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SUBJECT: Characterization of Decontamination Factors for Evaporators Used in the Treatment of Low and Intermediate Level Liquid Radioactive Wastes

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ABSTRACT

Evaporator decontamination factors were studied as functions of boiloff rate, volume reduction, and feed pH. A bench-scale vertical tube evaporator operating on simulated intermediate level nuclear wastes was used. Decontamination factors were not found to be strong functions of volume reduction or boiloff below vapor velocities of 25 lb/ft^2-hr. At higher vapor fluxes, splashing was encountered. Foaming occurred at a feed pH of 6 but not at higher values. The presence of radioisotopes in the feed had no effect on evaporator performance.

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Contents

1. SUMMARY

The performance of a nuclear waste evaporator was characterized as a function of boiloff rate, feed pH, and the extent of volume reduction. The effect of radioisotopes in the feed and the effect of physical properties of the evaporator thick liquor on performance were also evaluated.

Entrainment of small liquid droplets by the rising vapor, direct splashover of large liquid parcels into the condenser, and foaming limit evaporator decontamination performance. Physical and chemical properties of the feed, evaporator geometry, and the degree of turbulence in the boiler are known to affect these phenomena.

A bench-scale, semi-batch evaporator system similar to the full-scale models used at nuclear facilities was employed. The feed used was typical of intermediate level nuclear wastes containing Na^+, NH_4^+, Ca^{+2}, Sr^{+2}, Cs^{+1}, NO_3^-, and SO_4^{-2} ions. Ten runs of approximately 12-hr duration were made in which each parameter studied was varied independently.

Results show that boiloff rate has little effect on decontamination performance in the range of 4 to 25 lb/ft^2-hr. Higher boilup rates produced splashover. This behavior is not in agreement with the correlation given in Perry's Handbook (18). Sodium decontamination factors (concentration of impurities in feed/average concentration of impurities in condensate) at various boiloff rates compare favorably with data from the Cessna and Badger (2) study using sodium chloride feed. Overall decontamination factors (DFs) were somewhat lower ($\sim 10^3$ versus 10^4 for Na^+) probably due to the presence of unstable compounds, e.g., NH_3OH, and particulates, e.g., $CaCO_3$, in the thick liquor.

Increasing the volume reduction factors (volume of feed processed over volume of thick liquor) up to sixty had no adverse effects on decontamination. Typical average system decontamination factors were on the order of 10^3. Entrainment apparently decreases as the volume reduction factor (VRF) increases, since if it did not, the greater concentration of impurities in entrained droplets at high VRFs would lower the decontamination factor.

The effect of pH was studied by adjusting its value of 11 in the original feed with nitric acid. A feed pH of six produced severe foaming while pHs of 8 and 11 did not. Sudden changes in the thick liquor pH and surface tension corresponded to the onset of foaming. An abrupt change in particulate loading in the liquor may have caused these effects. The presence of radioisotopes ^{137}Cs and ^{85}Sr had no effect on decontamination performance.

Different decontamination factors were obtained for different chemical species during the same run. Calcium DFs were significantly lower (1-2 orders of magnitude) than sodium DFs. However, strontium DFs were more comparable to sodium which suggests that the entrainment mechanism is component dependent.

The ratio of volume of liquor to volume of vapor in the evaporator was found to be a critical parameter in evaluating evaporator performance. Further study of this variable is recommended. More intense study of the chemistry of the typical waste and the mechanism of entrainment is also recommended. Physical de-entrainment devices should also be evaluated.

2. INTRODUCTION

With the exponential growth in demand for electricity and increasingly stringent air pollution control legislation, nuclear power looks attractive for the future. Disposal of liquid radioactive wastes must be accomplished safely and efficiently before nuclear power can be fully utilized to meet future energy demands. Evaporation is one step in concentrating radioactive waste and reclaiming a large percentage of the water for recycling.

The effects of boiloff rate and feed pH were studied to optimize conditions for evaporating typical nuclear installation wastes. The extent of volume reduction which is permissible was also examined. To accomplish these objectives, a simulated waste was evaporated at various vapor fluxes, feed pHs, and to various volume reduction factors.

The performance of an evaporator is characterized by a decontamination factor. Four DFs have been used to describe semi-batch operation:

1. Instantaneous equipment DF,

$$(DF)_{ei} = \frac{\text{thick liquor concentration at any time}}{\text{condensate concentration at that time}}$$

2. Instantaneous system DF,

$$(DF)_{si} = \frac{\text{feed concentration at any time}}{\text{condensate concentration at that time}}$$

3. Average equipment DF,

$$(\overline{DF})_{e} = \frac{\text{average thick liquor concentration}}{\text{average condensate concentration}}$$

4. Average system DF,

$$(\overline{DF})_{s} = \frac{\text{average feed concentration}}{\text{average condensate concentration}}$$

The volume reduction factor is defined as:

$$\mathrm{VRF} = \frac{\text{volume of feed processed}}{\text{volume of thick liquor}}$$

$(\overline{\mathrm{DF}})_e$ is related to $(\overline{\mathrm{DF}})_s$ as follows:

$$(\overline{\mathrm{DF}})_e = \frac{1}{2}(\overline{\mathrm{DF}})_s(1 + \mathrm{VRF})$$

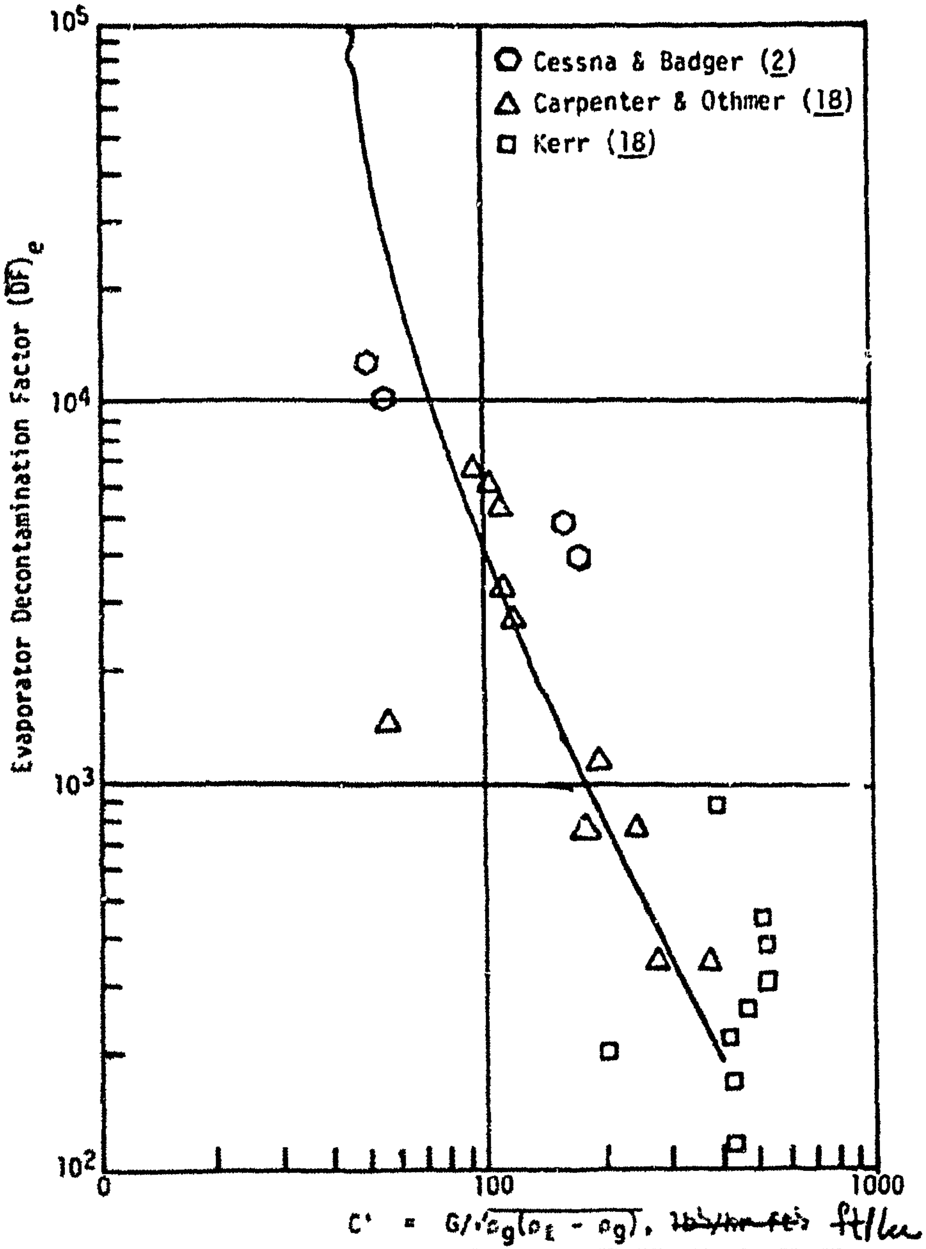
The DF of greatest interest to the nuclear industry is the average system DF because it gives the most precise measurement of actual condensate quality.

