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MATHEMATICAL MODELING OF WIPED-FILM EVAPORATORS

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by

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ABSTRACT

A mathematical model and associated computer program were developed to simulate the steady-state operation of wiped-film evaporators for the concentration of typical waste solutions produced at the Savannah River Plant.

In this model, which treats either a horizontal or a vertical wiped-film evaporator as a plug-flow device with no backmixing, three fundamental phenomena are described: sensible heating of the waste solution, vaporization of water, and crystallization of solids from solution.

Physical property data were coded into the computer program, which performs the calculations of this model. Physical properties of typical waste solutions and of the heating steam, generally as analytical functions of temperature, were obtained from published data or derived by regression analysis of tabulated or graphical data. Preliminary results from tests of the Savannah River Laboratory semiworks wiped-film evaporators were used to select a correlation for the inside film heat transfer coefficient.

This model should be a useful aid in the specification, operation, and control of the full-scale wiped-film evaporators proposed for application under plant conditions. In particular, it should be of value in the development and analysis of feed-forward control schemes for the plant units. Also, this model can be readily adapted, with only minor changes, to simulate the operation of wiped-film evaporators for other conceivable applications, such as the concentration of acid wastes.

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INTRODUCTION

Aqueous waste solutions from the processing of radioactive fuel elements at the Savannah River Plant (SRP) are stored in underground carbon steel tanks with capacities of 3/4 to 1-1/3 million gallons. These solutions are alkaline, with an initial dissolved solids content of 30 to 35%. The dissolved species are sodium salts, including the carbonate, sulfate, nitrate, nitrite, hydroxide, and aluminate.

Tank storage costs are presently reduced by evaporative reduction of the volume of the waste solutions in bent-tube evaporators. Semiworks tests at the Savannah River Laboratory (SRL) with two small wiped-film evaporators[1] have shown that synthetic alkaline wastes from the plutonium and recovery process (Purex wastes) can be converted to free-flowing slurries that form a wet salt cake upon cooling to ambient temperature. The desired concentration can be theoretically obtained in one pass through the evaporator rather than several passes required for other methods of evaporation.

Wiped-film evaporators are used extensively in industry to convert aqueous solutions and slurries to pastes, purees, and even free-flowing powders. For the application described in this report, the heat-transfer surface is not actually wiped or scraped; rather, a highly agitated thin film is spread onto the metallic heat-transfer surface. The unique feature of this equipment is not the thin film itself, but rather the wiper blade and rotor for producing and agitating the film.[2] A vertical wiped-film evaporator is shown in Figure 1.

A mathematical model for the simulation of wiped-film evaporators was developed as an aid in resolving some of the questions pertaining to the specification, operation, and control of wiped-film evaporators used for evaporation of radioactive waste solutions. It was particularly desired to quantify the effects of various equipment and operating parameters on the performance of the unit in the proposed environment. This model and associated computer program for performing the necessary calculations are described in this report.

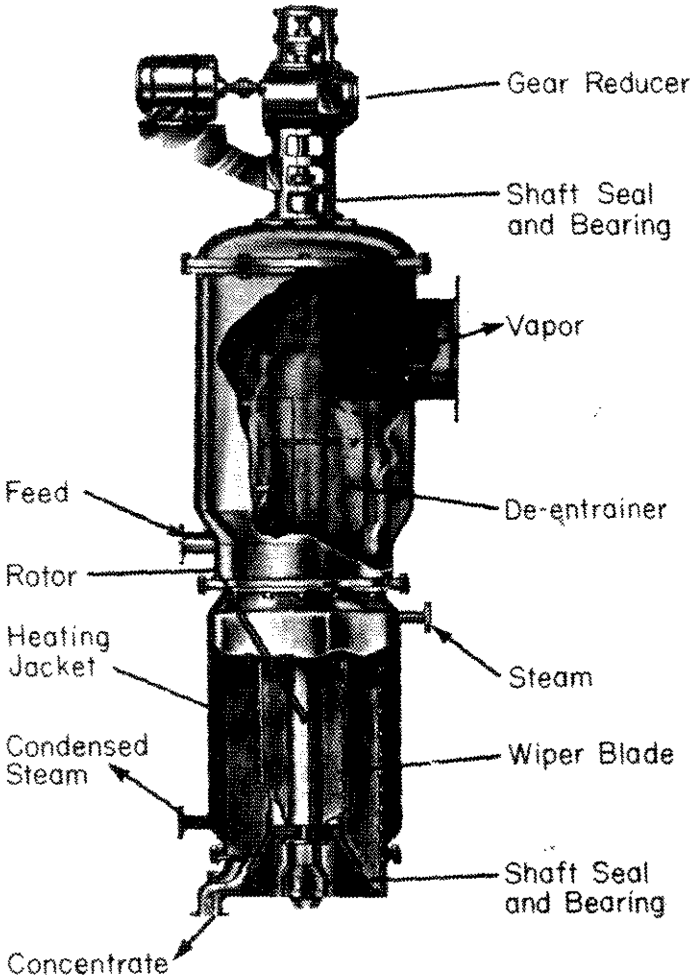


FIGURE 1. Vertical Wiped-Film Evaporator

SCOPE OF MODEL

The objective of this work was to develop a mathematical model that would be a useful aid in the specification, operation, and control of wiped-film evaporators for SRP applications. The model simulates the steady-state operation of wiped-film evaporators as plug-flow units with no backmixing.[3,4] An unsteady-state or dynamic model was not attempted for three reasons: *(1)* the extreme complexity that would be associated with such a dynamic model, *(2)* the very rapid response to changes in operating conditions characteristic of wiped-film evaporators (a typical residence time in wiped-film units is about 15 to 20 sec),[2,4] and *(3)* the primary control schemes for the plant-scale evaporators will probably be of a feedforward rather than a feedback nature.

The model was constructed to simulate the operation of wiped-film evaporators (of any size or configuration) for the concentration of three distinct types of SRP wastes: Purex, coating, and HM. Pertinent physical properties for these types of wastes were coded into the computer program for performing the model calculations. Physical property data for other types of wastes would have to be developed and incorporated into the computer program to simulate concentration of these; provision has been made in the program to extend the model to other types of wastes.

Tests of these semiworks wiped-film evaporators are currently ongoing and will continue for some time. Results of these tests will probably indicate the need for some modification or refinement of the correlation for the inside film heat transfer coefficient. Similarly, it may be desirable to incorporate improved physical property correlations, as the latter become available, into this model.

PHYSICAL PROPERTIES OF WASTES

To perform a valid design or simulation of any chemical operation or process, accurate values of pertinent physical and chemical properties for the components of interest must be available. The acquisition of appropriate data is generally no problem in the case of single-component processes or processes involving ideal mixtures of multiple components. Significant difficulties arise, however, in characterizing the physical properties of nonideal liquid mixtures or of solutions of electrolytes. The latter category includes the waste solutions processed at SRP. In this work, a variety of theoretical and empirical tools have been used to characterize the physical properties of SRP waste solutions.

A second consideration arises when the process design or simulation calculations are to be programmed on a digital computer. It has been traditional in chemical engineering to report and present physical property data in forms easily visualized and adapted to manual calculations--charts, graphs, tables, nomographs, etc. None of these forms, however, can be directly implemented on a digital computer. Rather, physical property data must be represented in the form of equations that can be readily programmed in a source language such as FORTRAN. Thus, it is often necessary to regress discrete data values from a table or graph into analytical form or, better yet, locate the original equation, if such exists, upon which the data values are based. A considerable amount of such effort in the early stages of this project was devoted to correlating and regressing physical property data on SRP wastes; the results of this work are described below.

Boildown Ratio

The extent of volume reduction that occurs after evaporative concentration can be characterized by the boildown ratio[5] (defined as the volume of evaporator feed measured at 25°C divided by the volume of supernate remaining after evaporation). Data on boildown ratio as a function of evaporation temperature have been reported for various typical SRP wastes.[5] Data for three typical wastes--synthetic Purex, coating, and synthetic HM--were regressed and fit to a polynomial equation of the following form:

$$BDR = b_o + b_1(t - t_{BP}) + b_2(t - t_{BP})^2 \qquad (1)$$

Constants for each of the three wastes are presented in Table 1; in all cases the first constant (b_o) was constrained to be equal to unity. For synthetic HM waste, a better fit of the available data can be obtained if a second-order polynomial expression is used ($b_2 \neq 0$). A relatively small amount of data are available in this case, however, and a second-order polynomial causes the boildown ratio to turn around and decrease shortly after the high-temperature end of the data range. For this reason, the slightly less accurate first-order representation was chosen.

TABLE 1

Regression Coefficients for the Boildown Ratio of Typical SRP Wastes

Waste	b_o	b_1	b_2	t_{BP}, °C
Synthetic Purex	1.0	0.1282	0.0	106
Coating	1.0	0.07453	-4.406×10^{-4}	112
Synthetic HM	1.0	0.06342	0.0	115

Specific Gravity

The specific gravities of SRP wastes[5] are required to convert between volumetric and mass flow rates in the material balance calculations of this model. The specific gravities of these wastes generally decrease with increasing temperature before boiling; after boiling commences, the specific gravities increase with temperature as the solutions become more concentrated. Hence, separate correlations of

$$s = a_o + a_1(t - t_{BP}) + a_2(t - t_{BP})^2 \tag{2}$$

were developed to represent the specific gravities before and during boiling. The first constant (a_o) is constrained to be equal to the specific gravity at the initial normal boiling point (s_{BP}) in both correlations for each waste. The purpose of this constraint was to ensure bumpless transfer from the nonboiling or preheating regime to the boiling regime in the model calculations. Regression coefficients for the specific gravity correlations before and during boiling for the three typical SRP wastes are given in Table 2. Again, a slightly more accurate fit of the raw data for HM waste during boiling could be obtained if a second-order polynomial expression were used; however, the specific gravity would begin to decrease shortly beyond the high-temperature limit of the data range.

TABLE 2

Regression Coefficients for the Specific Gravity of Typical SRP Wastes

Waste	a_o	a_1	a_2
Before boiling			
Synthetic Purex	1.216	-4.181×10^{-4}	0.0
Coating	1.268	-5.169×10^{-4}	0.0
Synthetic HM	1.331	-9.76×10^{-4}	0.0
During boiling			
Synthetic Purex	1.216	0.0210	0.0
Coating	1.268	0.01899	-1.833×10^{-4}
Synthetic HM	1.331	0.02124	0.0

Heat Capacity

The heat capacity (strictly speaking, the enthalpy content) of the waste solutions at various temperatures and concentrations is needed for heat balance calculations in this model. Six different sodium salts that may be present in the various SRP waste solutions are: Na_2SO_4, Na_2CO_3, $NaNO_3$, $NaNO_2$, NaOH, and $NaAlO_2$. Not all of these six salts will necessarily be present in a given waste. The heat capacity of these solutions was computed from a linear average of the heat capacities for the pure components (liquid water and solid salts) based upon the weight fractions of each of the dissolved species. The average value of the product of the mass flow rate times the heat capacity for each component is

$$\overline{Wc_p} = \sum_{i=0}^{6} W_i c_{p_i} \qquad (3)$$

where i = 0 pertains to liquid water, and i = 1, 2,...., 6 correspond to the six sodium salts in the order of increasing solubility.

The expression for computing the heat capacity of liquid water will be presented later in the section on the physical properties of water. Molar heat capacities of the various sodium salts as a function of temperature were computed from

$$C_p = A + B\times10^{-3}T + \frac{C\times10^{+5}}{T^2} + D\times10^{-6}T^2 \qquad (4)$$

The constants A, B, C, and D in Equation 4 were obtained from a standard source of thermodynamic data[6] and are presented in Table 3. No values were found for sodium nitrite; the values corresponding to sodium nitrate were used.

TABLE 3

Coefficients for Computing the Molar Heat Capacities of Solid Salts

Component					
Number	*Formula*	*A*	*B*	*C*	*D*
1	Na_2SO_4	19.676	36.893	0.0	0.0
2	Na_2CO_3	2.633	58.326	5.854	0.0
3[a]	$NaNO_3$	6.140	53.99	0.0	0.0
5	NaOH	17.15	-26.5	0.0	56.35
6	$NaAlO_2$	21.307	3.655	-4.286	0.0

---

a. The values for component 4 ($NaNO_2$) were assumed to be the same as those for component 3 ($NaNO_3$).

Equation 4 was also used for computing the heat capacities of the solid salts themselves (for example, after crystallization). A comparison of solution heat capacities computed from Equation 4 with published data for sodium nitrate solutions[7] showed very close agreement. Poor agreement is observed if mole fractions rather than mass fractions of the dissolved species are used to compute the solution heat capacities.

Thermal Conductivity

The thermal conductivity of the waste solutions is needed for calculating inside film heat transfer coefficients for wiped-film evaporators in this model. Unfortunately, very little data on this particular physical property are available. The following correlation, based upon the thermal conductivity of liquid water, is presented in the *International Critical Tables*[7] for the thermal conductivity of aqueous solutions:

$$k = k_w(1 - 10^{-3}\alpha x) \tag{5}$$

where α is a constant for a given dissolved species, and x is the weight fraction of that species in solution. For sodium nitrate (one of the major components in SRP wastes), a value of $\alpha = 235$ is reported.[7] This value was used to characterize the effects of the various other components on the thermal conductivity of the aqueous waste solutions:

$$k = k_w(1 - 235\times10^{-3}x_s) \tag{6}$$

For complete or partial crystallization of the dissolved solid species, an estimate of the thermal conductivity of the solid phase is required to compute the heat transfer rate in the model. A value of 1.21 Btu/(hr)(ft)(°F) is reported[8] for the thermal conductivity of solid potassium nitrate and was used for this purpose.

Viscosity

The heat transfer coefficient of the inside film is a function of the viscosity of the aqueous waste solutions. Viscosity data on synthetic Purex waste (first, second, and third concentrations) and on coating waste are given in Reference 5. Viscosity estimates for synthetic HM waste were obtained as averages between the viscosities for the supernates of the first and second concentrations of synthetic Purex waste.

In analogous fashion to specific gravity, the viscosities of these wastes decrease monotonically with increasing temperature before boiling, and then increase with temperature during boiling as the solutions become more concentrated. Thus, separate polynomial correlations were also developed for the viscosities of the waste solutions before and during boiling (in centipoises):

$$\mu = u_o + u_1(t - t_{BP}) + u_2(t - t_{BP})^2 \tag{7}$$

Regression coefficients for these viscosity correlations are presented in Table 4. Again, in order to ensure bumpless transfer from the nonboiling regime to the boiling regime in the model calculations, the first constant (u_o) in both cases was constrained to be equal to the viscosity of the solution at the initial normal boiling point (μ_{BP}).

TABLE 4

Regression Coefficients for the Viscosity (in centipoises) of Typical SRP Wastes

Waste	u_o	u_1	u_2
Before boiling			
Synthetic Purex	1.40	-7.042×10^{-4}	2.422×10^{-4}
Coating	2.70	0.06526	1.618×10^{-3}
Synthetic HM	1.50	7.658×10^{-3}	3.802×10^{-4}
During boiling			
Synthetic Purex	1.40	-0.01251	0.01093
Coating	2.70	0.03865	8.537×10^{-3}
Synthetic HM	1.50	0.2752	0.0

Heats of Crystallization

The heat effects of crystallization of the dissolved species out of solution, when this phenomenon occurs, are incorporated into this model. Although the crystals formed during evaporative concentration most probably form various hydrated species in the waste tanks as they cool down to ambient temperature, a cursory inspection of published data[8] disclosed that none of these solid hydrates are thermodynamically stable above 100°C. That is, only the anhydrous forms of the various salts in SRP wastes should be crystallized out of solution during evaporation. Heats of solution (generally at infinite dilution) for the dissolved components of SRP wastes in water at 18°C, except for sodium aluminate, were located,[9] and the negatives of these values were taken as the heats of crystallization (Table 5). The standard heat of crystallization of sodium aluminate was determined via a standard thermochemical calculation procedure and using data from various sources.[8,10,11] This calculation of the heat of crystallization for sodium aluminate is given in Appendix A.

TABLE 5

Heats of Crystallization (ΔH_C) of the Dissolved Components of SRP Wastes[3]

Component	*Molecular Weight*	*Heat of Crystallization* kcal/(g-mole)	*Heat of Crystallization* Btu/(lb-mole)
Na_2SO_4	142.04	0.28	500
Na_2CO_3	105.99	5.57	10,030
$NaNO_3$	84.99	-5.05	-9,090
$NaNO_2$	69.00	-3.6	-6,480
NaOH	40.00	10.18	18,320
$NaAlO_2$[a]	81.97	7.18	12,920

---

[a] See Appendix A for the determination of the heat of crystallization for sodium aluminate.

Solubility Products

The precipitation of dissolved species during concentration in a wiped-film evaporator was predicted from solubility products. This procedure assumes that the activity coefficients for all of the dissolved ionic species are equal to unity, not only under the given processing conditions but also under the conditions at which solubility data are used to calculate the solubility products. A more accurate representation of this phenomenon would require an exhaustive research study to investigate the liquid-solid phase equilibrium relationships for typical SRP wastes.

A salt consisting of m cations C and n anions A dissolves in water according to the following reaction:

$$C_mA_{n(s)} \rightleftharpoons mC^{+n}_{(aq)} + nA^{-m}_{(aq)} \qquad (8)$$

If the saturated solubility C_s of this salt in water is known at a given temperature and if the activity coefficients of the cation and the anion are assumed equal to unity, the solubility product for this salt can be calculated by

$$K_{SP} = (mC_s)^m\ (nC_s)^n = m^m n^n (C_s)^{m+n} \qquad (9)$$

The saturated solubilities for the pertinent sodium salts, except for the aluminate, in hot water (100°C)[8] were used to calculate solubility products (Table 6). No effects of temperature on the solubility products were included in this model. Prediction of the amount of aluminum precipitated from SRP wastes is difficult. Various data[12] on the solubility of aluminum hydroxide in aqueous solutions of sodium hydroxide show that the solubility of sodium aluminate cannot be characterized by a mere solubility product. The resolution of this problem would again require a massive research study on the pertinent phase equilibria. For the purpose of this model, the same solubility product was assigned to sodium aluminate as that calculated for sodium hydroxide. These two components were thus treated as identical insofar as one is concerned with their solubilities in SRP wastes.

TABLE 6

Saturated Solubilities and Solubility Products for the Sodium Salts of SRP Wastes in Hot Water (100°C)

	Saturated Solubility		
Component	*g/100 cc of solution*[8]	*(g-moles)/liter*	*Solubility Products*
Na_2SO_4	42.7	3.01	108.7
Na_2CO_3	45.5	4.29	316
$NaNO_3$	180	21.2	449
$NaNO_2$	163	23.6	558
$NaOH$[a]	347	86.8	7530

---

[a] Solubility product for $NaAlO_2$ is assumed to be the same as that for NaOH.

TABLE 7

Specific Gravities of the Solid Sodium Salts in Typical SRP Wastes[8]

Component	*Specific Gravity*
Na_2SO_4	2.68
Na_2CO_3	2.532
$NaNO_3$	2.261
$NaNO_2$	2.168
$NaOH$	2.130
$NaAlO_2$	2.2[a]

---

[a] Arbitrarily assumed value for the specific gravity of solid $NaAlO_2$.

