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THE OPERATION AND CONTROL OF A CONTINUOUS EVAPORATOR
FOR THE WASTE POT CALCINATION PROCESS

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ABSTRACT

The control problems associated with the continuous evaporator for the waste calcination Pilot Plant are reviewed. Data given for the control system were developed experimentally and simplified expressions for necessary proportional actions and characteristic response times are presented for comparison.

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The specifications on an evaporator for service in the pot calcination process include the following:

1. The decontamination factor from liquid to vapor should be very high. The decontamination factor for this evaporator is the decontamination factor for the entire process.
2. It should provide a high concentration feed for the pot as the pot demands it. The pot demand will vary from several liters a minute to a few liters per hour.
3. It must be able to operate while receiving condensate from the pot at varying rates and varying acid concentrations.
4. It must maintain the free acid concentration within the evaporator to some specified value (about 5 M) by the addition of water.

The streams then that are not subject to control include the product withdrawal rate and the pot condensate return. The streams that must be controlled include the feed addition rate, the water addition rate, and the steam to the steam chest.

The system variables which may be observed include:

1. The liquid level.
2. The density.
3. The liquid temperature.
4. The vapor temperature.
5. The electrical conductivity of the evaporator condensate.

Subsidiary variables which should be observed include the pressure in the steam chest and the pressure in the evaporator. It is theoretically possible to measure the feed rate, the water addition rate, and, probably by heat balance, the rate of pot condensate return and the product withdrawal rate; but due to the inherent erratic nature of these streams and the undesirable physical properties of several of them, this is not thought practical.

RECOMMENDED METHOD OF CONTROL

After attempting to operate with several modes of control the system found most satisfactory was:

1. Control liquid level by feed addition rate.
2. Control evaporator condensate electrical conductivity by water addition rate.

3. Control boilup rate by density measurement.

This control scheme is depicted in Fig. 1.

