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**Krypton Absorption in Liquid CO₂ (KALC):
Campaign III in the Experimental
Engineering Section Off-Gas
Decontamination Facility**

T. M. Gilliam
V. L. Fowler
D. J. Inman

OAK RIDGE NATIONAL LABORATORY

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KRYPTON ABSORPTION IN LIQUID CO₂ (KALC): CAMPAIGN III
IN THE EXPERIMENTAL ENGINEERING SECTION
OFF-GAS DECONTAMINATION FACILITY

T. M. Gilliam, V. L. Fowler, and D. J. Inman

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ABSTRACT

Results are presented for the third major campaign for quantifying krypton removal from simulated High-Temperature Gas-Cooled Reactor reprocessing off-gas by the KALC process. The Experimental Engineering Section Off-Gas Decontamination Facility used in the campaign provides engineering-scale experiments with nominal gas and liquid flows of 5 scfm and 0.5 gpm, respectively.

Mass transfer experiments for the CO₂-O₂-Kr system are described for the absorption, fractionation, and stripping operations of the KALC process. A detailed discussion of the data analysis is included. The analysis indicates nominal HTU values for the absorber, fractionator, and stripper on the order of 0.4, 0.5, and 0.7 ft, respectively.

Flooding data for the packed columns are combined with previous data and are shown to be well represented by an empirical flooding equation.

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1. INTRODUCTION

As part of the Thorium Utilization Program,^{1,2} developmental work was performed to quantify the mass transfer characteristics of the KALC (Krypton Absorption in Liquid CO₂) process. The KALC process

(see Fig. 1) is being developed as a means of removing and concentrating ^{85}Kr from the off-gas of an HTGR reprocessing plant.

The Experimental Engineering Section Off-Gas Decontamination Facility (EES-ODF, see Fig. 2) utilized for this work has been described previously.^{3,4} Therefore, discussion of the facility and its operation will be limited to those areas necessary for clarification of the experiments completed during the report period (September 1, 1975, through July 31, 1976). These experiments will be referred to, hereafter, as Campaign III. Previously completed campaigns dealt mainly with equipment performance and absorber mass-transfer studies.^{5,6} Campaign III extended the range of the previous absorber studies and produced similar mass transfer information for the fractionator and stripper columns. Absorber mass-transfer experiments were performed at substantially lower liquid flow rates than those previously reported. Seventy-three mass transfer experiments were performed to obtain HTU (height of a transfer unit) information on the fractionator and stripper columns. Fluid dynamic data on the two columns were also obtained and compared with previous values.

2. FLOODING STUDIES

In the past, the Goodloe wire mesh packing⁷ used in these experiments had become distorted⁵ to the extent that the gas throughput of the two columns was reduced to approximately 15% of that predicted by the manufacturer. Routine flooding tests on the absorber column indicated at the beginning of this campaign (later confirmed by column

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Fig. 1. Simplified drawing of the KALC system.

Fig. 2. Experimental Engineering Section Off-Gas Decontamination Facility.

x rays) that packing distortion had again occurred, thus necessitating the repacking of the column. The addition of samplers to the stripper column for mass transfer studies (described in another section) necessitated its repacking also. Both columns were packed with 6-in. canisters of Goodloe wire mesh packing,* with gratings installed above and below each section of packing. The repacking of both columns made additional flooding studies desirable.

The absorber flooding studies were performed using CO_2 vapor saturated with O_2 in contact with a liquid stream of essentially pure CO_2 . The liquid rate was determined by the throughput of the positive displacement pump. The vapor rate was taken to be an average of the inlet and outlet gas rates. The column was considered flooded when the pressure drop across the column became greater than 10 in. H_2O . The pressure drop measurements were taken from pressure taps located as shown (along with the general column features) in Fig. 3. Flooding points were obtained by increasing the vapor rate (with a fixed pump setting) until the pressure taps showed a pressure drop greater than 10 in. H_2O .

The stripper flooding studies were performed with saturated CO_2 . The stripper column was operated with no off-gas rate (i.e., total reflux); thus, the vapor rate (V) was determined by the boilup rate in the reboiler:

---

* A product of the Packed Column Co., a Division of Metex Corp., Edison, N.J.

Fig. 3. Detailed engineering drawing of the absorber column.

$$V = (KW)(B), \quad (1)$$

where

KW = reboiler heat input, kW; and

B = conversion factor at reboiler temperature (nominally
4.2 scfm/kW).

The liquid rate (L) would then be a function of pump rate and boilup:

$$L = (GPM)(A) + (KW)(B), \quad (2)$$

where

GPM = pump rate, gal/min; and

A = conversion factor at the pump suction temperature (nominally
77.0 scfm/gpm).

As in the absorber experiments, the stripper column was considered to be flooded when the pressure drop across the column became greater than 10 in. H₂O. The flooding points were obtained by increasing the boilup rate (at a fixed pump rate) until a pressure drop of 10 in. H₂O across the column was obtained. The pressure taps, as well as the general stripper column configuration, are shown in Fig. 4.

Summaries of the absorber and stripper flooding experiments are shown in Tables 1 and 2, respectively. Flooding points are usually obtained by plotting the log of the pressure drop vs the log of the gas velocity at a constant liquid velocity.⁸ The flooding point is then determined as the point at which the pressure drop increases rapidly for a very small change in the gas velocity (or more

Fig. 4. Detailed engineering drawing of the stripper column.

practically, the point at which the curve undergoes a second slope change). The reliability of this method is greatly reduced by a small number of data points and a lack of visual confirmation of flooding. Consequently, a more convenient method of determining the flooding point is to use a modified Sherwood, Shipley, and Holloway correlation.⁹ The data are presented as a plot of

$$\frac{U_m^2 \rho_G \mu_L^{0.2}}{g \rho_L} \quad (\text{as the ordinate value})$$

vs

$$\frac{L}{G} \sqrt{\rho_G / \rho_L} \quad (\text{as the abscissa value}),$$

where

U_m = vapor velocity, ft/sec;

ρ_G = vapor phase density lb/ft³;

μ_L = liquid phase viscosity, cps;

g = constant, 32.2 ft/sec²;

ρ_L = liquid phase density, lb/ft³;

L = liquid rate, lb/hr·ft²; and

G = vapor rate, lb/hr·ft².

This correlation differs from that of Sherwood, Shipley, and Holloway in that the packing factor normally included in the ordinate value has been neglected. The flooding data for the absorber and stripper are shown in Figs. 5 and 6, respectively. The nominal flooding point for each liquid flow rate was determined as the midpoint between the lowest gas flow that caused flooding and the highest gas flow for

Fig. 5. Absorber flooding point determination.

Fig. 6. Stripper flooding point determination.

which the column was not flooded. A summary of the flooding points is presented in Table 3.

A comparison of the Campaign III flooding points with previously reported data^{5,10} is shown in Fig. 7. The collective data were fitted to an equation of the form:

$$y' = a + bx' + c(x')^2,$$

where

$$y' = \log \left[\frac{U_m^2 \rho_G \mu_L^{0.2}}{g \rho_L} \right],$$

$$a = -3.6035,$$

$$b = 0.5317,$$

$$x' = 2.0 + \log \left[\frac{L}{G} \sqrt{\frac{\rho_G}{\rho_L}} \right], \text{ and}$$

$$c = -0.3488.$$

The data agree quite favorably, although the experimentally determined flooding velocities show considerably less (~50%) gas throughput than that predicted by the manufacturer.⁷ It should be noted that the data include flooding points for the 1 1/2-in. absorber, and the 3-in. stripper in the ORNL facility, and the 3-in. fractionator column in the ORGDP facility. Thus, there is no apparent relationship between the flooding velocity and column diameter over the range presented.

The installation of gratings above and below each section of packing, as well as greater care during operations, apparently eliminated the problem of packing distortion. Although there are no experimental data to explicitly determine the cause of the distortion,

Fig. 7. Generalized flooding curve for Goodloe Packing.

it is suspected that it occurred during system purging operations. In the past, system purging consisted of releasing the system's contents to the atmosphere by simply opening two purge valves. The high volume of gas (reaching sonic velocity) through these valves could have conceivably generated enough momentum in the liquid to cause packing distortions. Subsequently, during all future purging operations, the escaping gas rate will be greatly reduced and the pressure drop across the two columns will be monitored continuously during the operation.

3. MASS TRANSFER STUDIES

During the mass transfer experiments, the EES-ODF was operated in total recycle. The system feed gas (nominally 10% O_2 - 90% CO_2 and tracer levels of ^{85}Kr) was compressed to slightly more than the desired absorber pressure and then routed to the bottom of the absorber. As the gas travels up the absorber column, it is contacted with a counter-current stream of liquid carbon dioxide. The liquid stream absorbs essentially all of the krypton, and a large portion of the oxygen, as well. The solute-laden liquid is then routed to the top of the stripper by an operating pressure differential (nominally 2 atm) between the two columns. In the stripper column, the dissolved gas is distilled and leaves the column via the stripper off-gas. The liquid stream leaving the bottom of the stripper is relatively free of krypton and O_2 and is pumped to the top of the absorber as scrub liquid. The absorber and stripper off-gas streams are routed to the compressor where they combine to form the system feed gas.

As with all mass transfer operations, some operating variables are designated as independent and others are designated as dependent. Since the analysis was performed during steady state, the choice of independent-dependent operating variables became academic. Therefore, during the experiments the independent variables were chosen on the basis of their ability to be maintained at a desired value.

The variable of primary concern in the operation of both columns was the liquid to vapor ratio, the liquid rate being determined by the pump rate. The vapor rate in the absorber column was fixed by controlling the feed gas rate. The off-gas rate was set manually to complement the feed gas rate (nominally 80% of feed rate). The absorber pressure and temperature were then allowed to seek their own levels. The stripper vapor rate was controlled by fixing the reboiler heat input. The stripper column pressure was set by controlling the amount of refrigerant to the condensers. The stripper temperature was allowed to seek its own level.