Three phenomena are known to cause undesirably low decontamination factors. The first is the entrainment of small liquid droplets by the rising vapor. Small droplets form in a boiling liquid in two ways: (1) as a vapor bubble reaches the surface, the skin of liquid on top breaks scattering droplets whose diameters are on the order of 60 μ (8) and (2) the rarefaction caused by the passing of the bubble causes much larger droplets to be jetted into the vapor space. The size and rate of ascent of vapor bubbles in the liquid largely determine droplet sizes. The larger droplets produced in the bubbles' wake are a major source of entrainment unless they fall back into the liquid. Whether a droplet falls back into the liquid is determined by whether the terminal falling velocity is greater than or less than the vapor velocity. At Reynolds numbers < 0.3 the terminal falling velocity of a droplet may be calculated from Stokes Law: $u_T = gD_D^2(\rho_D - \rho)/18\mu$. At a vapor mass velocity of 20 lb/hr-ft^2 the smallest droplet which would fall back into liquid water is 280 μ in diameter.

For a given evaporator, boiloff rate affects the size and rate of ascent of vapor bubbles and hence droplet size. This effect is complicated and poorly understood. At high boilup rates entrainment increases with increasing mass velocity since droplet size apparently changes more slowly than mass velocity. The empirical correlation depicted in Fig. 1 shows this effect. The curve plotted is the best average of data in which there is considerable spread.

In contrast, at very low boilup rates ($G/\sqrt{\rho_g(\rho_\ell - \rho_g)} < 10$) entrainment increases with decreasing boilup rate, since very gentle boiling allows the vapor bubbles more time to collapse and hence produce smaller droplets (18). Therefore, an optimal vapor mass velocity for minimum entrainment should exist between these two regimes of behavior.

Another phenomenon affecting evaporator performance is splashover. When boiling becomes very turbulent, large parcels of liquid can splash over into the condenser. This occurs at very high boilup rates and is usually combated with impingement baffles covering the condenser inlet, or by using a large vapor space.



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CORRELATION OF DECONTAMINATION
FACTOR VERSUS C′ (18)

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The third phenomenon affecting DFs is foaming. Foaming is a coarse dispersion of a gas in a liquid, most of the volume being gas with thin films of liquid separating the gas bubbles. Foaming lowers evaporator DFs by raising the effective liquid level and can be caused by surface tension depressing agents or finely suspended particles.

Several factors affect the stability and persistence of foams. High dynamic surface tension and viscosity make bubbles less apt to burst. For a given feed composition, the pH of the boiling liquid has been found to affect foaming. Figure 2 shows one such correlation for a forced circulation evaporator employing a cyclone demister. Foam is very sensitive to sudden changes in liquid surface tension and hence foam-breaking heating coils at the liquid surface are sometimes effective.

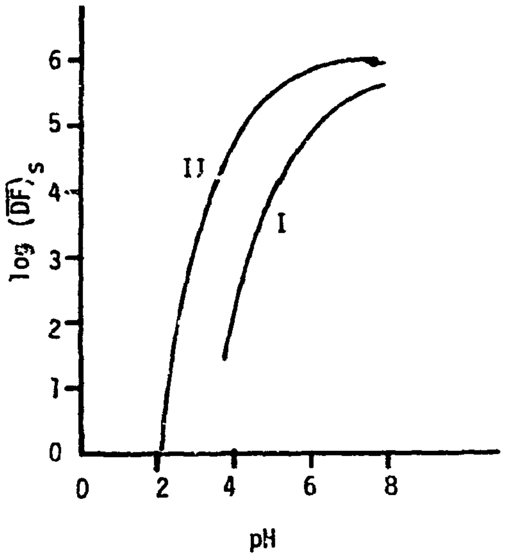
3. APPARATUS AND PROCEDURE

A bench-scale vertical tube evaporator was used for the experiments. The process flow schematic diagram is shown in Fig. 3 while photographs of the apparatus are presented in Appendix 8.2. A simulated nuclear facility intermediate level waste (see Appendix 8.1) was fed into the evaporator. The feed tanks were agitated to keep solids ($CaCO_3$, $SrCO_3$, $CaSO_4$, and $SrSO_4$) in suspension. The feed was transferred to the evaporator bottom by bellows pumps, and the liquid volume was maintained approximately constant at 200 ml for most runs. Vapor exiting from the dome was condensed in a shell and tube heat exchanger and collected in a catch tank.

For startup an initial charge of waste was placed in the feed tanks and pumped over into the evaporator to the desired level. Electrical power was then applied to the tubes, and the feed rate was matched to the boiloff rate to keep the liquid level constant. Eleven to twelve liters of feed were evaporated on a typical run, and periodically the three-liter condensate tank was emptied. At this time 100 ml of condensate was withdrawn from the condenser effluent line (see Figs. 13 and 14 in Appendix 8.2). This sample was considered to be instantaneous. A 10-15 ml concentrate sample was also withdrawn. Electrical conductivity and pH measurements were made on all samples. Samples were coded and saved for later physical property measurements and analysis.

At the end of a run the condensate tank was drained and power and pumps shut down. Evaporator concentrate and residual condensate were drained and a mass balance closed on the evaporator. For runs with radioactive feeds, all samples were counted on a gamma scintillation counter to determine DFs for the radioisotopes.

Five runs were made at boiloff rates from 4 to 28 lb/ft^2-hr with a volume reduction factor of sixty achieved on most runs. Another series of runs was made at feed pHs of 11, 8, and 6, and a final series compared nonradioactive feed to feeds containing intermediate levels of ^{85}Sr and ^{137}Cs.



I. Feed Stabilized with $SO_3^=$

II. Feed Stabilized with $S_2O_3^=$

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CORRELATION OF AVERAGE SYSTEM DECONTAMINATION FACTOR VERSUS FEED pH (4)

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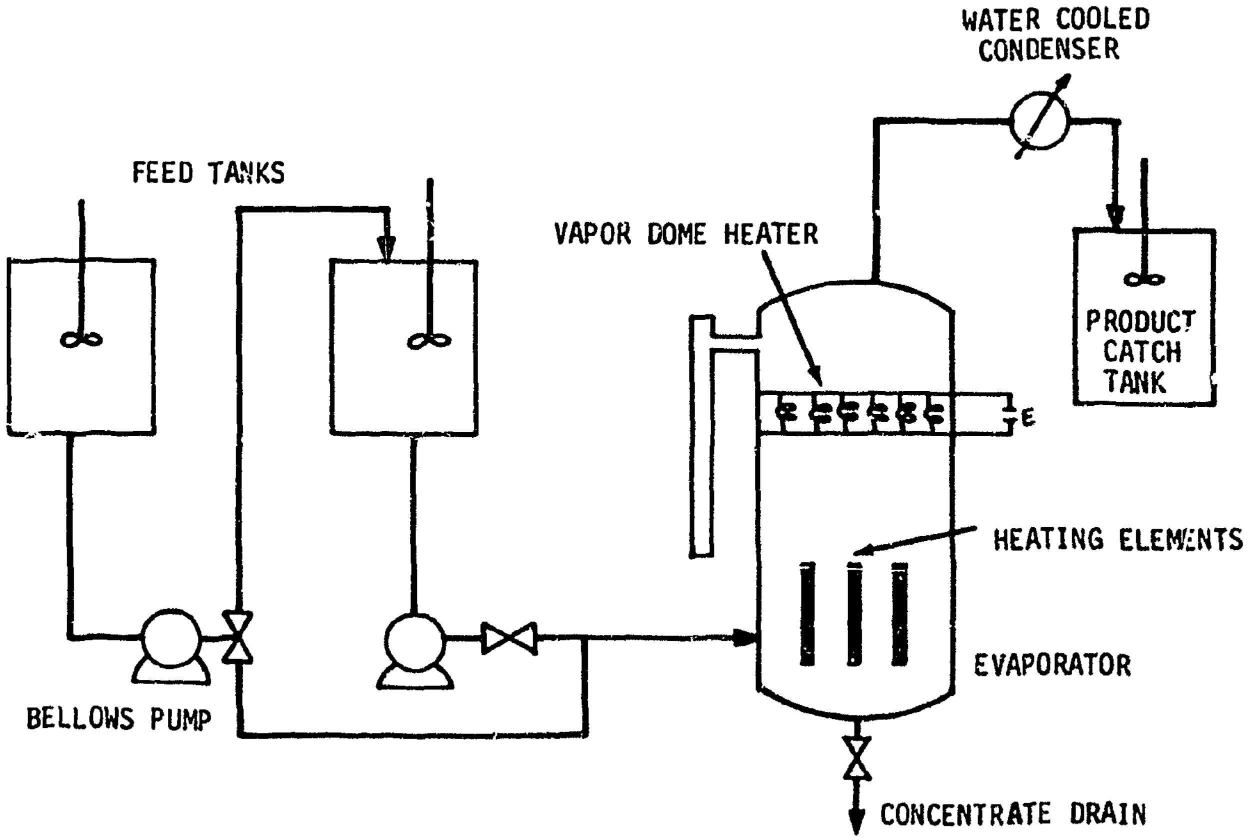


FIG. 3. EVAPORATOR PROCESS FLOW

4. RESULTS AND DISCUSSION OF RESULTS

Figures 4 through 10 and Table 1 show the major results. Variable operating conditions are indicated. All decontamination factors are based on electrical conductivity measurements as described in Appendix 8.2. Additional results are given in Appendix 8.1.