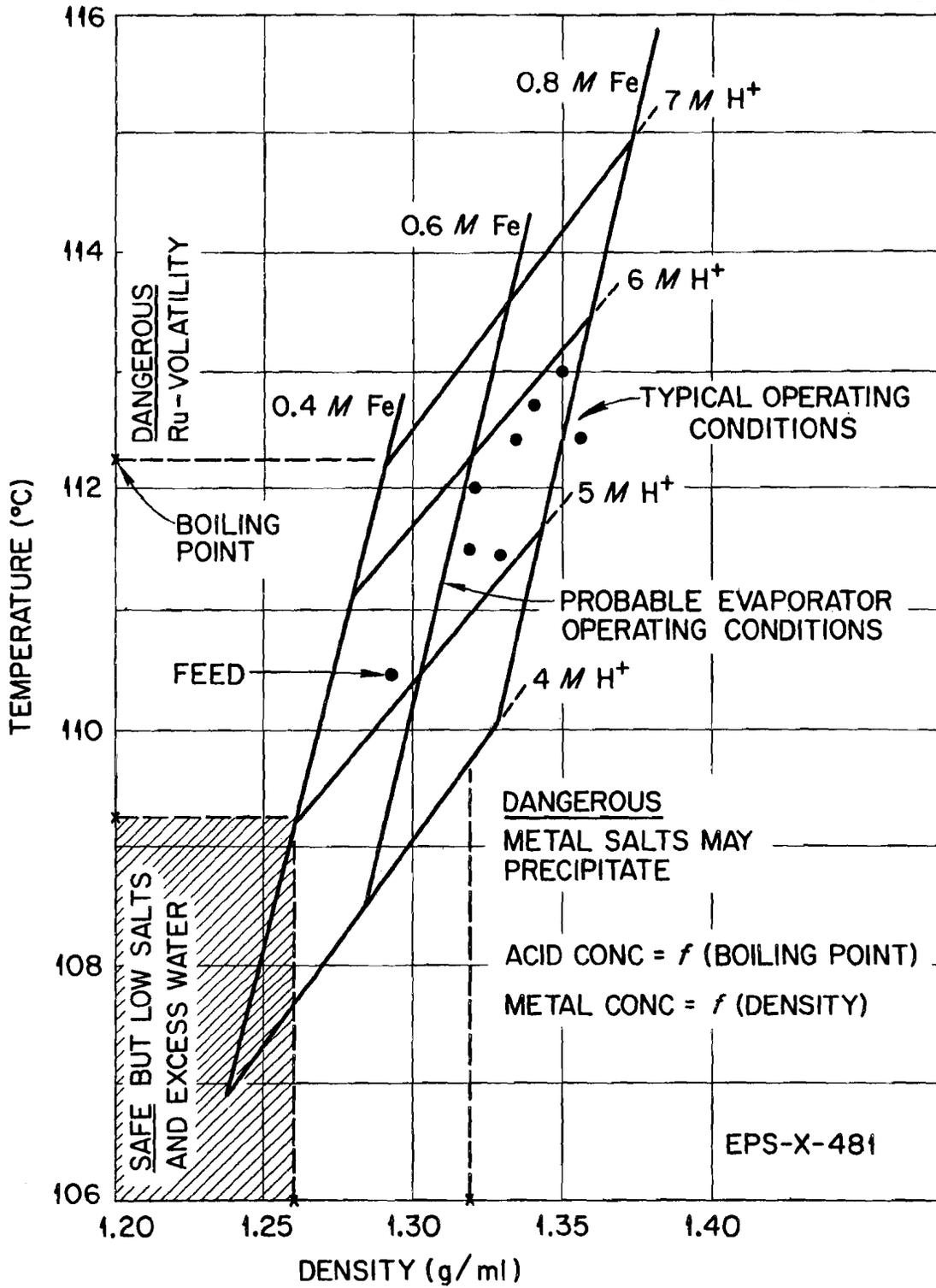
INTERDEPENDENCE OF VARIABLES

It is impossible in this system to cleanly separate the effects of the control loops from each other. One of the most serious cross effects is the density-solids concentration-nitric acid concentration effect. Figure 2 shows that for the Purex system the density is a function of both the solids concentration and nitric acid concentration. Similarly, the volatility of nitric acid is increased by high concentrations of solids. The system works because the density is increased more by increasing the solids concentration than by increasing the acid concentration and the composition of the vapor is dependent upon total nitrate concentration. An operational upset of either variable produces a transient in the other.

An effect of some significance which was observed is the dependence of vapor composition upon boilup rate. In a thermosiphon evaporator appreciable evaporation can take place between the time that the liquid enters the tube bundle and it is discharged into the disengaging space. The vapor then is not in equilibrium with the bulk of the liquid but in equilibrium with the liquid leaving the tube bundle. At high boilup rates where the fraction of the liquid evaporated is high the concentration of the vapor can be significantly above the bulk equilibrium concentration. Since this is most important during a transient, it is desirable to stabilize boilup rate.

The liquid level is also dependent upon boilup rate since the effective liquid level observed includes vapor bubbles, and the observed level is increased by increasing boilup rate. In an attempt to control liquid level by boilup rate, this effect coupled with the effect of adding cold feed to the system set up a wide oscillation.

Difficulty was also encountered in attempts to use vapor temperature as an index to vapor composition. Because the solution is highly salted, the vapor leaving the boiling liquid is superheated. As it passes through the disengager and into the vapor lines, some of the superheat is lost and eventually some of the vapor tends to condensate. Since the vapor is a binary system, partial condensation results in a lowering of the temperature. Were it possible to cool the vapor to its dew point precisely, this could be an excellent method for determining vapor composition. However, due to the wide variation in boilup rates and the smooth variation of temperature from superheated vapor to partially condensed vapor, it was found impractical to do this. An important system variable is the evaporator pressure. Adequate control of this variable was achieved only after considerable development. The important aspect appears to be provision for adequate off-gas capacity and throttling control to maintain the desired pressure. In our system the pressure-sensing element was in the evaporator itself. Pressure fluctuations can again influence vapor temperature and aggravate attempts to use it for control.



Boiling Point vs Density as Function of Acid and Metal Salts at Atmospheric Pressure for Purex Waste.

Fig. 2.

In Unit Operations experimental work it was found desirable to use a cascade system for the steam chest pressure. The density signal was sent to a controller which sets the setpoint on the steam chest pressure controller which activated the steam valve. While this arrangement operated satisfactorily, its necessity probably arose from inadequate steam supply. The static header pressure was 100 psig but the steam chest pressure rarely exceeded 30 psig. Where header lines are adequately sized, a cascaded pressure control system should not be needed.