Once these independent variables were set, sufficient time was allowed for the entire system to reach steady state. Various temperatures, pressures, liquid holdups, stream concentrations, and flow rates were monitored during the experiments and were used to indicate when steady state had been attained (i.e., no appreciable change in monitored variables for at least 2 hr). As the system approached steady state operation, the various controllers were fine tuned to alleviate any controller-induced oscillations. The wide variety of conditions studied caused this to be a time-consuming

operation to the extent that controller fine tuning became a major part of each experiment.

4. DATA ANALYSIS

Experiments of this magnitude are, by nature, complex and necessitate certain engineering assumptions in the analyses of the data collected. Although many of these assumptions are based on sound engineering principles, many are based on experience gained from operating the facility. For example, the composition analyses of the gas streams ($> 1\%$ light gas content) were found to be more reliable than the analyses of the liquid streams. These considerations have been incorporated into the following data analysis model.

To aid in the analysis, a schematic of the EES-ODF is shown in Fig. 8, with various streams of interest indicated. The streams are as follows:

- ① Absorber column liquid feed,
- ② Absorber column feed gas,
- ③ Liquid leaving absorber packing,
- ④ Vapor entering absorber packing,
- ⑤ Liquid entering absorber packing,
- ⑥ Vapor leaving absorber packing,
- ⑦ Liquid feed to stripper column,
- ⑧ Absorber column off-gas,
- ⑨ Stripper column off-gas,
- ⑩ Liquid leaving stripper packing,

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Fig. 8. Schematic of KALC system used in stream analysis.

- ⑪ Vapor entering stripper packing,
- ⑫ Vapor leaving stripper packing, and
- ⑬ Liquid entering stripper packing.

During the experiments, only streams 2, 8, and 9 could be identified by both flow rate (via calibrated rotameters) and composition (via sampling and analyses). Knowledge of the compositions of these three streams allows the following component and overall material balance:

$$Q_9 = Q_2^m \frac{y_2 - y_8}{y_9 - y_8}, \quad (3)$$

$$Q_8 = Q_2^m - Q_9, \quad (4)$$

where

Q_9 = calculated stripper column off-gas, scfm;

Q_2^m = measured absorber column feed gas, scfm;

y_2 = O_2 or krypton concentration in stream 2;

y_8 = O_2 or krypton concentration in stream 8;

y_9 = O_2 or krypton concentration in stream 9; and

Q_8 = calculated absorber column off-gas, scfm.

Thus, Eqs. (3) and (4) provide an alternate method of determining the measured (via rotameters) off-gas rates.

The determination of a stream's light gas content involves both sampling and analyses. Oxygen concentrations were determined using a AERO-VAC mass spectrometer¹¹ and teledyne electrolytic cell,¹² whereas the ⁸⁵Kr concentrations were determined by a beta detector.¹¹ Experience has proven that the determination of krypton concentrations is

more reliable than that of O_2 , thus a 100% krypton balance was assumed. The values Q_8 and Q_9 were calculated using Eqs. (3) and (4) and the appropriate krypton concentrations. The resulting O_2 balance was then calculated to be:

$$B = \frac{Q_8 y_8 + Q_9 y_9}{Q_2 y_2}, \quad (5)$$

where

B = oxygen balance factor,

Q_2, Q_8, Q_9 = flow rates as defined by Eqs. (3) and (4), and

y_2, y_8, y_9 = measured O_2 concentrations.

The O_2 concentrations were then normalized by:

$$\begin{aligned} y_8^N &= y_8^n (1 + 1/B)/2, \\ y_9^N &= y_9^n (1 + 1/B)/2, \text{ and} \\ y_2^N &= y_2^n (1 + B)/2, \end{aligned}$$

where

y_i^N = normalized O_2 concentration of stream i ,

y_i^n = measured O_2 concentration of stream i , and

B = O_2 balance factor as calculated by Eq. (5).

Comparisons of the calculated and measured values for these flow rates and compositions are shown in Tables 4A, 4B, and 4C. Future reference to the oxygen concentrations in these three streams will refer to the normalized concentrations.

Although gas flow rates readily lend themselves to units of scfm, liquid flow rates do not. Hence, stream 1 must be expressed in terms

of "pseudo-equivalent scfm." Stream 1 is the only flow rate of concern, at this point, since all other flow rates will be determined by material balance and will naturally be expressed in units of scfm. Stream 1 is calculated by:

$$Q_1 = \frac{(\rho_L^*) (Q_1')}{(C) (\rho_G^s)}, \quad (6)$$

where

- Q_1 = liquid flow rate to the absorber column, scfm;
- ρ_L^* = density of saturated liquid CO_2 at fluid temperature, lb/ft³;
- Q_1' = liquid flow rate to the absorber column, gpm;
- C = conversion factor, 7.481 gal/ft³; and
- ρ_G^s = density of gas at standard conditions (70°F, 1 atm), lb/ft³.

Tables 5A, 5B, and 5C present the results of these conversions.

Stream 7 and its composition are calculated by an overall and component mass balance around the absorber column:

$$Q_7 = Q_2 + Q_1 - Q_8,$$

$$x_7 = (Q_2 y_2 + Q_1 x_1 - Q_8 y_8) / Q_7. \quad (8)$$

The calculated values for flow rate and composition of stream 7 are shown in Tables 6A, 6B, and 6C.

Streams 3 and 4 at the bottom of the absorber are calculated on the assumption that O_2 is pinched at the bottom of the column. This leads to the equation:

$$x_3 = \frac{y_4}{K_{O_2}} \quad , \quad (9)$$

where

x_3 = O_2 concentration in stream 3,

y_4 = measured O_2 concentration in stream 4, and

K_{O_2} = O_2 equilibrium constant based on the temperature and pressure at the bottom of the absorber (as calculated by Glass^{*}).

An overall and component mass balance around the absorber level tank yields the flow rates of streams 3 and 4:

$$Q_4 = \frac{Q_7(x_7 - x_3) - Q_2(y_2 - x_3)}{(x_3 - y_4)} \quad , \quad (10)$$

$$Q_3 = Q_4 + Q_7 - Q_2 \quad , \quad (11)$$

where x_7 , x_3 , y_2 , and y_4 are the O_2 concentrations in the indicated streams.

The krypton concentration in stream 3 is then determined by a component material balance around the absorber column:

$$x_3 = (Q_4 y_4 - Q_8 y_8 + Q_1 x_1) / Q_3 \quad , \quad (12)$$

where y_4 , y_8 , and x_1 represent the Kr concentrations in the indicated streams.

Streams 5 and 6 are then readily calculated by an overall and component mass balance around the absorber packing:

$$Q_5 = Q_3 + Q_6 - Q_4 \quad , \quad (13)$$

---

* All equilibrium constants used in this report are calculated using the Glass model.¹³

$$Q_6 = \frac{Q_4(y_4 - x_5) + Q_3(x_5 - x_3)}{y_6 - x_5} , \quad (14)$$

where y_4 , x_5 , x_3 , and y_6 are the krypton concentrations in the indicated streams.

Table 7 represents the results of calculations pertaining to streams 3, 4, 5, and 6.

Stream 11 is calculated based on the assumption that all of the heat supplied by the reboiler is utilized in the vaporization of the liquid (stream 10) entering the reboiler:

$$Q_{11} = (KW)(B), \quad (15)$$

where

KW = heat supplied by the reboiler, kW; and

B = factor for conversion from kW to scfm, nominally 4.0 scfm/kW.

Stream 10 can then be calculated based on an overall material balance around the reboiler:

$$Q_{10} = Q_{11} + Q_1 . \quad (16)$$

The compositions of these streams are calculated based on the assumption that the reboiler acts as a single stage (i.e., the vapor and liquid leaving the reboiler are in equilibrium). Experience has shown the sample analysis of stream 11 to be the most reliable; consequently, the following equation is used:

$$x_1 = y_{11}/K , \quad (17)$$

where

$x_1 = O_2$ or krypton liquid composition of stream 1,

$y_{11} = O_2$ or krypton vapor composition of stream 11, and

K = equilibrium constant for O_2 or krypton based on reboiler temperature and pressure.

The composition of stream 10 can then be calculated based on a component balance around the reboiler:

$$x_{10} = \frac{Q_1 x_1 + Q_{11} y_{11}}{Q_{10}}, \quad (18)$$

where x_1 , y_1 , and x_{10} are the krypton or O_2 compositions of the indicated streams. The results of these calculations and a comparison with the measured concentrations of streams 10, 11, and 1 are shown in Tables 8A and 8B.

The use of an overall and component balance around the column to calculate the flow rates of streams 12 and 13 proved to be inadequate. The low solute concentrations at the bottom of the column made such a balance insensitive to changes in the composition of stream 10 and, to a large extent, in stream 11 also. Consequently, the assumptions that

$$Q_{13} = Q_{10} \quad (19)$$

and

$$Q_{12} = Q_{11} \quad (20)$$

were used. In the case of stripping operations where the light gas concentration in the column is $\ll 1\%$ at all times, the assumption of

constant liquid and vapor rates is certainly viable. During fractionation operations, the light gas concentration in the column is generally on the order of 1 to 5% at the top of the column and <1% throughout the rest of the column. The error introduced by assuming constant liquid and vapor rates under these conditions is not clear, although it is certainly less than that associated with the calculation of liquid and vapor at the top of the column using a component mass balance.

In calculating the compositions of streams 12 and 13, a component mass balance around the column is made. Experience has shown the composition analysis of stream 12 to be the most reliable; consequently, the composition of stream 13 is calculated using the following equation:

$$x_{13} = \frac{Q_{12}y_{12} + Q_{10}x_{10} - Q_{11}y_{11}}{Q_{13}}, \quad (21)$$

where x_{13} , y_{12} , x_{10} , and y_{11} are the krypton or O_2 concentrations of the indicated streams. Tables 9A and 9B present a comparison between calculated and measured compositions of stream 13.