Table 1. Specific Ion System $(\overline{DF})_s$

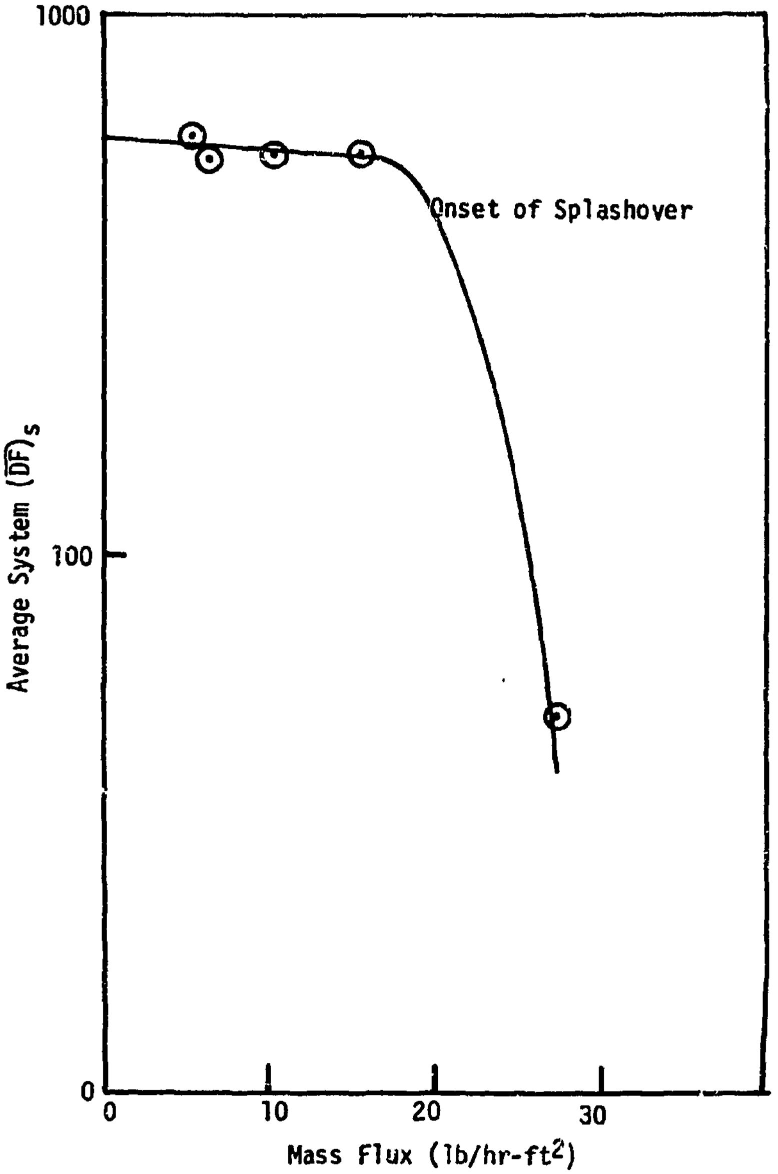
Boiloff Rate (lb/ft^2-hr)	Na $(\overline{DF})_s$	Ca(S) $(\overline{DF})_s$	Ca(T) $(\overline{DF})_s$
5.32	1.3×10^4	4.08	866.7
5.42	5.6×10^3	3.77	800.0
6.48	3.23×10^4	3.27	693.3
10.17	7.6×10^3	2.72	577.8

$(\overline{DF})_s$ = average system decontamination factor
(S) = supernate
(T) = total of supernate and solid

Figure 4 shows that vapor flux has little effect on evaporator performance until mass velocities in excess of 25 lb/ft^2-hr are reached. At this point the $(\overline{DF})_s$ falls precipitously, due to direct splashover of liquid into the condenser. This splashover was visually apparent, as the condensate became cloudy when the $(\overline{DF})_s$ fell off. The arrangement of heating tubes around the condenser inlet may have acted as a funnel, increasing the likelihood of splashover.

Figure 5 shows a comparison of boiloff rate data to that of Cessna and Badger taken on a pilot plant scale forced circulation evaporator (3, 18). Cessna's evaporator was operated in a quasi-continuous mode, and the thick liquor composition remained approximately constant at 10 wt % NaCl. The overall system DFs obtained were an order of magnitude lower than Cessna's, but available sodium DF data compare favorably (see Table 1). The lower overall system DF was probably caused by the presence of unstable compounds such as NH_4OH and $Al(NO_3)_3$ and particulates such as $CaCO_3$ and $CaSO_4$ in the thick liquor. Also, the forced circulation evaporator employs deflectors which decrease entrainment.

Specific ion decontamination factors show that calcium was apparently entrained preferentially to sodium at all boilup rates (see Table 1). Based on the composition of the feed (Table 2, Appendix 8.1) no calcium complex



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EFFECT OF VAPOR FLUX ON SYSTEM
DECONTAMINATION FACTOR

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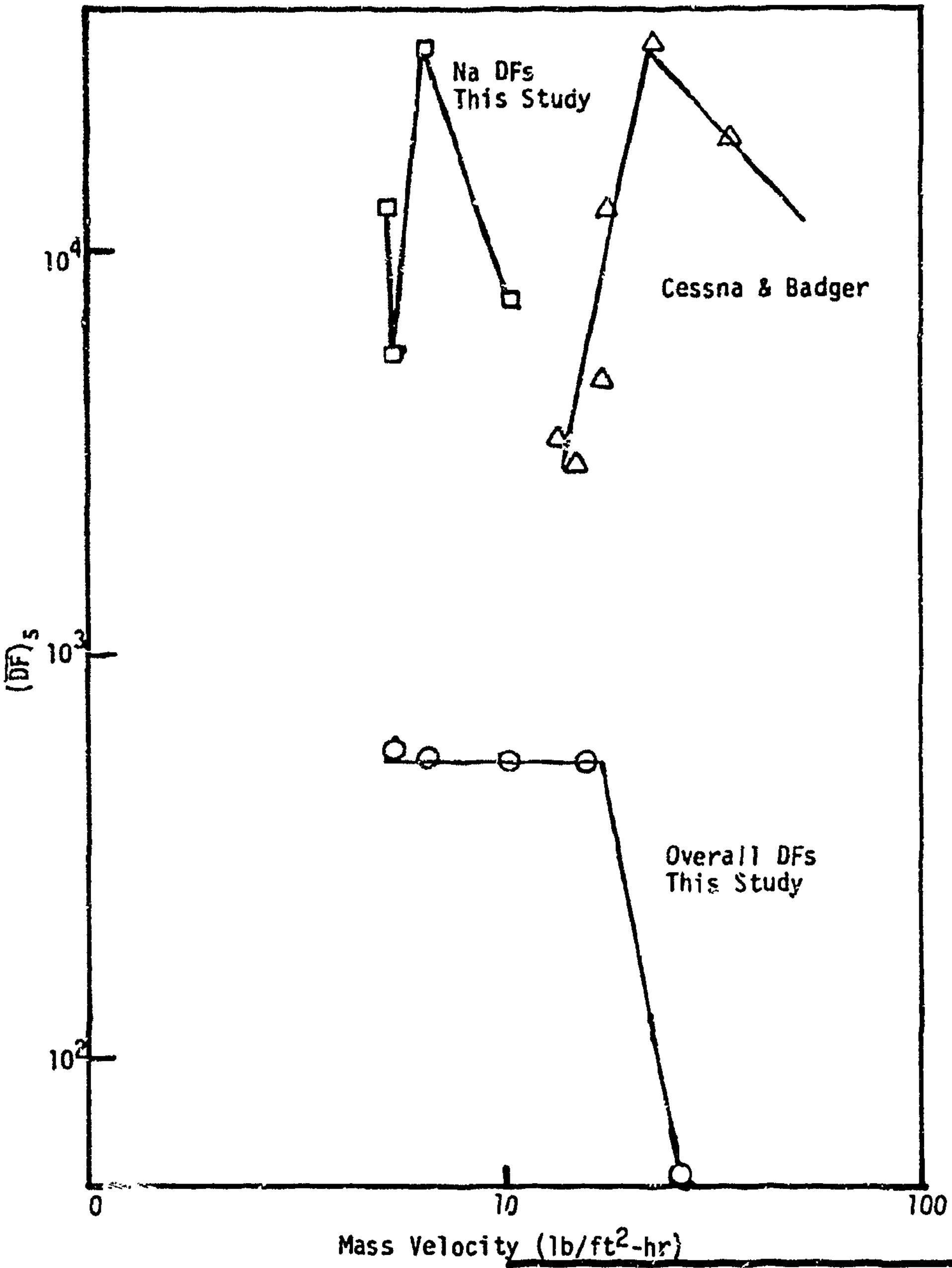

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COMPARISON OF DATA FROM THIS STUDY TO
THAT OF CESSNA AND BADGER

DATE	DRAWN BY	FILE NO.	FIG.
9-25-72	CGL	CEPS-X-152	5

which is volatile could be found. The only likely explanation is that calcium solids (sulfate and carbonate) formed colloidal sized particles, became separated from the feed by the turbulence of boiling, and were carried into the condensate stream as aerosols. The maximum particle size which would be carried over at boilup rates studied is 220 μ. The analytical techniques used could not differentiate between colloidal and ionic calcium. In contrast, DFs obtained by counting ^{85}Sr were not as low as calcium DFs.