Solid Specific Gravities

The volume percent solid phase is an important parameter in the evaporative reduction of SRP wastes and is calculated as an output result in this mathematical model. The specific gravities of the solid salts in SRP wastes are reported[8] for all of the salts, except again for sodium aluminate (Table 7). An arbitrary value of 2.2 was assumed for the specific gravity of solid sodium aluminate.

PHYSICAL PROPERTIES OF WATER

Several of the physical property correlations for SRP waste solutions described in the preceding section require a knowledge of some physical properties of water. Also, the usage of steam as the heating medium in wiped-film evaporators requires the knowledge of a number of physical properties of water in order to calculate the outside (steam side) heat transfer coefficient. As in the preceding section, these physical properties of water must be represented in an analytical form readily adaptable to programming on a digital computer. The analytical relationships for the physical properties of water used in this model are presented in the remainder of this section. Some of these correlations have an accuracy and complexity much greater than that required in this model. The reason for selection of these relationships lies not in their extreme accuracy, however, but rather their ready availability and ease of programming on a digital computer.

Liquid Density

The density of liquid water,[13] which enters into the calculation of the outside film heat transfer coefficient, is

$$\rho = (a_o + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5)/(1 + bt) \qquad (10)$$

where

$a_o = 999.8396$

$a_1 = 18.224944$

$a_2 = -7.922210\times10^{-3}$

$a_3 = -55.44846\times10^{-6}$

$a_4 = 149.7562\times10^{-9}$

$a_5 = -393.2952\times10^{-12}$

$b = 18.159725\times10^{-3}$

ρ = density of liquid water, kg/m^3

t = temperature, °C (0 to 150°C)

Equation 10 was converted to g/cc and then coded as a statement function in the computer program based upon this mathematical model.

Liquid Viscosity

The viscosity of liquid water, which also enters into the calculation of the outside film heat transfer coefficient, is based upon the following formula:[9]

$$\frac{1}{\mu} = 2.1482[(t - 8.435) + \sqrt{8078.4 + (t - 8.435)^2}] - 120 \quad (11)$$

where, μ is in poises and t is in °C. Equation 11 was rearranged to solve directly for μ, converted to viscosity units of lb/(hr)(ft), and also coded in statement function form.

Liquid Heat Capacity

The heat capacity of liquid water, used in various enthalpy balance calculations in this model, has also been represented in very accurate analytical form[13]

$$c_p = 4.1855\{0.996185 + 0.0002874[(t + 100)/100]^{5.26} + 0.011160\times10^{-0.036t}\} \quad (12)$$

where c_p is in joules/(g)(°C), and t is in °C. Equation 12 was converted to Btu/(lb)(°F) and also coded in statement function form.

Liquid Thermal Conductivity

The thermal conductivity of liquid water is used in calculating the thermal conductivity of the aqueous waste solutions as well as in computing the outside film heat transfer coefficient. Haywood[14] presents an extremely accurate expression for the thermal conductivity of liquid water as a function of both temperature and pressure. If it is assumed that the liquid is always at its saturation pressure, as would be the condensate in equilibrium with saturated steam, the expression reduces to

$$k = a_0 + a_1\tau + a_2\tau^2 + a_3\tau^3 + a_4\tau^4 \quad (13)$$

where

$a_0 = -922.47$

$a_1 = 2839.5$

$a_2 = -1800.7$

$a_3 = 525.77$

$a_4 = -73.440$

$\tau = T/273.15$

and T is in °K and k is in mw/(m)(°K). Equation 13 was converted to thermal conductivity units of Btu/(hr)(ft)(°F) and then coded in statement function form.

Heat of Vaporization

The heat of vaporization for water is used not only in the enthalpy balance calculations of this model but also in the determination of the heating steam requirements. The Watson correlation[15] was used to represent the heat of vaporization of water as a function of temperature

$$\frac{\lambda_2}{\lambda_1} = \left(\frac{1 - T_{r_2}}{1 - T_{r_1}}\right)^{0.38} \tag{14}$$

With Equation 14 and the critical temperature and the heat of vaporization at one temperature, the heat of vaporization at any other temperature can be computed. The reference condition selected was the normal boiling point of water. The critical temperature of water is 647.27°K, and its heat of vaporization at 100°C is 970.3 Btu/lb.[16] With this reference condition, Equation 14 then becomes

$$\lambda = 970.3 \left(\frac{1 - \frac{T}{647.27}}{1 - \frac{373.16}{647.27}}\right)^{0.38} \tag{15}$$

which is readily programmable in statement function form.

Vapor Enthalpy

The enthalpy content of steam is needed for a preliminary estimate of the heating steam consumption, which in turn is required for a preliminary calculation of the outside film heat transfer coefficient. Thus, not a great deal of accuracy is required in the estimation of this particular physical property.

With a reference temperature for enthalpy content of 32°F or 0°C, Equation 15 can be used to calculate the vapor enthalpy content at any temperature as

$$H_V = 1.8t + \lambda(T) \tag{16}$$

The primary assumption in Equation 16 is that the heat capacity of liquid water is 1.0 cal/(g)(°C) or 1.8 Btu/(lb)(°C) over the temperature range of interest.

Boiling Point

The pressure of the heating steam, rather than its temperature, is generally measured and/or controlled under both pilot-plant and full-plant conditions. It is thus of some convenience to be able to compute the heating steam temperature (boiling point) given its pressure. Keenan and Keyes[16] used the following expression for calculating the vapor pressure of water as a function of temperature between 10 and 150°C in their construction of the steam tables:

$$\log_{10} \frac{P_C}{P^O} = \frac{\xi}{T} \left(\frac{a' + b'\ \xi + c'\ \xi^3}{1 + d'\ \xi} \right) \tag{17}$$

where

$a' = 3.2437814$

$b' = 5.86826 \times 10^{-3}$

$c' = 1.1702379 \times 10^{-8}$

$d' = 2.1878462 \times 10^{-3}$

$\xi = T_C - T$, °K

$P_C = 218.167$ atm

Given a value of the heating steam pressure P^O, Equation 17 cannot be easily solved directly for T. Rather, some search procedure is required. The method selected for this search was Newton-Raphson interpolation. In the general case, given a function $y = F(x) = 0$ where the value of x is implicitly defined, this procedure operates as follows. An initial guess of the proper value of x is made; successive values of the variable x are then obtained from

$$x_{j+1} = x_j - \frac{y(x_j)}{y'(x_j)} \tag{18}$$

until two successive values of x are sufficiently close to one another. In Equation 18, $y'(x_j)$ denotes the derivative dy/dx evaluated at $x = x_j$.

If the required derivative in Equation 18 cannot be easily formed analytically, as in Equation 17, this derivative can be approximated numerically. Equation 17 can be written as

$$y(T) = \frac{\xi}{T}\left(\frac{a' + b'\xi + c'\xi^3}{1 + d'\xi}\right) - \log_{10}\frac{P_c}{P^o} = 0 \qquad (19)$$

With numerical approximation of the derivative dy/dT, the search algorithm for the solution of Equation 19 for T then is

$$T_{j+2} = T_{j+1} - \frac{y(T_{j+1})}{\dfrac{y(T_{j+1}) - y(T_j)}{T_{j+1} - T_j}} \qquad (20)$$

The procedure described by Equation 20 is sometimes referred to as the secant method. In this method, two initial estimates of the independent variable (T) must be made. Initial values of T = 100 and 150°C were used for this purpose in the model.

HEAT TRANSFER COEFFICIENTS

Customary practice is to quote the inside surface area as the heat transfer area in wiped-film evaporation equipment. Thus, all local overall heat transfer coefficients computed in this model are based upon the inside heat transfer surface area. With this convention and with consideration of the general case of a protective cladding on the inside of the vessel wall, the local overall heat transfer coefficient from classical heat transfer theory for a number of resistances in series is

$$\frac{1}{U_i} = \frac{1}{h_i} + \left(\frac{\ell_1}{k_1}\right)\left(\frac{A_i}{A_{M_1}}\right) + \left(\frac{\ell_2}{k_2}\right)\left(\frac{A_i}{A_{M_2}}\right) + \left(\frac{1}{h_o}\right)\left(\frac{A_i}{A_o}\right) \qquad (21)$$

The details of computing these various components in this model are described below.

Outside Film

When a single pure vapor (such as steam), saturated or unsaturated, is condensed on a horizontal or vertical tube, the condensate wets the tube and film-wise condensation occurs. So long as the condensate flows in streamline fashion ($4\Gamma/\mu_W < 2100$), the dimensionless equations of Nusselt[9] may be used to calculate the value of the outside film heat transfer coefficient.

For a horizontal unit, the condensate flows normal to the length of the evaporator, and

$$\Gamma = \frac{W_c}{2L} \tag{22}$$

The outside film heat transfer coefficient is given by the following Nusselt relationship:

$$Nu_o = \frac{h_o D_o}{k_w} = 0.76 \left(\frac{D_o^3 \rho_w g}{\mu_w \Gamma} \right)^{1/3} \tag{23}$$

Equation 23 is a dimensionless relationship, and the units of the various parameters must be dimensionally consistent.

For a vertical unit, the condensate flows normal to the outside circumference of the evaporator, and

$$\Gamma = \frac{W_c}{\pi D_o} \tag{24}$$

The dimensionless Nusselt relationship for calculating h_o is

$$Nu_o = \frac{h_o L}{k_w} = (1.2)(0.93) \left(\frac{L^3 \rho_w g}{\mu_w \Gamma} \right)^{1/3} \tag{25}$$

In Equation 25, the multiplying factor 1.2 is incorporated only for the special cases of film-wise condensation of water or of certain organic vapors on vertical tubes.[9]

Wall Resistance(s)

The calculation of the thermal resistances of the wall and of the cladding (if any) is quite straightforward. The thermal conductivities of these metallic resistances in the temperature range of interest are available in most handbooks.[9] The area ratios in Equation 21 are readily calculated as

$$\frac{A_i}{A_{M_1}} = \frac{D_i}{D_i + \ell_1} \tag{26}$$

$$\frac{A_i}{A_{M_2}} = \frac{D_i}{D_i + 2\ell_1 + \ell_2} \tag{27}$$

The third area ratio, A_i/A_o, in Equation 21 is obviously equal to D_i/D_o.

Inside Film

Overall heat transfer coefficients from 250 to 400 Btu/(hr)(ft^2)(°F) are often quoted for wiped-film evaporators processing aqueous solutions.[1,17,18,19] Only a small number of studies in the open literature have been specifically directed to the determination and correlation of inside film heat transfer coefficients for wiped-film evaporators. These various studies are summarized below. The correlations from some of these studies are given in dimensionless form in which the Nusselt number for the inside film is

$$Nu_i = \frac{h_i D_i}{k} \tag{28}$$

with the various parameters in appropriate units to ensure a dimensionless relationship.

Bott and Romero[20] investigated the sensible heating of water and water-glycerol mixtures flowing vertically down a heated inside surface that was continuously scraped by rotating blades. As a result of these experiments, the following equation was proposed:

$$Nu_i = 0.018(Re)^{0.46}(Re')^{0.6}(Pr)^{0.87}(D_i/L)^{0.48}(n_B)^{0.24} \tag{29}$$

In Equation 29, the film Reynolds number is defined as

$$Re = \frac{4\tau}{\mu} = \frac{D_i u \rho}{\mu} \tag{30}$$

the rotary Reynolds number as

$$Re' = \frac{D_i^2 N \rho}{\mu} \tag{31}$$

and the Prandtl number as

$$Pr = \frac{c_p \mu}{k} \tag{32}$$

Equation 29 is stated to be accurate within ±20% over the range of variables studied ($Re = 40.5\text{-}2{,}600$; $Re' = 347\text{-}23{,}200$; $Pr = 4.6\text{-}129$; $L/D = 6.25\text{-}23.94$; $n_B = 1\text{-}4$).

In a related study on evaporation, Bott and Sheikh[21,22] report the following correlation:

$$Nu_i = 0.65(Re)^{0.25}(Re')^{0.43}(Pr)^{0.3}(n_B)^{0.33} \tag{33}$$

In this study they found, in agreement with others, that the agitation suppresses nucleation.

Skelland[23] presents the following correlation:

$$Nu_i = 4.9(Re)^{0.57}(Pr)^{0.47}\left(\frac{D_iN}{u}\right)^{0.17}\left(\frac{Di}{L}\right)^{0.37} \tag{34}$$

for the inside film heat transfer coefficient in a machine manufactured by Votator Division of Chemetron Corporation. This correlation is restricted to the range $40 \leq Re' \leq 2030$.

Kirschbaum and Dieter[24] investigated the evaporation of pure liquids, aqueous sugar solutions, and binary mixtures, as well as distillation of the latter, in a *Sambay* apparatus manufactured by the Luwa Corporation. In this device, swivelling blades are pressed against the heated wall by centrifugal force during operation. As a result of their studies, Kirschbaum and Dieter developed the following correlation for the inside film heat transfer coefficient:

$$h_i = 963\left(\frac{N}{\mu}\right)^{1/3}k \tag{35}$$

In this dimensional equation, h_i is in Btu/(hr)(ft^2)(°F), N is in rpm, μ is in lb/(ft)(hr), and k is in Btu/(hr)(ft)(°F). The original correlation is given in the International System of Units (SI) and was converted to the form of Equation 35 in English units. This equation is valid for liquid systems exhibiting true Newtonian behavior, that is, for systems wherein a direct proportionality between shear stress and shear rate holds. A nomograph for evaluating heat transfer coefficients from this correlation has also been constructed by Sestak.[25]

A novel and interesting approach to the problem of determining inside film heat transfer coefficients in scraped-surface vessels has been taken by Kool.[26] He considers the problem of heating of a laminar film between successive scrapings as an unsteady-state heat conduction problem in one dimension (normal to the heated surface). He solves the linear partial differential equation governing this process, using the Laplace transform, and obtains the following result:

$$\frac{h_i}{h'} = \frac{2S\pi^{-1/2} + \exp(S^2)\mathrm{erfc}(S) - 1}{S^2 - 2S\pi^{-1/2} - \exp(S^2)\mathrm{erfc}(S) + 1} \tag{36}$$

where h' represents the partial coefficient of heat transfer from the heating medium to the scraped surface (exclusive of h_i) and results from one of the boundary conditions assumed in the analytical solution of this problem. The dimensionless quantity S is defined as

$$S = h'\sqrt{\frac{t'}{kc_p\rho}} \tag{37}$$

where t' is the time between successive scrapings and is given by

$$t' = \frac{1}{Nn_B} \tag{38}$$

For values of S between 0.2 and 30, h_i can be calculated from

$$h_i = 1.24\ h'\ S^{-1.03} \tag{39}$$

with an error of less than 1%.

Inside film heat transfer coefficients were computed from the above correlations. Synthetic Purex waste[5] was chosen as the process material; the required physical properties were obtained according to the methods outlined earlier in this report. Values of h_i were computed at various temperatures (before and during boiling); a partial summary of these results is given in Table 8.

The results of these calculations show that the inside film heat transfer coefficient increases monotonically as the temperature increases prior to boiling, irrespective of the correlating equation used. The thermal conductivity of the solution is increasing, and the viscosity of the solution is decreasing during preheating. Once boiling commences, the opposite picture is observed; that is, the value of h_i, again irrespective of correlation, decreases with increasing temperature (and boildown ratio). Under these conditions, the thermal conductivity decreases and the viscosity increases as the waste solution is boiled down and the concentration of salts increases.

The correlations of Bott and Romero[20] for heating and of Bott and Sheikh[21,22] for evaporation yield similar values for h_i, generally 500-1000 Btu/(hr)(ft^2)(°F), indicating little difference in their correlations between the mechanisms for heating and boiling. The values of h_i resulting from Skelland's correlation[23] appear to be abnormally low. The correlation of Kirschbaum and

TABLE 8

Inside Film Heat Transfer Coefficient for Synthetic Purex Waste as Computed from Various Correlations[a]

			h_i from Various Correlations, Btu/(hr)(ft^2)(°F)					
Temp °C	*Boildown Ratio*	*Weight Fraction Salts*	*Bott and Romero*[20]	*Bott and Sheikh*[21,22]	*Skelland*[23]	*Kirschbaum and Dieter*[24,25]	*Kool*[26]	*Drew*[27]
Before boiling								
30	1.00	0.316	714	678	158	1556	3140	107
60	1.00	0.316	775	813	170	1868	3225	143
90	1.00	0.316	823	924	178	2120	3282	176
106	1.00	0.316	835	949	181	2179	3302	183
During boiling								
108	1.26	0.395	719	875	159	2128	3209	166
110	1.51	0.460	636	807	143	2044	3133	149
112	1.77	0.521	565	735	131	1934	3058	130
114	2.03	0.578	503	665	119	1812	2986	113
116	2.28	0.632	450	600	110	1689	2915	97
118	2.54	0.683	403	542	101	1571	2845	83
120	2.80	0.731	363	490	94	1462	2775	71
122	3.05	0.777	328	445	87	1364	2707	61
124	3.31	0.820	297	406	81	1275	2639	53

---

[a] The feed rate was 0.29 gpm at 30°C. The machine characteristics were taken as those of the horizontal Artisan unit at SRL semiworks; namely, A_i = 10 ft^2, D_i = 10 in., N = 804 rpm, n_B = 6, L = 3.82 ft, and h' = 300 Btu/(hr)(ft^2)(°F).

Dieter[24,25] yields values of h_i in the general range of 1500-2000 Btu/(hr)(ft^2)(°F). The theoretical development of Kool[26] yields the largest values of h_i, of the general order of 3000.

The correlation by Drew[27] for heating of fluids in turbulent (Re > 2000), but not agitated, flow down vertical walls and is written as

$$h_i = 0.01\left(\frac{k^3\rho^2 g}{\mu^2}\right)^{1/3} (Pr)^{1/3} \left(\frac{4\tau}{\mu}\right)^{1/3} \qquad (40)$$

This correlation is included in Table 8 merely for comparison purposes. Inasmuch as it does not incorporate any effects of agitation, it should predict values of h_i lower than those resulting from correlations for agitated devices. The results of Table 8 confirm this assertion.

Preliminary experiments were performed on the horizontal Artisan wiped-film evaporator installed at SRL semiworks to determine the order of magnitude of the inside film heat transfer coefficient and to provide some guidance in the selection of a correlating equation. Synthetic Purex waste was used as the feed stream in these experiments that, for purposes of simplicity, were designed to occur under nonboiling (preheating only) conditions. The log mean temperature differences between the heating steam and the feed and product temperatures could then be used to evaluate U_i and, subsequently, h_i.

This experimental unit has a stainless steel heat transfer wall (no cladding) with a thickness of 5/16 inch. The thermal conductivity of the wall metal under the processing conditions is approximately 9.4 Btu/(hr)(ft)(°F). In this construction (the proposed plant construction consists of a stainless steel cladding on a carbon steel wall), the primary resistance to heat transfer is the wall thickness. This circumstance poses some difficulties in accurately evaluating the magnitude of a relatively minor resistance such as that of the inside film. Extremely accurate instruments for measuring temperatures and flow rates are and will be required to support any experimental program to elucidate the actual effects of process parameters on the value of the inside film heat transfer coefficient.