At this point, all major streams and their compositions have been determined and can now be used in the appropriate mass transfer equations.

The decontamination factor (DF_c) for the absorber column is based on the inlet and outlet krypton concentrations as follows:

$$DF_c = \frac{Q_4 y_4}{Q_6 y_6}, \quad (22)$$

where y_4 and y_6 are the krypton concentrations of the indicated streams. Figure 9 presents a plot of the resulting DF_c vs the classic absorption factor (i.e., L/VK), where L/V is determined by an average of Q_5/Q_6 and Q_3/Q_4 . The variable K is the average of the krypton equilibrium

Fig. 9. Absorber DF_c (based on krypton) vs absorption factor.

constants (calculated at the top and bottom column conditions). Similarly, an overall absorber DF (DF_o) can be calculated to include the mass transfer taking place in the absorber level tank and "column condenser":

$$DF_o = \frac{Q_2 y_2}{Q_8 y_8}, \quad (23)$$

where y_2 and y_8 are the krypton concentrations of the indicated streams.

A HTU (Height of a Transfer Unit) is calculated (based on resistance in the vapor phase) using the following two equations:¹⁴

$$HTU = Z/NTU \quad (24)$$

and

$$NTU = \frac{y_o - y_i}{(y^* - y)_{lm}}, \quad (25)$$

where

HTU = height of a transfer unit, ft;

Z = height of column packing, ft;

NTU = number of transfer units;

y_o = gas outlet krypton composition;

y_i = gas inlet krypton composition;

$$(y^* - y)_{lm} = \frac{(y_o^* - y_o) - (y_i^* - y_i)}{\ln \left[\frac{y_o^* - y_o}{y_i^* - y_i} \right]} \quad (26)$$

y_o^* = krypton concentration in equilibrium with the liquid outlet; and

y_i^* = krypton concentration in equilibrium with the liquid inlet.

For the absorber,

$$Z = 8.24 \text{ ft,}$$

$$y_o = y_6,$$

$$y_i = y_4,$$

$$y_o^* = K_o x_5, \text{ and}$$

$$y_i^* = K_i x_3,$$

where

K_o = krypton equilibrium constant based on the pressure and temperature at the top of the column, and

K_i = krypton equilibrium constant based on the pressure and temperature at the bottom of the column.

Thus, Eq. (24) becomes

$$HTU = \frac{8.24 (K_o x_5 - y_6 - K_i x_3 + y_4)}{(y_6 - y_4) \ln \left(\frac{K_o x_5 - y_6}{K_i x_3 - y_4} \right)} \quad (27)$$

A summary of the absorber mass-transfer information is presented in

Table 10, and a graphical presentation of HTU vs DF_c is shown in Fig. 10.

The stripper column DF is calculated using:

$$DF_c = \frac{Q_{13} x_{13}}{Q_{10} x_{10}} \quad (28)$$

Fig. 10. Absorber HTU vs DF_c (based on krypton).

where x_{13} and x_{10} are the krypton concentrations of the indicated streams.

Figure 11 presents the DF_c values vs the column stripping factor (i.e., VK/L , where K = krypton equilibrium constant). As with the absorber, the stripping factor is an average between the values at the column top and bottom. An overall DF (DF_o) is calculated to include the effects of the reboiler and column condensers by:

$$DF_o = \frac{Q_7 x_7}{Q_1 x_1}, \quad (29)$$

where x_7 and x_1 are the krypton concentrations of the indicated streams.

A HTU value is calculated (based on resistance in the liquid phase) by equations analogous to (24) and (25):

$$HTU = Z/NTU, \quad (30)$$

$$NTU = \frac{x_i - x_o}{(x - x^*)_{lm}}, \quad (31)$$

and

$$(x - x^*)_{lm} = \frac{(x_o - x_o^*) - (x_i - x_i^*)}{\ln \frac{x_o - x_o^*}{x_i - x_i^*}} \quad (32)$$

where

x_i = inlet liquid krypton concentrations,

x_o = outlet liquid krypton concentration,

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Fig. 11. Stripper DF_c (based on krypton) vs stripping factor.

x_o^* = krypton concentration in equilibrium with the outlet gas, and

x_i^* = krypton concentration in equilibrium with the inlet gas.

For the stripper calculations,

$$Z = 11.53 \text{ ft},$$

$$x_i = x_{13},$$

$$x_o = x_{10},$$

$$x_i^* = y_{12}/K_i, \text{ and}$$

$$x_o^* = y_{11}/K_o,$$

where

K_o = krypton equilibrium constant based on pressure and temperature at the bottom of the column, and

K_i = krypton equilibrium constant based on pressure and temperature at the top of the column.

Thus, Eq. (30) becomes,

$$HTU = \frac{11.53 (x_{10} - y_{11}/K_o - x_{13} + y_{12}/K_i)}{(x_{13} - x_{10}) \ln \left[\frac{x_{10} - y_{11}/K_o}{x_{13} - y_{12}/K_i} \right]} \quad (33)$$

Table 11 presents a summary of the stripper mass-transfer data. Figure 12 presents a plot of HTU vs DF_c for the stripper column.

The fractionator DF_c is calculated using Eq. (28) where x_{13} and x_{10} represent the oxygen concentrations of the indicated streams.

A graphical representation of DF_c vs average stripping factor (i.e.,

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Fig. 12. Stripper HTU (based on krypton) vs DF_c .

VK/L, where $K = O_2$ equilibrium constant) is shown in Fig. 13. An overall DF (DF_o) is calculated to include the effects of the reboiler and column condensers using Eq. (29), where x_7 and x_1 represent the oxygen concentrations of the indicated streams. A HTU value is calculated using Eq. (33) with the following modifications:

1. x_{10} and x_{13} represent the oxygen concentrations of the indicated streams,
2. y_{11} and y_{12} represent the oxygen concentrations of the indicated streams,
3. K_o represents the oxygen equilibrium constant based on pressure and temperature at the bottom of the column, and
4. K_i represents the oxygen equilibrium constant based on pressure and temperature at the top of the column.

Table 12 presents a summary of the fractionator mass transfer data.

Figure 14 presents a graph of HTU vs column decontamination factor.

5. DISCUSSION OF MASS TRANSFER RESULTS

In general, the mass transfer data collected for all three columns showed no unexpected results. Figures 9, 11, and 13, showing the exponentially increasing relationship between DF_c and the column absorption/stripping factor, conform to previously published work.¹⁵ Figures 10, 12, and 14, showing the relationship between HTU and DF_c , indicate that at normal KALC operating conditions ($DF_c > 100$), HTU is independent of DF_c . The significance of the large scatter and increase in HTU values

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Fig. 13. Fractionator DF_c (based on oxygen) vs stripping factor.

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Fig. 14. Fractionator HTU (based on oxygen) vs DF_c.

at low DFs (< 10) is not explicitly clear. It is possible that the decreasing driving force causes an increase in the HTU values or that the mathematics of HTU calculations involving small driving forces becomes insensitive. The DF is low (< 10) for all runs where the absorption/stripping factor is < 1 . Normally, mass transfer data are not taken at such low absorption/stripping factors because of the inherent insensitivity to the number of transfer units or stages. In any case, the KALC process will not be affected because these values are an order of magnitude below normal operations.

The absorber mass-transfer studies covered a wide range of operating variables, including:

<u>Variable</u>	<u>Range</u>
pressure, psig	310.2 to 387.5
temperature, °C	-11.3 to -18.5
O ₂ composition in feed gas, %	5.2 to 11.0
vapor rate, scfm	2.86 to 5.22
liquid rate, scfm	23.67 to 44.87

As indicated by Figs. 9 and 10, the absorber mass-transfer data obtained in Campaign III agree with previously reported values⁶ quite favorably. This is to be expected from existing, generalized mass transfer relationships based on resistance in the vapor phase. These past parameter studies, as well as data taken during Campaigns II and III, indicate that HTU_G is not a strong function of liquid rate. Although several attempts were made to correlate absorber HTU_G values with various operating parameters (K, G, L, etc.), no correlation was found to have a correlation coefficient¹⁶ > 0.3 .

Included in the absorber data are five experiments (Nos. 700, 710, 720, 730, and 740) which were run with the feed gas cooler turned off. This caused the heat-laden feed gas to induce substantial vaporization of the exiting liquid stream in the absorber level tank. This vaporization resulted in (1) extreme difficulty in maintaining the absorber pressure at a desired value, (2) a reduction in feed gas rates to the absorber, (3) and warmer temperatures at the bottom of the column which could, of course, cause substantial deabsorption of solute from the liquid stream.

In calculating HTU values for the absorber, as well as the fractionator and the stripper, column end effects were ignored. An experiment was performed on the absorber (the smaller of the two columns, and consequently, the most susceptible to possible end effects) to test this assumption.

Experiment 690 is a duplication of experiment 680, except that in experiment 690 the liquid scrub (stream 1) is introduced into the absorber at the second sampler from the top. This effectively eliminates the top section of packing for mass transfer and reduces the column packing height to 5.5 ft. As expected, the DF_c was reduced (from 631.2 to 355.6), but the HTU remained relatively constant (0.39 vs 0.33), thus indicating that end effects are indeed negligible.

The pertinent operating variables and their ranges explored during the stripper mass-transfer studies are:

<u>Variable</u>	<u>Range</u>
pressure, psig	220 to 280
temperature, °C	-18.6 to -28.1
vapor rate, scfm	4.3 to 10.5
liquid rate, scfm	47.1 to 64.0

Although 41 stripper experiments were conducted, only 14 exhibit a high degree of confidence. Eight experiments were deleted because the stripping factor was < 1.05 , indicating that the column was operating at or near a pinched condition (i.e., the krypton concentrations in the column top vapor and liquid were approaching, or were in fact already at, equilibrium). This is, of course, far from the normal operating conditions of the stripper column.