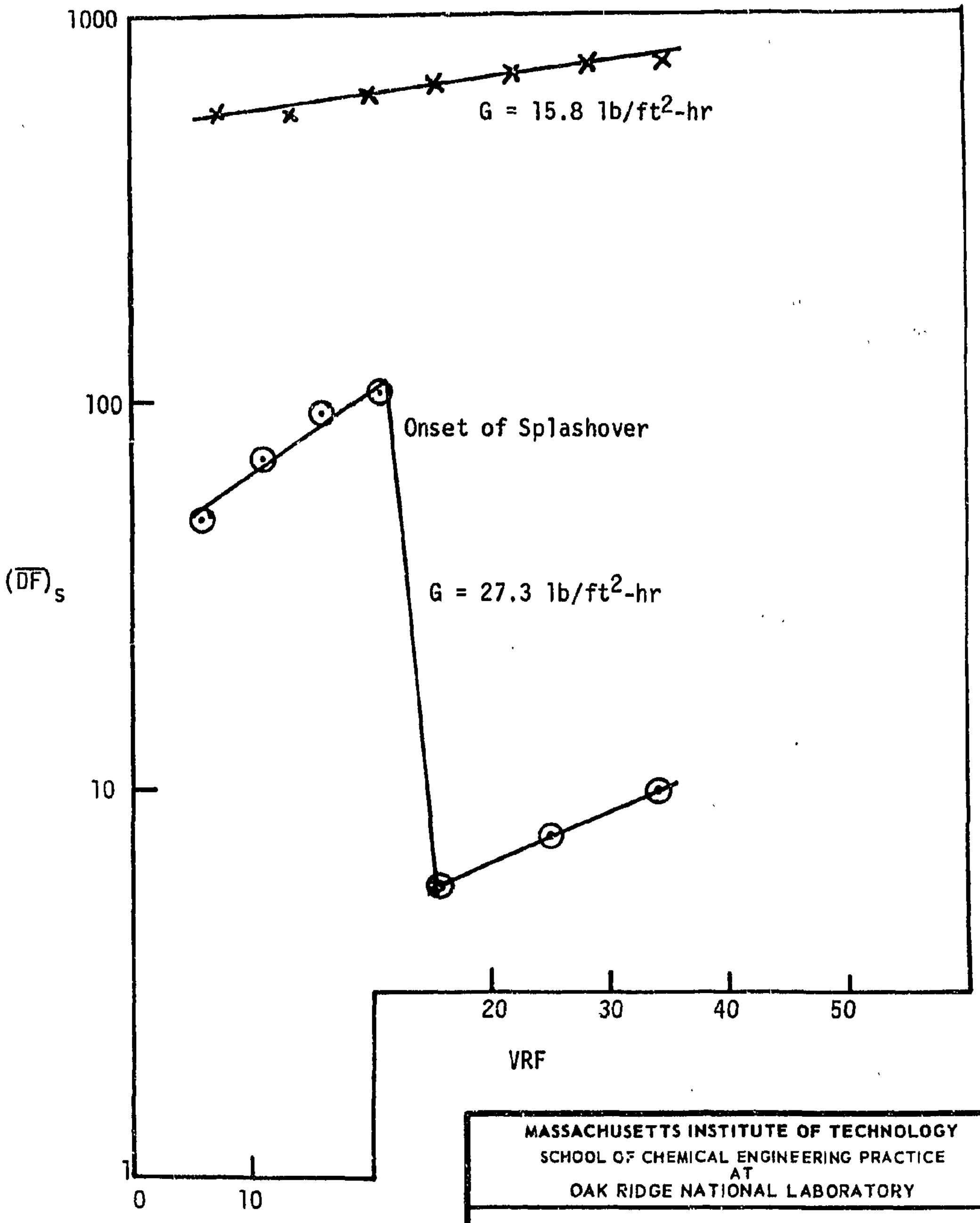
At boiloff rates below 25 lb/ft^2-hr, volume reduction factors had little effect on evaporator performance, at least up to 60:1. The upper line on Fig. 6 is representative of most runs. The lower line shows a sharp discontinuity resulting from splashover and emphasizes the fact that one serious splash can ruin a large volume of product.

One might predict that if the degree of entrainment remained the same throughout a run, DFs would fall off with an increase in VRF because the entrained liquid would have a progressively higher concentration. Since most results are inconsistent with this prediction (see Figs. 6, 7, and 8), apparently entrainment decreases (possibly due to surface tension changes) as VRF increases. High speed photography might clarify this.

Figure 7 shows the time history of three runs at a fixed boilup rate of 27 lb/ft^2-hr in which feed pH was varied by adding HNO_3. At the original feed pH of 11 some splashover was encountered. The line representing this run is an average which is representative of what the run should look like without the splashover. The line for pH = 8 is a good fit to the data since little splashover was encountered due to better liquid level control. The line for feed pH = 6 shows an abrupt discontinuity which corresponds to excessive foaming. Since no foaming occurred on the other runs plotted, basic feed pHs appear to be optimal.

The effect of ^{137}Cs and ^{85}Sr on evaporator performance is shown in Fig. 8. These runs were essentially identical and produced similar results. The line for the cold feed has a slightly different slope than the others since startup liquid level problems developed on that run and hence the initial DFs were low. Feeds were adjusted with ^{85}Sr and ^{137}Cs at concentration levels of 10^5 counts/min/ml. DFs determined by counting the radioactivity in the condensate are included in Table 5 of Appendix 8.1.

Near the end of the feed pH = 6 run, severe foaming occurred. Surface tension and pH histories of the thick liquor are plotted in Fig. 9. The same curves for a non-foaming run are shown in Fig. 10. In Fig. 9 the peaks in both curves correspond to a point just before foaming began. This correlation is believed to result from an abrupt change in particulate loading in the liquor which would severely lower the surface tension by disturbing the symmetry of intermolecular forces at the liquid surface. A bicarbonate-carbonate shift might have precipitated calcium carbonate, but bicarbonates should have shifted at a lower pH. It is also possible that small amounts of calcium and strontium reached saturation with hydroxide and began to precipitate accounting for the relatively constant pH and the sudden dip in surface tension. It is interesting to note that based on a



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EVAPORATOR PERFORMANCE AS A FUNCTION
OF VOLUME REDUCTION FACTOR

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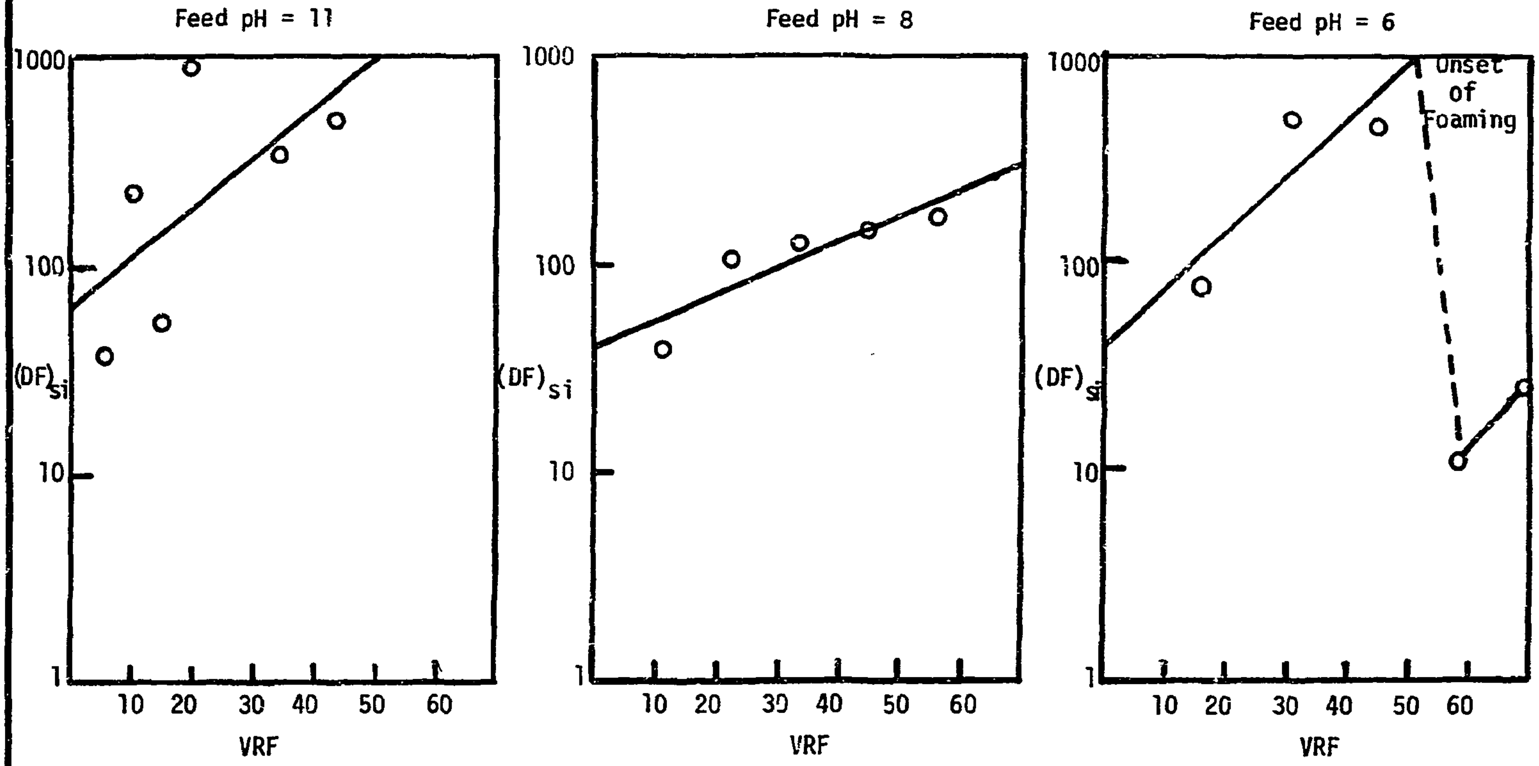