The results of these preliminary experiments are summarized in Table 9. These data, taken under preheating conditions, exhibit

TABLE 9

Experimental Values of the Inside Film Heat Transfer Coefficient from the SRL Horizontal Wiped-Film Evaporator Operating on Synthetic Purex Waste[a]

Feed		*Product*	*Steam Pressure,*	*Heat Transfer Coefficients, Btu/(hr)(ft²)(°F)*		
Rate, gpm	*Temp, °C*	*Temp, °C*	*psig*	U_i	h_o	h_i
6.0	28.0	96.0	48.5	247	1180	1749
5.0	27.5	100.0	48.5	227	1227	1042
6.0	27.0	91.0	40.0	237	1196	1345
5.0	27.0	96.0	40.0	223	1239	964
6.0	27.3	89.0	30.0	248	1198	1802
5.0	27.3	94.0	29.5	237	1239	1285
4.0	27.3	104.0	30.0	244	1274	1474
6.0	28.0	84.5	20.0	249	1215	1781
5.0	27.7	91.0	20.0	249	1243	1764
6.0	28.5	79.0	9.5	255	1230	2138
5.0	28.5	83.0	9.5	242	1274	1398
4.0	28.5	91.0	9.5	250	1310	1675

---

[a] $A_i = 10$ ft², $D_i = 10$ in., $L = 3.82$ ft; $\ell_1 = 0$, $\ell_2 = 0.3125$ in., $k_2 = 9.4$ Btu/(hr)(ft)(°F), $\delta = 40$ mils, $N = 800$ rpm, and $n_B = 6$

much scatter but nonetheless indicate that the inside film heat transfer coefficient under these conditions has a value of 1200-2000 Btu/(hr)(ft^2)($^\circ$F). As far as general order of magnitude, these results then are in good agreement with the heat transfer coefficients predicted by the correlation of Kirschbaum and Dieter.[24,25] Since the resistance offered by the inside film remains a relatively minor contribution to the overall heat transfer resistance, this correlation was selected for representing h_i in the mathematical model described below.

MATHEMATICAL MODEL

This mathematical model describes steady-state operation of wiped-film evaporators for the concentration of typical SRP wastes. Thus, there are no accumulation terms in any of the material or enthalpy balance equations that comprise this model; a wiped-film evaporator is treated in this work as a plug-flow unit with no backmixing. The evaporator is assumed to operate in adiabatic fashion; that is, there are no heat losses from the evaporator to the ambient surroundings. Similarly, in view of the generally low viscosities of the waste streams being processed, any energy input from the rotating wiper blades to the stream was neglected.

The mathematical description of any plug-flow device operating at steady state and without radial mixing generally consists of one or more ordinary differential equations. The dependent variable(s) in these equation(s) can be temperatures, concentrations, pressures, etc.; in a wiped-film evaporator, the original dependent variable is the stream temperature. The independent variable in the mathematical description of a plug-flow device is generally some measure of position, e.g., height or length. If the governing differential equations are linear with constant coefficients of the dependent variables and of the derivatives of the dependent variables with respect to the independent variable, these differential equations can normally be integrated analytically. Otherwise, some numerical integration involving finite increments of the independent variable is normally used.

The various physical properties of chemical compounds and of process streams are generally dependent upon temperature and often correlated as functions thereof. These physical properties can then occur as nonconstant coefficients in the governing differential equation for a nonisothermal process, thus occasioning the necessity of numerical integration. In this work, the original differential equations describing the evaporation process are inverted such that height or length became the dependent variable and temperature the independent variable. The numerical integration was then performed by incrementing the temperature in finite steps. As a result of this inversion procedure, the temperatures, and hence all pertinent physical properties, were known at the beginning and end of each integration increment. Arithmetic average values for these properties could then be readily computed over a given increment.

The wiped-film evaporator for concentrating SRP wastes is divided into three sections according to the primary phenomenon occurring therein: sensible heating of the waste solution, vaporization of water, and crystallization of solids from solution. This division is shown schematically in Figure 2. The governing material and enthalpy balance equations for each of these sections are presented below.

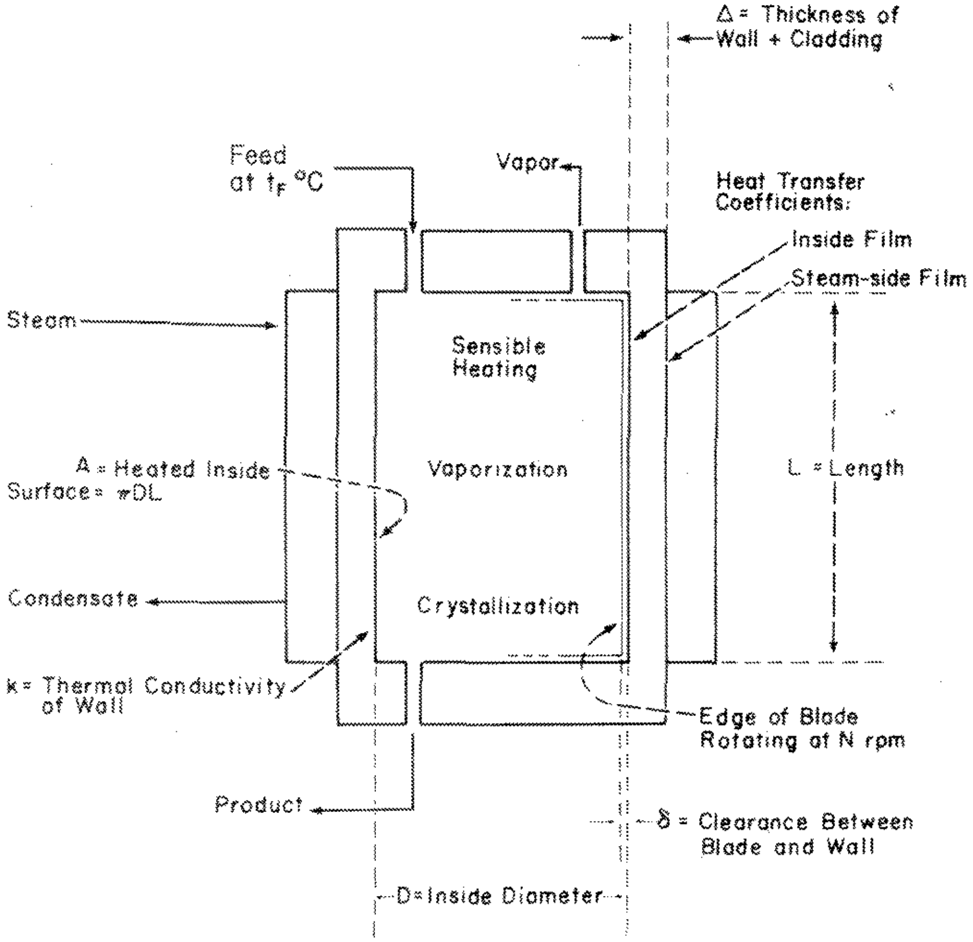


FIGURE 2. Schematic Diagram of a Wiped-Film Evaporator

Sensible Heating

In the sensible heating (or preheating) section, the waste stream is heated from its feed temperature to its initial normal boiling point. There is thus no phase change in this section and no change in the mass flow rate of the waste stream.

In an enthalpy balance about a dz increment (Figure 3) in this section

$$\text{Rate of input} = H + q$$

$$\text{Rate of output} = H + \frac{dH}{dz}\,dz$$

where $H = Wc_p(t - t_R)$, and $q = U_i a_i (t_s - t)dz$. With no accumulation term, the rate of input must equal the rate of output, and the differential enthalpy balance equation is

$$q - \frac{dH}{dz}\,dz = 0 \tag{41}$$

or

$$U_i a_i (t_s - t)dz - \frac{d}{dz}\,[Wc_p(t - t_R)]dz = 0 \tag{42}$$

Neglecting any change in c_p over a dz increment and recognizing that t_R = constant,

$$U_i a_i (t_s - t) - Wc_p \frac{dt}{dz} = 0 \tag{43}$$

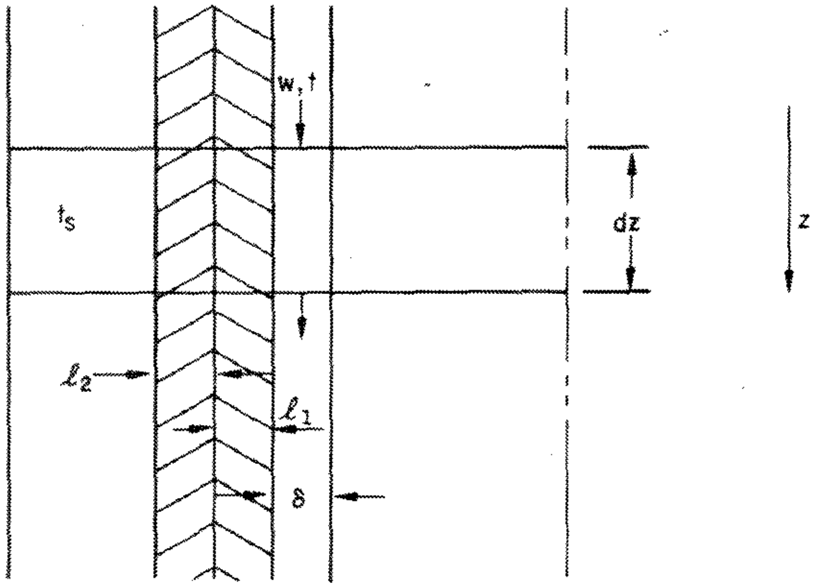


FIGURE 3. Sketch of a dz Increment of a Wiped-Film Evaporator

Equation 43 can be integrated analytically between the limits of $t = t_F$ and $t = t_{BP}$ if U_i and c_p are assumed constant over this interval. Admittedly this is not true, but the height or length of the preheating zone is quite small (generally less than 10% of the total height or length of the heat transfer zone) in the proposed SRP applications. Hence, average values of U_i and c_p based upon their values at the feed temperature and at the initial normal boiling point can be used in Equation 43. Integration of this equation then yields

$$\Delta z = \frac{W\bar{c}_p}{\bar{U}_i a_i} \ln_e \frac{t_s - t_F}{t_s - t_{BP}} \tag{44}$$

Equation 44 thus determines the required height or length (Δz) to the preheating section.

Vaporization

Once boiling commences, the boildown ratio function developed previously enters into the calculations. The temperature of the waste stream is incremented in uniform step sizes of Δt. The mass flow rate (in lb/hr) of this stream at any temperature greater than the initial normal boiling point is computed from the boildown ratio as

$$W = \frac{(60)(\rho)(F_{25})}{(7.481)(BDR)} \tag{45}$$

and

$$F_{25} = \frac{\rho_F F}{\rho_{25}} \tag{46}$$

and the numerical constants are included to effect the desired units conversion. The rate of water vaporized over the Δz increment corresponding to the temperature increase of Δt is then given by

$$\Delta V = W(t) - W(t + \Delta t) \tag{47}$$

The enthalpy balance equation in this section has one additional output term:

$$\text{Rate of input} = H + q$$

$$\text{Rate of output} = H + \left(\frac{dH}{dz}\right) dz + rH_v dz$$

where $r = dV/dz = -dW/dz$. Subtracting the output term from the input term and equating the difference to zero,

$$q - \frac{dH}{dz}\, dz - rH_v dz = 0 \tag{48}$$

or

$$U_i a_i (t_s - t)dz - \frac{d}{dz}\,[Wc_p(t - t_R)]dz - rH_v dz = 0 \tag{49}$$

Again neglecting any change in c_p over an increment and recalling that $dW/dz = -r$,

$$U_i a_i (t_s - t) - Wc_p \frac{dt}{dz} + c_p(t - t_R)r - rH_v = 0 \tag{50}$$

Thermodynamically, however, for water,

$$H_v - c_p(t - t_R) = \lambda \tag{51}$$

where λ is the heat of vaporization of water at the temperature t. Equation 50 can then be rewritten as

$$U_i a_i (t_s - t) - Wc_p \frac{dt}{dz} - r\lambda = 0 \tag{52}$$

With the variable values of U_i, W, c_p, and λ, Equation 52 cannot be integrated analytically. Using average values of these quantities based upon their values at the beginning and end of the finite Δt increment, this equation can be written in the following finite difference form

$$\Delta z = \frac{\overline{Wc_p}\ \Delta t}{\overline{U}_i a_i (t_s - \overline{t}) - \overline{\lambda} r} \tag{53}$$

Finally, after approximating r with $\Delta V/\Delta z$, Equation 53 can be solved explicitly for Δz to yield

$$\Delta z = \frac{\overline{\lambda}\Delta V + \overline{Wc_p}\Delta t}{\overline{U}_i a_i (t_s - \overline{t})} \tag{54}$$

which represents the incremental height or length required to heat the waste stream from t to $(t + \Delta t)$. Water is vaporized at the rate of ΔV lb/hr over this temperature range.

Crystallization

No distinction is actually made in the computer program associated with this model between vaporization and crystallization. In theory, crystallization can begin as soon as boiling commences. For each Δt increment that occurs after the beginning of boiling, a check is made, using solubility products, to determine whether any crystallization has occurred. Only in the latter event are additional enthalpy balances performed.

The solution flow rate and rate of water evaporated are computed as before, using Equations 45 and 47. At the new temperature (t + Δt) and with the new solution flow rate, tentative molar concentrations of each of the anions and of the sodium cations in solution are computed. These tentative concentrations are then compared with the maximum allowable concentrations as predicted from the component solubility products, and the smaller of the two is selected for each of the dissolved salts

$$C_{A_i} = \min \left\{ \frac{W_{d,i}/M_i}{0.06243G} , \frac{K_{SP,i}}{C_{Na}^{m_i}} \right\} \tag{55}$$

where

$$G = W/\rho - G_s \tag{56}$$

$$C_{Na} = \frac{\sum_{i=1}^{6} \frac{m_i W_{d,i}}{M_i}}{0.06243G} \tag{57}$$

and the numerical constant 0.06243 in Equations 55 and 57 is to convert the component concentrations from (lb-moles)/ft^3 to g-moles/liter. The rate of crystallization of a given component out of solution [ΔN_i (lb-moles)/hr] over a Δt increment is then equal to either zero or some positive quantity

$$\Delta N_i = \max \left\{ 0.0, \quad \frac{W_{d,i}}{M_i} - \frac{0.06243GK_{SP,i}}{C_{Na}^{m_i}} \right\} \tag{58}$$

For each component that experiences crystallization in a given Δt increment, that amount of crystallization is subtracted out from the amount in solution

$$W_{d,i}(t + \Delta t) = W_{d,i}(t) - M_i \Delta N_i \tag{59}$$

and added to the amount in the solid phase:

$$W_{s,i}(t + \Delta t) = W_{s,i}(t) + M_i \Delta N_i \tag{60}$$

The volumetric flow rate of the solid phase is computed as the sum of the volumetric flow rates of each of the crystallized solid species:

$$G_s = \sum_{i=1}^{6} \frac{W_{s,i}}{\rho_{s,i}} \tag{61}$$

where the densities of the various solid species are obtained from Table 7.

In view of the manner in which the heat capacity of the solution is computed (linear average of the heat capacities of all of the components including water and based upon weight fractions or mass flow rates), it is convenient to perform the enthalpy balance in the presence of crystallization about the complete mixture of liquid and solid phases. That is, it makes no difference in the calculation of sensible heating requirements over a Δt increment whether the sodium salts are in the dissolved or solid state. In this case, one must then add a consumption term to this enthalpy balance:

Rate of consumption = ΔQ_c

where ΔQ_c represents the total rate of heat consumed (in Btu/hr) on crystallization over a Δz increment and is given by

$$\Delta Q_c = \sum_{i=1}^{6} \Delta N_i \Delta H_{c,i} \tag{62}$$

The input and output rate terms remain the same as for the sensible heating and vaporization sections. Subtracting both the output and consumption terms from the input term and equating the result to zero, the differential enthalpy balance equation is

$$U_i a_i (t_s - t)dz - \frac{d}{dz} [Wc_p(t - t_R)]dz - rH_v ds - \Delta Q_c = 0 \tag{63}$$

Using the same assumptions and substitutions that were made in the derivation of Equation 54,

$$\Delta z = \frac{\Delta Q_c + \overline{\lambda}\Delta V + \overline{Wc}_p \Delta t}{\overline{U}_i a_i (t_s - \overline{t})} \tag{64}$$

which determines the incremental height or length required to heat the waste stream from t to $(t + \Delta t)$ with the simultaneous occurrence of both vaporization and crystallization.

One additional modification is required in these calculations when crystallization occurs. The correlation given by Equation 35 and used to calculate the inside film heat transfer coefficient employs the physical properties (k, μ) of the solution. The resulting value can then be considered as representing an extreme case, namely that with no solid phase present. One would certainly expect some change in the heat transfer characteristics of the inside film upon the precipitation of solids.

The opposite extreme can be considered as the case of a dry solid phase with no liquid or solution present. In such a case (obviously undesirable from a practical point of view), one can envision a thin annulus of solid material adhering to the inside wall. The thickness of this film would be equal to the clearance between the inside wall and the wiper blades, and would be essentially undisturbed by the action of the blades. The mechanism for heat transfer through this thin solid annulus would be pure thermal conduction, the conductance of which would be equal to k_s/δ.

A mixture of liquid and solid phases can then be considered as intermediate between these two extreme cases. As opposed to the outside film, vessel wall and cladding thickness that constitute thermal resistances in series, the two phases comprising the inside film are assumed to be parallel resistances insofar as the latter film is concerned. Their conductances are thus additive, and the volume fraction of each phase was selected for the mixing rule. The inside film heat transfer coefficient in the presence of a solid phase was formed as the sum of that for the liquid phase times its volume fraction plus the thermal conductance of the solid phase times the volume fraction of the latter:

$$h_i = 963\left(1 - \frac{G_s\rho}{W}\right)\left(\frac{N}{\mu}\right)^{1/3} k + \left(\frac{G_s\rho}{W}\right)\left(\frac{k_s}{\delta}\right) \qquad (65)$$

where $G_s\rho/W$ represents the volume fraction of the solid phase present. The value of h_i obtained from this equation was then inserted into Equation 21 to determine U_i.

COMPUTER PROGRAM

A digital computer program in the FORTRAN IV language was written to perform the various calculations described in the preceding sections. A listing of this program is given in

Appendix B of this report. This program was written in accordance with a series of standards[28] to maximize its clarity, readability, and imbedded documentation.

Definition of Program Variables

At the very beginning of the program, a dictionary of all of the FORTRAN names used in this program is given. This dictionary consists of a series of comment statements in which all of the names are defined, in alphabetical order, in terms of their physical meaning. The units for all of the variables are also given.

Stored Data

Following the DIMENSION statements that create the various arrays required in this program is a large number of DATA statements. The primary function of these DATA statements is to minimize the amount of information a prospective user must input to the program. Thus, various physical properties of the pure salt components (heat capacity correlation constants, heats of crystallization, molecular weights, and solid specific gravities) are stored within this program. Also, the constants in the various correlations for physical properties of the typical SRP wastes (synthetic Purex, coating, synthetic HM) are stored via DATA statements. As described earlier, these physical properties include specific gravity, boildown ratio, viscosity, and thermal conductivity. This program provides for the addition of two more typical wastes (for a total of five), if the requisite physical property data are available. In principle, any number of such wastes could be characterized by merely increasing the array sizes specified in the appropriate DIMENSION statements. Miscellaneous information stored via these DATA statements includes the waste names, component formula names, critical properties of water, and certain constants such as g and π.