Nineteen experiments were deleted due to poor counting statistics. In the analysis of the stripper data, the measured vapor inlet krypton concentration is of extreme importance because it is the basis for all material balances associated with the column. Thus, the reliability of this sample is of the utmost necessity. A statistical analysis of the measured count rate proved to be the most convenient test of reliability. The standard deviation for any sample is defined as:¹⁷

$$\sigma_N = \sqrt{\sigma_C^2 + \sigma_B^2} ,$$

where

σ_N = standard deviation of sample,

σ_C = standard deviation of total number of counts registered, and

σ_B = standard deviation of the number of background counts registered.

Statistical analysis indicates that there is a 99.7% probability that the true count rate lies within $\pm 3 \sigma_N$ of the measured count rate.¹⁷ Thus, a somewhat arbitrary decision was made to accept a sample whose count rate was such that the magnitude of $3 \sigma_N$ was 10% or less of the actual counts registered. The resulting data (see Table 13) were then fitted to an equation of the following form:

$$HTU_L = \frac{aL^b}{V^c K^d}, \quad (34)$$

where

HTU_L = height of a transfer unit, ft;

L = average liquid rate, scfm;

V = average vapor rate, scfm;

K = average krypton equilibrium constant;

$a = 1.798$;

$b = 2.877$;

$c = 2.138$; and

$d = 3.643$.

The resulting empirical correlation (see Fig. 15) with a correlation coefficient¹⁶ of 0.88 was found to be consistent with the findings of Sherwood and Holloway.¹⁸ The average HTU was found to be 0.7 ft.

The stripper experiments were conducted at liquid to vapor ratios (L/V) substantially higher than the expected operating conditions of KALC (hence, the VK/L values ≤ 1.05) because of the poor counting statistics at the lower L/V ratios. As indicated by the empirical correlation, HTU_L

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Fig. 15. Experimental stripper HTU vs HTU as calculated by correlation.

increases with increasing values of L/V . This is to be expected from conventional mass transfer theory which states that mass transfer in a column is decreased (i.e., HTU_L increased) as the concentrations in the liquid and vapor approach their equilibrium values (i.e., the column approaches a pinched condition, $VK/L < 1.0$).¹⁵ Thus, the average HTU_L value of 0.7 ft is most certainly a conservative one. Figures 16 and 17 are plots of DF_c vs average stripping factor and HTU vs DF_c , respectively, using the experiments listed in Table 13. It should be noted that the curve shown in Fig. 16 was fitted by hand.

Fractionation experiments were conducted with pertinent operating variables covering the following ranges:

<u>Variable</u>	<u>Range</u>
pressure, psig	250.5 to 311.5
temperature, °C	-17.2 to -23.4
vapor rate, scfm	2.02 to 4.06
liquid rate, scfm	44.5 to 56.6

Although 36 experiments were completed, eight were deleted due to stripping factor values < 1.05 , and four were deleted because steady state had not been reached. An empirical correlation similar to Eq. (34) was developed with the following modifications:

$$HTU_L = \frac{aL^b}{V^c K^d} \quad (35)$$

where

K = average O_2 equilibrium constant,

$a = 0.013$,

Fig. 16. Stripper DF_c (based on krypton) vs stripping factor.

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Fig. 17. Stripper HTU (based on krypton) vs DF_c.

$$b = 1.78,$$

$$c = 0.858, \text{ and}$$

$$d = 0.764.$$

The results of this correlation are shown in Fig. 18. The correlation appears to be inadequate with a correlation coefficient of 0.55. One possible reason for the poor correlation is the range of variables used in the correlation attempt. Two main components of the correlation, liquid rate and O_2 equilibrium constant, only vary by $\sim 10\%$. Thus, their significance can not be reliably calculated. Also there exists no consistent method of determining the reliability of the O_2 analyses of stream 11, thus, there may be substantial inherent data scatter. Figures 19 and 20 show plots of DF_c vs average stripping factor and HTU vs DF_c , respectively, using the experiments listed in Table 14. Again it should be noted that the curve in Fig. 19 was fitted by hand.

The average HTU_L for the fractionator was found to be 0.5 ft. This would tend to lend credibility to existing computer models of the KALC process.^{19,20} All existing models assume that O_2 and krypton stage heights are identical.

In calculating the HTU values for the various columns, no attempt has been made to include the effects of the samplers, although mass transfer most certainly takes place in them. No viable experimental method of determining sampler effect is known and possibly the effect is not negligible. Of more concern, however, is the accuracy of the nominal HTU values for the three columns.

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Fig. 18. Experimental fractionator HTU vs HTU as calculated by correlation.

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Fig. 19. Fractionator DF_c (based on oxygen) vs stripping factor.

Fig. 20. Fractionator HTU (based on oxygen), vs DF_c .

6. CONCLUSIONS AND RECOMMENDATIONS

Campaign III provided a wealth of information concerning the performance of the individual columns in the KALC system. By their very nature these experiments also provide more operating experience, thus making problems associated with future experiments more predictable and more quickly solvable.

The flooding characteristics of the columns studied are consistent, but the experimental throughput capacity is well below (by ~ 50%) that predicted by the manufacturer. Nominal HTU values for the absorber, fractionator, and stripper have been found to be 0.4, 0.5, and 0.7 ft, respectively, for the $\text{CO}_2\text{-O}_2\text{-Kr}$ system under the range of operating conditions studied. An empirical correlation relating stripper HTU with its operating variables has been found to be:

$$\text{HTU}_L = \frac{1.798 L^{2.877}}{V^{2.138} K^{3.643}},$$

where

L = liquid rate, scfm;

V = vapor rate, scfm; and

K = krypton equilibrium constant.

This equation had a correlation coefficient of 0.88.

Recommendations for future work in the EES-ODF include:

1. improvement of light gas composition analysis,
2. introduction of other light gas components such as N_2 , CO, and Xe and evaluation of their effect on the mass transfer data obtained with an $\text{O}_2\text{-Kr-CO}_2$ system,

3. testing the performance of some other type of column packing (preferably a random packing),
4. development and testing of a transient model of the KALC system to determine system performance during nonsteady state conditions,
5. introduction of potential contaminants to the system such as NO, tritiated water, and iodine to determine their effect on the system's performance and operation.

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TABLES

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Table 1. Absorber column fluid dynamic data

Liquid pump rate (gpm)	Liquid rate (scfm) ^a	Average vapor rate (scfm) ^a	Column pressure (psig)	Average column temperature (°C)	ΔP between pressure taps ^b (in. H ₂ O)				Flooded (f = yes)	L/V (mole/mole)	$\frac{L}{G} \sqrt{\frac{\rho_G}{\rho_L}}$	$\frac{U_m^2 \rho_G \mu_L^{0.2}}{g \rho_L}$
					0-1	0-2	0-3	0-4				
0.484	38.04	2.90	287.0	-22.4	0.3	1.1	1.8	2.6		13.12	2.95	0.0000204
0.484	38.04	6.47	295.5	-21.9	0.3	1.7	3.1	4.5		5.88	1.35	0.0000988
0.484	38.04	7.37	296.5	-21.6	0.3	2.1	4.1	7.0		5.16	1.18	0.000129
0.484	38.04	7.69	296.5	-21.4	0.3	3.3	5.4	>10.0	f	4.95	1.13	0.000140
0.553	43.46	4.68	288.0	-22.3	0.3	1.4	2.5	3.7		9.29	2.09	0.0000537
0.553	43.46	6.21	288.5	-22.3	0.3	2.0	3.5	5.5		7.00	1.57	0.0000940
0.553	43.46	6.38	288.5	-22.2	0.4	3.4	>10.0	>10.0	f	6.81	1.53	0.000100
0.6225	48.73	2.72	276.0	-23.5	0.3	1.1	2.0	2.9		17.92	3.96	0.0000186
0.6225	48.73	4.21	279.5	-23.0	0.3	1.6	2.9	4.5		11.58	2.55	0.0000448
0.6225	48.73	5.39	280.0	-22.9	0.3	>10.0	>10.0	>10.0	f	9.04	1.99	0.0000733
0.6917	53.72	2.77	280.0	-22.9	0.2	1.4	2.3	3.5		19.39	4.27	0.0000194
0.6917	53.72	4.00	284.0	-22.5	0.2	--	3.4	5.5		13.43	2.96	0.0000404
0.6917	53.72	4.87	285.0	-22.5	0.3	--	>10.0	>10.0	f	11.03	2.47	0.0000576
0.6917	53.72	4.57	285.5	-22.7	0.3	--	4.3	>10.0	f	11.76	2.64	0.0000505
0.4150	32.62	2.25	288.0	-19.2	0.2	1.0	1.7	2.3		14.50	3.26	0.0000126
0.4150	32.62	3.55	288.0	-19.0	0.2	1.1	1.9	2.8		9.19	2.06	0.0000318
0.4150	32.62	5.65	290.0	-18.8	0.3	1.4	2.4	3.5		5.77	1.30	0.0000806
0.4150	32.62	7.66	295.5	-18.1	0.3	2.0	3.6	5.4		4.26	0.98	0.0000983
0.4150	32.62	8.62	296.4	-17.9	0.3	3.4	>10.0	>10.0	f	3.78	0.87	0.000143

^aSTP = 70°F, 1 atm.^bDistance between pressure taps: 0-1 2.25 ft
0-2 5.79 ft
0-3 9.29 ft
0-4 12.77 ft

