenser with the purge gas =						
28	Mass of Water Vapor / Mass of Dry Purge Gas =						
29	[Mol.Wt.H2O/Mol.Wt.Purge Gas]/[P(atmosphere)/(RH*P(water vapor@sat)) - 1] =						
30	(note:At condensor outlet:RH = relative humidity = 1, i.e., condensing conditions)						
31							
32	**0.0093**	**kg-H2O/kg-Gas**		(Not valid for Tcond,inlet > Tcond,outlet)			
33	(Uncertainty:	0.0015	kg-H2O/kg-Gas) (because RH <> 100%)				
34							
35	Mass of water which ENTERS the CONDENSER with the purge gas =						
36	Mass of water which LEAVES the TANK with the purge gas =						
37	(from Step 1)						
38	[Mol.Wt.H2O/Mol.Wt.Purge Gas] / [P(atmosphere)/P(reduced) - 1]						
39							
40	Preduced =	19.81	millibars		(from Step 1)		
41		(Uncertainty:	6.1	millibars)			
42							
43							
44							
45							
46							
47							

	AJ	AK	AL	AM	AN	AO	AP
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 2: Continued						
4							
5	and then [Mol.Wt.H2O/Mol.Wt.Purge Gas] / [P(atmosphere)/P(reduced) - 1] =						
6							
7	**0.0123**	**kg-H2O/kg-Gas**			(from Step 1)		
8	(Uncertainty:	0.0041	kg-H2O/kg-Gas)				
9							
10	The Mass of water which is condensed and returned to the tank:						
11							
12	0.0123	-	0.0093	=	3.0443E-03	kg-H2O/kg-Gas	
13							
14				(Uncertainty:	1.14E-03	kg-H2O/kg-Gas)	
15	(Note: Only valid if this is a positive result, evaporation is not possible for a gas)						
16							
17	Assuming the volumetric flow rate of purge gas is that of dry gas then:						
18							
19	Mass Flow Rate of Gas =		320	x density (Table 3)			
20		=	676	kg-Gas / hour			
21	(A 1% uncertainty of density excluding the uncertainty of pressure and temperature values)						
22	(therefore, uncertainty of flow rate due to density is:				9.3	kg-Gas/hour)	
23							
24	Rate of change of water in the tank is:						
25							
26	0.0030	x	676	=	2058.11	g-H2O / hour	
27				=	49.39	kg-H2O/period	
28				(period =	24	hours)	
29							
30	Vol-to-hght =	3510	gal./inch =	13286795	cm3/inch then:		
31							
32	Water Density =		0.9970	g/cm3 at T =	25	°C	
33			(uncertainty:	0.0067	g/cm3)		
34	(Uncertainty of water density due to uncertainty in Temperature only, see Table 2)						
35	**Waste height change=**		**0.004**	**Inch,**	**uncertainty =**	0.001	
36							
37							
38							
39							
40							
41							
42							
43							
44							
45							
46							
47							

	AQ	AR	AS	AT	AU	AV	AW
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 3: Determine the change in height due to the transfer of mass between the						
4	Salt Cake and the Supernate.						
5							
6		IS THERE SALTCAKE IN TANK:			YES		
7	*LIQUID AND SOLID PRESENT: MASS TRANSFER IS POSSIBLE*						
8							
9	Assumptions:						
10	For this step, some of the assumptions are considered poor and can only be made						
11	better by obtaining more information as to the solubility properties for the waste						
12	mixture.						
13	1. The liquid is chemically saturated and in equilibrium with the solid.						
14	2. Interpolated values of solubility from similar mixtures will give representative						
15	values of the true mixture solubility.						
16	3. Average temperatures are uniform and constant throughout the substance.						
17	4. The mass transfer occurs much faster than the day's time over which this						
18	step's calculation is carried out.						
19	5. The new density of the supernate, which is determined after the mass transfer						
20	has occurred, is uniform throughout the liquid.						
21	The sub-steps are:						
22	1. Use the molar concentrations of NaOH and NaNO3* to determine which mixture						
23	solubility relationship is appropriate (i.e., mixtures - 1, 2, 3, 4, or 7 of which the						
24	compositions are from Goodlett, DP-1135, June 1968).						
25							
26	2. Interpolate to obtain one relationship for each compound.						
27							
28	3. Interpolate to obtain one relationship for the tank mixture.						
29							
30	4. Determine the amount of mass exchanged between solid and liquid by						
31	determining the change in solubility of the supernate.				This is done in two		
32	steps: Above and below the salt cake because of the temperature difference						
33							
34	Substep 1: Determine appropriate solubility mixtures (from Table 4b).						
35							
36	For NaOH with Molarity:		5.33	the mixtures to use are:		1 & 4	
37			giving an interpolation multiplier A of:			0.716	
38							
39	For NaNO3 with Molarity:		1.56	the mixtures to use are:		only 4	
40			giving an interpolation multiplier B of:			0.000	
41							
42							
43							
44							
45							
46							
47							