CONTROL SETTINGS USED

The evaporator used for study had 22 sq ft of heat transfer area and a holdup of 22 liters at liquid level setpoint. The liquid level was measured in a 10-in.-dia section which comprised the base of the disengaging section. The liquid level signal ranged from 0 to 100% as the evaporator was filled from 10 to 30 liters. The density signal was obtained from a float type cell with a differential transformer output that ranged from 0 to 100% as the density ranged from 1 to 2 g/cc. Vapor composition was obtained from the electrical conductivity of the evaporator condensate. The electronic system used put out a 0 to 100% signal as the acid normality increased from 1.0 to 3.0 normal. The previous method for measuring vapor composition depended upon a temperature measurement which yielded a 0 to 100% signal as the vapor temperature increased from 100 to 125 °C. This was equivalent to a vapor-acid normality from 0 to 16 normal. All of these signals except the vapor temperature vs concentration were essentially linear.

The control valves used for the evaporator feed and water had maximum capacities of 4 and 10 liters/min, respectively, and had square function characteristics. The evaporator boilup rate ranged to a maximum of about 6 liters/min and was roughly proportional to the square root of the steam pressure in psig. The calciner feed rate had a maximum value of about 2 liters/min and the calciner condensate return was usually less than 1 liter/min. The control settings found most desirable are given in Table 1. The conductivity measurements in the evaporator condensate were used for only the last two runs. All other settings in the table are the result of numerous tests. The vapor temperature control was found workable but troublesome.

At the onset of the experimental program with a continuous evaporator the differential equation thought to describe the control system were solved on an Analog computer. Subsequent experience with the experimental unit revealed, however, that inherent nonlinearities and cross dependence of variables made the computer solution of little value. Further attempts at system analysis are planned. For the purpose of this memo it should be sufficient merely to look at the magnitude of normalized control functions for a linear simplification and characteristic times.

Table 1. Control Settings and Range of Variables

Variable	Range	Signal	Scale	Proportional Band	Reset Time	Set Point
Evaporator liquid level	10-30 liters	0-20 in H ₂ O	0-100%	35%	10 min	50%
Density	1-2 gm/cm ³	26 in.-52 in. H ₂ O	0-100%	100%	10 min	30%
Vapor composition	0-16 normal	100-125 °C	0-100%	100%	10 min	40%
Vapor composition	1-3 normal	0.3-0.67 mhos	0-100%	200%	9 min	40%
Steam pressure	0-100 psi	0-100 psi	0-100%	50%	8 min	--
Calciner liquid level	56-60 liters	150-450 °C	0-100%	200%	240 min	60%
Evaporator pressure	-5 to +5 psi	-5 to +5 psi	0-100%	25%	1 min	40%

Range of Flows

	<u>Normal</u>	<u>Maximum</u>
Water	0-2 liters/min	0-10 liters/min
Feed	0-1 liters/min	0-4 liters/min
Condensate (calciner)	0-0.8 liters/min	0-1 liters/min
Calciner feed	0-1.2 liters/min	0-2 liters/min
Evaporator boilup	0-3 liters/min	0-6 liters/min

Evaporator Boilup

$$q = 84,000(p-9)^{1/2} \text{ (BTU/hr)}$$

$$Y = 0.7(p-9)^{1/2} \text{ (liters/min)}$$

P = steam pressure, psig

Valve Characteristics

where flow is in liters/min and v is fraction open

Water	$W = 10(v)^2$
Feed	$F = 4.0(v)^2$
Calciner Feed	$P = 2.0(v)^2$
Steam*	$p = 100(v)$ p is pressure in chest

* Effected by cascade controller.

PROPORTIONAL ACTION

Neglecting reset action for the moment, the control equations are of the form

$$df = -G_u du \quad (1)$$

$$dw = G_y dY \quad (2)$$

$$ds = -G_r dr \quad (3)$$

where u , y , and r are the input control signals ranging from 0 to 1 for the liquid level, the vapor acidity, and the density, respectively; and f , w , and s are the output control signals, ranging from 0 to 1 for the evaporator feed valve, the water addition valve, and the pressure setting. G is the proportional action (100/proportional band).