Table 2. Stripper column fluid dynamic data

Liquid pump rate (gpm)	Liquid rate (scfm) ^a	Vapor rate (scfm) ^a	Column pressure (psig)	Average column temperature (°C)	ΔP between pressure taps ^b (in. H ₂ O)								Flooded (f = yes)	L/V (mole/mole)	$\frac{L}{G} \sqrt{\frac{\rho_G}{\rho_L}}$	$\frac{U_m^2 \rho_G \mu_L^{0.2}}{g \rho_L}$
					0-1	0-2	0-3	0-4	0-11	0-12	0-13	0-14				
0.0	5.51	5.51	300.0	-16.6	0.20	0.37	0.50	0.75	1.95	2.20	2.30	2.50		1.00	0.236	0.000006
0.0	8.80	8.80	300.0	-17.1	0.20	0.38	0.50	0.72	2.02	2.27	2.50	2.58		1.00	0.236	0.000009
0.0	21.51	21.51	300.0	-16.6	0.21	0.38	0.60	0.90	2.50	2.80	3.10	3.20		1.00	0.238	0.000057
0.0	32.84	32.84	300.0	-17.0	0.20	0.38	0.70	0.60	3.45	3.81	4.30	4.35		1.00	0.236	0.000143
0.0	40.15	40.15	300.5	-17.5	0.27	0.45	0.95	1.55	4.65	3.20	5.80	5.80		1.00	0.234	0.000212
0.0	43.29	43.29	300.6	-17.6	0.20	0.40	0.92	1.70	5.10	5.89	6.50	6.60		1.00	0.233	0.000252
0.0	39.62	39.62	300.6	-16.4	0.50	0.63	1.12	1.79	4.76	5.34	5.75	5.75		1.00	0.238	0.000200
0.0	47.31	47.31	300.3	-16.0	0.50	0.67	1.45	3.10	9.25	>10.00	>10.00	>10.00	f	1.00	0.240	0.000279
0.4155	41.80	11.03	300.2	-17.0	0.29	0.44	0.60	0.87	2.35	2.61	2.86	2.73		3.79	0.894	0.000017
0.4155	46.81	16.03	300.2	-17.0	0.32	0.44	0.64	0.93	2.52	2.83	3.11	3.11		2.92	0.689	0.000034
0.4155	52.88	22.22	300.2	-17.0	0.32	0.44	0.68	1.03	2.76	3.22	3.52	3.52		2.38	0.561	0.000062
0.4155	63.08	29.20	300.2	-17.0	0.31	0.45	0.81	1.23	3.51	3.98	4.41	4.41		2.05	0.484	0.000112
0.4155	66.57	35.79	300.0	-16.9	0.30	0.40	0.90	1.55	4.50	5.12	5.60	5.45		1.86	0.439	0.000168
0.4155	70.48	39.82	300.0	-16.9	0.34	0.47	1.07	1.82	5.42	6.02	6.82	6.72		1.77	0.418	0.000206
0.4155	73.40	42.43	300.0	-16.8	0.33	0.53	1.53	3.26	8.38	9.13	>10.00	>10.00	f	1.73	0.408	0.000216
0.4842	66.78	28.91	300.0	-16.6	0.31	0.44	0.80	1.24	3.60	4.00	4.45	4.35		2.31	0.545	0.000105
0.4842	73.80	36.00	300.0	-16.9	0.32	0.46	0.99	1.68	4.80	5.30	6.15	5.95		2.05	0.484	0.000168
0.4842	77.34	39.46	300.0	-16.9	0.36	0.49	1.11	1.98	5.77	6.43	7.34	7.24		1.96	0.462	0.000206
0.4842	79.42	41.58	300.0	-16.9	0.34	0.47	1.21	3.41	8.43	9.16	>10.00	>10.00	f	1.91	0.451	0.000226
0.5535	77.59	34.33	300.0	-16.9	0.32	0.42	0.94	1.52	4.59	5.09	5.67	5.67		2.26	0.533	0.000151
0.5535	80.87	37.44	300.0	-16.9	0.33	0.42	1.08	1.86	5.38	5.00	6.65	6.58		2.16	0.509	0.000177
0.5535	84.07	40.81	300.0	-16.9	0.35	0.47	4.67	>10.00	>10.00	>10.00	>10.00	>10.00	f	2.06	0.486	0.000216
0.6225	77.58	28.85	300.0	-16.9	0.34	0.50	0.89	1.33	3.74	4.18	4.62	4.63		2.69	0.634	0.000105
0.6225	80.28	32.11	300.0	-17.1	0.30	0.33	0.92	1.46	4.30	4.75	5.25	5.25		2.50	0.590	0.000135
0.6225	83.62	35.43	300.0	-16.9	0.31	--	1.01	1.68	4.88	5.49	6.19	6.19		2.36	0.557	0.000160
0.6225	86.76	38.22	300.0	-16.8	0.37	--	1.13	2.02	5.89	6.49	7.29	7.39		2.27	0.535	0.000187
0.6225	88.78	40.17	300.0	-16.8	0.33	--	1.23	5.07	>10.00	>10.00	>10.00	>10.00	f	2.21	0.521	0.000206
0.6917	83.24	29.31	300.0	-16.9	0.32	--	0.95	1.34	4.05	4.35	4.75	4.75		2.84	0.670	0.000112
0.6917	86.72	33.10	300.0	-16.9	0.34	--	0.98	1.56	4.61	5.16	5.71	5.76		2.62	0.618	0.000143
0.6917	90.25	36.39	300.0	-16.9	0.35	--	1.07	1.90	5.72	6.30	7.00	7.05		2.48	0.585	0.000168
0.6917	92.84	39.01	300.0	-16.9	0.36	--	6.95	>10.00	>10.00	>10.00	>10.00	>10.00	f	2.38	0.561	0.000196
1.0370	103.22	22.44	300.0	-17.2	0.28	--	0.77	1.17	3.38	3.77	4.15	4.23		4.60	1.085	0.000067
1.0370	108.07	27.64	300.0	-17.1	0.34	--	0.95	1.50	4.40	4.85	5.30	5.30		3.91	0.922	0.000098
1.0370	111.85	30.90	301.8	-17.4	0.35	--	1.25	2.05	5.59	6.20	6.80	6.80		3.61	0.851	0.000127
1.0370	114.74	34.25	300.0	-17.6	>10.00	>10.00	>10.00	>10.00	>10.00	>10.00	>10.00	>10.00	=	3.35	0.776	0.000154

^aSTP = 70°F, 1 atm.
^bDistance between pressure taps:

0-1	2.75 ft
0-2	3.08 ft
0-3	4.42 ft
0-4	5.83 ft
0-11	13.49 ft
0-12	14.84 ft
0-13	15.21 ft
0-14	15.54 ft

Table 3. Summary of calculated
flooding point data

$\frac{L}{G} \sqrt{\frac{\rho_G}{\rho_L}}$	$\frac{U_m^2 \rho_G \mu_L^{0.2}}{g \rho_L}$	Column
0.930	0.000121	Absorber
1.160	0.000135	Absorber
1.550	0.000097	Absorber
2.220	0.000059	Absorber
2.800	0.000045	Absorber
0.239	0.000267	Stripper
0.413	0.000211	Stripper
0.457	0.000216	Stripper
0.498	0.000197	Stripper
0.528	0.000197	Stripper
0.573	0.000182	Stripper
0.814	0.000141	Stripper

Table 4-A. Gas stream values for absorber

Experiment number	Measured Kr ⁸⁵ concentration (ppb)			Measured O ₂ concentration (%)			Measured flow rate (scfm) ^a			Calculated flow rate (scfm) ^a		O ₂ balance factor	Calculated O ₂ concentration (%)		
	Stream 2	Stream 8	Stream 9	Stream 2	Stream 8	Stream 9	Stream 2	Stream 8	Stream 9	Stream 8	Stream 9		Stream 2	Stream 8	Stream 9
669	72.30	0.0530	182.4	11.02	6.50	17.91	3.18	1.78	1.35	1.92	1.26	1.00	11.02	6.50	17.91
675	63.40	1.7300	178.5	10.06	7.33	15.57	3.98	2.68	1.40	2.66	1.32	1.01	10.06	7.33	15.57
680	59.01	0.0530	153.5	9.31	4.95	16.32	3.18	1.80	1.35	1.96	1.22	1.05	9.31	4.95	16.30
690	57.19	0.0720	147.1	10.51	6.47	16.85	3.15	1.76	1.32	1.93	1.22	1.00	10.51	6.41	16.85
700	49.31	1.6300	213.2	5.16	3.65	10.34	2.79	2.03	0.76	2.16	0.53	1.00	5.16	3.66	10.34
710	52.36	0.3630	99.1	7.33	6.38	8.19	2.83	1.06	1.67	1.34	1.49	1.00	7.33	6.38	8.19
720	53.66	0.0096	113.3	8.51	5.38	12.23	2.11	0.83	0.99	1.11	0.99	1.00	8.61	5.38	12.23
730	41.23	0.9210	180.5	8.13	5.75	16.34	4.38	3.54	1.00	3.40	0.98	1.00	8.13	5.75	16.34
740	45.16	0.0124	147.3	6.49	3.62	12.98	4.37	3.53	1.00	3.03	1.34	1.00	6.49	3.62	12.98

^a
STP = 70°F, 1 atm.