	AX	AY	AZ	BA	BB	BC	BD
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 3: Continued						
4							
5	Substep 2. For the two compounds obtain the necessary solubility relationships						
6	(obtain coefficients for the equation wt% = a0 + a1*T + a2*T^2 from Table 5).						
7							
8	a0_NaOH =	57.911			a0_NaNO3 =	48.532	
9	a1_NaOH =	-0.1048			a1_NaNO3 =	0.2115	
10	a2_NaOH =	0.0037			a2_NaNO3 =	0.0000	
11	(uncertainty:	3.04	wt%)	(uncertainty:	6.66	wt%)	
12	(uncertainties do not include effect of uncertainty of the concentration of NaOH and NaNO3)						
13							
14	Substep 3: The overall assumed supernate solubility relation is:						
15							
16	**Solubility (wt%) =**						
17	**53.2214**	**+**	**0.0534**	***T (°C) +**	**0.00185**	***T^2 (°C)**	
18	(uncertainty:	4.85	wt%), not including uncertainty in T				
19							
20	Substep 4: Determine the mass exchange between the solid and liquid phases						
21	(Both following parts assume that the chemical make-up of the supernate above and below the salt cake						
22	supernate interface is similar to allow the use of the above-solubility relationship.)						
23							
24	Part a: Change due to the solubility change of supernate above salt cake						
25	Supernate above the salt cake -						
26	wt% on previous measurement =			55.57			
27	wt% on current measurement =			55.71			
28	Previous mass of Supernate =			1200357883	grams		
29			(uncertainty:	145994267			
30	therefore the change in mass of the upper supernate is:						
31							
32	d(mass) =	3899708	grams	(uncertainty:	676236	grams)	
33							
34	Part b: Change due to the solubility change of supernate within salt cake						
35	Supernate within the salt cake -						
36	wt% on previous measurement =			56.32			
37	wt% on current measurement =			56.49			
38	Previous mass of Supernate =			1572758069	grams		
39			(uncertainty:	324500253			
40	therefore the change in mass of the lower supernate is:						
41							
42	d(mass) =	5868242	grams	(uncertainty:	1212011	grams)	
43							
44							
45							
46							
47							

	BE	BF	BG	BH	BI	BJ	BK
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 3: Continued						
4							
5	therefore the change in mass of the from parts a & b is:						
6							
7	d(mass) =	9767950	grams	(uncertainty:	1888247	grams)	
8							
9							
10	Approximately densities of individual compounds in solid state are:						
11							
12	NaOH @ 20° =		2.13	g/cm3	(uncertainty unknown)		
13	NaNO3 @ 20°C =		2.261	g/cm3	(uncertainty unknown)		
14	NaNO2 @ 0°C =		2.168	g/cm3	(uncertainty unknown)		
15							
16	To determine the height of the mass which was either removed or added to the						
17	solid the density values listed above will be used at other temperatures. The small						
18	height change will not be affected significantly over the temperatures of interest,						
19	i.e., the thermal expansion of two compounds may be represented as:						
20							
21	dV/V)_NaNO2 = 1.038191e-4 + 2.540877e-7*T + 4.527648e-9*T^2 /°C						
22	(standard deviation = 2.441e-6 /°C); Range: -23.2°C to 126.9°C, and						
23	dV/V)_NaNO3 = 1.200175e-4 + 1.045949e-8*T + 2.086346e-9*T^2 /°C						
24	(standard deviation = 1.707e-6 /°C); Range: 19.9°C to 126.9°C						
25							
26	Example: at 20°C dV/V_NaNO2 = 0.00011 representing a 1/100 % change in						
27	density, which is insignificant.						
28							
29	Then from the tank chemistry and assuming the solid has a similar chemistry:						
30							
31	Density of Salt Cake is =		2.178	g/cm3			
32							
33	The change of waste level due solely to an exchange of mass is:						
34							
35	**level change of the solid waste:**			**-0.34**	**inch**		
36	(uncertainty:	0.07	inch)				
37	**level change of the liquid waste:**			**0.54**	**inch**		
38	(uncertainty:	0.10	inch)				
39							
40	**Total change of mass transfer:**			**0.20**	**inch**		
41	(uncertainty:	0.12	inch)				
42							
43							
44							
45							
46							
47							