Boiloff rate = 27 lb/hr-ft^2

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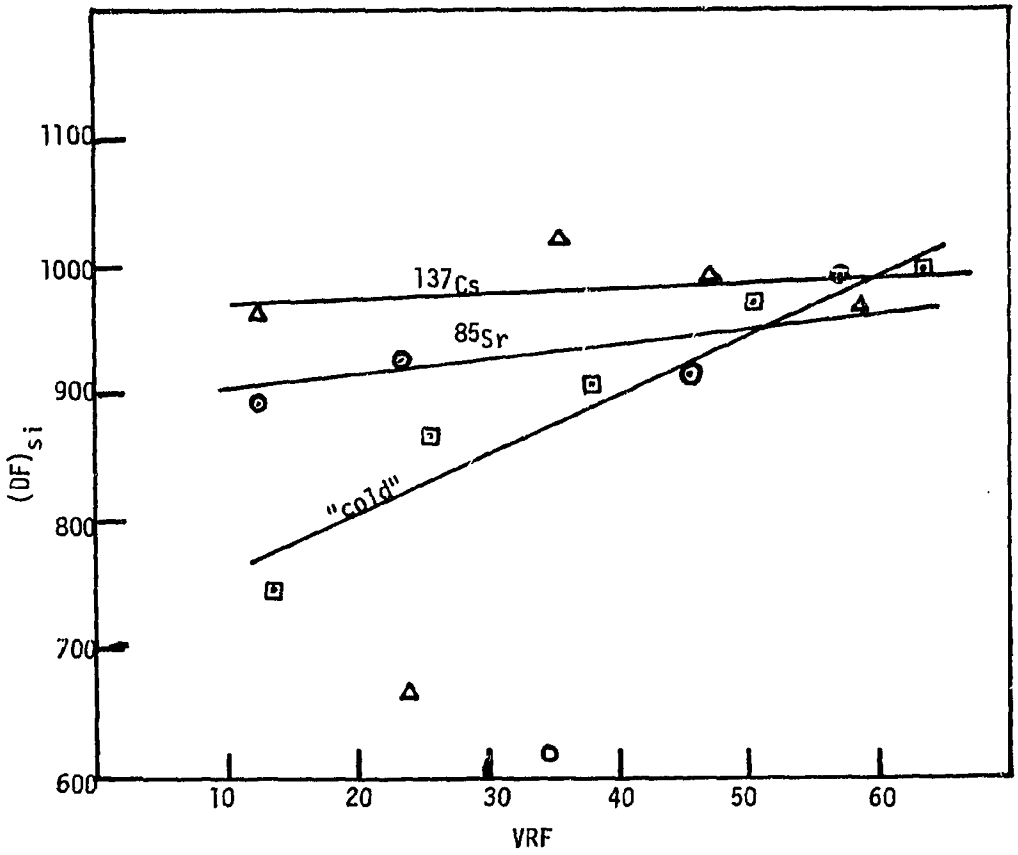
TIME HISTORIES OF $(DF)_{si}$
FOR VARIOUS FEED pHs

DATE	DRAWN BY	FILE NO.	FIG.
9-25-72	LBR	CEPS-X-152	7



Boiloff rate = 15.8 lb/hr-ft^2

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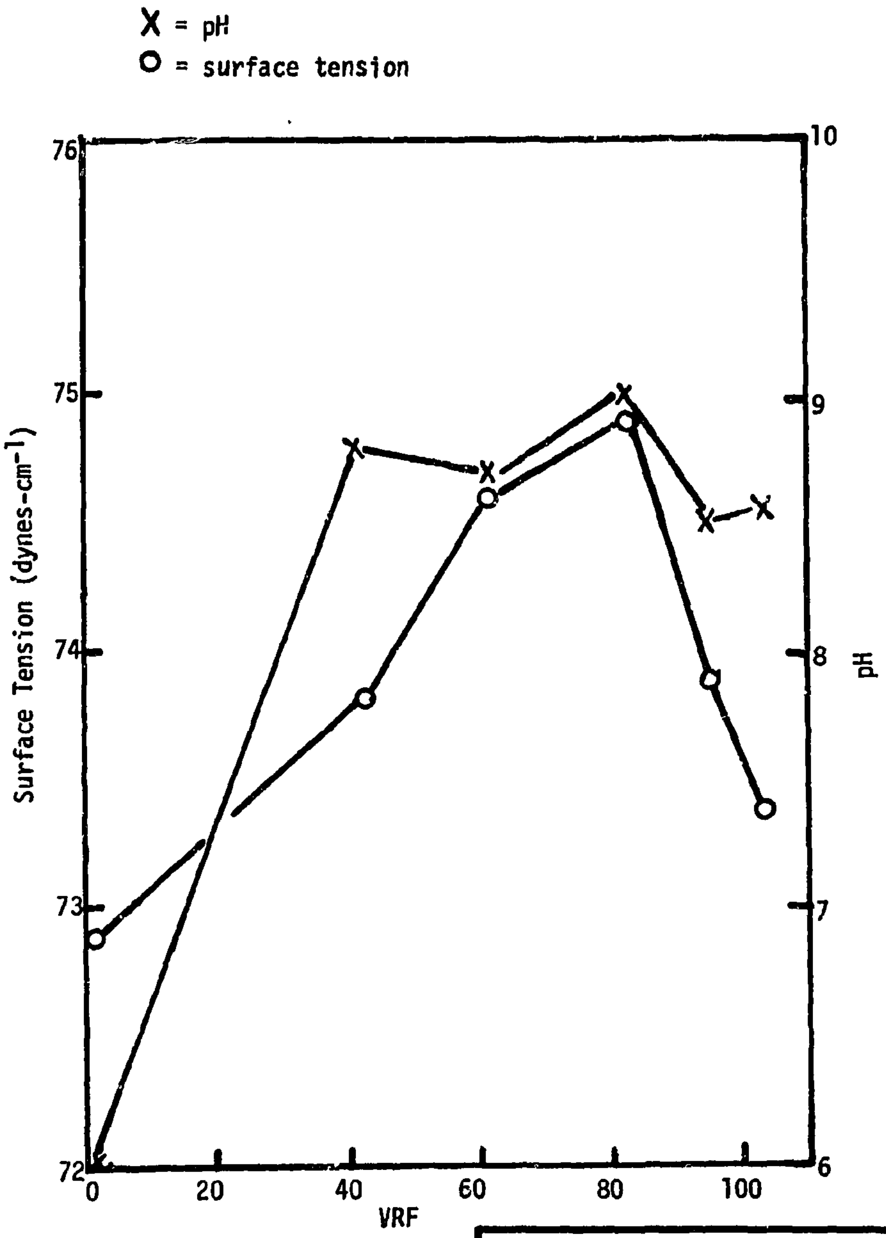
TIME HISTORY OF THE EFFECT OF RADIOISOTOPES ON EVAPORATOR PERFORMANCE