Define:

F = evaporator feed rate (liter/min)

V = evaporator liquid volume (liter)

W = water rate (liter/min)

Y = boilup rate (liter/min)

C = calciner condensate return rate (liter/min)

P = product withdrawal rate (liter/min)

ρ = density (g/cc)

a = acid concentration (N)

From instrument characteristics

$$u = \frac{V - 10}{20}, \quad V = 20u + 10 \quad (4)$$

$$y = \frac{a - 1}{2}, \quad a = 2Y + 1 \quad (5)$$

$$r = \rho - 1, \quad \rho = r + 1 \quad (6)$$

From valve and control characteristics

$$dF = 8fdF = 4\sqrt{F} dF \quad (7)$$

$$dW = 20wdW = 20\sqrt{\frac{W}{10}} dW \quad (8)$$

$$dY = \frac{0.35}{(p - 9)^{1/2}} dp = \frac{24.5}{Y} ds \quad (9)$$

Combining the above equation to eliminate the control signals

$$dF = -\frac{\sqrt{F}}{5} G_v dV \quad (10)$$

$$dW = \sqrt{10W} G_y da \quad (11)$$

$$dY = -\frac{24.5}{Y} G_r d\rho \quad (12)$$

Using the top of the normal range for the flow variables, and putting in the proportional action settings,

$$\frac{dF}{dV} = -0.572 \text{ min}^{-1} \quad (13)$$

$$\frac{dW}{da} = 2.25 \text{ (liter/min/unit normality)} \quad (14)$$

$$\frac{dY}{d\rho} = -8.1 \text{ (liter/min/g/cc)} \quad (15)$$

These settings are characteristic of the particular evaporator used, with its ratio of capacity to holdup, and were satisfactory not only for the top of the normal range, but also for transients which exceeded this by a reasonable amount and for the low demand associated with the end of the runs. They could be applied directly to any similar evaporator in this service and should be a good guide to control of an evaporator with slightly different ratios of capacity to holdup. Some adjustment would probably be desirable.

SYSTEM CHARACTERISTICS

As has been pointed out, the system variables are highly interdependent and analysis is not simple. It is illuminating, however, to consider the much simplified equations that result from considering separately the control loops for the three interesting variables. From these, characteristic times can be calculated.

A mass balance around the evaporator gives the equation

$$\frac{d(V\rho)}{dt} = \rho \frac{dV}{dt} + V \frac{d\rho}{dt} = \rho_f F + \rho_c C + \rho_w W - \rho_y Y - \rho P \quad (16)$$

where C = calciner condensate return.

If it is assumed that the volumes are additive

$$\frac{dV}{dt} = F + C + W - Y - P \quad (17)$$

The acid balance gives

$$V \frac{da}{dt} + \frac{adV}{dt} = Fa_f + Ca_c - Pa - Ya_y \quad (18)$$

If, for control of the liquid level, all streams remain constant except the feed, eq. (17), by differentiation, becomes

$$\frac{d^2V}{dt^2} = \frac{dF}{dt} \quad (19)$$

Using relation (13),

$$\frac{d^2V}{dt^2} = -0.572 \frac{dV}{dt} \quad (20)$$

This has the general solution

$$V - V_0 = ke^{-t/\tau} \quad (21)$$

where τ is the characteristic time, and is

$$\tau = \frac{1}{0.572} = 1.75 \text{ min} \quad (22)$$

In treating the density control, assume that the liquid level is maintained during increased boilup by the appropriate addition of feed ($dY = dF$, $dV/dt = 0$). Equation (16) becomes

$$V \frac{d^2\rho}{dt^2} = \rho_f \frac{dF}{dt} - \rho_Y \frac{dY}{dt} - P \frac{d\rho}{dt} = (\rho_f - \rho_Y) \frac{dY}{dt} - P \frac{d\rho}{dt} \quad (23)$$

Using relation (15)

$$\frac{d^2\rho}{dt^2} = - \frac{[(\rho_f - \rho_Y)8.1 + P]}{V} \frac{d\rho}{dt} \quad (24)$$

For typical values, $V = 22$ liters, $(\rho_f - \rho) = 0.2$, the characteristic time at zero product withdrawal is 13.6 min, and with a high product rate of 1.2 liters/min, the characteristic time is 7.8 min.