Table 4-B. Gas stream values for stripper

Experiment number	Measured Kr ⁸⁵ concentration (ppb)			Measured O ₂ concentration (%)			Measured flow rate (scfm) ^a			Calculated flow rate (scfm) ^a		O ₂ balance factor	Calculated O ₂ concentration (%)		
	Stream 2	Stream 8	Stream 9	Stream 2	Stream 8	Stream 9	Stream 2	Stream 8	Stream 9	Stream 8	Stream 9		Stream 2	Stream 8	Stream 9
752	24.92	0.5540	104.30	6.04	3.45	14.48	4.31	3.37	1.00	3.30	1.01	1.00	6.04	3.45	14.48
770	21.62	0.6520	85.97	6.76	6.02	9.06	4.36	3.37	1.12	3.29	1.07	1.00	6.76	6.02	9.06
782	21.54	0.0917	89.82	2.99	1.53	7.62	4.63	3.70	1.15	3.52	1.11	1.00	2.99	1.53	7.62
790	20.19	0.8830	85.67	3.04	1.98	6.50	4.63	3.68	1.11	3.54	1.09	1.00	3.04	1.98	6.50
800	15.95	0.6200	61.15	10.57	0.50	2.71	4.52	3.47	1.22	3.37	1.14	1.00	10.56	0.50	2.71
810	13.68	1.4700	51.54	1.62	0.96	3.66	4.82	3.83	1.30	3.64	1.18	1.00	1.62	0.96	3.66
820	37.67	0.1030	197.50	6.85	2.10	15.68	3.59	2.22	1.36	2.33	1.25	1.00	6.85	2.10	15.69
832	38.16	0.4350	102.20	7.03	2.76	14.28	3.35	1.92	1.39	2.11	1.24	1.00	7.03	2.76	14.28
842	36.01	1.9400	86.02	7.71	3.09	14.48	3.22	1.76	1.43	1.92	1.31	1.00	7.71	3.10	14.48
852	30.65	3.7400	76.76	6.95	3.28	13.24	3.50	2.10	1.39	2.21	1.29	1.00	6.95	3.28	13.24
864	24.10	0.9980	73.07	3.85	1.57	8.66	3.83	2.79	1.41	2.60	1.23	1.00	3.84	1.57	8.66
874	23.04	0.3440	70.47	5.16	2.24	11.24	3.76	2.70	1.46	2.54	1.22	1.00	5.15	2.24	11.25
884	21.57	0.0953	58.80	5.98	2.51	11.99	3.58	2.44	1.50	2.27	1.31	1.00	5.98	2.51	11.99
896	20.12	0.0135	58.23	6.29	2.52	13.42	3.67	2.52	1.47	2.40	1.27	1.00	6.29	2.52	13.42
901	15.41	0.0579	55.47	4.93	2.46	11.39	4.61	3.63	1.43	3.33	1.28	1.00	4.93	2.46	11.39
914	9.88	0.1020	39.41	9.96	5.17	24.41	4.47	1.41	1.43	3.36	1.11	1.00	9.96	5.17	24.41
926	9.85	0.1530	33.83	9.25	3.83	22.65	4.33	3.34	1.44	3.08	1.25	1.00	9.25	3.83	22.65
938	9.26	0.5070	31.04	9.47	5.59	19.11	4.62	3.63	1.47	3.30	1.33	1.00	9.47	5.59	19.11
954	20.99	0.5760	79.45	6.42	5.04	10.38	4.44	3.53	1.41	3.29	1.14	1.00	6.42	5.04	10.38
966	21.43	0.2550	77.22	7.00	4.42	13.79	4.37	3.44	1.39	3.17	1.20	1.00	7.00	4.42	13.79
978	22.69	0.2330	83.80	10.74	5.21	25.81	4.62	3.65	1.40	3.37	1.24	1.00	10.74	5.21	25.80
990	23.78	0.6650	81.15	5.97	4.18	10.42	4.44	3.48	1.44	3.17	1.28	1.00	5.97	4.18	10.42
1002	21.38	0.8640	73.78	5.24	5.15	10.58	4.49	3.54	1.46	3.23	1.26	1.00	5.24	3.15	10.58
1014	18.70	4.6000	55.78	4.82	4.08	6.75	4.99	3.67	1.38	3.62	1.37	1.00	4.82	4.08	6.75
1030	9.05	1.1800	29.28	10.45	6.61	15.18	4.96	3.57	1.41	3.57	1.39	1.00	10.45	8.61	15.18
1042	80.89	0.1250	274.80	8.92	5.46	17.25	4.42	3.01	1.33	3.12	1.30	1.00	8.92	5.46	17.25
1056	43.52	0.4080	164.80	10.74	7.01	21.21	5.21	3.85	1.40	3.84	1.37	1.00	10.74	7.01	21.21
1067	25.72	0.0313	87.55	11.83	6.06	25.71	4.88	3.45	1.44	3.45	1.43	1.00	11.83	6.06	25.72
1078	23.73	0.2530	85.72	19.02	19.56	17.60	4.94	3.59	1.36	3.58	1.36	1.00	19.02	19.56	17.60
1090	23.02	1.0600	89.37	12.72	9.23	23.24	5.40	4.14	1.38	4.06	1.34	1.00	12.72	9.23	23.24
1100	20.27	0.0280	79.67	7.94	3.42	21.21	5.33	4.04	1.37	3.98	1.35	1.00	7.94	3.42	21.21
1110	18.67	0.0285	76.24	8.21	1.47	19.76	5.50	4.23	1.35	4.15	1.34	1.00	8.21	4.47	19.76
1120	17.55	0.0373	69.68	8.96	5.32	19.79	5.44	4.16	1.38	4.07	1.37	1.00	8.96	5.32	19.79
1130	16.74	0.0839	68.34	7.21	1.50	15.61	5.58	4.32	1.36	4.21	1.36	1.00	7.21	4.50	15.61
1140	15.93	0.0547	63.43	6.69	3.95	14.89	5.25	4.04	1.32	3.93	1.31	1.00	6.69	3.95	14.89
1148	14.91	0.0657	58.92	5.00	3.03	10.81	5.28	4.08	1.33	3.95	1.33	1.00	5.00	3.03	10.81
1158	14.39	0.0515	56.39	8.20	3.50	21.96	5.28	3.98	1.37	3.94	1.34	1.00	8.20	3.50	21.96
1168	13.16	0.1880	53.94	5.37	2.83	13.36	5.53	4.26	1.32	4.20	1.34	1.00	5.37	2.83	13.63
1178	11.10	0.1610	45.17	5.19	3.50	10.42	5.58	4.33	1.35	4.22	1.36	1.00	5.19	3.50	10.42
1188	10.04	0.1160	38.99	4.30	2.45	9.00	5.26	3.98	1.30	3.92	1.34	0.96	4.21	2.50	9.20
1200	26.12	5.5300	88.28	6.75	4.06	14.85	5.53	4.19	1.38	4.15	1.37	1.00	6.74	4.06	14.86

^a
STP = 70°F, 1 atm.

Table 4-C. Gas stream values for fractionator

Experiment number	Measured H_2^{85} concentration (ppb)			Measured O_2 concentration (%)			Measured flow rate (scfm) ^a			Calculated flow rate (scfm) ^a		O_2 balance factor	Calculated O_2 concentration (%)		
	Stream 2	Stream 8	Stream 9	Stream 2	Stream 8	Stream 9	Stream 2	Stream 8	Stream 9	Stream 2	Stream 9		Stream 2	Stream 8	Stream 9
1206	23.07	7.40	72.34	5.22	2.70	13.12	5.65	4.37	1.38	4.28	1.36	1.00	5.22	2.70	13.12
1214	21.08	12.03	48.93	6.10	3.30	13.35	5.31	4.01	1.39	4.01	1.30	0.95	5.93	3.40	13.74
1222	20.94	10.48	53.00	5.60	3.23	12.83	5.55	4.19	1.37	4.18	1.36	1.00	5.60	3.23	12.88
1230	20.54	9.10	55.36	5.39	2.70	13.56	5.48	4.19	1.37	4.13	1.36	1.00	5.39	2.70	1.36
1246	19.84	7.23	57.58	5.27	2.86	12.49	5.50	4.22	1.38	4.12	1.38	1.00	5.27	2.86	12.49
1254	13.35	5.48	36.86	7.27	3.48	18.60	5.42	4.13	1.40	4.06	1.36	1.00	7.27	3.48	18.60
1262	12.92	5.90	34.02	7.52	3.89	18.43	5.51	4.18	1.40	4.13	1.38	1.00	7.52	3.89	18.43
1270	12.28	6.03	31.01	6.53	3.30	16.21	5.48	4.18	1.39	4.11	1.37	1.00	6.53	3.30	16.21
1278	11.43	6.24	27.05	7.13	3.59	17.78	5.53	4.23	1.39	4.15	1.38	1.00	7.13	3.59	17.78
1286	8.99	3.58	25.13	5.46	3.08	12.58	5.59	4.30	1.38	4.18	1.40	1.00	5.46	3.08	12.58
1302	10.63	4.61	28.52	6.29	4.07	12.86	5.56	4.24	1.38	4.16	1.40	1.00	6.28	4.07	12.86
1310	9.95	4.49	27.34	5.94	3.40	14.03	5.58	4.26	1.39	4.24	1.33	1.00	5.94	3.40	14.03
1318	9.62	4.57	24.32	5.58	3.00	14.35	5.42	4.10	1.38	4.04	1.39	1.06	5.74	2.92	13.96
1326	9.47	4.88	22.94	5.70	2.75	14.39	5.55	4.82	1.39	4.14	1.41	1.00	5.70	2.75	14.39
1359	5.44	3.25	11.89	6.20	2.20	14.00	3.17	3.73	1.43	3.86	1.31	0.84	5.69	2.41	15.37
1368	5.83	2.63	13.37	5.20	1.34	14.19	4.65	3.23	1.42	3.25	1.40	1.00	5.20	1.34	14.18
1376	4.65	2.11	11.67	7.59	2.60	21.36	5.18	3.83	1.32	3.80	1.38	1.00	7.59	2.60	21.36
1386	4.51	1.86	12.24	8.14	2.83	23.62	5.22	3.90	1.33	3.88	1.33	1.00	8.14	2.83	23.62
1396	4.44	1.53	10.89	5.36	0.86	15.32	5.78	3.15	1.42	3.98	1.80	1.00	5.35	0.86	15.32
1404	1.55	0.61	4.60	5.35	2.05	14.50	5.41	4.17	1.43	4.14	1.27	0.93	5.16	0.21	15.04
1425	52.01	16.95	107.30	6.10	2.21	16.25	5.39	3.92	1.53	3.90	1.50	1.00	6.10	2.21	16.25
1433	41.05	16.89	105.50	5.64	1.67	16.22	5.09	3.69	1.41	3.70	1.39	1.00	5.64	1.67	16.22
1442	37.65	17.42	82.24	7.66	3.02	17.90	5.20	3.58	1.62	3.58	1.62	1.00	7.66	3.02	17.90
1450	31.03	7.08	111.24	6.51	3.24	17.47	5.45	4.20	1.35	4.20	1.25	1.00	6.51	3.24	17.47
1460	31.86	8.36	100.95	5.09	2.45	12.83	5.39	4.02	1.41	4.02	1.37	1.00	5.09	2.45	12.83
1468	29.15	7.57	91.46	7.29	3.93	17.01	5.42	4.07	1.41	4.03	1.39	1.00	7.29	3.93	17.01
1484	15.84	7.92	41.00	9.03	4.39	23.77	5.50	4.64	1.47	4.18	1.32	1.00	9.03	4.39	23.77
1485	15.44	8.05	33.56	8.13	3.85	18.62	5.61	4.12	1.81	3.98	1.63	1.00	8.13	3.85	18.62
1494	14.56	6.17	48.17	7.08	2.38	25.92	4.84	4.26	1.01	3.87	0.97	1.00	7.08	2.38	25.92
1501	12.04	5.12	46.23	8.15	3.30	31.00	5.31	4.51	0.84	4.42	0.89	0.98	8.06	3.34	31.37
1510	12.34	6.02	29.25	8.43	3.45	21.75	5.42	4.32	1.70	3.95	1.47	1.00	8.43	3.45	21.76
1531	12.87	9.66	18.89	9.57	6.98	14.61	4.83	3.34	2.03	3.15	1.68	1.00	9.57	6.88	14.61
1539	13.56	9.67	20.38	8.70	4.78	15.56	4.83	3.32	2.03	3.08	1.75	1.00	8.70	4.78	15.56
1547	11.59	7.56	17.90	6.22	2.21	12.51	4.70	3.20	1.99	2.87	1.83	1.00	6.22	2.21	12.51
1560	10.22	6.87	16.94	7.23	3.94	14.05	4.84	3.30	2.01	3.23	1.61	1.00	7.23	3.84	14.04
1568	7.56	4.33	13.78	11.05	2.51	27.54	4.81	3.23	2.03	3.16	1.64	1.00	11.05	2.50	27.52