Utility Functions

Prior to the actual executable part of the program, a number of statement functions are defined. These fall into two general categories. This first category consists of general mathematical utility functions including calculation of the arithmetic average of two quantities, evaluation of a second-order polynomial, and conversion of temperature values from units of °C to °F and vice versa. The second category pertains to various physical property functions and includes, among others, the heat capacity, specific gravity, thermal conductivity and viscosity of liquid water, and the heat capacities of the solid salts, all as functions of temperature. Actual arguments are of course supplied to these statement functions at execution time.

Input Data

In view of the large amount of data stored within this program, only a small amount of information relating to feed conditions, processing conditions, and equipment parameters needs to be supplied for each case study or simulation. Each case study requires four input lists or data cards (Table 10).

TABLE 10

Input Data Lists to the Computer Program for Simulation of Wiped-Film Evaporators[a]

Name	*Description*	*Card Column Location*
List 1 - (type information)		
NTYPE	Type of machine: 1 - vertical, 2 - horizontal (must be right-adjusted in the field)	1-5
NFEED	Type of feed: 1 - synthetic Purex, 2 - coating, 3 - synthetic HM (must be right-adjusted in the field)	6-10
List 2 (feed and processing conditions)		
GPM	Waste feed rate to evaporator, gpm	1-10
TFEEDC	Waste feed temperature, °C	11-20
TFINAL	Estimate of final product temperature, °C	21-30
DELTAT	Temperature increment size during vaporization, °C (typically 1°C)	31-40
PSTEAM	Heating steam pressure, psig	41-50
List 3 (equipment parameters)		
DIIN	Inside diameter of evaporator, in.	1-10
TH1IN	Cladding thickness, in.	11-20
TH2IN	Evaporator wall thickness, in.	21-30
AREA	Heat transfer area of evaporator, ft^2	31-40
TC1	Thermal conductivity of cladding, Btu/(hr)(ft)(°F)	41-50
TC2	Thermal conductivity of evaporator wall, Btu/(hr)(ft)(°F)	51-60
SPEED	Rotor speed, rpm	61-70
CLEAR	Clearance between rotor blades and evaporator wall (or cladding), mils	71-80
List 4 (feed composition)		
	Molar concentration [(g-moles)/liter] in the waste feed of:	
CMOLAR(1)	Na_2SO_4	1-10
CMOLAR(2)	Na_2CO_3	11-20
CMOLAR(3)	$NaNO_3$	21-30
CMOLAR(4)	$NaNO_2$	31-40
CMOLAR(5)	NaOH	41-50
CMOLAR(6)	$NaAlO_2$	51-60

---

[a] The variables in List 1 are integer quantities and cannot have a decimal point. The variables in List 2, 3, and 4 are noninteger quantities and must have a decimal point. Each case study must have all four of these lists. Succeeding case studies follow sequentially. The end of the job is denoted by a single card (corresponding to List 1) on which a negative or zero value is supplied for either NTYPE of NFEED; a blank card will suffice for this purpose.

The first list supplies merely type information (two quantities) in an integer format. The first of these specifies the type of wiped-film evaporator, and must be right-adjusted in column five of the card. A value of 1 corresponds to a vertical machine, and a value of 2 to a horizontal machine. The second quantity pertains to the type of feed waste and must be right-adjusted in column ten. This quantity can presently assume values of 1, 2, or 3, corresponding to synthetic Purex, coating, or synthetic HM waste, respectively. These are integer quantities and must be punched without a decimal point.

Lists 2, 3, and 4 supply various processing and equipment parameters. The quantities in these three lists are noninteger quantities and must be punched with a decimal point (even if they are round numbers such as 30 or 100). Each quantity in these lists can appear anywhere in the column fields designated in Table 10, so long as it is confined within its appropriate field (no overlapping into adjacent fields).

The first two entries of List 2 are the waste feed rate (in gpm) and its temperature (in °C). The third entry (the estimate of the final product temperature in °C) is required to make an initial estimate of the total heat duty of the evaporator (Q) and hence initial estimates of the required steam consumption and outside film heat transfer coefficient. The fourth entry in this list is the finite temperature increment (in °C) for use after vaporization commences. Experience has shown that a value of 1°C is convenient here. Very little difference occurs in the computed results when, for example, the size of this increment has been reduced to 0.5°C. The heating steam pressure comprises the fifth and last entry in this second list.

List 3 supplies the various equipment parameters of the evaporator in conventional engineering units. If the evaporator has no cladding, values of zero should be supplied for the thickness and thermal conductivity of the cladding; actually, the appropriate fields in this list can be left blank for this purpose. The composition of the waste feed is supplied in List 4. The concentrations of the various salts, in the order of increasing solubility maintained throughout this report, are read in units of (g-moles)/liter. Again, a zero concentration value should be supplied for any component(s) not present in a given waste feed.

Any number of cases can be run in a given job. Succeeding case studies merely follow sequentially, with the requirement of the four lists supplied for each case and with no form of delimiter between succeeding cases. The end of a job is denoted by a single card (corresponding to a new List 1) on which a negative or zero value is supplied for either of the two integer quantities in this list; a blank card will actually suffice for this purpose. An example of the input data cards for a job where three cases are run is given in Appendix C.

In the program itself, the input data are immediately printed out after being read in. This information comprises the first page of output in each case study.

Geometric Calculations

The first calculations of the program convert various dimensions from inches or mils to feet, determine the height or length of the heat transfer zone, and compute the various area ratios required in Equation 21. The thermal resistances of the wall and of the cladding are then computed. In either case (cladding or wall), if a zero value is read in for either the thickness or thermal conductivity, that particular resistance is set equal to zero; although this result is natural enough, another important purpose is to prevent a division by zero.

Calculation of Heating Steam Temperature

The heating steam pressure supplied in psig is converted to atm and, with the stored critical properties of water and the water vapor pressure function, the Newton-Raphson interpolation search procedure for the heating steam temperature is begun. This procedure has been summarized by Equations 19 and 20. The two initial guesses of the steam temperature required to initiate this procedure are 100 and 150°C. This search procedure continues until the relative absolute difference between two successive steam temperatures (in °K) is less than 10^{-4}. The final converged value of the steam temperature, the earlier determined height or length of the heat transfer zone, and the initial normal boiling point of the feed as retrieved from the stored data are then printed out, also on the first page of output.

Preliminary Process Calculations

Mass and molar feed rates of all of the dissolved salts are calculated from the feed rate and feed composition, which were read in. The total flow rates of dissolved solids and sodium cations are also computed. Several parameters are computed at both the feed temperature and initial boiling point: namely, product of mass flow rate times heat capacity, viscosity and thermal conductivity of the solution, and inside film heat transfer coefficient.

The required steam consumption is estimated from the estimated final temperature, which was read in. This estimate should always be greater than the boiling point of the solution. The boildown ratio at the estimated final temperature is computed and the amount of water vaporized is determined by difference. The total heat duty is then approximated as the product of this amount of water times its vapor enthalpy content; sensible heating and crystallization heat effects are ignored in this approximation. The first estimate of the required steam consumption is then obtained as the quotient of this heat duty divided by the heat of vaporization of water at the steam temperature (saturated steam condensing to saturated liquid is assumed throughout this model). All of the previous calculations are performed only once for each case study.

Calculation of Outside Film Coefficient

With a value for the heating steam flow rate, the outside film heat transfer coefficient can be readily determined. Equation 23 or Equation 25 is used for this purpose, depending upon whether the evaporator is a horizontal or a vertical unit. At this point, all of the heat transfer resistances except that of the inside film remain fixed until a new estimate of the steam consumption is obtained.

Simulation of Preheating Section

With the outside film coefficient and the previously computed inside film coefficients at the feed and initial boiling conditions, the overall heat transfer coefficients at these same conditions are obtained. These values are then averaged, as is the solution heat capacity over this temperature range, and Equation 44 is used to compute the height or length of the preheating section.

If the processing conditions are such (e.g., high feed rate and/or low steam pressure) that the distance computed above is greater than that available in the given evaporator, the latter value is chosen as the height or length of the preheating section and the program proceeds to compute the resulting outlet product temperature. Because of the slight variation with temperature of U_i and c_p, this is a modest trial-and-error computation. An initial estimate of the outlet temperature is made from

$$t = t_F + (t_{BP} - t_F)\left(\frac{L}{z}\right) \qquad (66)$$

where z exceeds L in this case. This estimate is used to compute new values of U_i and c_p and average values thereof, which are then inserted into an equivalent form of Equation 44 to obtain a new estimate of the outlet temperature.

$$t = t_s - (t_s - t_F)\exp\left(\frac{-\bar{U}_i a_i L}{W\bar{c}_p}\right) \tag{67}$$

and the procedure is repeated with this new estimate. As opposed to Newton-Raphson interpolation, this search procedure is known as direct substitution. This procedure is continued until the relative absolute difference between two successive values of the outlet product temperature (in °K) is less than 0.001.

Simulation of Vaporization/Crystallization Section

Once established that boiling commences before the end of the heat transfer zone, the solution temperature is increased by the temperature increment size read in at the beginning of the program. Equations 45 and 47 are used to determine the new solution flow rate and the amount of water vaporized over this increment. Equations 55 through 58 are used to determine whether crystallization of any of the dissolved salts occurs. If there is no crystallization, Equation 54, with averaged values of Wc_p, λ, U_i, and t over this Δt increment, is used to determine the required increment of height or length (Δz). If any crystallization does occur, Equation 64 is used for this purpose; also, in this case, Equation 65 rather than Equation 35 is employed to evaluate the inside film heat transfer coefficient.

The procedure described in the above paragraph is repeated until, normally, the variable length of the heat transfer zone as determined by summing up the individual values of Δz is greater than that available in the given evaporator. An exception here occurs when the volumetric flow rate of the solution, as computed from Equation 56, becomes negative. Physically, this corresponds to too high of a boildown ratio and obviously represents a highly undesirable situation in practice. In this case, further calculations with the current value of the steam flow rate are suspended.

Determination of Steam Consumption

The total amounts of heat transferred in each individual Δt (or Δz) increment are totaled as the simulation progresses to yield the total heat duty (Q) of the evaporator. When the end of the heat transfer zone is reached, this value of Q is used to determine a new estimate of the heating steam consumption:

$$W_c = \frac{Q}{\lambda(T_s)} \tag{68}$$

With this result the program returns to the point where the outside film heat transfer coefficient is computed, and the simulation is repeated from that point on. This whole procedure is repeated, using direct substitution of the new value of the steam flow rate in each trial, until the relative absolute difference between two successive values of the steam flow rate is less than or equal to 1%. This relatively loose convergence criterion is justified in view of the rather small contribution of the outside film to the overall resistance to heat transfer. Having satisfied this convergence criterion, program control is transferred back to the very beginning to read the input data for a new case study.

Output Format

The various input-output format statements associated with the reading and displaying of information are collected at the end of the program. The input format statements appear first, followed by normal and then abnormal output format statements.

An example of the typical output from this program is given in Appendix D. This example corresponds to the first case study in the input data shown in Appendix C. The first page of output, as mentioned previously, is essentially a recap of the input data read in for this case study. Simulation results follow on succeeding pages. A table of output is printed for each estimate of the required steam consumption. Typically, no more than two or three trials are required for achieving convergence on the steam consumption. Reading from left to right, the values of the dependent variable z and of the independent variable t (in °C and °F) are printed out. The remaining columns of this tabular output are devoted to various dependent variables of engineering interest, the significance of which should be apparent from the column headings. Among others, these include: the heat duty in Btu/hr, boildown ratio, volume percent solids, and the overall and inside film heat transfer coefficients in Btu/(hr)(ft^2)(°F). This information is printed out for every increment. The last page of output for each case study, printed out after convergence has been attained on the steam consumption, represents a complete process material balance about the evaporator.

Error Messages

The abnormal output format statements at the end of the program represent warning messages to the user when certain unusual or error conditions arise. These messages are printed out at the time the conditions occur to facilitate detection of the reason for the abnormality. Three of these messages have to do with abnormal process calculation results: a computed solution boildown ratio less than unity, a negative value for the amount of water vaporized over an increment, and an outside film Reynolds number greater than 2100. In the last event, the Nusselt relationships for evaluating the outside film heat transfer coefficient are not applicable. The remaining two messages pertain to trial-and-error calculations. An upper limit of ten iterations has been assigned to the evaluation of the outlet product temperature when no boiling occurs, as well as to the calculation of the required steam consumption. In either case, if the upper limit is reached, the simulation proceeds with the current estimate of the variable after printing out the warning message.

APPLICATIONS

The mathematical model and associated computer program should be a useful aid in the specification, operation, and control of wiped-film evaporators for the concentration of typical SRP wastes. In particular, with this model one has the capability of quantitatively determining the effects of broad changes in three categories of variables: *(1)* feedstock conditions (rate, temperature, and composition), *(2)* operating conditions (heating steam pressure and rotor speed), and *(3)* equipment parameters (heat transfer area, wall and/or cladding material, and thickness).

The results of a series of case studies investigating the effect of heating steam pressure on evaporator performance for various waste feed rates are given in Figures 4-6. These case studies pertain to the concentration of synthetic Purex waste in a machine with characteristics identical to that of an experimental horizontal unit installed at the SRL semiworks.

The dependent variables in Figures 4-6 are the outlet product temperature, the boildown ratio, and the weight percent solids plus solute in the product, respectively. These variables are obviously related to one another and behave similarly. Each of these variables increases monotonically as the heating steam pressure is raised and, at a given steam pressure, decreases with increasing feed rate. The outlet product temperature is of interest from an engineering point of view in the experimental determination of inside film heat transfer coefficients. The boildown ratio and the weight percent solids plus solute in the product are obvious important variables from an operations standpoint. The actual positions of the curves in Figures 4-6 may be subject to adjustment resulting from more-refined experimental determinations of the inside film heat transfer coefficient and more-refined physical property correlations. The general behavior of these curves as functions of heating steam pressure and waste feed rate, however, should remain unchanged.

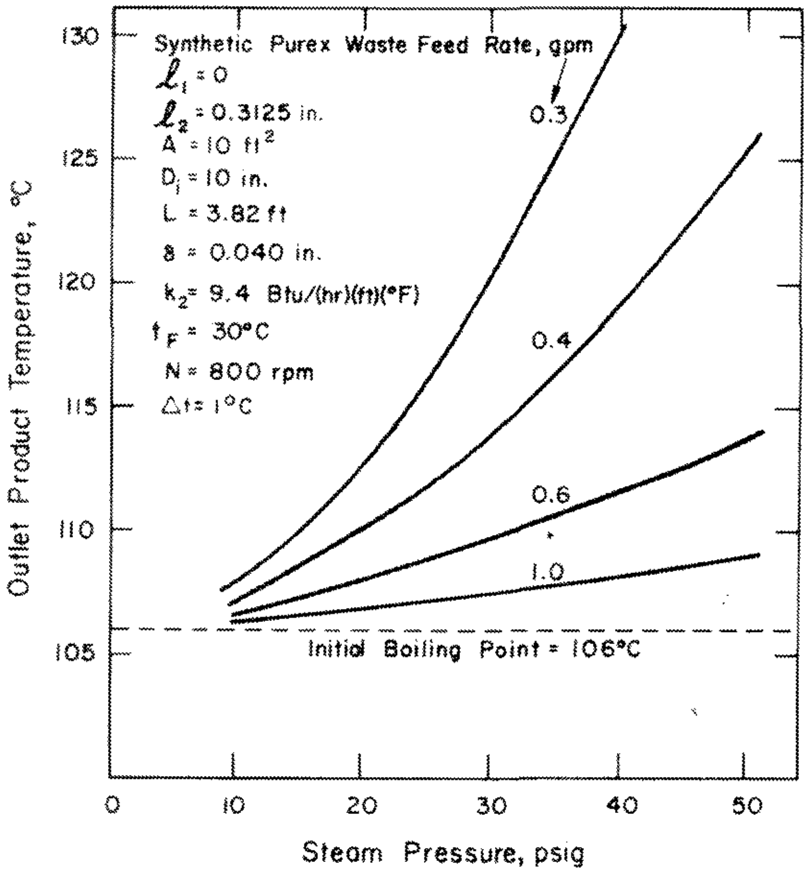


FIGURE 4. Effect of Heating Steam Pressure on Outlet Product Temperature for Various Feed Rates of Synthetic Purex Waste

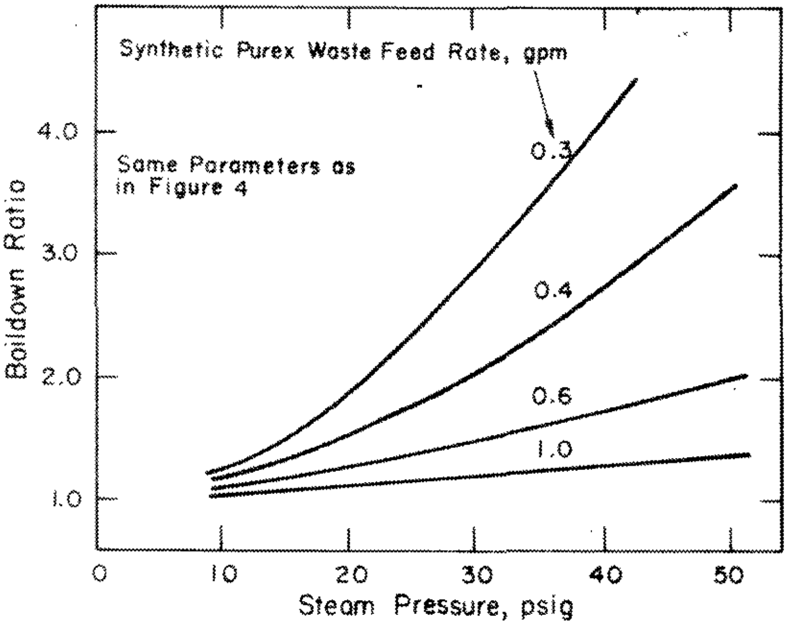


FIGURE 5. Effect of Heating Steam Pressure on the Boildown Ratio for Various Feed Rates of Synthetic Purex Waste

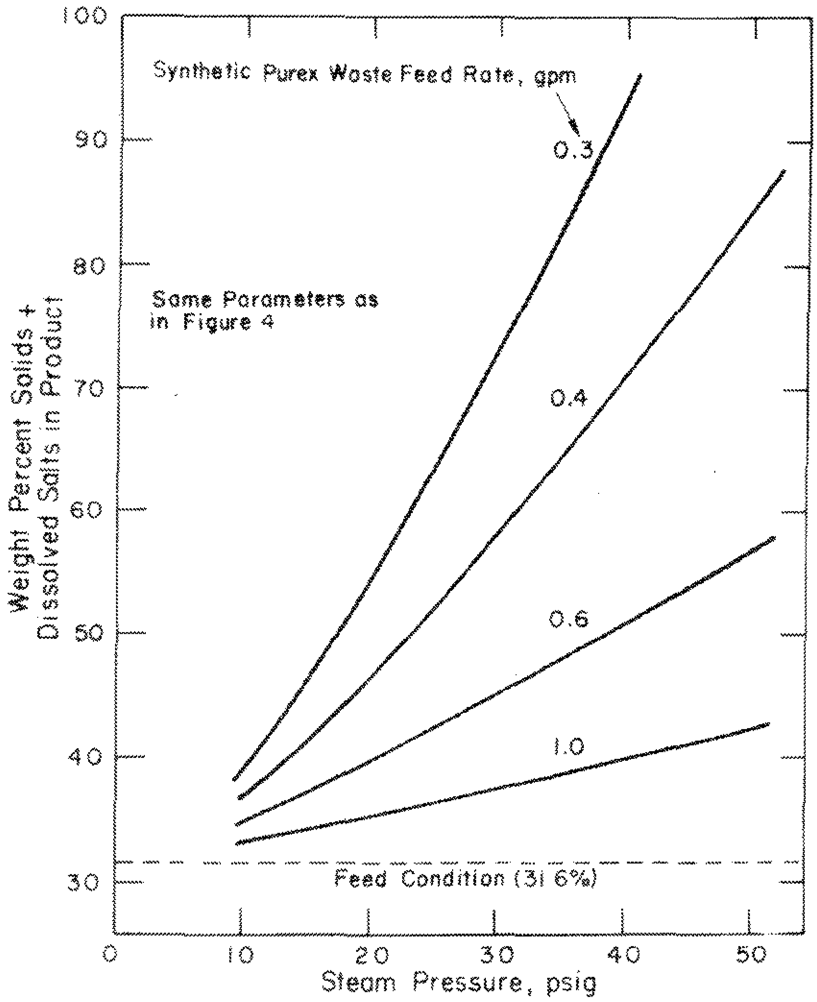


FIGURE 6. Effect of Heating Steam Pressure on the Weight Percent Solids Plus Solute for Various Feed Rates of Synthetic Purex Waste

This model is also of practical value insofar as any feedforward control schemes are implemented in the proposed plant installation. In a feedforward control scheme, one must have *a priori* knowledge of the effect of a change in any one of the load variables on the controlled variable in order to effect any desired change in setpoint. This model provides a basis for that capability.