The treatment of the acid control requires an equilibrium relation. In the operating range of the evaporator, the vapor concentration (a_y) is related to the total nitrate in the liquid (a_e) approximately by $da_y = 3da_e$. If it is again assumed that the liquid level is maintained by

properly adjusting the feed rate as water is added to adjust the acid, $dF = -dW$. Differentiating equation (18) and making the indicated substitutions gives:

$$V \frac{d^2 a_e}{dt^2} = a_f \frac{dF}{dt} - P \frac{dA}{dt} - Y \frac{da}{dt} = - (2.25a_f + Y) \frac{da}{dt} - P \frac{da_e}{dt} \quad (25)$$

$$\frac{d^2 a_e}{dt^2} = - \frac{1}{V} \left[\frac{(2.25a_f + Y)}{3} + P \right] \frac{da_e}{dt} \quad (26)$$

Using $a_f = 6 \text{ N}$, $Y = 3 \text{ liters/min}$, $P = 1.2 \text{ liters/min}$, and $V = 22 \text{ liters}$, the characteristic time is 3.3 min. Again, the characteristic time increases as P and Y decrease.

These characteristic times are significant in two aspects: they give a basis for the reset rates on the controllers, and they give criteria for the tolerance in dead times and lag times in instrument response (which should be an order of magnitude less than the characteristic times). The reset times given for all three controllers were 10 min. The characteristic time for the density control had a hidden reset time in the cascade control of pressure which increased the effective reset time to about 16 min. This is probably fast but was necessary in order to accommodate changes in load imposed by the other variables.

It is to be emphasized that the gross simplification of this analysis destroys its utility for direct application to the system, and its purpose was only to form a rational basis for presenting experimentally derived numbers in a form that, at least in part, separates them from the peculiarities of the particular instruments used.

The possibility of using derivative control on some of the controllers was considered and found to be unnecessary.

BATCH EVAPORATION

In the Unit Operations studies the control system for the batch evaporator which was used, and the one which is recommended consists of using the density signal to control the boilup rate and the acid concentration of the vapor to control the water addition rate. Since an entire batch was added to the evaporator at the start of the run, it was not necessary to control the liquid level. The batch was initially concentrated to the desired density, and as the condensate from the calciner pot being run at the same time was introduced to the evaporator, water adequate to effect proper dilution was automatically added and the boilup rate automatically increased. The settings for proportional band and reset rate were the same as used in the continuous runs. Because of the large capacitance of the system and the fewer number of variables, this is a much simpler system to control and elaboration is not felt warranted.

GENERAL COMMENTS

The control system presented here was selected after considering all of the attractive alternatives. Some alternatives were discarded because they involved the measurement of flow rates of difficult to handle streams. The alternative which received the most attention used the boilup rate to control the liquid level, and the feed addition rate to control the density. The small density difference between the evaporator product and the feed along with the cross effect of boilup rate on apparent liquid level gave instabilities which could not be overcome.

Similarly, the instrumentation used in this control system evolved through much trial and error, and is thought to be adaptable directly to the hot pilot plant. In most cases the precision of the instruments, which is the necessary feature for stable control, was good. The accuracy of the instruments was acceptable, and, with the normal course of sampling and general observation of the process, should give no trouble. The estimated precisions and accuracy are given below.

	<u>Precision</u>	<u>Accuracy</u>
Evaporator density measured by air bubblers in an external chamber	1%	3%
Evaporator density by a float device	2%	5%
Evaporator liquid level by air bubbler	1%	4%
Evaporator pressure	1%	3%
Vapor acid concentration by electrical conductivity	2%	5%
Vapor acid concentration by vapor temperature	5%	45%
Liquid level in the calciner pot by temperature probe	1%	10%

These numbers are representative of the system in service, not emaculate, but not badly fouled.

An interesting note on density control is that a 1% change in density represents about a 4% change in solids concentration under operating conditions. Although the float type density instrument (the "Mackey cell") situated on a recycle line was used for most of the work, it is thought that an external chamber with an air bubbler would be preferable for reliability and probably for precision. The chamber used had a volume of about one liter. These instruments were used in the pump loop which recirculated the evaporator solution to the calciner feed valve.

When using the electrical conductivity of the evaporator condensate for control, particularly if the whole vapor stream is not condensed, care should be taken to avoid excessive lag times which might be introduced by the transport of the stream to the instrument. It is also necessary to avoid a fractionation due to partial condensation and to make some provision for adequate drainage and removal of noncondensables.

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