	BL	BM	BN	BO	BP	BQ	BR
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 4: Determine the change in height due to the expansion of the Salt Cake						
4							
5	Assumptions:						
6	1. If sludge is present, its volume changes, due to temperature, similarly to that						
7	of the salt cake						
8	2. Tank diameter is not affected by the temperature change.						
9	3. Solid is at a uniform temperature.						
10	4. Salt cake expands and contracts freely.						
11	5. The salt cake has a volumetric thermal expansion coefficient similar to an						
12	HM-type salt. (given in Bull,Harcourt, III,"Thermal Expansion of Waste Salts,"						
13	Report No. DPST-70-575, Dec. 30, 1970. i.e., (1/V)*dV/dT = 102 x 10^-6 /°C, but						
14	this value is 10% under that for another similar mixture "Purex", and is as much						
15	30% under pure compounds values [NaNO3 and NaNO2] therefore is uncertainty						
16	is assumed to be 20%).						
17	6. (1/V)*dV/dT is independent of temperature (the assumed uncertainty in						
18	assumption 5 should envelope changes that occur to the expansion coefficient						
19	with temperature).						
20							
21	From the input sheet the original salt cake height is:				203	inches	
22	From Step 3 the change in the salt cake height						
23	due to the mass exchange is:				-0.34	inches	
24							
25	Total height is:				202.66	inches	
26				(uncertainty:	34	inches)	
27	Previous salt cake temperature =			29	℃		
28	Current salt cake temperature =			30	℃		
29	Therefore, dT =			1	℃		
30							
31	From assumption 2. then dV/V = dh/h and from assumption 5.:						
32							
33	dh/h =	1.02E-04	/ °C				
34							
35	and for a	1	°C change dh/h =		1.02E-04		
36				(uncertainty:	2.04E-05	)	
37							
38	**the change in height of the salt cake is:**				**0.021**	**inches**	
39				(uncertainty:	0.005	inches)	
40							
41							
42							
43							
44							
45							
46							
47							

	BS	BT	BU	BV	BW	BX	BY
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 5a: Determine the change in height due to the expansion/contraction						
4	of the Supernate above the Salt Cake						
5							
6	Assumptions:						
7							
8	1. Tank diameter is not affected by the temperature change.						
9	2. Liquid is at a uniform supernate temperature.						
10	3. Waste consists of NaNO3, NaNO2, and NaOH only.						
11	4. NaNO3 and NaNO2 liquids have the same density-temperature response.						
12	5. Density values in Tables 5 & 6 are in error by 5%.						
13							
14	From inputs the supernate height above saltcake is:				66.4	inches	
15	From Step 3 the change in the supernate height						
16	due to the mass exchange is:				0.54	inches	
17							
18	Total liquid height above supernate is:				66.94	inches	
19				(uncertainty:	0.2	inches)	
20	Previous supernate temperature =			24	°C		
21	Current supernate temperature =			25	°C		
22	Avg. temperature to determine thermal expansion =				24.5	°C	
23							
24	The combined weight percentage of NaNO3 and NaNO2 =					14.31 wt %	
25	The weight percentage of NaOH =					15.67 wt %	
26							
27	(NOTE: uncertainty of tabular values is not known)						
28	Interpolation Work Box to determine			Interpolation Work Box to determine			
29	d(density)/dT for NaNO3 and NaNO2			d(density)/dT for NaOH			
30	at the variable given above from Table 6			at the variable given above from Table 7			
31	beginning row in Table 6 is:		6	beginning row in Table 7 is:		6	
32	beginning col in Table 6 is:		2	beginning col in Table 7 is:		3	
33	(unc. of tabular values assumed: 1%)			(unc. of tabular values assumed: 1%)			
34		Temperature, °C			Temperature, °C		
35	wt%	20	40	wt%	20	40	
36	12.00 wt %	1.0819	1.0724	12.00 wt %	1.1309	1.121	
37	16.00 wt %	1.1118	1.1013	16.00 wt %	1.1751	1.1645	
38							
39	14.31 wt %	1.06463179	1.055709	15.67 wt %	1.09034819	1.081090	
40	therefore at T= and wt% =			therefore at T= and wt% =			
41		24.5	14.31		24.5	15.67	
42							
43	density =	1.0626	g/cm3	density =	1.0883	g/cm3	
44							
45							
46							
47							