RECOMMENDATIONS

In future work, a number of possible improvements to this model can be suggested in the correlation of physical properties. In the correlation currently used (and, most probably, in any such correlation in the future) for the inside film heat transfer coefficient, the thermal conductivity of the waste solution is an important variable. Thus, a representation of this variable more accurate than the rather approximate one of Equation 6 would be a valuable improvement. Also, in comparison with the other expressions for the physical properties of water, Equation 15 for the heat of vaporization of water (Watson correlation) is rather crude and could probably be refined somewhat.

Using solubility products for predicting the precipitation of dissolved solids in this model was discussed earlier. In the computation of the solubility products from solubility data, as well as in the employment of these solubility products in the model, molar concentrations of the cation and various anions were assumed. That is, the activity coefficients for all ionic species in solution were set equal to unity. This model would certainly be improved if some reasonably tractable approximation of these activity coefficients based upon rational considerations could be developed.

Finally, work remains to be done in the area of accurate determination of the inside film heat transfer coefficient. This problem is complicated by the fact that the inside film is one of the minor resistances to heat transfer (as compared to a wall or cladding thickness), and experimental determination of this coefficient is extremely sensitive to instrument or operator error. Nonetheless, it remains important to refine the estimate of this quantity and, in particular, to establish its dependence upon operating conditions and physical properties to at least an approximate extent. The results of such work could lead to a different empirical correlation; any such new correlation could be similar to one of the others examined earlier in this report or it could be entirely original.

APPENDIX A

DETERMINATION OF THE STANDARD HEAT OF CRYSTALLIZATION OF SODIUM ALUMINATE

The chemical reaction is

$$Na^{+}_{(aq)} + AlO_2^{-}{}_{(aq)} \rightarrow NaAlO_{2\,(s)} \qquad \text{(A-1)}$$

Reaction A-1 can be constructed from the following reactions:

$$Na^{+}_{(aq)} + Al^{+++}_{(aq)} + 2H_2O_{(\ell)} \rightarrow NaAlO_{2\,(s)} + 4H^{+}_{(aq)} \qquad \text{(A-2)}$$

$$2H^{+}_{(aq)} + 2OH^{-}_{(aq)} \rightarrow 2H_2O_{(\ell)} \qquad \text{(A-3)}$$

$$2H^{+}_{(aq)} + AlO_2^{-}{}_{(aq)} \rightarrow Al^{+++}_{(aq)} + 2OH^{-}_{(aq)} \qquad \text{(A-4)}$$

The heat of reaction (A-1), designated as ΔH_1, is then the algebraic sum of the heats of reactions (A-2, A-3, and A-4):

$$\Delta H_1 = \Delta H_2 + \Delta H_3 + \Delta H_4 \qquad \text{(A-5)}$$

The heat of reaction (A-2), namely ΔH_2, has been reported by Coughlin[10] as 51.22 kcal/(g-mole). The heats of reactions (A-3 and A-4) can be computed in each case as the sum of the heats of formation of the products less the sum of the heats of formation of the reactants. The following data are required for these calculations:

Species	ΔH°_f, kcal/(g-mole)	Reference
$H_2O_{(\ell)}$	-68.32	8
$H^{+}_{(aq)}$	0.0	-
$OH^{-}_{(aq)}$	-54.957	8
$Al^{+++}_{(aq)}$	-127.	11
$AlO_2^{-}{}_{(aq)}$	-219.6	11

Thus, for Reaction A-3,

$$\Delta H_3 = (2)(-68.32) - (2)(0) - (2)(-54.957)$$

$$= -26.726 \text{ kcal/(g-mole)}$$

and for Reaction A-4,

$$\Delta H_4 = -127. + (2)(-54.957) - (2)(0) - (-219.6)$$

$$= -17.314 \text{ kcal/(g-mole)}$$

Finally, from Equation A-5,

$$\Delta H_1 = 51.22 - 26.726 - 17.314 = 7.18 \text{ kcal/(g-mole)}$$

$$= 12{,}920 \text{ Btu/(lb-mole)}$$

which was used as the heat of crystallization for sodium aluminate in this model.

APPENDIX B

LISTING OF FORTRAN PROGRAM FOR SIMULATION OF THE OPERATION OF WIPED-FILM EVAPORATORS

```
          OS/360  FORTRAN H      COMPILER OPTIONS -

    NAME=  MAIN,OPT=00,LINECNT=58,SIZE=0000K,
    SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF

              DEFINITION OF PROGRAM VARIABLES

  AIAM1   - RATIO OF INSIDE HEAT TRANSFER AREA TO MEAN HEAT
            TRANSFER AREA OF CLADDING
  AIAM2   - RATIO OF INSIDE HEAT TRANSFER AREA TO MEAN HEAT
            TRANSFER AREA OF EVAPORATOR WALL
  AIAO    - RATIO OF INSIDE HEAT TRANSFER AREA TO OUTSIDE
            HEAT TRANSFER AREA OF EVAPORATOR
  ALPHA(I) - CONSTANT IN THE THERMAL CONDUCTIVITY EQUATION FOR
             WASTE TYPE I:  TC  = TCH2O*(1.0 - ALPHA(I)*XS/1000.0
  AREA    - TOTAL INSIDE HEAT TRANSFER AREA OF EVAPORATOR, FT2
  AVG     - FUNCTION WHICH COMPUTES THE ARITHMETIC AVERAGE OF
            TWO QUANTITIES
  A0(I), A1(I), A2(I)  -
            CONSTANTS IN THE SECOND-ORDER POLYNOMIAL EQUATION
            FOR THE SPECIFIC GRAVITY OF WASTE TYPE I BEFORE BOILIN
  BDR     - BOILDOWN RATIO, GPM OF FEED AT 25 DEG C/GPM OF PRODUCT
  BDRF    - MAXIMUM BOILDOWN RATIO, GPM OF FEED AT 25 DEG C/
            GPM OF PRODUCT
  BD0(I), BD1(I), BD2(I)  -
            CONSTANTS IN THE SECOND-ORDER POLYNOMIAL EQUATION
            FOR THE BOILDOWN RATIO FOR WASTE TYPE I
  B0(I), B1(I), B2(I)  -
            CONSTANTS IN THE SECOND-ORDER POLYNOMIAL EQUATION
            FOR THE SPECIFIC GRAVITY OF WASTE TYPE I DURING BOILIN
  CA(J), CB(J), CC(J), CD(J)  -
            CONSTANTS IN THE POLYNOMIAL EQUATION FOR THE HEAT
            CAPACITY OF COMPONENT J
  CATCON - MOLAR CONCENTRATION OF CATIONS (SODIUM IONS) IN
            SOLUTION, GM IONS/LITER
  CATS(J) - NUMBER OF SODIUM ATOMS IN A MOLECULE OF COMPONENT J
  CHARL   - CHARACTERISTIC LINEAR DIMENSION NORMAL TO THE
            STEAM FLOW RATE, FT
  CIRCUM - OUTSIDE CIRCUMFERENCE OF EVAPORATOR, FT
  CLEAR   - CLEARANCE BETWEEN BLADES AND INSIDE WALL, MILS
  CLRFT   - CLEARANCE BETWEEN BLADES AND INSIDE WALL, FT
  CMOLAR(J) - MOLAR CONCENTRATION OF COMPONENT J IN THE FEED,
               GM MOLES/LITER
  CMPLEX - CUBE ROOT OF ((GRAV*RHOH2O**2)/(GAMMA*VISH2O)),
            RECIPROCAL FEET
  COMPS   - ALPHANUMERIC ARRAY OF WASTE COMPONENT NAMES
  CONCJ   - MOLAR CONCENTRATION OF THE ANIONS OF COMPONENT J IN
            SOLUTION, GM IONS/LITER
  CPH2O   - FUNCTION WHICH COMPUTES THE HEAT CAPACITY OF LIQUID
            WATER IN BTU/LB-DEG F
  CPSLD   - POLYNOMIAL FUNCTION WHICH COMPUTES THE HEAT CAPACITY
            OF SOLIDS IN BTU/LB MOLE-DEG F
  CTIONF - TOTAL MASS FLOW RATE OF CATIONS (SODIUM IONS)
            ORIGINALLY IN THE FEED, LB IONS/HR
  CTIONS - TOTAL MASS FLOW RATE OF CATIONS (SODIUM IONS)
```

IN THE SOLUTION, LB IONS/HR

DELTAT - TEMPERATURE INCREMENT SIZE READ IN BY THE USER, DEG C

DERIV - DERIVATIVE OF THE VAPOR PRESSURE OF WATER WITH RESPECT TO TEMPERATURE, ATM/DEG K

DHCRYS(J) - HEAT OF DISSOLUTION OF COMPONENT J OUT OF SOLUTION, BTU/LB MOLE

DHVAVG - ARITHMETIC AVERAGE OF DHV1 AND DHV2, BTU/LB

DHVH2O - FUNCTION WHICH COMPUTES THE HEAT OF VAPORIZATION OF WATER IN BTU/LB

DHV1 - HEAT OF VAPORIZATION OF WATER AT THE BEGINNING OF A DZ INCREMENT, BTU/LB

DHV2 - HEAT OF VAPORIZATION OF WATER AT THE END OF A DZ INCREMENT, BTU/LB

DIFT - INSIDE DIAMETER OF EVAPORATOR, FT

DIIN - INSIDE DIAMETER OF EVAPORATOR, IN

DMCRJ - RATE OF DISSOLUTION OF COMPONENT J OUT OF SOLUTION OVER A DZ INCREMENT, LB MOLES/HR

DOFT - OUTSIDE DIAMETER OF EVAPORAOR, FT

DQ - RATE OF HEAT TRANSFERRED OVER A DZ INCREMENT, BTU/HR

DQC - RATE OF HEAT CONSUMPTION ON DISSOLUTION OVER A DZ INCREMENT, BTU/HR

DTC - TEMPERATURE INCREMENT SIZE, DEG C

DTF - TEMPERATURE INCREMENT SIZE, DEG F

DVH2O - RATE OF EVAPORATION OF WATER OVER A DZ INCREMENT, LBS/

DZ - HEIGHT OR LENGTH INCREMENT, FT

ERROR1 - ERROR IN THE CALCULATED VAPOR PRESSURE OF WATER BASED UPON THE OLD ESTIMATE OF THE STEAM TEMPERATURE, ATM

ERROR2 - ERROR IN THE CALCULATED VAPOR PRESSURE OF WATER BASED UPON THE NEW ESTIMATE OF THE STEAM TEMPERATURE, ATM

FLITHR - VOLUMETRIC FEED RATE, LITERS/HR

FMWSLD(J) - MOLECULAR WEIGHT OF SOLID COMPONENT J, LBS/LB MOLE

FT2FT - INSIDE HEAT TRANSFER AREA OF EVAPORATOR PER UNIT HEIGHT OR LENGTH, FT2/FT

FT3HR - TOTAL VOLUMETRIC FLOW RATE OF SOLUTION + SOLIDS, FT3/H

GAMMA - CONDENSATE (STEAM) MASS FLOW RATE PER UNIT LENGTH NORMAL TO FLOW, LBS/HR-FT

GPM - VOLUMETRIC FEED RATE, GAL/MIN

GPMF - ESTIMATE OF THE FINAL VOLUMETRIC FLOW RATE OF THE PRODUCT, GAL/MIN

GPMTLH - FUNCTION WHICH CONVERTS A FLOW RATE FROM UNITS OF GAL/MIN TO UNITS OF LITERS/HR

GPM25 - VOLUMETRIC FEED RATE AT 25 DEG C, GAL/MIN

GRAV - ACCELERATION DUE TO THE FORCE OF GRAVITY = 4.173E+08 FT/HR2

HEIGHT - HEIGHT OR LENGTH OF THE EVAPORATOR (HEAT TRANSFER ZONE), FT

HI - INSIDE FILM HEAT TRANSER COEFFICIENT, BTU/HR-FT2-DEG F

HIBL - INSIDE FILM HEAT TRANSFER COEFFICIENT AT THE NORMAL BOILING POINT, BTU/HR-FT2-DEG F

HIFD - INSIDE FILM HEAT TRANSFER COEFFICIENT AT THE FEED CONDITIONS, BTU/HR-FT2-DEG F

HO - OUTSIDE FILM HEAT TRANSFER COEFFICIENT, BTU/HR-FT2-DEG

HOK - RATIO OF THE OUTSIDE FILM HEAT TRANSFER COEFFICIENT TO THE THERMAL CONDUCTIVITY OF THE CONDENSATE FILM, RECIPROCAL FEET

HVH2O - FUNCTION WHICH COMPUTES THE ENTHALPY OF WATER VAPOR

```
           IN BTU/LB
I        - SAME AS NFEED
J        - COMPONENT NUMBER:  1 - NA2SO4, 2 - NA2CO3, 3 - NANO3,

           4 - NANO2, 5 - NAOH, 6 - NAALO2
K        - INTEGER COUNTER FOR ALPHANUMERIC OUTPUT
KOUNT    - INTEGER COUNTER FOR THE NUMBER OF ITERATIONS ON THE
           REQUIRED STEAM CONSUMPTION (MAXIMUM OF 10)
KSOLID - 0 IF LIQUID WATER IS STILL PRESENT, 1 IF NOT
KTEMPF - INTEGER COUNTER FOR THE NUMBER OF ITERATIONS ON THE
           FINAL PRODUCT TEMPERATURE (MAXIMUM OF 10)
MACHIN - ALPHANUMERIC ARRAY OF MACHINE TYPE NAMES
NFEED    - TYPE OF WASTE FEED:  1 - PUREX, 2 - COATING, 3 - HM,
           4, 5 - CURRENTLY UNASSIGNED
NTYPE    - TYPE OF EVAPORATOR:  1 - VERTICAL, 2 - HORIZONTAL
OTHER    - SUM OF THE HEAT TRANSFER RESISTANCES OTHER THAN THE
           INSIDE FILM, HR-FT2-DEG F/BTU
PCWAT    - CRITICAL PRESSURE OF WATER, ATM
PI       - 3.1416
POLY     - FUNCTION WHICH EVALUATES A SECOND-ORDER POLYNOMIAL
PSTATM - HEATING STEAM PRESSURE, ATM
PSTEAM - HEATING STEAM PRESSURE, PSIG
Q        - TOTAL RATE OF HEAT TRANSFERRED, BTU/HR
RCPUI    - RECIPROCAL OF THE OVERALL HEAT TRANSFER COEFFICIENT
           BASED ON THE INSIDE AREA, HR-FT2-DEG F/BTU
REFILM - CONDENSATE FILM REYNOLDS NUMBER
RES1     - THERMAL RESISTANCE OF CLADDING, HR-FT2-DEG F/BTU
RES2     - THERMAL RESISTANCE OF EVAPORATOR WALL, HR-FT2-DEG F/BT
RHOF     - ESTIMATE OF THE FINAL DENSITY OF THE PRODUCT, GMS/CC
RHOFD    - DENSITY OF THE FEED AT THE FEED TEMPERATURE, GMS/CC
RHOH2O - DENSITY OF LIQUID WATER, LBS/FT3
RHOSLD(J) - DENSITY OF SOLID COMPONENT J, GMS/CC
RHOSLN - DENSITY OF THE SOLUTION, GMS/CC
RHO25    - DENSITY OF THE FEED AT 25 DEG C, GMS/CC
SGH2O    - FUNCTION WHICH COMPUTES THE SPECIFIC GRAVITY OF
           LIQUID WATER
SPEED    - ROTATIONAL SPEED OF WIPER SHAFT, RPM
SP100(J) - SOLUBILITY PRODUCT FOR COMPONENT J AT 100 DEG C,
             (GM MOLES/LITER)**(CATS(J) + 1.)
TBOILC(I) - NORMAL BOILING POINT FOR WASTE TYPE I, DEG C
TBOILF - NORMAL BOILING POINT OF FEED, DEG F
TBOILK - NORMAL BOILING POINT OF THE FEED, DEG K
TCBL     - THERMAL CONDUCTIVITY OF THE SOLUTION AT THE NORMAL
           BOILING POINT, BTU/HR-FT-DEG F
TCFD     - THERMAL CONDUCTIVITY OF THE FEED, BTU/HR-FT-DEG F
TCH2O    - FUNCTION WHICH COMPUTES THE THERMAL CONDUCTIVITY OF
           LIQUID WATER IN BTU/HR-FT-DEG F
TCSLD    - THERMAL CONDUCTIVITY OF THE SOLID PHASE, BTU/HR-FT-DEG
TCSLN    - THERMAL CONDUCTIVITY OF THE SOLUTION, BTU/HR-FT-DEG F
TCTOF    - FUNCTION WHICH CONVERTS A TEMPERATURE VALUE FROM
           UNITS OF DEG C TO DEG F
TCWAT    - CRITICAL TEMPERATURE OF WATER, DEG K
TC1      - THERMAL CONDUCTIVITY OF CLADDING, BTU/HR-FT-DEG F
TC2      - THERMAL CONDUCTIVITY OF EVAPORATOR WALL, BTU/HR-FT-DEG
TFAVG    - ARITHMETIC AVERAGE OF TSLNF1 AND TSLNF2, DEG F
TFEEDC - FEED TEMPERATURE, DEG C
TFEEDF - FEED TEMPERATURE, DEG F
```