DATE	DRAWN BY	FILE.NO.	FIG.
9-25-72	LBR	CEPS-X-152	8



Boiloff rate = 27 lb/hr-ft^2

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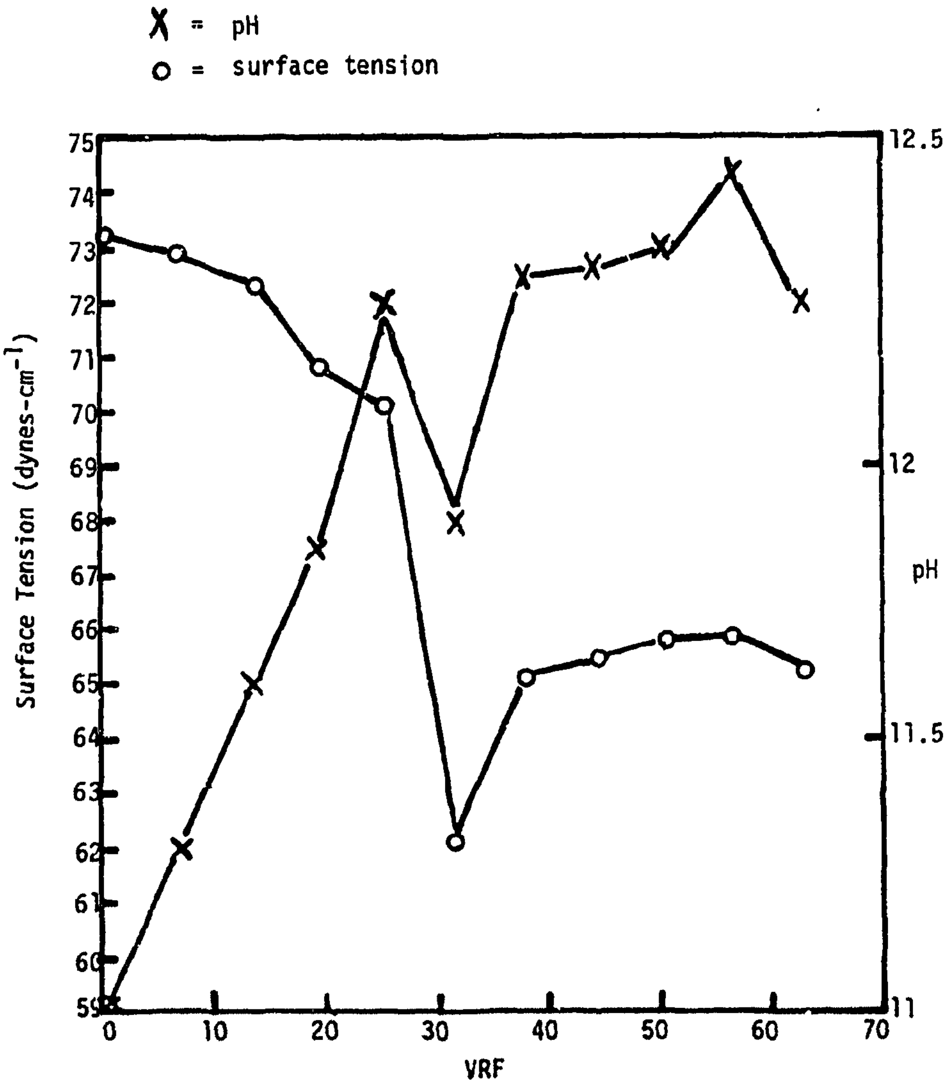
TIME HISTORY OF THICK LIQUOR pH AND
SURFACE TENSION AT FEED pH = 6
(See Table 3)

DATE	DRAWN BY	FILE NO.	FIG.
9-25-72	LBR	CEPS-X-152	9



Boiloff rate = 15.8 lb/hr-ft^2

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TIME HISTORY OF THICK LIQUOR pH AND
SURFACE TENSION FOR FEED pH = 11
(See Table 4)

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9-25-72	LBR	CEPS-X-152	10

qualitative settling study, the precipitates from this run were more finely divided than for the higher pH runs. The viscosity of the final thick liquor for the foaming run is also much higher than for other runs (see Fig. 11). High viscosity is known to stabilize foams possibly by increasing the resistance of liquid films to breakage. A thorough study of the solubilities of all possible complexes in the pH range of this run might produce considerable insight into the foaming problem. Analytical results of liquor samples pulled before and during foaming are not yet available.

Several operating problems were encountered. Good control of liquid level was not possible with existing apparatus. Variations in liquid level of up to 25% were encountered; 10-15% was typical. Since the ratio of liquid volume to vapor volume is a critical factor for carryover phenomena, much of the spread in experimental data may be due to liquid level fluctuations.

Another possible operating problem was reflux. During initial runs, vapor chamber temperatures were at 90°C and heat losses were significant. Reflux could account for the lack of variation in decontamination factors as boiling rate was increased below 25 lb/ft^2-hr, by physically sweeping away entrained liquid. This effect has been noted by other investigators (21). However, a vapor dome heater was added for later runs, and results were about the same at low boilup rates. Since none of the initial runs were repeated, it is not possible to judge the effect of reflux.

5. CONCLUSIONS

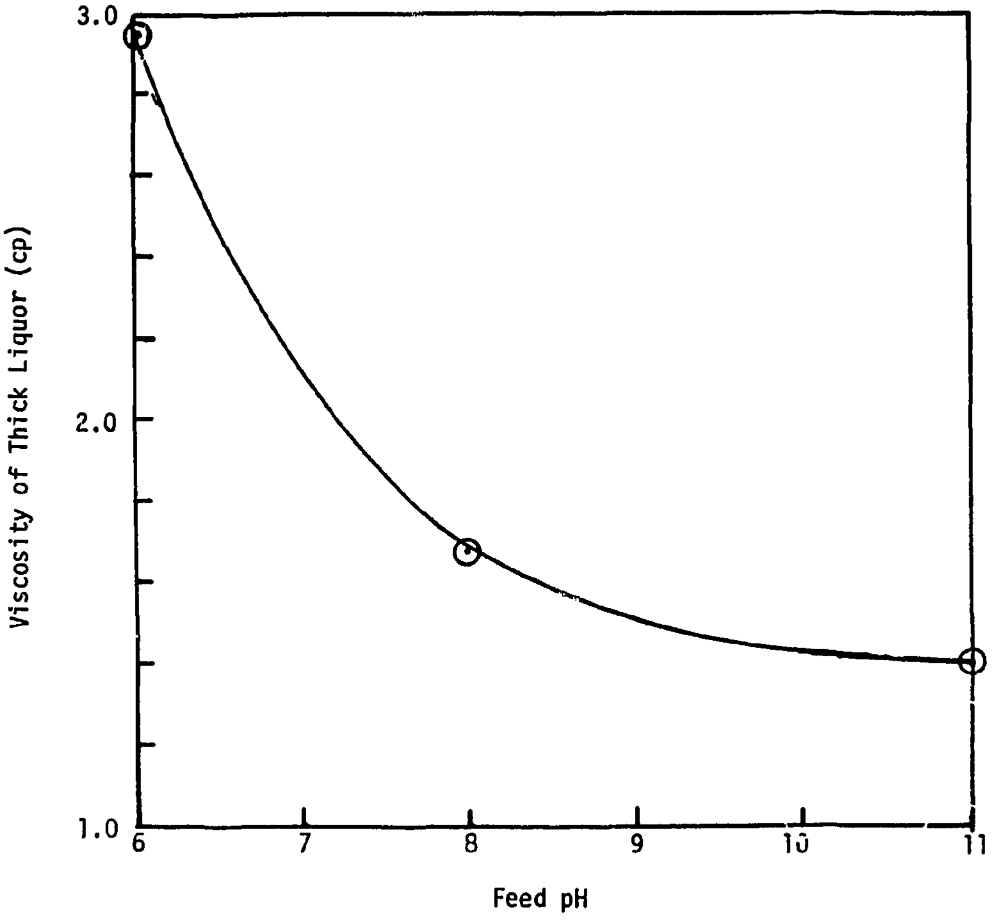
Based on our results, evaporators can be operated at high boilup rates (<25 lb/ft^2-hr) without excessive product contamination until splashover begins. For our feed composition, the entrainment mechanism is apparently component specific, since calcium decontamination factors are much lower than those for sodium, implying that calcium (mostly in particulate form) is a major cause of unacceptable evaporator performance.

High volume reduction factors (at least up to sixty) are entirely feasible provided splashover or foamover are avoided. Basic feed pHs (8 - 11) are optimal since foaming occurs at slightly acid pH (∿6). Radioisotopes apparently have little or no effect upon evaporator performance.

6. RECOMMENDATIONS

1. The effect of liquid level on evaporator performance needs further study. To achieve better liquid level control on the present equipment, the following changes should be made:

   a. Feed and condensate tanks should be accurately calibrated so that liquid level in the evaporator can be determined by difference.



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FINAL THICK LIQUOR VISCOSITY
VERSUS FEED pH

DATE	DRAWN BY	FILE NO.	FIG.
9-25-72	LBR	CEPS-X-152	11

b. A constant displacement pump should replace the bellows pump so that pumping rate into the evaporator can be precisely measured and matched to boiloff rate.

c. Conductivity probes should be placed along the walls of the flash chamber to indicate rising liquid level or to control the level automatically.

2. The effect of reflux could be studied by installing a glass vapor dome. Entrainment studies would also be facilitated since high speed photography could be used on the vapor space.

3. The effect of feed pH on foaming tendencies requires further study under conditions less susceptible to splashover. The use of an impingement baffle to reduce splashover is suggested. A larger glass boiler to provide more liquid surface would also reduce splashover by reducing the tendency for jets of liquid to funnel into the condenser between heating elements.