	BZ	CA	CB	CC	CD	CE	CF
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 5a: Continued						
4							
5	and - (1/V)*(dV/dT) =			and - (1/V)*(dV/dT) =			
6							
7	4.1983E-04	/°C unc =	2.8176E-05	4.2535E-04	/°C unc =	9.3032E-06	
8							
9	Based on the molar percentage then:						
10							
11	NaOH =		52.3%				
12	NaNO3 & NaNO2 =		47.7%				
13							
14	therefore -(1/dens)*(ddens/dT) = (1/V)*(dV/dT) =				4.2271E-04	/°C	
15							
16	and for dT =	1	°C then	dV/V =	4.2271E-04		
17				(uncertainty:	4.0709E-05	)	
18	From assumption 1: dV/V = dh/h therefore,						
19							
20							
21	**the change in height of the supernate is:**				**0.028**	**inches**	
22				(uncertainty:	0.003	inches)	
23							
24							
25							
26							
27							
28							
29							
30							
31							
32							
33							
34							
35							
36							
37							
38							
39							
40							
41							
42							
43							
44							
45							
46							
47							

	CG	CH	CI	CJ	CK	CL	CM
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 5b: Determine the change in height due to the expansion/contraction						
4	of the Supernate within the Salt Cake						
5							
6	Assumptions:						
7	1. Tank diameter is not affected by the temperature change.						
8	2. Liquid is at a uniform Salt Cake temperature.						
9	3. Waste consists of NaNO3, NaNO2, and NaOH only.						
10	4. NaNO3 and NaNO2 liquids have the same density-temperature response.						
11	5. Density values in Tables 5 & 6 are in error by 5%.						
12	6. Chemical make-up of supernate above and within salt cake is similar						
13							
14	From inputs the supernate "height "within salt cake is:				87	inches	
15	From Step 3 the change in the supernate height						
16	due to the mass exchange is:				-0.34	inches	
17							
18	Total liquid "equivalent height" is:				86.66	inches	
19				(uncertainty:	14.5	inches)	
20	Previous salt cake temperature =			29	℃		
21	Current salt cake temperature =			30	℃		
22	Avg. temperature to determine thermal expansion =				29.5	℃	
23							
24	The combined weight percentage of NaNO3 and NaNO2 =					14.31 wt %	
25	The weight percentage of NaOH =					15.67 wt %	
26							
27	(NOTE: uncertainty of tabular values is not known)						
28	Interpolation Work Box to determine			Interpolation Work Box to determine			
29	d(density)/dT for NaNO3 and NaNO2			d(density)/dT for NaOH			
30	at the variable given above from Table 6			at the variable given above from Table 7			
31	beginning row in Table 6 is:		6	beginning row in Table 7 is:		6	
32	beginning col in Table 6 is:		2	beginning col in Table 7 is:		3	
33	(unc. of tabular values assumed: 1%)			(unc. of tabular values assumed: 1%)			
34		Temperature, °C			Temperature, °C		
35	wt%	20	40	wt%	20	40	
36	12.00 wt %	1.0819	1.0724	12.00 wt %	1.1309	1.121	
37	16.00 wt %	1.1118	1.1013	16.00 wt %	1.1751	1.1645	
38							
39	14.31 wt %	1.06463179	1.055709	15.67 wt %	1.09034819	1.081090	
40	therefore at T= and wt% =			therefore at T= and wt% =			
41		29.5	14.31		29.5	15.67	
42							
43	density =	1.0604	g/cm3	density =	1.0860	g/cm3	
44							
45							
46							
47							