TFEEDK - FEED TEMPERATURE, DEG K

TFINAL - ESTIMATED FINAL TEMPERATURE OF PRODUCT, DEG C

TFTOC - FUNCTION WHICH CONVERTS A TEMPERATURE VALUE FROM UNITS OF DEG F TO DEG C

THIRD - ONE THIRD = 0.333333

TH1IN - THICKNESS OF CLADDING, IN

TH2IN - THICKNESS OF EVAPORATOR WALL, IN

TSEST1 - OLD ESTIMATE OF THE HEATING STEAM TEMPERATURE, DEG K

TSEST2 - NEW ESTIMATE OF THE HEATING STEAM TEMPERATURE, DEG K

TSLNC1 - SOLUTION TEMPERATURE AT THE BEGINNING OF A DZ INCREMENT, DEG C

TSLNC2 - SOLUTION TEMPERATURE AT THE END OF A DZ INCREMENT, DEG

TSLNC3 - OLD ESTIMATE OF THE FINAL PRODUCT TEMPERATURE IF THERE IS NO BOILING, DEG C

TSLNC4 - NEW ESTIMATE OF THE FINAL PRODUCT TEMPERATURE IF THERE IS NO BOILING, DEG C

TSLNF1 - SOLUTION TEMPERATURE AT THE BEGINNING OF A DZ INCREMENT, DEG F

TSLNF2 - SOLUTION TEMPERATURE AT THE END OF A DZ INCREMENT, DEG

TSLNF3 - OLD ESTIMATE OF THE FINAL PRODUCT TEMPERATURE IF THERE IS NO BOILING, DEG F

TSLNF4 - NEW ESTIMATE OF THE FINAL PRODUCT TEMPERATURE IF THERE IS NO BOILING, DEG F

TSLNK2 - SOLUTION TEMPERATURE AT THE END OF A DZ INCREMENT, DEG

TSLNK3 - OLD ESTIMATE OF THE FINAL PRODUCT TEMPERATURE IF THERE IS NO BOILING, DEG K

TSLNK4 - NEW ESTIMATE OF THE FINAL PRODUCT TEMPERATURE IF THERE IS NO BOILING, DEG K

TSTMC - HEATING STEAM TEMPERATURE, DEG C

TSTMF - HEATING STEAM TEMPERATURE, DEG F

TSTMK - HEATING STEAM TEMPERATURE, DEG K

UIAVG - ARITHMETIC AVERAGE OF UI1 AND UI2, BTU/HR-FT2-DEG F

UI1 - OVERALL HEAT TRANSFER COEFFICIENT BASED ON THE INSIDE AREA AT THE BEGINNING OF A DZ INCREMENT, BTU/HR-FT2-DE

UI2 - OVERALL HEAT TRANSFER COEFFICIENT BASED ON THE INSIDE AREA AT THE END OF A DZ INCREMENT, BTU/HR-FT2-DEG F

U0(I), U1(I), U2(I) - CONSTANTS IN THE SECOND-ORDER POLYNOMIAL EQUATION FOR THE VISCOSITY OF WASTE TYPE I BEFORE BOILING

VFINAL - VOLUMETRIC FLOW RATE OF THE PRODUCT IF THERE IS NO WATER PRESENT, FT3/HR

VH2O - TOTAL RATE OF WATER EVAPORATED, LBS/HR

VISBL - VISCOSITY OF THE SOLUTION AT THE NORMAL BOILING POINT, LBS/FT-HR

VISFD - VISCOSITY OF THE FEED, LBS/FT-HR

VISH2O - FUNCTION WHICH COMPUTES THE VISCOSITY OF LIQUID WATER IN LBS/FT-HR

VISSLN - VISCOSITY OF THE SOLUTION, LBS/FT-HR

VPCSLD - VOLUME PERCENT SOLID PHASE IN THE TOTAL FLOW

VPH2O - FUNCTION WHICH COMPUTES THE VAPOR PRESSURE OF WATER IN ATM AT A GIVEN TEMPERATURE

VSOLDS - VOLUMETRIC FLOW RATE OF THE SOLID PHASE, FT3/HR

VSOLN - VOLUMETRIC FLOW RATE OF THE LIQUID PHASE, FT3/HR

V0(I), V1(I), V2(I) - CONSTANTS IN THE SECOND-ORDER POLYNOMIAL EQUATION FOR THE VISCOSITY OF WASTE TYPE I DURING BOILING

WASTE - ALPHANUMERIC ARRAY OF WASTE TYPE NAMES
WCPAVG - ARITHMETIC AVERAGE OF WCP1 AND WCP2, BTU/HR-DEG F
WCPBL - MASS FLOW RATE-HEAT CAPACITY PRODUCT FOR THE SOLUTION AT THE NORMAL BOILING POINT, BTU/HR-DEG F
WCPFD - MASS FLOW RATE-HEAT CAPACITY PRODUCT FOR THE FEED, BTU/HR-DEG F
WCP1 - MASS FLOW RATE-HEAT CAPACITY PRODUCT AT THE BEGINNING OF A DZ INCREMENT, BTU/HR-DEG F
WCP2 - MASS FLOW RATE-HEAT CAPACITY PRODUCT AT THE END OF A DZ INCREMENT, BTU/HR-DEG F
WCR1(J) - MASS FLOW RATE OF THE SOLID FORM OF COMPONENT J AT THE BEGINNING OF A DZ INCREMENT, LBS/HR
WCR2(J) - MASS FLOW RATE OF THE SOLID FORM OF COMPONENT J AT THE END OF A DZ INCREMENT, LBS/HR
WDSDS - MASS FLOW RATE OF DISSOLVED SOLIDS, LBS/HR
WDSLVD(J) - MASS FLOW RATE OF THE DISSOLVED FORM OF COMPONENT J, LBS/HR
WDSLVF(J) - MASS FLOW RATE OF THE DISSOLVED FORM OF COMPONENT J IN THE FEED, LBS/HR
WDSTOT - TOTAL MASS FLOW RATE OF DISSOLVED SOLIDS IN THE FEED, LBS/HR
WFEED - TOTAL MASS FLOW RATE OF THE FEED, LBS/HR
WH2O - MASS FLOW RATE OF LIQUID WATER, LBS/HR
WH2OFD - MASS FLOW RATE OF WATER FED, LBS/HR
WLIQ - MASS FLOW RATE OF THE LIQUID PHASE, LBS/HR
WMPHR(J) - MOLAR FLOW RATE OF THE DISSOLVED FORM OF COMPONENT J, LB MOLES/HR
WMPHRF(J) - MOLAR FLOW RATE OF THE DISSOLVED FORM OF COMPONENT J IN THE FEED, LB MOLES/HR
WPCSLD - WEIGHT PERCENT SOLIDS + SOLUTE IN THE TOTAL FLOW
WSLNF - ESTIMATE OF THE FINAL MASS FLOW RATE OF THE PRODUCT, LBS/HR
WSLN1 - MASS FLOW RATE OF SOLUTION + SOLIDS AT THE BEGINNING OF A DZ INCREMENT, LBS/HR
WSLN2 - MASS FLOW RATE OF SOLUTION + SOLIDS AT THE END OF A DZ INCREMENT, LBS/HR
WSOLDS - MASS FLOW RATE OF THE SOLID PHASE, LBS/HR
WSTM1 - OLD ESTIMATE OF REQUIRED STEAM CONSUMPTION, LBS/HR
WSTM2 - NEW ESTIMATE OF REQUIRED STEAM CONSUMPTION, LBS/HR
XS - WEIGHT FRACTION DISSOLVED SOLIDS IN SOLUTION
XS0 - INITIAL DISSOLVED SOLIDS WEIGHT FRACTION IN THE FEED
Z - VARIABLE HEIGHT OR LENGTH OF HEAT TRANSFER ZONE, FT
ZERO - NUMERIC CONSTANT EQUAL TO ZERO

DIMENSION STATEMENTS

```
0DIMENSION      ALPHA(5)  , A0(5)     , A1(5)     , A2(5)     ,
1               B00(5)    , B01(5)    , B02(5)    , B0(5)     ,
2               B1(5)     , B2(5)     , TBOILC(5) , U0(5)     ,
3               U1(5)     , U2(5)     , V0(5)     , V1(5)     ,
4               V2(5)
0DIMENSION      CA(6)     , CATS(6)   , CB(6)     , CC(6)     ,
1               CD(6)     , CMOLAR(6) , DHCRYS(6) , FMWSLD(6) ,
2               RHOSLD(6) , SP100(6)  , WCR1(6)   , WCR2(6)   ,
3               WDSLVD(6) , WDSLVF(6) , WMPHR(6)  , WMPHRF(6)
 DIMENSION      MACHIN(3, 2), WASTE(2, 5), COMPS(2, 6)
```

DATA STATEMENTS

```
 DATA MACHIN /24HVERTICAL    HORIZONTAL  /
 DATA WASTE  /40HPUREX   COATING HM      RESERVEDRESERVED/
 DATA COMPS  /48HNA2SO4   NA2CO3  NANO3   NANO2   NAOH    NAALO2  /
 DATA PI     /3.14159/,  THIRD /0.333333/,  GRAV/4.173E+08/
 DATA PCWAT  /218.167/, TCWAT /647.27/
 DATA TCSLD  /1.21/, ZERO /0.0/
```

PHYSICAL PROPERTIES OF THE WASTES

```
 DATA ALPHA  /5*235.0/
 DATA A0     /1.216, 1.268, 1.331, 2*1.2/
 DATA A1     /-4.1811E-04, -5.1689E-04, -9.7595E-04, 2*0.0/
 DATA A2     /5*0.0/
 DATA B00    /5*1.0/
 DATA B01    /0.12823, 7.4534E-02, 6.3417E-02, 2*0.0/
 DATA B02    /0.0, -4.4057E-04, 3*0.0/
 DATA B0     /1.216, 1.268, 1.331, 2*1.2/
 DATA B1     /0.0210, 1.8987E-02, 2.1238E-02, 2*0.0/
 DATA B2     /0.0, -1.8326E-04, 3*0.0/
 DATA TBOILC /106.0, 112.0, 115.0, 2*110.0/
 DATA U0     /1.40, 2.70, 1.50, 2*2.0/
 DATA U1     /-7.0422E-04, 6.5255E-02, 7.6582E-05, 2*0.0/
 DATA U2     /2.4217E-04, 1.6181E-03, 3.8020E-04, 2*0.0/
 DATA V0     /1.40, 2.70, 1.50, 2*2.0/
 DATA V1     /-1.2511E-02, 3.8654E-02, 0.27524, 2*0.0/
 DATA V2     /1.0927E-02, 8.5369E-03, 3*0.0/
```

PHYSICAL PROPERTIES OF THE PURE COMPONENTS

```
 DATA CA     /19.676, 2.633, 6.140, 6.140, 17.15, 21.307/
 DATA CATS   /2*2.0, 4*1.0/
 DATA CB     /36.895, 58.326, 53.99, 53.99, -26.5, 3.655/
 DATA CC     /0.0, 5.854, 3*0.0, -4.286/
 DATA CD     /4*0.0, 56.35, 0.0/
 DATA DHCRYS /504., 10030., -9090., -6480., 18320., 12920./
 DATA FMWSLD /142.04, 105.99, 84.99, 69.00, 40.00, 81.97/
 DATA RHOSLD /2.68, 2.532, 2.261, 2.168, 2.130, 2.2/
 DATA SP100  /108.7, 316.4, 448.5, 558.1, 7526., 7526./
```