4. Trace organics should be added to feed to determine their effect on foaming.

5. Antifoam agents should be studied.

6. The effectiveness of several physical entrainment devices should be evaluated.

7. ACKNOWLEDGEMENTS

We wish to thank our consultant, H.W. Godbee, for his invaluable advice and help. We would also like to express our gratitude to R.C. Lovelace and J.R. Collins for their assistance with taking data.

8. APPENDIX

8.1 Additional Data

Tables 2 through 5 give additional information discussed in Sect. 4. Figure 12 shows the calibration of the electrical conductivity meter used to determine decontamination factors.

Table 2. Feed Composition
(feed pH $\cong$ 11)

Species	Concentration (eq/ℓ)
NaOH	0.013
$Al(NO_3)_3 \cdot 9H_2O$	0.00042
NH_4NO_3	0.00010
$NaNO_3$	0.027
NaCl	0.0031
$Na_2SO_4 \cdot 10H_2O$	0.0028
Na_2CO_3	0.013
$Ca(NO_3)_2 \cdot 4H_2O$	0.0026
$Sr(NO_3)_2$	0.0050
$CsNO_3$	0.0091

Table 3. Data for Fig. 9

VRF	Surface Tension (dynes/cm)[a,c]	Liquor pH[c]
Feed	72.9	6.00
15.1	73.3	8.80
29.3	73.8	8.80
43.3	74.6	8.65
57.5	74.9	9.00
66.8[b]	73.9	8.50
71.7	73.4	8.46

Boiloff rate = 27 lb/ft^2-hr

[a] Ninety-five percent confidence limit on surface tension measurements is ±0.104 using t distribution.

[b] Time averaged.

[c] Measurements conducted at 25°C.

Table 4. Data for Fig. 10

VRF	Surface Tension (dynes/cm)[a]	Liquor pH[a]
Feed	73.3	10.9
7.2	72.9	11.3
13.4	72.3	11.6
19.6	70.8	11.85
25.6	70.1	12.3
31.9	62.1	11.9
38.1	65.1	12.35
44.4	65.5	12.37
50.6	65.8	12.4
56.8	65.9	12.54
63.1	65.3	12.3

Boiloff rate = 15.8 lb/ft^2-hr

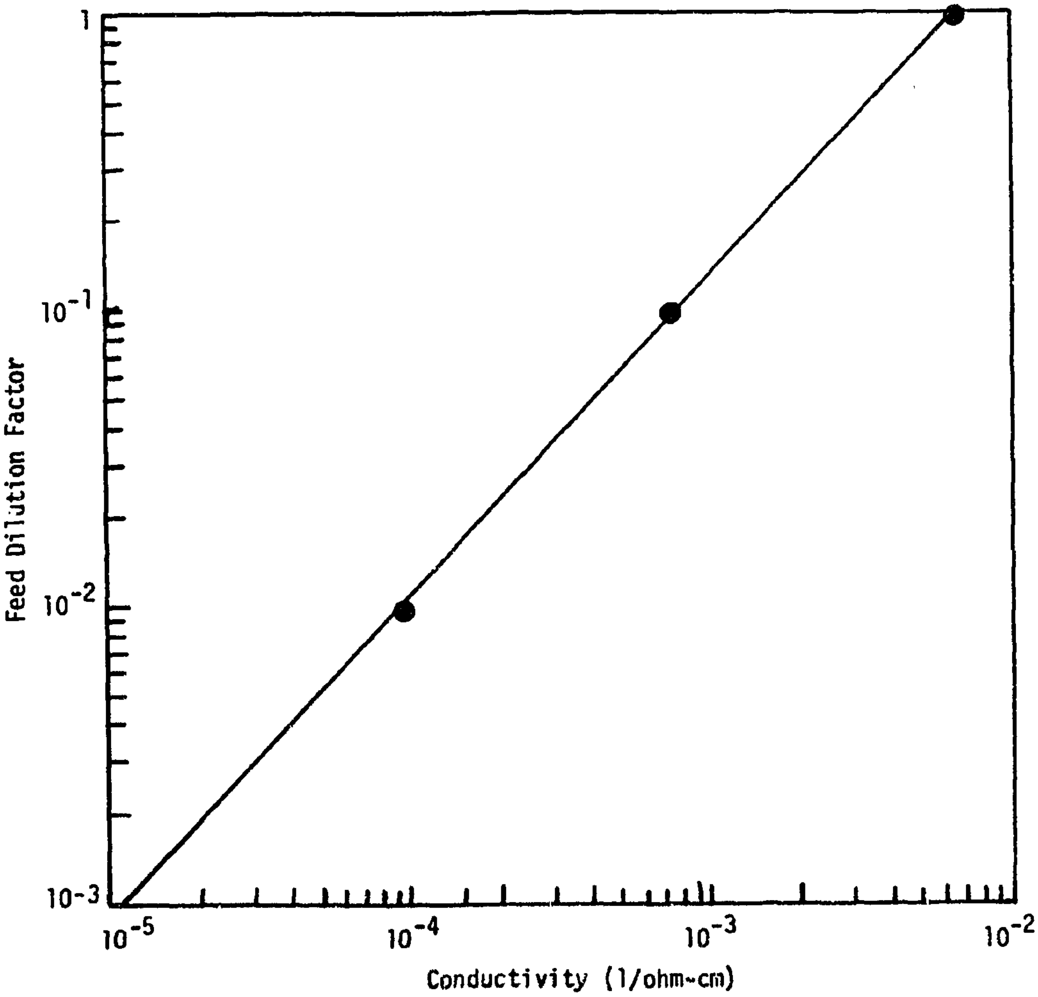
[a] Measurements conducted at 25°C.

Table 5. Decontamination Factors for ^{137}Cs Run Based on Radioactive Counting

VRF	$(DF)_{si}$ x 10^4	$(\overline{DF})_s$ x 10^4
12.24	2.11	1.55
23.5	2.69	4.97
34.7	2.07	6.30
45.9	2.01	0.11
57.1	1.33	1.61

Boiloff rate = 15.8 lb/ft^2-hr

$$\text{feed dilution factor} = \frac{\text{ml of feed at standard concentration}}{\text{ml of total dilution}}$$



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CALIBRATION OF RADIOMETER
WITH SIMULATED WASTE

DATE	DRAWN BY	FILE NO.	FIG.
9-25-72	LBR	CEPS-X-152	12

8.2 Description of Instrumentation

Temperatures at selected positions in the evaporator bottom are recorded and controlled. Three thermocouples are located equidistantly along the heating coils. Their temperature is recorded continuously on a Brown recorder. A Wheelco controller shuts off the power supply if the temperature reaches 150°C to insure against coil burnout. Three stainless steel heaters with a power output of 500 w each are utilized.

A heating coil is used to maintain a constant temperature in the vapor space. This is a precautionary measure to guard against refluxing of the rising vapor. A Leeds-Northrup controller and recorder were used.

Physical property measurements were made on samples using standard equipment. Readings taken on the Beckman pH meter, Dunouy tensiometer, and the radiometer conductivity meter are actual values. These instruments are calibrated and their calibration checked periodically. The (LAV) Brookfield viscosimeter reading is converted to an actual value using the appropriate conversion table provided with the instrument. Density measurements were obtained using standard pycnometric methods. Mass measurements were to the nearest 10,000th of a gram. Figures 13 and 14 are photographs of the equipment and instrumentation.

8.3 Sample Calculations

Sample calculations were made using Run 9-12-72A.

1. Entrainment Factor C'

$$\text{average condensate rate} = \begin{array}{r} 8.05\ \text{ml/min} \\ 10.20 \\ 9.10 \\ \underline{8.67} \\ 36.02 = 9.01\ \text{ml/min average} \end{array}$$

$$9.01\ \text{ml/min}(1\ \text{g/ml})(\text{lb}/454\ \text{g})(1/0.1837\ \text{ft}^2)(60\ \text{min/hr})$$

$$G = 6.48\ \text{lb/ft}^2\text{-hr}$$

$$C' = \frac{G}{\sqrt{\rho_g(\rho_\ell - \rho_g)}} = \frac{6.48\ \text{lb/ft}^2\text{-hr}}{\sqrt{(1\ \text{lb}/26.8\ \text{ft}^3)[(1\ \text{lb}/0.01672\ \text{ft}^3) - (1\ \text{lb}/26.8\ \text{ft}^3)]}}$$