	CN	CO	CP	CQ	CR	CS	CT
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 5: Continued						
4							
5	and - (1/V)*(dV/dT) =			and - (1/V)*(dV/dT) =			
6							
7	4.2071E-04	/°C unc =	2.8226E-05	4.2625E-04	/°C unc =	9.2941E-06	
8							
9	Based on the molar percentage then:						
10							
11	NaOH =		52.3%				
12	NaNO3 & NaNO2 =		47.7%				
13							
14	therefore -(1/dens)*(ddens/dT) = (1/V)*(dV/dT) =				4.2361E-04	/°C	
15							
16	and for dT =	1	°C then	dV/V =	4.2361E-04		
17				(uncertainty:	4.0782E-05	)	
18	From assumption 1: dV/V = dh/h therefore,						
19							
20							
21	**the change in height of the supernate is:**				**0.037**	**inches**	
22				(uncertainty:	0.007	inches)	
23							
24							
25							
26	**Total height change from step 5a & step 5b:**				**0.065**		
27				(uncertainty:	0.010	inches)	
28							
29							
30							
31							
32							
33							
34							
35							
36							
37							
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40							
41							
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43							
44							
45							
46							
47							

++ SCOPING ANALYSIS ++

	CU	CV	CW	CX	CY	CZ	DA
1	measured by:	DUIGNAN	on date:	5/11/92	at hour:	6	
2							
3	Step 6: Determine the change in height due to the change in Carbon Steel Waste						
4	Tank Volume.						
5							
6	Assumptions:						
7							
8	1. The entire tank is made of carbon steel.						
9	2. The thermal coefficient of expansion is constant with temperature.						
10	3. The linear thermal coefficient of expansion in Table 8 is valid.						
11	(valid: 10°C < T < 100°C).						
12	4. Area Thermal coefficient of expansion is twice the linear coefficient.						
13	5. The entire tank expands and contracts freely.						
14	6. The measured annular temperatures are constant and uniform throughout the tank wall.						
15							
16	From the input sheet the original waste level is:				356.4	inches	
17							
18	Previous tank wall temperature =			27	°C		
19	Current tank wall temperature =			28	°C		
20	Average wall temperature =			27.5	°C		
21	Temperature change			1	°C		
22							
23	From assumptions 3 and 4, then 2 x (1/l) dl/dT = (1/Area) dArea/dT:						
24							
25	(1/A)dA/dT=	2.19E-05	/ °C				
26							
27							
28	and for a	1	°C change dA/A =		2.19E-05		
29				(uncertainty:	4.39E-06	)	
30							
31	For the contents in the tank if the volume remains constant then the waste						
32	level changes with tank area therefore:			dA/A = dh/h			
33							
34			dh/h =	2.19E-05			
35							
36	**the change in height of the salt cake is:**				**-0.008**	**inches**	
37				(uncertainty:	0.002	inches)	
38							
39							
40							
41							
42							
43							
44							
45							
46							
47							

	A	B	C	D	E	F	G
48	**Table 1: Water Vapor at Saturation Conditions***						
49	Least-sq. fit: (Press = wv0 + wv1 x Temp.(°C) + ..., MPa) x 10000, millibars						
50	0.01 to 50°C			50 to 110°C			
51	(Curve Fit Uncert. = 2xstd.dev = 2%FS)			(Curve Fit Uncert. = 2xstd.dev = 1%FS)			
52	wv0_l	6.124E-04		wv0_h	1.009E-02		
53	wv1_l	4.273E-05		wv1_h	-5.700E-04		
54	wv2_l	1.695E-06		wv2_h	1.699E-05		
55	wv3_l	1.202E-08		wv3_h	-1.656E-07		
56	wv4_l	6.177E-10		wv4_h	1.439E-09		
57	corr. coef.	0.99999990		corr. coef.	1.00000000		
58	*Least-square fitting of data from Reynolds, W. C., and H. C. Perkins, "Eng. Thermo.," 2nd ed., 1977 (623)						
59	**Table 2: Density of Liquid Water***						
60	Least-sq. fit: Density = w_0 + w_1x(T,°C) + w_2x(T,°C)^2 + w_3x(T,°C)^3, g/cm3						
61							
62	Pressure: 1 atmosphere						
63	(Curve Fit Uncertainty = 2xstd.dev. = 0.001%FS)						
64	w_0	1.00E+00					
65	w_1	5.16E-05	**Valid Range of Correlation: 5°C to 38°C**				
66	w_2	-7.53E-06					
67	w_3	3.61E-08		Density =	0.99704567	g/cm3	
68	corr. coef.	0.999999		at Temp. =	25	°C	
69	*van der Leeden, F.,Troise,F.L., and D.K. Todd,"The Water Encyclopedia", 2nd ed.,1990,(p. 774)						
70	**Table 3a: Density of Air**						
71	Assume Ideal Gas						
72	(Uncertainty assumed to be 1% excluding the uncertainty of P and T)						
73	Density = Mol.Wt. x Pressure/(R x Temperature)						
74	Molecular Weight of Air =		28.97	g/gmole			
75	Universal Gas Constant =		8.3143	J/gmoleK			
76	Atmospheric Pressure =		1021.2	=	102120	Pa	
77	Atmospheric Temperature =		16.6	=	289.75	K	
78	Cond.Exit Temperature =		13	=	286.15	K	
79	therefore, Density =		1.2280E-03	g/cm3 at	289.75	K	
80	therefore, Density =		1.2435E-03	g/cm3 at	286.15	K	
81	**Table 3b: Density of Nitrogen**						
82	Assume Ideal Gas						
83	(Uncertainty assumed to be 1% excluding the uncertainty of P and T)						
84	Density = Mol.Wt. x Pressure/(R x Temperature)						
85	Molecular Weight of Air =		28.02	g/gmole			
86	Universal Gas Constant =		8.3143	J/gmoleK			
87	Atmospheric Pressure =		1021.2	=	102120	Pa	
88	Atmospheric Temperature =		16.6	=	289.75	K	
89	Cond.Exit Temperature =		13	=	286.15	K	
90	therefore, Density =		1.1878E-03	g/cm3 at	289.75	K	
91	therefore, Density =		1.2027E-03	g/cm3 at	286.15	K	