FUNCTION STATEMENTS

```
         AVG(X1, X2)  = (X1 + X2)/2.0
0        CPH2O(T) = 0.99993*(0.996185 + (2.874E-04)*((T + 100.0)/
1                    100.0)**5.26) + 0.011160/(10.0**(0.036*T))
0        CPSLD(A, B, C, D, T) = A + B*T*1.0E-03 + (C*1.0E+05)/(T*T) +
1                                D*T*T*1.0E-06
0        DHVH2O(T) = 970.3*((1.0 - ((T + 273.16)/647.3))/(1.0 -
1                    (373.16/647.3)))**0.38
         GPMTLH(Y) = 3.785*60.0*Y
0        HVH2O(T)  = 1.8*T + 970.3*((1.0 - ((T + 273.16)/647.3))/
1                    (1.0 - (373.16/647.3)))**0.38
         POLY (A, B, C, X) = A + B*X + C*X**2
0        SGH2O(T) = (999.8396 + 18.2249*T - (7.92221E-03)*T**2 -
```

```
   1                  (55.448E-06)*T**3 + (149.756E-09)*T**4 -
   2                  (393.295E-12)*T**4)/(1000.0*(1.0 + (18.1597E-03)*
   3                  T))
   0      TCH2O(T) = (5.7794E-04)*(-922.47 + 2839.5*T - 1800.7*T**2 +
   1                  525.77*T**3 - 73.440*T**4)
          TCTOF(T) = 1.8*T + 32.0
          TFTOC(T) = (T - 32.0)/1.8
   0      VISH2O(T) = 242.0/(2.1482*((T - 8.435) + SQRT(8078.4 + (T -
   1                   8.435)**2)) - 120.0)
   0      VPH2O(PC, X, T) = PC*10.0**((-X/T)*(3.24378 + (5.86826E-03)*
   1                         X + (1.17024E-08)*X**3)/(1.0 +
   2                         (2.187846E-03)*X))

                       READ THE INPUT DATA

20 CONTINUE
    READ (5, 1000) NTYPE , NFEED
    IF ((NTYPE.LE.0).OR.(NFEED.LE.0)) GO TO 920
    READ (5, 1020) GPM   , TFEEDC, TFINAL, DELTAT, PSTEAM
   0READ (5, 1020) DIIN  , TH1IN , TH2IN , AREA  , TC1   , TC2   ,
   1               SPEED , CLEAR
    READ (5, 1020) (CMOLAR(J) , J = 1, 6)

                       PRINT THE INPUT DATA

    WRITE(6, 2000)
    WRITE(6, 2020) (MACHIN(K, NTYPE), K = 1, 3)
    WRITE(6, 2040) (WASTE(K, NFEED), K = 1, 2)
    WRITE(6, 2060) GPM   , TFEEDC, PSTEAM
   0WRITE(6, 2080) DIIN  , TH1IN , TH2IN , AREA  , TC1   , TC2   ,
   1               SPEED , CLEAR
    WRITE(6, 2100) (((COMPS(K, J) , K = 1, 2), CMOLAR(J)), J = 1, 6)

                       PRELIMINARY GEOMETRIC CALCULATIONS

          I      = NFEED
          KOUNT  = 0
          DIFT   = DIIN/12.0
          DOFT   = (DIIN + 2.0*TH1IN + 2.0*TH2IN)/12.0
          CIRCUM = PI*DOFT
          FT2FT  = PI*DIFT
          HEIGHT = AREA/FT2FT
          AIAM1  = DIIN/(DIIN + TH1IN)
          AIAM2  = DIIN/(DIIN + 2.0*TH1IN + TH2IN)
          AIAO   = DIFT/DOFT
          CLRFT  = CLEAR/12000.

                       CALCULATION OF THERMAL RESISTANCES

          RES1   = 0.0
          RES2   = 0.0
    IF ((TH1IN.LE.0.0).OR.(TC1.LE.0.0)) GO TO 40
          RES1   = (TH1IN*AIAM1)/(12.0*TC1)
40  IF ((TH2IN.LE.0.0).OR.(TC2.LE.0.0)) GO TO 60
          RES2   = (TH2IN*AIAM2)/(12.0*TC2)
```

```
                        NEWTON-RAPHSON INTERPOLATION FOR THE HEATING
                        STEAM TEMPERATURE

 60 CONTINUE
          PSTATM = (PSTEAM + 14.696)/14.696
          TSEST1 = 373.16
          ERROR1 = VPH2O(PCWAT, TCWAT - TSEST1, TSEST1) - PSTATM
          TSEST2 = 423.16
 70       ERROR2 = VPH2O(PCWAT, TCWAT - TSEST2, TSEST2) - PSTATM
          DERIV  = (ERROR2 - ERROR1)/(TSEST2 - TSEST1)
          TSTMK  = TSEST2 - ERROR2/DERIV
    IF (ABS((TSTMK - TSEST2)/TSTMK).LE.1.0E-04) GO TO 75
          ERROR1 = ERROR2
          TSEST1 = TSEST2
          TSEST2 = TSTMK
    GO TO 70
 75       TSTMC  = TSTMK - 273.16
    WRITE(6, 2110) HEIGHT, TBOILC(I) , TSTMC

                        CONVERT TEMPERATURES FROM DEGREES C TO DEGREES

          TBOILF = TCTOF(TBOILC(I))
          TFEEDF = TCTOF(TFEEDC)
          TSTMF  = TCTOF(TSTMC)
          DTF    = DELTAT/1.8

                        DETERMINE CHARACTERISTIC LENGTH OF MACHINE

    GO TO (80, 100), NTYPE
 80       CHARL  = CIRCUM
    GO TO 120
100       CHARL  = 2.0*HEIGHT

                        PRELIMINARY MATERIAL BALANCE CALCULATIONS

120 CONTINUE
          RHO25  = POLY(A0(I), A1(I), A2(I), 25.0 - TBOILC(I))
          RHOFD  = POLY(A0(I), A1(I), A2(I), TFEEDC - TBOILC(I))
          GPM25  = RHOFD*GPM/RHO25
          FLITHR = GPMTLH(GPM)

                        DETERMINE COMPONENT FLOW RATES

          CTIONF = 0.0
          VFINAL = 0.0
          WDSTOT = 0.0
    DO 140 J = 1, 6
       WMPHRF(J) = FLITHR*CMOLAR(J)/453.6
       WDSLVF(J) = WMPHRF(J)*FMWSLD(J)
          VFINAL = VFINAL + WDSLVF(J)/(62.43*RHOSLD(J))
          WDSTOT = WDSTOT + WDSLVF(J)
          CTIONF = CTIONF + CATS(J)*WMPHRF(J)
140 CONTINUE
          BDRF   = GPM25/(7.481*VFINAL/60.0)
          WFEED  = 1000.0*RHOFD*FLITHR/453.6
          WH2OFD = WFEED - WDSTOT
```

```
         XS0    = WDSTOT/WFEED

                      PRELIMINARY ENTHALPY BALANCE CALCULATIONS

         TFEEDK = TFEEDC + 273.16
         TBOILK = TBOILC(I) + 273.16
         WCPFD  = WH2OFD*CPH2O(TFEEDC)
         WCPBL  = WH2OFD*CPH2O(TBOILC(I))
   DO 150 J = 1, 6
  0      WCPFD  = WCPFD + WMPHRF(J)*CPSLD(CA(J), CB(J), CC(J), CD(J),
  1               TFEEDK)
  0      WCPBL  = WCPBL + WMPHRF(J)*CPSLD(CA(J), CB(J), CC(J), CD(J),
  1               TBOILK)
150 CONTINUE

                      PRELIMINARY HEAT TRANSFER CALCULATIONS

         VISFD  = 2.42*POLY (U0(I), U1(I), U2(I), TFEEDC - TBOILC(I))
         TCFD   = TCH2O(TFEEDK/273.15)*(1.0 - XS0*ALPHA(I)/1000.0)
         HIFD   = 963.0*((SPEED/VISFD)**THIRD)*TCFD
         VISBL  = 2.42*POLY (U0(I), U1(I), U2(I), 0.0)
         TCBL   = TCH2O(TBOILK/273.15)*(1.0 - XS0*ALPHA(I)/1000.0)
         HIBL   = 963.0*((SPEED/VISBL)**THIRD)*TCBL

                      PRELIMINARY ESTIMATE OF STEAM CONSUMPTION

         BDR    = POLY (BD0(I), BD1(I), BD2(I), TFINAL - TBOILC(I))
   IF (BDR.LT.1.0) WRITE (6, 3020) BDR
         GPMF   = GPM25/BDR
         RHOF   = POLY (B0(I), B1(I), B2(I), TFINAL - TBOILC(I))
         WSLNF  = 1000.0*RHOF*GPMTLH(GPMF)/453.6
         VH2O   = WFEED - WSLNF
   IF (VH2O.LT.0.0) WRITE (6, 3040) VH2O
         WSTM1  = VH2O*HVH2O(TFINAL)/DHVH2O(TSTMC)
100 CONTINUE
         KOUNT  = KOUNT + 1
   WRITE(6, 2000)
   WRITE(6, 2100) WSTM1

                      CALCULATION OF OUTSIDE FILM COEFFICIENT

         GAMMA  = WSTM1/CHARL
         REFILM = 4.0*GAMMA/VISH2O(TSTMC)
   IF (REFILM.GT.2100.0) WRITE (6, 3060) REFILM
         RHOH2O = 62.43*SGH2O(TSTMC)
         CMPLEX = ((GRAV*RHOH2O**2)/(GAMMA*VISH2O(TSTMC)))**THIRD
   GO TO (180, 200), NTYPE
180      HOK    = 1.20*0.93*CMPLEX
   GO TO 220
200      HOK    = 0.76*CMPLEX
220      HO     = HOK*TCH2O(TSTMK/273.15)
   WRITE(6, 2200) HO
         OTHER  = AIAO/HO + RES1 + RES2

                      SIMULATION OF PREHEATING SECTION
```

```
            KSOLID = 0
            KTEMPF = 0
            DTC    = DELTAT
            Q      = 0.0
            Z      = 0.0
            WSLN1  = WFEED
            XS     = XS0
            WPCSLD = 100.0*XS0
            BDR    = 1.0
            VH2O   = 0.0
            VPCSLD = 0.0
            WH2O   = WH2OFD
      DO 230 J = 1, 6
         WDSLVD(J) = WDSLVF(J)
          WMPHR(J) = WMPHRF(J)
           WCR1(J) = 0.0
           WCR2(J) = 0.0
  230 CONTINUE
            WDSDS  = WDSTOT
            VSOLDS = 0.0
            WSOLDS = 0.0
            CTIONS = CTIONF
            TSLNF1 = TFEEDF
            TSLNC1 = TFEEDC
      WRITE(6, 2210)
      WRITE(6, 2220)
      WRITE(6, 2240)
            RCPUI  = CTHER + 1.0/HIFD
            UI1    = 1.0/RCPUI
            WCP1   = WCPFD
     0WRITE(6, 2260) Z     , TSLNF1, TSLNC1, Q     , VH2O  , WSLN1 ,
     1               WSOLDS, XS    , BDR   , VPCSLD, WPCSLD, UI1   ,
     2               HIFD

                    DETERMINE CONDITIONS AT END OF PREHEATING SECTION

            RCPUI  = CTHER + 1.0/HIBL
            UI2    = 1.0/RCPUI
            WCP2   = WCPBL
            UIAVG  = AVG (UI1, UI2)
            WCPAVG = AVG (WCP1, WCP2)
     0      DZ     = (WCPAVG/(UIAVG*FT2FT))*ALOG((TSTMF - TFEEDF)/(TSTMF
     1             - TBOILF))
            Z      = Z + DZ
      IF (Z.GT.HEIGHT) GO TO 232
            DQ     = WCPAVG*(TBOILF - TFEEDF)
            Q      = Q + DQ
            TSLNC2 = TBOILC(I)
            TSLNF2 = TBOILF
            WSLN2  = WSLN1
            WLIQ   = WSLN2
            WH2OL  = WH2O
     0WRITE(6, 2260) Z     , TSLNF2, TSLNC2, Q     , VH2O  , WSLN2 ,
     1               WSOLDS, XS    , BDR   , VPCSLD, WPCSLD, UI2   ,
     2               HIBL
            DHV1   = DHVH2O(TBOILC(I))
```

```
          TSLNC1  = TSLNC2
          TSLNF1  = TSLNF2
          UI1     = UI2
          WCP1    = WCP2
          WSLN1   = WSLN2
      GO TO 240

                         CALCULATION OF FINAL PRODUCT TEMPERATURE WHEN
                         THERE IS NO BOILING

 232      TSLNC3  = TFEEDC + (TBOILC(I) - TFEEDC)*(HEIGHT/Z)
          TSLNF3  = TCTOF(TSLNC3)
          TSLNK3  = TSLNC3 + 273.16
          Z       = HEIGHT
 234      KTEMPF  = KTEMPF + 1
          VISSLN  = 2.42*POLY (U0(I), U1(I), U2(I), TSLNC3 - TBOILC(I))
          TCSLN   = TCH2O(TSLNK3/273.15)*(1.0 - XS *ALPHA(I)/1000.0)
          HI      = 563.0*((SPEED/VISSLN)**THIRD)*TCSLN
          RCPUI   = CTHER + 1.0/HI
          UI2     = 1.0/RCPUI
          WCP2    = WH2O*CPH2O(TSLNC3)
      DO 235 J = 1, 6
    0     WCP2    = WCP2 + WMPHR(J)*CPSLD(CA(J), CB(J), CC(J), CD(J),
    1                TSLNK3)
 235 CONTINUE
          UIAVG   = AVG (UI1, UI2)
          WCPAVG  = AVG (WCP1, WCP2)
    0     TSLNF4  = TSTMF - (TSTMF - TFEEDF)*EXP(-UIAVG*FT2FT*HEIGHT/
    1                WCPAVG)
          TSLNC4  = TFTOC(TSLNF4)
          TSLNK4  = TSLNC4 + 273.16
          Q       = WCPAVG*(TSLNF4 - TFEEDF)
      IF (ABS((TSLNK4 - TSLNK3)/TSLNK4).LE.0.001) GO TO 238
      IF (KTEMPF.GE.10) GO TO 236
          TSLNC3  = TSLNC4
          TSLNF3  = TSLNF4
          TSLNK3  = TSLNK4
      GO TO 234
 236 WRITE(6, 3080)
 238 CONTINUE
    0WRITE(6, 2260) Z     , TSLNF4, TSLNC4, Q     , VH2O  , WSLN2 ,
    1                WSOLDS, XS    , BDR   , VPCSLD, WPCSLD, UI2   ,
    2                HI
      GO TO 800

                        SIMULATION OF VAPORIZATION/CRYSTALLIZATION SECTION

 240      TSLNC2  = TSLNC1 + DTC
          TSLNF2  = TCTOF(TSLNC2)
          TSLNK2  = TSLNC2 + 273.16
          BDR     = POLY (BD0(I), BD1(I), BD2(I), TSLNC2 - TBOILC(I))
      IF (BDR.LT.1.0) WRITE (6, 3020) BDR

                        DETERMINE CONDITIONS AT END OF INTEGRATION INCREMEN

          GPM     = GPM25/BDR
```

```
          FT3HR  = 60.0*GPM/7.481
          VSOLN  = FT3HR - VSOLDS
      IF (VSOLN.LE.0.0) GO TO 800
          RHOSLN = POLY (B0(I), B1(I), B2(I), TSLNC2 - TBOILC(I))
          WSLN2  = 62.43*RHOSLN*FT3HR

                         CHECK TO SEE IF ALL OF THE WATER HAS BEEN VAPORIZED

      IF (WSLN2.GT.WDSTOT) GO TO 360
          WSLN2  = WDSTOT
          DVH2O  = WSLN1 - WSLN2
      IF (DVH2O.LT.0.0) WRITE (6, 3040) DVH2O
          BOR    = BORF
          DQC    = 0.0
          DMCRJ  = 0.0
          VH2O   = VH2O + DVH2O
          WH2O   = 0.0
      IF (KSOLID.GT.0) GO TO 540
          CTIONS = 0.0
          WDSDS  = 0.0
          KSOLID = 1
      DO 300 J = 1, 6
          DMCRJ  = (WDSLVF(J) - WCR1(J))/FMWSLD(J)
        WMPHR(J) = 0.0
       WDSLVD(J) = 0.0
         WCR2(J) = WDSLVF(J)
          DQC    = DQC + DMCRJ*DHCRYS(J)
  300 CONTINUE
          VSOLDS = VFINAL
          WSOLDS = WDSTOT
          VPCSLD = 100.0
          WPCSLD = 100.0
          WLIQ   = 0.0
          XS     = 0.0
      GO TO 540
  360     DVH2O  = WSLN1 - WSLN2
      IF (DVH2O.LT.0.0) WRITE (6, 3040) DVH2O
          VH2O   = VH2O + DVH2O
          WH2O   = WH2O - DVH2O

                         CHECK SOLUBILITY PRODUCTS FOR CRYSTALLIZATION

          DQC    = 0.0
          VSOLDS = 0.0
          WSOLDS = 0.0
          WDSDS  = 0.0
      DO 400 J = 1, 6
          CATCON = CTIONS/(0.06243*VSOLN)
          CONCJ  = WMPHR(J)/(0.06243*VSOLN)
          CONCJ  = AMIN1(CONCJ, SP100(J)/(CATCON**CATS(J)))
          DMCRJ  = AMAX1(0.0, WMPHR(J) - 0.06243*CONCJ*VSOLN)
        WMPHR(J) = WMPHR(J) - DMCRJ
       WDSLVD(J) = FMWSLD(J)*WMPHR(J)
         WCR2(J) = WCR1(J) + DMCRJ*FMWSLD(J)
          WDSDS  = WDSDS + WDSLVD(J)
          WSOLDS = WSOLDS + WCR2(J)
```

```
          VSOLDS = VSOLDS + WCR2(J)/(62.43*RHOSLD(J))
          CTIONS = CTIONS - DMCRJ*CATS(J)
          DQC    = DQC + DMCRJ*DHCRYS(J)
400 CONTINUE

                        MATERIAL BALANCE CALCULATIONS FOR CRYSTALLIZATION

          WPCSLD = 100.0*(WDSDS + WSOLDS)/WSLN2
          VPCSLD = 100.0*VSOLDS/FT3HR
          WLIQ   = WSLN2 - WSOLDS
    IF (WLIQ.GT.0.0) GO TO 520
          XS     = 0.0
    GO TO 540
520       XS     = WDSDS/WLIQ

                        HEAT TRANSFER CALCULATIONS FOR CRYSTALLIZATION

540 CONTINUE
          TCSLN  = TCH2O(TSLNK2/273.15)*(1.0 - XS*ALPHA(I)/1000.0)
          VISSLN = 2.42*POLY (V0(I), V1(I), V2(I), TSLNC2 - TBOILC(I))
   0      HI     = 963.0*(1.0 - VPCSLD/100.0)*((SPEED/VISSLN)**THIRD)*
   1               TCSLN + (VPCSLD/100.0)*(TCSLD/CLRFT)
          RCPUI  = CTHER + 1.0/HI
          UI2    = 1.0/RCPUI
          UIAVG  = AVG (UI1, UI2)
          WCP2   = WH2O*CPH2O(TSLNC2)
    DO 660 J = 1, 6
   0      WCP2   = WCP2 + WMPHRF(J)*CPSLD(CA(J), CB(J), CC(J), CD(J),
   1               TSLNK2)
660 CONTINUE
          WCPAVG = AVG (WCP1, WCP2)
          DHV2   = DHVH2O(TSLNC2)
          DHVAVG = AVG (DHV1, DHV2)
          TFAVG  = AVG (TSLNF1, TSLNF2)
          DQ     = DHVAVG*DVH2O + DQC + WCPAVG*DTF
          Q      = Q + DQ
          DZ     = ABS(DQ/(UIAVG*FT2FT*(TSTMF - TFAVG)))
          Z      = Z + DZ
   0WRITE(6, 2260) Z     , TSLNF2, TSLNC2, Q     , VH2O  , WLIQ  ,
   1               WSOLDS, XS    , BCR   , VPCSLD, WPCSLD, UI2   ,
   2               HI
    IF (Z.GE.HEIGHT) GO TO 800

                        SWITCH FINAL CONDITIONS TO INITIAL CONDITIONS
                        FOR NEXT INTEGRATION INCREMENT

          DHV1   = DHV2
          TSLNC1 = TSLNC2
          TSLNF1 = TSLNF2
          UI1    = UI2
          WCP1   = WCP2
          WSLN1  = WSLN2
    DO 680 J = 1, 6
        WCR1(J) = WCR2(J)
680 CONTINUE
    GO TO 240
```

```
                         CHECK FOR CONVERGENCE ON STEAM CONSUMPTION

 800        WSTM2  = Q/DHVH2C(TSTMC)
     IF (ABS((WSTM2 - WSTM1)/WSTM2).LE.0.01) GO TO 900
     IF (KOUNT.GE.10) GO TO 820
          WSTM1  = WSTM2
     GO TO 160
 820 WRITE(6, 3120)
 900 CONTINUE

                         PRINT OUT COMPLETE PROCESS MATERIAL BALANCE

     WRITE(6, 2000)
     WRITE(6, 2300)
     WRITE(6, 2320)
     WRITE(6, 2340)
     WRITE(6, 2360)
     DO 910 J = 1, 6
    0WRITE(6, 2380) (COMPS(K, J), K = 1, 2),
    1               WDSLVF(J),  WDSLVD(J),  WCR2(J),  ZERO  , ZERO
 910 CONTINUE
     WRITE(6, 2400) WH2OFD, WH2O  , ZERO  , VH2O  , WSTM2
     WRITE(6, 2420) WFEED , WLIQ  , WSOLOS, VH2O  , WSTM2
     WRITE(6, 2440) TFEEDC, TSLNC2, TSLNC2, TBOILC(1),  TSTMC
     GO TO 20
 920 CONTINUE
     STOP

                         INPUT FORMAT STATEMENTS

1000 FORMAT (2I5)
1020 FORMAT (8F10.0)

                         OUTPUT FORMAT STATEMENTS (NORMAL)

20000FORMAT (1H1, 38X,  44HCOMPUTER SIMULATION OF WIPED-FILM EVAPORATOR
    1, //)
2020 FORMAT (1H0, 43X,  21HTYPE OF MACHINE  --   , 3A4)
2040 FORMAT (1H0, 43X,  21HTYPE OF WASTE    --   , 2A4, //)
20600FORMAT (1H0, 43X,  24HFEED RATE                =, F6.2, 4H GPM, //,
    1             44X,  24HFEED TEMPERATURE         =, F6.1, 6H DEG C,//,
    2             44X,  24HSTEAM PRESSURE           =, F7.2, 5H PSIG, //)
20800FORMAT (1H0, 43X,  24HINSIDE DIAMETER          =, F6.2, 3H IN, //,
    1             44X,  24HCLADDING THICKNESS       =, F7.4, 3H IN, //,
    2             44X,  24HWALL THICKNESS           =, F7.4, 3H IN, //,
    3             44X,  24HHEAT TRANSFER AREA       =, F6.1, 4H FT2, //,
    4             44X,  24HTHERM COND OF CLADDING =, F7.3, 16H BTU/HR-F
    5T-DEG F, //, 44X,  24HTHERM COND OF WALL       =, F7.3, 16H BTU/HR-F
    6T-DEG F, //, 44X,  24HROTOR SPEED              =, F6.1, 4H RPM, //,
    7             44X,  24HMACHINE CLEARANCE        =, F6.1, 5H MILS)
21000FORMAT (1H0, 43X,  17HWASTE COMPOSITION,//, 6(46X, 2A4, 2X, F7.3,
    12H M, /), //)
21100FORMAT (1H0, 43X,  24HHEIGHT (OR LENGTH)       =, F6.2, 3H FT, //,
    1             44X,  24HINITIAL BOILING POINT    =, F7.1, 6H DEG C,//,
    2             44X,  24HSTEAM TEMPERATURE        =, F7.1, 6H DEG C)
```

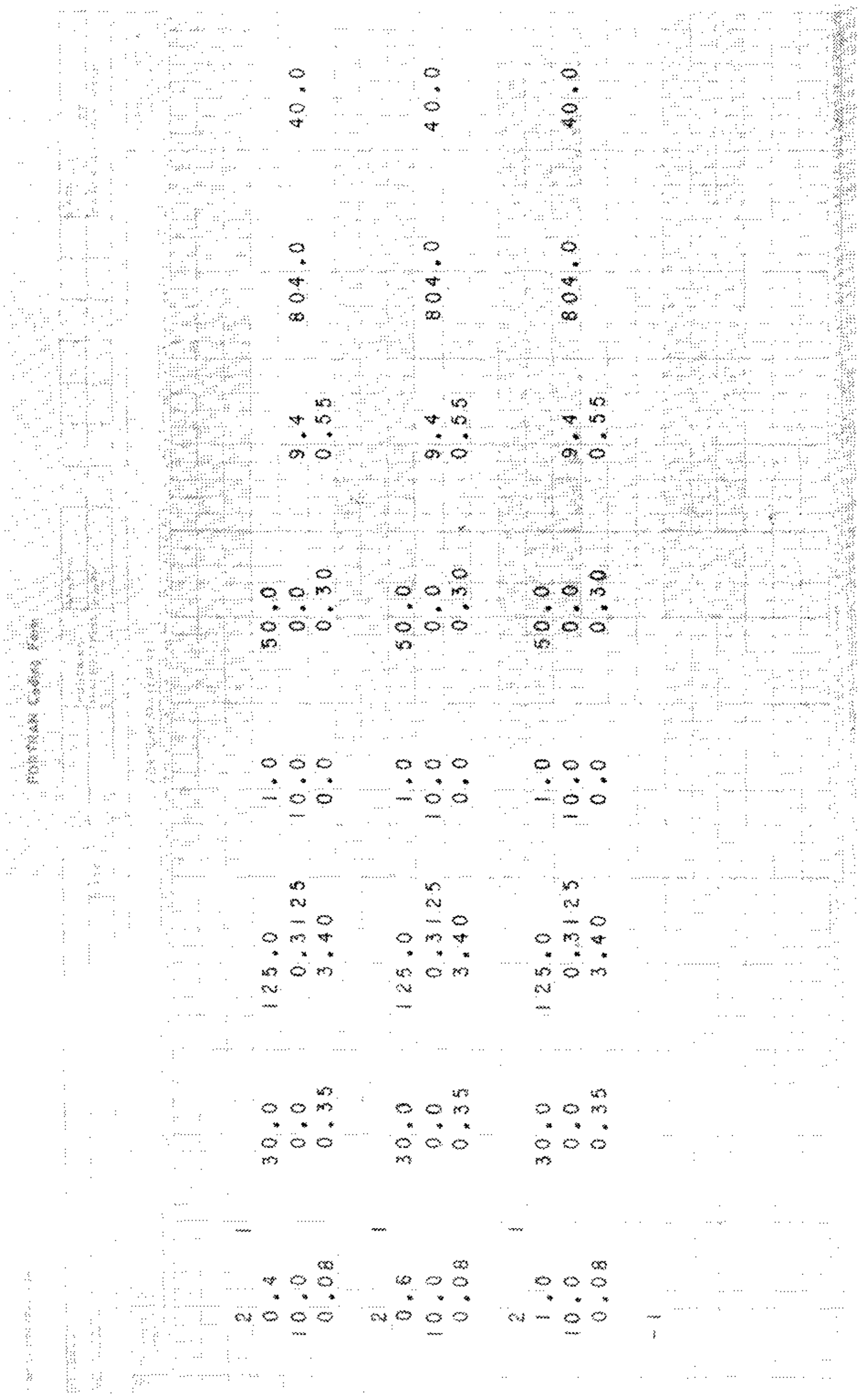
```
21600FORMAT (1H0, 43X,  31HREQUIRED STEAM CONSUMPTION  =  , F8.2,
    1  7H LBS/HR)
22000FORMAT (1H0, 43X,  31HOUTSIDE FILM COEFFICIENT    =  , F8.1,
    1 17H BTU/HR-FT2-DEG F, //)
2210 FORMAT (1H0, 99X,    30H    WT PCT   OVERALL    INSIDE)
22200FORMAT (    40H                                   DUTY ,
    1            40H      VAPOR  SOLUTION  CRYSTALS  FRACTION,
    2            50H  BOILDOWN    VOL PCT  SOLIDS +    U, BTU/   H, BTU/)
22400FORMAT (    40H        Z, FT  T, DEG F  T, DEG C    BTU/HR,
    1            40H     LBS/HR     LBS/HR     LBS/HR      SALTS ,
    2            50H     RATIO      SOLIDS     SOLUTE  HR-FT2-F  HR-FT2-F)
2260 FORMAT (1H0, F9.3, 2F10.2, F10.0, 3F10.3, 2F10.4, 2F10.2, 2F10.1)
2300 FORMAT (1H0, //, 39X,  35HCOMPLETE PROCESS MATERIAL BALANCE, //)
23200FORMAT (    40H0                             FEED     PRODUCT,
    1            30H   PRODUCT  OVERHEAD   HEATING)
23400FORMAT (    40H                             WASTE  SOLUTION,
    1            30H  CRYSTALS     VAPOR      STEAM )
2360 FORMAT (    20H0COMPONENT FLOW     , /,    20H RATES, LBS/HR       )
2380 FORMAT (1H0, 9X, 2A4, 2X, 5F10.2)
2400 FORMAT (1H0, 9X, 3HH2O, 7X, 5F10.2)
2420 FORMAT (1H0, 11X, 6HTOTALS, 2X, 5F10.2)
2440 FORMAT (    20H0TEMPERATURES, DEG C, 5F10.2, //)

                        OUTPUT FORMAT STATEMENTS (ABNORMAL)

30200FORMAT (1H0,   9X,   44H*******   FLAG  --  COMPUTED BOILDOWN RATIO (
    1, E10.3, 29H) IS LESS THAN UNITY   *******)
30400FORMAT (1H0,   9X,   55H*******   FLAG  --  COMPUTED AMOUNT OF WATER
    1VAPORIZED (, E10.3, 22H) IS NEGATIVE  *******)
30600FORMAT (1H0,   9X,   58H*******   FLAG  --  COMPUTED OUTSIDE FILM REY
    1NOLDS NUMBER (, E10.3, 31H) IS GREATER THAN 2100  *******)
30800FORMAT (1H0,   5X, 109H*******   FLAG  --  NUMBER OF ITERATIONS ON T
    1HE FINAL PRODUCT TEMPERATURE HAS REACHED THE LIMIT OF 10  *******)
31200FORMAT (1H0,   9X, 101H*******   FLAG  --  NUMBER OF ITERATIONS ON T
    1HE STEAM CONSUMPTION HAS REACHED THE LIMIT OF 10  *******)
     END
```