^a
STP = 70°F, 1 atm.

Table 5-A. Equivalent pump rate
for absorber experiments

Experiment number	Pump rate (gpm)	Temperature (°C)	Q ₁ (equiv scfm) ^a
669	0.327	-28.2	25.29
675	0.327	-27.8	25.26
680	0.294	-28.5	22.78
690	0.294	-28.4	22.77
700	0.294	-28.9	22.80
710	0.294	-30.5	22.87
720	0.294	-30.0	22.85
730	0.554	-29.8	43.05
740	0.554	-29.5	43.02

^a STP = 70°F, 1 atm.

Table 5-B. Equivalent pump rate for stripper experiments

Experiment number	Pump rate (gpm)	Temperature (°C)	Q ₁ (equiv scfm) ^a
752	0.554	-28.6	42.93
770	0.553	-28.4	42.85
782	0.623	-26.4	47.99
790	0.623	-26.5	48.00
800	0.623	-26.6	48.02
810	0.623	-27.2	48.11
820	0.692	-27.6	53.45
832	0.692	-28.0	53.51
842	0.692	-27.2	53.39
852	0.692	-26.5	53.27
864	0.693	-28.1	53.53
874	0.693	-27.5	53.44
884	0.692	-27.7	53.47
896	0.692	-28.5	53.58
901	0.623	-28.5	48.29
914	0.623	-29.0	48.35
926	0.623	-29.0	48.35
938	0.623	-28.9	48.33
954	0.553	-28.3	42.82
966	0.553	-27.5	42.74
978	0.553	-27.8	42.78
990	0.553	-28.5	42.86
1002	0.553	-28.2	42.83
1014	0.553	-28.7	42.88
1030	0.553	-28.8	42.90
1042	0.692	-28.0	53.51
1056	0.623	-26.5	47.94
1067	0.553	-25.7	42.50
1078	0.553	-27.3	42.74
1090	0.623	-27.5	48.09
1100	0.701	-27.7	54.21
1110	0.623	-27.5	48.15
1120	0.623	-26.8	47.99
1130	0.623	-27.1	48.03
1140	0.623	-27.8	48.19
1148	0.623	-28.1	48.17
1158	0.692	-28.4	53.57
1168	0.692	-27.9	53.50
1178	0.553	-28.5	42.86
1188	0.623	-28.5	48.29
1200	0.623	-25.8	47.76

^a STP = 70°F, 1 atm.

Table 5-C. Equivalent pump rate
for fractionator experiments

Experiment number	Pump rate (gpm)	Temperature (°C)	Q ₁ (equiv scfm) ^a
1206	0.623	-25.3	47.81
1214	0.623	-25.3	47.81
1222	0.623	-25.4	47.82
1230	0.623	-25.4	47.82
1246	0.623	-25.0	46.23
1254	0.623	-24.7	47.71
1262	0.623	-24.6	47.69
1270	0.623	-24.7	47.71
1278	0.623	-24.7	47.71
1286	0.623	-24.7	47.71
1302	0.553	-24.8	42.36
1310	0.553	-24.6	42.33
1318	0.553	-24.6	42.33
1326	0.553	-25.0	42.40
1359	0.623	-23.6	47.45
1368	0.623	-23.9	47.50
1376	0.623	-23.6	47.45
1386	0.623	-23.2	47.38
1396	0.692	-22.8	52.56
1404	0.657	-25.0	50.35
1425	0.657	-25.3	50.40
1433	0.657	-25.0	50.35
1442	0.657	-24.8	50.31
1450	0.657	-25.5	50.44
1460	0.657	-25.2	50.38
1468	0.657	-25.1	50.37
1484	0.623	-25.6	47.80
1485	0.623	-25.7	47.81
1494	0.623	-24.8	47.66
1501	0.623	-24.6	47.63
1510	0.623	-22.0	47.15
1531	0.553	-25.5	42.47
1539	0.553	-25.5	42.47
1547	0.553	-25.0	42.39
1560	0.553	-25.4	42.54
1568	0.553	-25.8	42.50

^a STP = 70°F, 1 atm.

Table 6-A. Calculated stripper liquid feed
for absorber experiments

Experiment number	Q_1 (scfm) ^a	Measured concentrations		Calculated concentrations	
		O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)
669	26.55	0.719	9.14	0.850	8.65
675	26.58	0.923	9.78	0.773	9.32
680	23.99	0.780	7.65	0.828	7.81
690	23.99	0.720	7.41	0.888	7.51
700	23.43	0.260	5.71	0.278	5.73
710	24.36	0.507	5.88	0.500	6.06
720	23.85	0.565	4.75	0.509	4.74
730	44.03	0.490	4.06	0.365	4.03
740	44.36	0.401	3.46	0.392	4.45

^a STP = 70°F, 1 atm.

Table 6-B. Calculated stripper liquid feed
for stripper experiments

Experiment number	Q ₇ (scfm) ^a	Measured concentrations		Calculated concentrations	
		O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)
752	43.94	-	2.33	0.33	2.42
770	43.92	-	-	0.39	2.13
782	49.09	0.02	1.98	0.17	2.03
790	49.09	0.03	1.86	0.15	1.90
800	49.16	0.18	0.63	0.06	1.47
810	49.28	-	1.34	0.09	1.35
820	54.70	0.70	2.33	0.37	2.47
832	54.75	0.25	2.42	0.33	2.34
842	54.69	0.52	2.08	0.35	2.20
852	54.56	1.80	2.00	0.32	2.10
864	54.75	0.96	1.75	0.20	1.71
874	54.65	0.61	1.58	0.26	1.60
884	54.78	2.25	1.43	0.29	1.42
896	54.85	1.40	1.29	0.32	1.35
901	49.56	0.15	1.40	0.30	1.43
914	49.46	-	-	0.56	0.89
926	49.59	0.12	0.91	0.58	0.87
938	49.66	0.60	0.84	0.52	0.87
954	43.97	2.00	2.37	0.28	2.10
966	43.95	0.90	2.13	0.38	2.13
978	44.02	0.07	2.44	0.73	2.36
990	44.14	0.60	2.46	0.31	2.35
1002	44.09	0.18	2.22	0.31	2.11
1014	44.26	0.02	2.41	0.21	1.73
1030	44.28	0.45	1.24	0.48	0.92
1042	54.81	0.85	7.67	0.41	6.52
1056	49.31	0.60	4.54	0.59	4.58
1067	43.93	1.10	3.25	0.84	2.86
1078	44.10	1.05	3.57	0.54	2.64
1090	49.43	1.20	3.44	0.63	2.43
1100	55.56	0.80	1.97	0.52	1.95
1110	49.50	0.70	2.05	0.54	2.07
1120	49.35	0.21	2.19	0.55	1.93
1130	49.39	0.27	1.90	0.43	1.89
1140	49.51	0.62	1.73	0.40	1.68
1148	49.50	1.25	1.51	0.29	1.59
1158	54.91	0.40	1.24	0.54	1.38
1168	54.83	0.45	1.28	0.57	1.34
1178	44.22	0.93	1.39	0.32	1.39
1188	49.63	0.80	1.05	0.25	1.06
1200	49.13	1.00	2.78	0.42	2.96

^aSTP = 70°F, 1 atm.