	H	I	J	K	L	M	N
48	**Table 4b: Supernatant Mixture** 1 at 25°C (Molarity)**						
49							
50	Compound	mixture #1	mixture #2	mixture #3	mixture #4	mixture #7	
51	Na NO2	0.64					
52	Na NO3	1.40	3.40	5.03	2.18	6.00	
53	Na OH	2.30	0.30	2.52	7.60	1.00	
54	Na AlO2	2.30	0.55	1.02	2.30		
55	Na2 CO3		0.35	0.18	0.11	0.30	
56	Na2 SO4		0.08	0.08	0.02	0.10	
57	*NaNO2 does not have sufficient data to be used as an indicator						
58	**mixtures 5 and 6 did not have sufficient information to determine solubilities						
59							
60	**Table 4b: Determine which mixture representation to use**						
61	Number for mixtures 1 & 2 differ from Table 4a because ...						
62							
63			** Increasing Salt Content **				
64			NaOH		NaNO3		
65		Molarity	Mixture #	Molarity	Mixture #		
66		0.59	2	2.18	4		
67		1	7	2.69	1		
68		2.52	3	5.03	3		
69		4.43	1	6	7		
70		7.6	4	6.64	2		
71							
72	**Table 5a: Solubility for Waste Mixture#1(see Table 4 for contents)**						
73							
74	Curve fit: wt% = a0+a1*T+a2*T^2						
75							
76	a0	61.6290324		**MIXTURE #1**			
77	a1	-0.23020301					
78	a2	0.00515966					
79	corr. coeff.	0.99623104					
80							
81	T,°C	g/cc	wt%	Pred'ed wt%	wt% - pred.		
82	20.00	1.57	59.00	59.10	0.09		
83	48.10	1.62	62.50	62.50	-0.01		
84	60.00	1.65	66.40	66.40	-0.01		
85	66.70	1.67	70.30	69.20	-1.07		
86	78.00	1.70	74.10	75.10	0.96		
87	83.80	1.74	77.80	78.60	0.77		
88	89.00	1.76	81.50	82.00	0.51		
89	91.90	1.78	85.30	84.00	-1.25		
90		standard deviation from the curve =			0.8		
91				std. dev. x 2 =	1.6		