APPENDIX C

Example of Input Data to the Computer Program for Simulation of the Operation of Wiped-Film Evaporators



```
 2    1
  0.4      30.0      125.0       1.0      50.0
 10.0       0.0        0.3125   10.0        0.0       9.4      804.0       40.0
  0.08      0.35       3.40      0.0        0.30      0.55

 2    1
  0.6      30.0      125.0       1.0      50.0
 10.0       0.0        0.3125   10.0        0.0       9.4      804.0       40.0
  0.08      0.35       3.40      0.0        0.30      0.55

 2    1
  1.0      30.0      125.0       1.0      50.0
 10.0       0.0        0.3125   10.0        0.0       9.4      804.0       40.0
  0.08      0.35       3.40      0.0        0.30      0.55

 -1
```

APPENDIX D

Example of Output from the Computer Program for Simulation of Wiped-Film Evaporators

```
          COMPUTER SIMULATION OF WIPED-FILM EVAPORATOR


               TYPE OF MACHINE   --  HORIZONTAL

               TYPE OF WASTE     --  PUREX


               FEED RATE                =  0.40 GPM

               FEED TEMPERATURE         =  30.0 DEG C

               STEAM PRESSURE           =  50.00 PSIG


               INSIDE DIAMETER          = 10.00 IN

               CLADDING THICKNESS       = 0.0     IN

               WALL THICKNESS           = 0.3125 IN

               HEAT TRANSFER AREA       =  10.0 FT2

               THERM COND OF CLADDING =  0.0    BTU/HR-FT-DEG F

               THERM COND OF WALL       =  9.400 BTU/HR-FT-DEG F

               ROTOR SPEED              = 804.0 RPM

               MACHINE CLEARANCE        =  40.0 MILS

               WASTE COMPOSITION

                 NA2SO4       0.080  M
                 NA2CO3       0.350  M
                 NANO3        3.400  M
                 NANO2        0.0    M
                 NAOH         0.300  M
                 NAALO2       0.550  M


               HEIGHT (OR LENGTH)       =  3.82 FT

               INITIAL BOILING POINT  =  106.0 DEG C

               STEAM TEMPERATURE        =  147.6 DEG C
```

```
                                   REQUIRED STEAM CONSUMPTION   =    200.53 LBS/HR

                                   OUTSIDE FILM COEFFICIENT     =    1478.1 BTU/HR-FT2-DEG F


                                                                                                                WT PCT    OVERALL     INSIDE
                                    DUTY        VAPOR   SOLUTION   CRYSTALS   FRACTION   BOILDOWN     VOL PCT   SOLIDS +   U, BTU/    H, BTU/
Z, FT   T, DEG F   T, DEG C        BTU/HR      LBS/HR     LBS/HR     LBS/HR      SALTS      RATIO      SOLIDS     SOLUTE   HR-FT2-F   HR-FT2-F

0.0         86.00      30.00           0.        0.0     249.885       0.0      0.3162     1.0000        0.0       31.62      252.1     1555.6

0.298      222.80     106.00       26488.        0.0     249.885       0.0      0.3162     1.0000        0.0       31.62      264.4     2178.5

0.876      224.60     107.00       56068.     30.660     219.225     0.000      0.3604     1.1282       0.00       36.04      264.1     2156.0

1.244      226.40     108.00       74427.     45.692     204.193     0.000      0.3946     1.2565       0.00       39.46      263.6     2127.8

1.552      228.20     109.00       89371.     65.199     184.686     0.000      0.4278     1.3847       0.00       42.78      263.0     2090.0

1.815      230.00     110.00      101769.     78.077     171.808     0.000      0.4598     1.5129       0.00       45.98      262.3     2044.0

2.043      231.80     111.00      112219.     88.942     160.943     0.000      0.4909     1.6411       0.00       49.09      261.4     1991.4

2.244      233.60     112.00      121145.     98.233     151.652     0.000      0.5210     1.7694       0.00       52.10      260.4     1934.1

2.424      235.40     113.00      128856.    106.268     143.617     0.000      0.5501     1.8976       0.00       55.01      259.3     1873.8

2.586      237.20     114.00      135584.    113.286     136.599     0.000      0.5784     2.0258       0.00       57.84      258.1     1812.0

2.733      239.00     115.00      141504.    119.468     130.417     0.000      0.6058     2.1541       0.00       60.58      256.8     1750.0

2.869      240.80     116.00      146753.    124.956     124.929     0.000      0.6324     2.2823       0.00       63.24      255.4     1688.7

2.994      242.60     117.00      151438.    129.860     120.025     0.000      0.6582     2.4105       0.00       65.82      254.0     1628.9

3.112      244.40     118.00      155645.    134.268     115.617     0.000      0.6833     2.5388       0.00       68.33      252.5     1571.0

3.222      246.20     119.00      159443.    138.253     111.632     0.000      0.7077     2.6670       0.00       70.77      251.1     1515.5

3.325      248.00     120.00      162888.    141.872     108.013     0.000      0.7314     2.7952       0.00       73.14      249.6     1462.4

3.424      249.80     121.00      166027.    145.173     104.712     0.000      0.7545     2.9234       0.00       75.45      248.0     1411.8

3.519      251.60     122.00      168859.    148.197     101.688     0.000      0.7769     3.0517       0.00       77.69      246.5     1363.8

3.609      253.40     123.00      171536.    150.977      98.908     0.000      0.7988     3.1799       0.00       79.88      245.0     1318.4

3.698      255.20     124.00      173999.    153.542      95.985     0.358      0.8194     3.3081       0.23       82.00      243.4     1273.4

3.786      257.00     125.00      176312.    155.915      92.887     1.083      0.8389     3.4364       0.74       84.08      241.7     1228.8

3.871      258.80     126.00      178449.    158.117      90.089     1.678      0.8583     3.5646       1.18       86.09      240.1     1187.0
```

```
                              COMPUTER SIMULATION OF WIPED-FILM EVAPORATOR

                                 REQUIRED STEAM CONSUMPTION  =    197.73 LBS/HR

                                 OUTSIDE FILM COEFFICIENT    =    1465.0 BTU/HR-FT2-DEG F

                                                                                          WT PCT   OVERALL    INSIDE
                             DUTY     VAPOR  SOLUTION  CRYSTALS  FRACTION  BOILDOWN   VOL PCT  SOLIDS +   U, BTU/   H, BTU/
Z, FT  T, DEG F  T, DEG C   BTU/HR   LBS/HR    LBS/HR    LBS/HR     SALTS     RATIO    SOLIDS    SOLUTE  HR-FT2-F  HR-FT2-F

0.0       86.00     30.00       0.     0.0    245.885     0.0      0.3162    1.0000     0.0       31.62     252.3    1555.6

0.297    222.80    106.00   26488.     0.0    249.885     0.0      0.3162    1.0000     0.0       31.62     264.6    2178.5

0.875    224.60    107.00   56068.   30.660   219.225     0.000    0.3604    1.1262     0.00      36.04     264.3    2156.0

1.243    226.40    108.00   74427.   49.692   200.193     0.000    0.3946    1.2565     0.00      39.46     263.8    2127.8

1.551    228.20    109.00   89371.   65.199   184.686     0.000    0.4278    1.3847     0.00      42.78     263.2    2090.0

1.814    230.00    110.00  101769.   78.077   171.808     0.000    0.4598    1.5129     0.00      45.98     262.5    2044.0

2.042    231.80    111.00  112219.   88.942   160.943     0.000    0.4909    1.6411     0.00      49.09     261.6    1991.4

2.243    233.60    112.00  121145.   98.233   151.652     0.000    0.5210    1.7694     0.00      52.10     260.6    1934.1

2.422    235.40    113.00  128856.  106.268   143.617     0.000    0.5501    1.8976     0.00      55.01     259.5    1873.8

2.584    237.20    114.00  135584.  113.286   136.599     0.000    0.5784    2.0258     0.00      57.84     258.3    1812.0

2.731    239.00    115.00  141504.  119.468   130.417     0.000    0.6058    2.1541     0.00      60.58     257.0    1750.0

2.867    240.80    116.00  146753.  124.956   124.929     0.000    0.6324    2.2823     0.00      63.24     255.6    1688.7

2.992    242.60    117.00  151438.  129.860   120.025     0.000    0.6582    2.4105     0.00      65.82     254.2    1628.9

3.109    244.40    118.00  155645.  134.268   115.617     0.000    0.6833    2.5388     0.00      68.33     252.7    1571.0

3.219    246.20    119.00  159443.  138.253   111.632     0.000    0.7077    2.6670     0.00      70.77     251.3    1515.5

3.323    248.00    120.00  162888.  141.872   108.013     0.000    0.7314    2.7952     0.00      73.14     249.7    1462.4

3.422    249.80    121.00  166027.  145.173   104.712     0.000    0.7545    2.9234     0.00      75.45     248.2    1411.8

3.516    251.60    122.00  168899.  148.197   101.688     0.000    0.7769    3.0517     0.00      77.69     246.7    1363.8

3.607    253.40    123.00  171536.  150.977    98.908     0.000    0.7988    3.1799     0.00      79.88     245.2    1318.4

3.695    255.20    124.00  173999.  153.542    95.985     0.358    0.8194    3.3081     0.23      82.00     243.6    1273.4

3.783    257.00    125.00  176312.  155.915    92.887     1.083    0.8389    3.4364     0.74      84.08     241.9    1228.8

3.868    258.80    126.00  178449.  158.117    90.089     1.678    0.8583    3.5646     1.18      86.09     240.2    1187.0
```

```
                         COMPUTER SIMULATION OF WIPED-FILM EVAPORATOR

                              COMPLETE PROCESS MATERIAL BALANCE


                              FEED     PRODUCT    PRODUCT    OVERHEAD    HEATING
                              WASTE    SOLUTION   CRYSTALS    VAPOR       STEAM

COMPONENT FLOW
RATES, LBS/HR

          NA2SO4               2.28      2.28       0.00       0.0         0.0

          NA2CO3               7.43      5.75       1.68       0.0         0.0

          NANO3               57.87     57.87       0.00       0.0         0.0

          NANO2                0.0       0.0        0.0        0.0         0.0

          NAOH                 2.40      2.40       0.00       0.0         0.0

          NAALO2               9.03      9.03       0.00       0.0         0.0

          H2O                170.88     12.76       0.0      158.12      197.73

            TOTALS           249.89     90.09       1.68     158.12      197.73

TEMPERATURES, DEG C           30.00    126.00     126.00     106.00      147.59
```

APPENDIX E

NOMENCLATURE

English Letters

A,B,C,D	coefficients in the polynomial expression for the heat capacity of solid salts as a function of temperature
A_i	inside heat transfer area of evaporator, ft^2
A_{M_1}	mean heat transfer area of evaporator cladding, ft^2
A_{M_2}	mean heat transfer area of evaporator wall, ft^2
A_o	outside heat transfer area of evaporator, ft^2
a_i	inside heat transfer area per unit of height or length, ft^2/ft
a_o, a_1, a_2	regression coefficients in the second-order polynomial expression for specific gravity as a function of temperature
a',b',c',d'	constants in Equation 17 for the vapor pressure of water as a function of temperature
BDR	boildown ratio, gpm @ 25°C/gpm
b_o, b_1, b_2	regression coefficients in the second-order polynomial expression for boildown ratio as a function of temperature
C_{A_i}	molar concentration of the anion of the i^{th} component in solution, (g-moles)/liter
C_{Na}	molar concentration of the sodium ions in solution, (g-moles)/liter
C_p	molar heat capacity, Btu/(lb-mole)(°F)
C_s	solubility of a salt in water at saturation, (g-moles)/liter
c_p	mass heat capacity, Btu/(lb)(°F)
D_i	inside diameter of evaporator, ft
D_o	outside diameter of evaporator, ft

e	base of natural logarithms
F	waste feed rate to evaporator, gpm
F_{25}	waste feed rate to the evaporator measured at 25°C, gpm
G	volumetric flow rate of the solution exclusive of the solid phase, ft^3/hr
G_s	volumetric flow rate of the solid phase, ft^3/hr
g	acceleration due to gravity = 4.173×10^8 ft/hr^2
H	enthalpy flow rate, Btu/hr
H_v	enthalpy content of water vapor, Btu/lb
ΔH_c	heat of crystallization, Btu/(lb-mole)
ΔH_f^o	standard heat of formation, kcal/(g-mole)
h_i	inside film heat transfer coefficient, Btu/(hr)(ft^2)(°F)
h_o	outside film heat transfer coefficient, Btu/(hr)(ft^2)(°F)
h'	partial coefficient of heat transfer from the heating medium to the wiped film exclusive of h_i, Btu/(hr)(ft^2)(°F)
K_{sp}	solubility product for a salt, units of (g-mole)/liter
k	thermal conductivity, Btu/(hr)(ft)(°F)
k_s	thermal conductivity of solid phase, Btu/(hr)(ft)(°F)
k_1	thermal conductivity of the evaporator cladding, Btu/(hr)(ft)(°F)
k_2	thermal conductivity of the evaporator wall, Btu/(hr)(ft)(°F)
L	height or length of the evaporator heat transfer zone, ft
ℓ_1	thickness of the evaporator cladding, ft
ℓ_2	thickness of the evaporator wall, ft
M	molecular weight
m	number of cations in a salt
N	rotor speed, rpm

ΔN_i	rate of crystallization of component i out of solution over a Δz increment, (lb-moles)/hr
Nu	Nusselt number for heat transfer
n	number of anions in a salt
n_B	number of blades on the wiper shaft
P_c	critical pressure of water, atm
p^o	vapor pressure of water, atm
Pr	Prandtl number = $c_p\mu/k$
Q	total rate of heat transfer in the evaporator, Btu/hr
ΔQ_c	rate of heat consumed on crystallization over a Δz increment, Btu/hr
q	rate of heat transfer from the heating steam over a Δz increment, Btu/hr
Re	film Reynolds number = $4\tau/\mu$
Re'	rotary Reynolds number = $D_i^2N\rho/\mu$
r	rate of water vaporization per unit height or length, lb/(hr)(ft)
S	dimensionless quantity defined by Equation 37
s	specific gravity
s_{BP}	specific gravity at the initial normal boiling point
T	absolute temperature, °K
T_c	critical temperature of water, °K
T_r	reduced temperature
T_s	heating steam temperature, °K
t	temperature, °C or °F
Δt	temperature increment size, °C or °F
t_{BP}	initial normal boiling point, °C or °F

t_F	feed temperature, °C or °F
t_R	reference temperature for enthalpy content = 32°F (0°C)
t_s	heating steam temperature, °F
t'	time between successive scrapings, hr
U_i	local overall heat transfer coefficient based upon the inside area, Btu/(hr)(ft^2)(°F)
u	axial flow velocity, ft/hr
u_0, u_1, u_2	regression coefficients in the second-order polynomial expression for viscosity as a function of temperature
V	total rate of water vaporized in the evaporator, lb/hr
ΔV	rate of water evaporated over a Δz increment, lb/hr
W	total mass flow rate of solution plus solid phase, lb/hr
W_c	heating steam flow rate, lb/hr
$W_{d,i}$	mass flow rate of component i dissolved in solution, lb/hr
W_i	total mass flow rate of component i, lb/hr
$W_{s,i}$	mass flow rate of component i in solid form, lb/hr
x	weight fraction of a dissolved component in solution
x_s	weight fraction of all dissolved solids in solution
z	variable height or length of the evaporator heat transfer zone, ft
Δz	size of a height or length increment, ft

Greek Letters

α	constant in Equation 5 for the thermal conductivity of aqueous solutions
Γ	condensate mass flow rate per unit length, lb/(ft)(hr)
δ	clearance between the wiper blades and heat transfer surface, ft
λ	heat of vaporization of water, Btu/lb
μ	viscosity, centipoise or lb/(ft)(hr)
π	3.1416
ρ	density, lb/ft^3
ρ_F	feed stream density at the feed temperature, lb/ft^3
ρ_s	solid density, lb/ft^3
ρ_{25}	feed stream density at 25°C, lb/ft^3
τ	T/273.15; solution mass flow rate per unit length = $W/\pi D_i$, lb/(ft)(hr)
ξ	$T_c - T$, °K

Subscripts

BP	initial normal boiling point
c	heating steam condensate
i	component number; inside area
j	trial number
o	outside area
s	dissolved solids or solid phase
w	water

Superscripts

$\bar{\ }$	average value

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