$$= 4.34\ \text{lb}^{1/2}/\text{hr-ft}^{1/2}$$

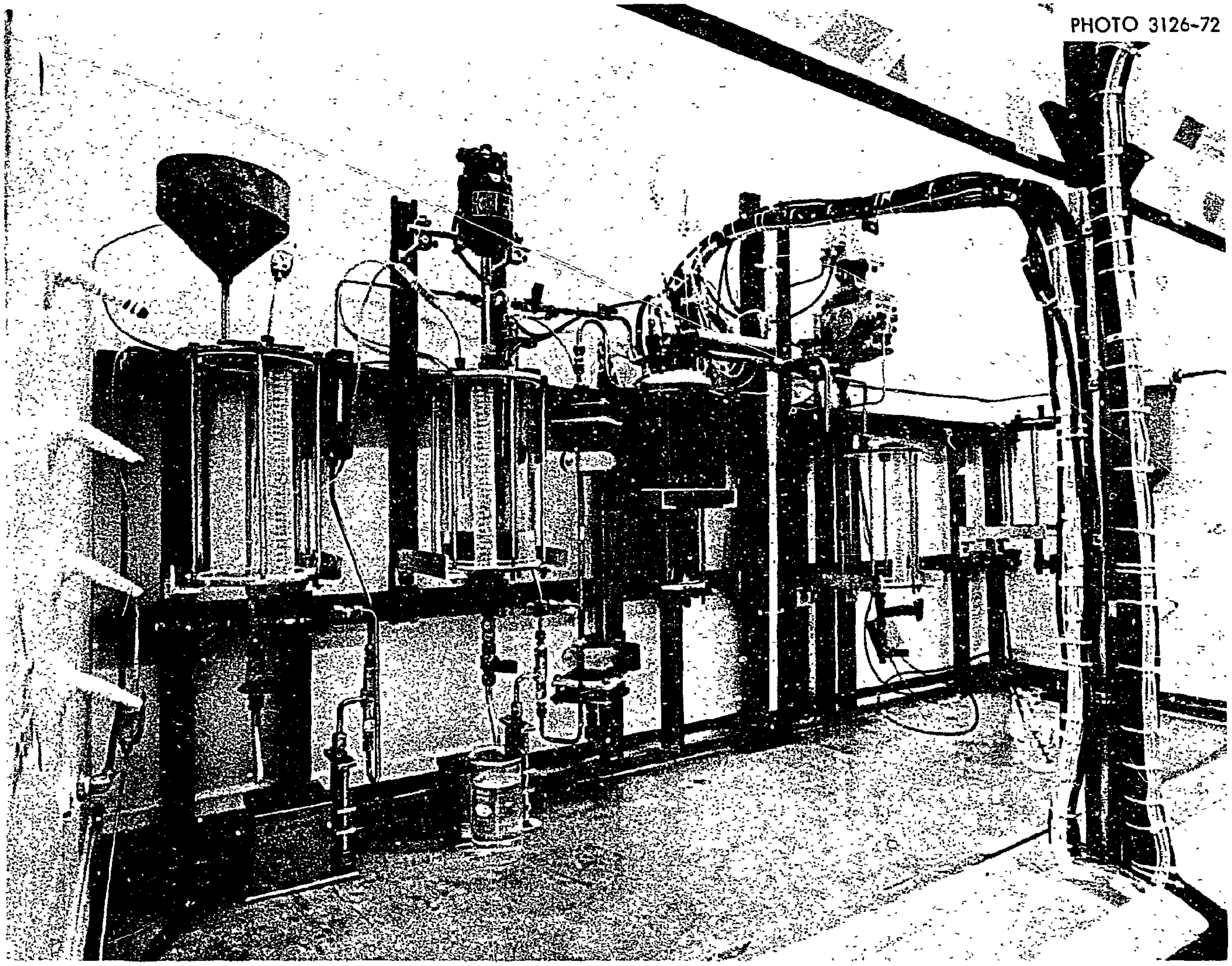

Fig. 13. Photograph of Equipment

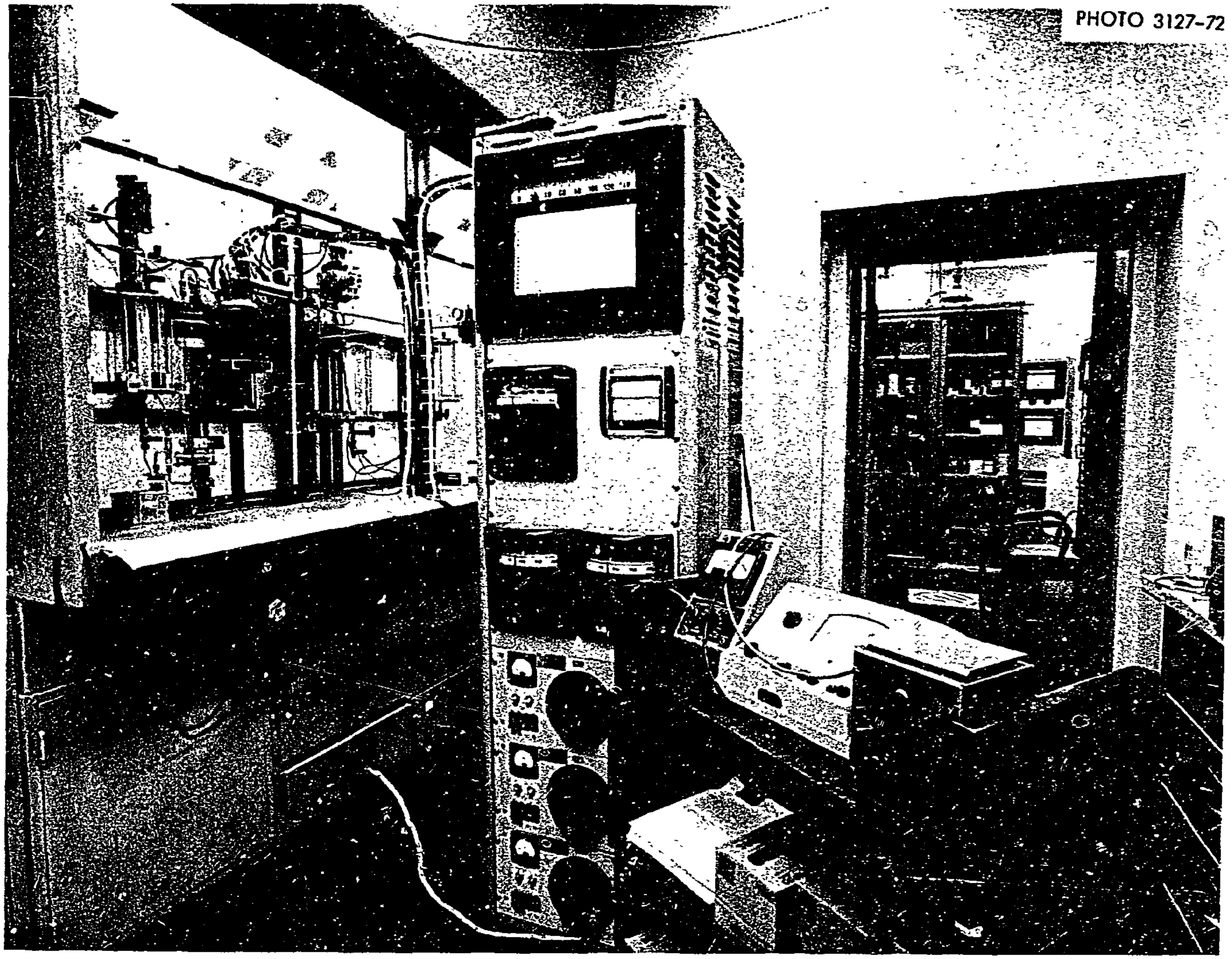

Fig. 14. Photograph of Instrumentation

2. System and Equipment DF

Average condensate conductivity = 18.5×10^{-6} (1/ohm-cm)

From Fig. 12, average condensate concentration = $(1.85 \times 10^{-3})C_f$

feed concentration = C_f

$$(\overline{DF})_s = \frac{C_f}{1.85 \times 10^{-3}\ C_f} = 540.5$$

$$(\overline{DF})_e = \frac{1}{2}\frac{C_f}{C_c}\left(1 + \frac{V_{f.p.}}{V_L}\right)$$

$$VRF = \frac{V_{f.p.}}{V_L} = \frac{V_{cond} + V_L}{V_L} = \frac{1050 + 385}{385} = 3.73$$

$$(\overline{DF})_e = \frac{1}{2}(540.5)(1 + 3.73) = 1278.3$$

8.4 Location of Original Data

The original data are located in ORNL Databook A-6708-G, pp. 1-70, on file at the M.I.T. School of Chemical Engineering Practice, Bldg. 1000, ORNL.

8.5 Nomenclature

C'	entrainment factor = $G/\sqrt{\rho_g(\rho_\ell - \rho_g)}$, $lb^{1/2}/hr\text{-}ft^{1/2}$ (18)
C_c	concentrate concentration
C_f	feed concentration
$(DF)_{ei}$	instantaneous equipment decontamination factor
$(DF)_{si}$	instantaneous system decontamination factor
$(\overline{DF})_e$	average equipment decontamination factor
$(\overline{DF})_s$	average system decontamination factor
G	mass velocity, $lb/ft^2\text{-}hr$
u_T	Stokes terminal settling velocity, cm/sec

$V_{f.p.}$	volume of feed processed, ml
V_{cond}	volume of condensate, ml
VRF	volume reduction factor
V_L	volume of thick liquor (concentrate), ml
ρ_g	density of water vapor, lb/ft^3
ρ_ℓ	density of liquid, lb/ft^3
μ	viscosity, cp

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