	O	P	Q	R	S	T	U
48	**Table 5b: Solubility for Waste Mixture#2(see Table 4 for contents)**						
49							
50	Curve fit: wt% = a0+a1*T						
51							
52	a0	48.9781098		**MIXTURE #2**			
53	a1	0.29534586					
54	a2	0					
55	corr. coeff.	0.99553027					
56							
57	T,°C	g/cc	wt%	Pred'ed wt%	wt% - pred.		
58	26.70	1.36	57.00	56.90	-0.14		
59	35.20	1.40	60.00	59.40	-0.63		
60	67.10	1.48	68.00	68.80	0.80		
61	84.80	1.50	74.00	74.00	0.02		
62	104.80	1.52	78.00	79.90	1.93		
63	111.00	1.56	83.00	81.80	-1.24		
64	126.20	1.63	87.00	86.30	-0.75		
65		standard deviation from the curve =			1.07		
66				std. dev. x 2 =	2.14		
67							
68	**Table 5c: Solubility for Waste Mixture#3(see Table 4 for contents)**						
69							
70	Curve fit: wt% = a0+a1*T						
71							
72	a0	34.8210958		**MIXTURE #3**			
73	a1	0.32776956					
74	a2	0					
75	corr. coeff.	0.97788875					
76							
77	T,°C	g/cc	wt%	Pred'ed wt%	wt% - pred.		
78	40.00	1.42	47.00	47.90	0.93		
79	60.00	1.46	52.00	54.50	2.49		
80	65.70	1.48	59.00	56.40	-2.64		
81	90.00	1.50	63.00	64.30	1.32		
82	97.10	1.54	68.00	66.60	-1.35		
83	104.30	1.54	72.00	69.00	-2.99		
84	138.60	1.65	78.00	80.20	2.25		
85		standard deviation from the curve =			2.3		
86				std. dev. x 2 =	4.6		
87							
88							
89							
90							
91							

	V	W	X	Y	Z	AA	AB
48	Table 5d: Solubility for Waste Mixture#4(see Table 4 for contents)						
49							
50	Curve fit: wt% = a0+a1*T						
51							
52	a0	48.5321135		MIXTURE #4			
53	a1	0.21152422					
54	a2	0					
55	corr. coeff.	0.94166942					
56							
57	T,°C	g/cc	wt%	Pred'ed wt%	wt% - pred.		
58	51.00	1.50	58.00	59.30	1.32		
59	87.10	1.59	64.00	67.00	2.96		
60	83.80	1.62	71.00	66.30	-4.74		
61	155.70	1.68	81.00	81.50	0.47		
62		standard deviation from the curve =			3.33		
63				std. dev. x 2 =	6.66		
64							
65	Table 5e: Solubility for Waste Mixture#7(see Table 4 for contents)						
66							
67	Curve fit: wt% = a0+a1*T						
68							
69	a0	45.45668		MIXTURE #7			
70	a1	0.12993107					
71	a2	0					
72	corr. coeff.	0.9742925					
73							
74	T,°C	g/cc	wt%	Pred'ed wt%	wt% - pred.		
75	22.60	1.33	47.00	48.40	1.39		
76	43.50	1.45	53.00	51.10	-1.89		
77	100.00	1.45	58.00	58.40	0.45		
78	120.00	1.49	61.00	61.00	0.05		
79		standard deviation from the curve =			1.38		
80				std. dev. x 2 =	2.76		
81							
82							
83							
84							
85							
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87							
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91							

	AC	AD	AE	AF	AG	AH	AI	AJ
48	Table 6: Density of NaNO3 (and assumed for NaNO2)*							
49								
50	wt %	Temperature (°C)						
51		0	20	40	60	80	100	
52	0.00 wt %	0.9999	0.9982	0.9922	0.9832	0.9718	0.9583	
53	1.00 wt %	1.0071	1.0049	0.9986	0.9894	0.9779	0.9644	
54	2.00 wt %	1.0144	1.0117	1.0050	0.9956	0.9840	0.9704	
55	4.00 wt %	1.0290	1.0254	1.0180	1.0082	0.9964	0.9826	
56	8.00 wt %	1.0587	1.0532	1.0447	1.0340	1.0218	1.0078	
57	12.00 wt %	1.0891	1.0819	1.0724	1.0609	1.0481	1.0340	
58	16.00 wt %	1.1203	1.1118	1.1013	1.0892	1.0757	1.0614	
59	20.00 wt %	1.1526	1.1429	1.1314	1.1187	1.1048	1.0901	
60	24.00 wt %	1.1860	1.1752	1.1629	1.1496	1.1351	1.1200	
61	28.00 wt %	1.2204	1.2085	1.1955	1.1816	1.1667	1.1513	
62	30.00 wt %	1.2380	1.2256	1.2122	1.1980	1.1830	1.1674	
63	35.00 wt %	1.2834	1.2701	1.2560	1.2413	1.2258	1.2100	
64	40.00 wt %	1.3316	1.3175	1.3027	1.2875	1.2715	1.2555	
65	45.00 wt %		1.3683	1.3528	1.3371	1.3206	1.3044	
66	*source: Perry's Chemical Engineers Handbook, 6th Edition, 1984, (pp.3-84,3-85)							
67								
68	Table 7: Density of NaOH*							
69								
70	wt. %	Temperature						
71		0 C	15 C	20 C	40 C	60 C	80 C	100 C
72	0.00 wt %	0.9999	0.9991	0.9982	0.9922	0.9832	0.9718	0.9583
73	1.00 wt %	1.0124	1.0107	1.0095	1.0033	0.9941	0.9824	0.9693
74	2.00 wt %	1.0244	1.0220	1.0207	1.0139	1.0045	0.9929	0.9797
75	4.00 wt %	1.0482	1.0444	1.0428	1.0352	1.0254	1.0139	1.0009
76	8.00 wt %	1.0943	1.0889	1.0869	1.0780	1.0676	1.0560	1.0432
77	12.00 wt %	1.1399	1.1333	1.1309	1.1210	1.1101	1.0980	1.0855
78	16.00 wt %	1.1849	1.1776	1.1751	1.1645	1.1531	1.1408	1.1277
79	20.00 wt %	1.2296	1.2218	1.2191	1.2079	1.1960	1.1833	1.1700
80	24.00 wt %	1.2741	1.2658	1.2629	1.2512	1.2388	1.2259	1.2124
81	28.00 wt %	1.3182	1.3094	1.3064	1.2942	1.2814	1.2682	1.2546
82	32.00 wt %	1.3614	1.3520	1.3490	1.3362	1.3232	1.3097	1.2960
83	36.00 wt %	1.4030	1.3933	1.3900	1.3768	1.3634	1.3498	1.3360
84	40.00 wt %	1.4435	1.4334	1.4300	1.4164	1.4027	1.3889	1.3750
85	44.00 wt %	1.4825	1.4720	1.4685	1.4545	1.4405	1.4266	1.4127
86	48.00 wt %	1.5210	1.5102	1.5065	1.4922	1.4781	1.4641	1.4503
87	50.00 wt %	1.5400	1.5290	1.5253	1.5109	1.4967	1.4827	1.4690
88	*source: Perry's Chemical Engineers Handbook, 6th Edition, 1984, (p. 3-84)							
89								
90								
91								

	AQ	AR	AS	AT	AU	AV	AW
48	Table 8: Thermal Expansion of Carbon Steel*						
49							
50					3 x Linear Expansion=		
51	Temp.°F	Temp.°C	Lin. Expan./°F	Lin. Expan./°C	Vol. Expan./°C		
52	25	-3.9	5.96E-06	1.07E-05	3.22E-05		
53	50	10	6.01E-06	1.08E-05	3.25E-05		
54	70	21.1	6.07E-06	1.09E-05	3.28E-05		
55	100	37.8	6.13E-06	1.10E-05	3.31E-05		
56	125	51.7	6.19E-06	1.11E-05	3.34E-05		
57	150	65.6	6.25E-06	1.13E-05	3.38E-05		
58	175	79.4	6.31E-06	1.14E-05	3.41E-05		
59	200	93.3	6.38E-06	1.15E-05	3.45E-05		
60	225	107.2	6.43E-06	1.16E-05	3.47E-05		
61							
62							
63	Linear. Expan/°C						
64	prediction from curve fit		(pred)-(measured)				
65	1.07E-05		-7.40E-09				
66	1.08E-05		9.54E-09				
67	1.09E-05		-1.29E-08				
68	1.10E-05		7.43E-09				
69	1.12E-05		6.38E-09				
70	1.13E-05		5.32E-09				
71	1.14E-05		4.26E-09				
72	1.15E-05		-1.48E-08				
73	1.16E-05		2.15E-09				
74		rms deviation	8.68E-09	length/(°C*length)			
75							
76		Curve fit uncertainty = 2 x rms dev. =			1.736E-08	/°C	
77							
78		Least-sq. fit: Volumetric Coefficient Thermal Expansion =					
79		b0 + b1x(T,°C), in/in°C, cm/cm°C					
80		Pressure: 1 atmosphere					
81		b0	1.08E-05				
82		b1	7.70E-09				
83		corr. coef.	0.999513				
84	*source: Perry's Chemical Engineers Handbook, 6th Edition, 1984, (p. 6-89)						
85							
86							
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