Table 6-C. Calculated stripper liquid feed
for fractionator experiments

Experiment number	Q ₇ (scfm) ^a	Measured concentrations		Calculated concentrations	
		O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)
1206	49.17	0.63	2.77	0.37	2.72
1214	49.11	0.43	2.53	0.38	2.46
1222	49.19	0.74	2.48	0.36	2.52
1230	49.18	0.50	2.42	0.38	2.39
1246	47.60	1.20	2.30	0.36	2.37
1254	49.07	1.18	1.57	0.52	1.56
1262	49.06	1.00	1.48	0.52	1.55
1270	49.08	0.80	1.46	0.45	1.38
1278	49.08	1.00	1.36	0.51	1.43
1286	49.11	0.54	1.06	0.36	1.11
1302	43.77	0.60	1.43	0.41	1.41
1310	43.67	0.34	1.43	0.43	1.31
1318	43.72	0.29	1.30	0.44	1.27
1326	43.80	0.34	1.30	0.47	1.30
1359	48.76	0.29	0.71	0.44	0.68
1368	48.90	0.33	0.65	0.41	0.64
1376	48.83	0.50	0.54	0.60	0.57
1386	48.71	0.45	0.52	0.65	0.54
1396	54.36	0.42	0.42	0.51	0.51
1404	51.62	0.26	0.17	0.37	0.17
1425	51.90	0.29	4.97	0.47	4.92
1433	51.74	0.28	4.70	0.44	4.41
1442	51.93	0.36	4.31	0.56	4.33
1450	51.70	0.42	3.51	0.42	3.39
1460	51.75	0.41	3.53	0.34	3.54
1468	51.76	0.51	3.28	0.46	4.43
1484	49.11	0.48	1.99	0.64	1.90
1485	49.44	0.55	1.98	0.62	1.94
1494	48.63	0.39	1.70	0.53	1.58
1501	47.70	0.39	1.39	0.58	1.42
1510	48.63	0.49	1.70	0.67	1.60
1531	44.15	0.78	1.94	0.80	1.94
1539	44.22	1.10	1.95	0.88	1.83
1547	44.23	0.75	1.68	0.62	1.54
1560	44.06	0.68	1.43	0.60	1.35
1568	44.15	0.58	1.03	1.04	1.00

^aSTP = 70°F, 1 atm.

Table 7. Absorber inlet and outlet stream information

Experiment number	Calculated flow rates (scfm) ^a				Measured concentration								Calculated concentration	
					Stream 3		Stream 4		Stream 5		Stream 6		Stream 3	
	Stream 3	Stream 4	Stream 5	Stream 6	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)
669	26.06	2.70	26.98	3.61	0.72	6.08	12.68	55.37	0.33	0.00430	6.01	0.063	0.83	5.72
675	25.82	3.23	26.63	4.03	0.87	8.64	12.61	66.97	0.31	0.13000	7.24	1.980	0.82	8.19
680	23.10	2.28	24.24	3.43	0.66	4.94	11.95	45.32	0.22	0.00300	4.85	0.048	0.76	4.48
690	23.23	2.39	25.06	4.22	0.98	4.75	12.62	45.84	0.56	0.00700	6.17	0.073	0.79	4.71
700	23.86	3.22	24.29	3.65	0.25	5.43	4.95	39.41	0.15	0.14000	3.18	1.840	0.34	5.18
710	24.66	3.13	24.73	3.20	0.53	5.00	6.50	37.11	0.46	0.03200	6.29	0.400	0.48	4.68
720	24.22	2.48	25.17	3.43	0.59	3.14	7.17	29.82	0.31	0.00086	5.42	0.0094	0.49	3.06
730	44.81	5.16	44.92	5.27	0.54	3.63	7.44	32.36	0.30	0.05200	5.20	0.1040	0.42	3.66
740	44.28	4.29	44.45	4.46	0.39	2.33	6.11	26.74	0.00	0.00008	3.28	0.017	0.34	2.59

^a STP = 70°F, 1 atm.

Table E-A. Calculated stripper bottom information

Experiment number	Calculated flow rates (scfm) ^a		Measured concentrations								Calculated concentrations			
			Stream 1		Stream 10		Stream 11				Stream 1		Stream 10	
	Stream 10	Stream 11	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)
752	49.11	6.1E	0.00	0.024	0.00	0.059	0.35	0.35	0.00	0.038	0.00	0.078		
770	48.59	5.7E	--	0.039	--	0.099	--	0.61	0.29	0.065	0.87	0.13		
782	56.00	8.01	0.0	0.00008	0.0	0.0017	0.0	0.154	0.00	0.016	0.0	0.036		
790	55.81	7.81	0.01	0.0042	0.01	0.011	0.01	0.063	0.00055	0.0068	0.0019	0.015		
800	54.03	6.0E	0.00	0.052	0.00	0.13	0.00	0.78	0.00	0.083	0.00	0.16		
810	53.39	5.23	--	0.12	--	0.26	--	1.78	0.0	0.19	0.00	0.35		
820	62.12	8.67	0.01	0.0099	0.01	0.020	0.01	0.12	0.00055	0.013	0.0019	0.028		
832	61.21	7.73	0.0055	0.023	0.0055	0.081	0.0055	0.44	0.00030	0.048	0.0010	0.098		
842	59.89	6.50	0.0018	0.15	0.06	0.34	0.0018	2.16	0.00010	0.23	0.00028	0.44		
852	59.00	5.73	0.0035	0.30	0.0035	0.63	0.0035	4.22	0.00019	0.45	0.00051	0.82		
864	52.20	5.67	0.0093	0.079	0.090	0.17	0.10	1.27	0.0048	0.12	0.014	0.23		
874	59.90	6.44	0.013	0.030	0.10	0.07	0.015	0.49	0.00072	0.047	0.0023	0.094		
884	60.78	7.3	0.0062	0.0086	0.0062	0.020	0.0062	0.046	0.0030	0.0044	0.0010	0.0094		
896	62.10	8.52	0.0058	0.00061	0.0058	0.0019	0.0058	0.015	0.00028	0.0014	0.0010	0.0032		
901	56.12	7.84	0.0062	0.00096	0.0062	0.0019	0.0062	0.010	0.00030	0.00099	0.0011	0.0023		
914	54.92	6.57	0.0082	0.0041	0.0082	0.0060	0.0082	0.032	0.00040	0.0031	0.0013	0.0066		
926	54.20	5.85	0.0070	0.015	0.0070	0.031	0.0070	0.020	0.00034	0.020	0.0011	0.039		
938	53.56	5.23	0.0070	0.041	0.0070	0.10	0.0070	0.69	0.00034	0.066	0.00099	0.13		
954	47.44	4.62	0.0051	0.027	0.0041	0.075	0.0067	0.54	0.00032	0.052	0.00095	0.099		
966	47.92	5.1E	0.0044	0.015	0.0045	0.04	0.005	0.28	0.00024	0.027	0.00076	0.055		
978	48.75	5.97	0.0041	0.0020	0.0060	0.0075	0.0060	0.048	0.00029	0.0046	0.00099	0.0099		
990	47.92	5.1E	0.0062	0.0097	0.0058	0.00077	0.0062	0.0077	0.00024	0.027	0.00076	0.055		
1002	51.08	8.2E	0.0050	0.00024	0.0073	0.0013	0.005	0.00	0.00024	0.00	0.0010	0.00		
1014	49.85	6.97	0.0048	0.000041	0.0038	0.0023	0.0047	0.00006E	0.00020	0.0000057	0.00083	0.000014		
1030	51.12	8.2E	0.00	0.00	0.00	0.00014	0.45	0.000061	0.000059	0.000059	0.091	0.000015		
1042	64.00	10.4E	0.00042	0.00041	0.00	0.0020	0.11	0.00067	0.00064	0.00064	0.022	0.00015		
1056	55.07	7.1E	0.00	0.018	0.00	0.066	0.00	0.38	0.00	0.040	0.00	0.084		
1067	49.33	6.84	0.00	0.0091	0.00	0.0014	0.00	0.0098	0.00	0.0011	0.00	0.0023		
1078	49.05	6.3E	0.00	0.0011	0.0030	0.00094	0.10	0.00	0.0048	0.00	0.017	0.00		
1090	55.14	7.05	0.00	0.00057	0.00	0.00	0.15	0.00089	0.0072	0.000085	0.025	0.00019		
1100	62.29	8.08	0.00	0.0030	0.00	0.0052	0.050	0.030	0.0024	0.0029	0.0086	0.0064		
1110	55.34	7.19	0.00	0.0000025	0.0050	0.0023	0.05	0.022	0.0024	0.0021	0.0086	0.0046		
1120	54.67	6.68	0.00	0.00054	0.00	0.00085	0.08	0.0072	0.0036	0.00066	0.13	0.0015		
1130	53.86	5.82	0.00	0.0040	0.0030	0.011	0.00	0.90	0.00	0.0081	0.00	0.017		
1140	54.28	6.09	0.0070	0.00016	0.00	0.00056	0.014	0.0052	0.00059	0.00045	0.0021	0.00099		
1148	53.56	5.39	0.0010	0.0029	0.0072	0.0099	0.043	0.081	0.0018	0.0069	0.0060	0.014		
1158	59.67	6.10	0.00	0.0042	0.10	0.015	0.00	0.086	0.00	0.0073	0.00	0.015		
1168	58.88	5.38	0.25	0.024	0.25	0.059	0.25	0.38	0.010	0.033	0.032	0.065		
1178	47.14	4.27	0.00	0.0072	0.00	0.018	0.0040	0.12	0.00017	0.010	0.00052	0.020		
1188	53.24	4.95	0.00	0.0073	0.00	0.020	0.0045	0.16	0.00019	0.014	0.00059	0.028		
1200	52.68	4.92	0.00050	0.50	0.00050	1.12	0.0080	6.85	0.00044	0.73	0.0011	1.30		

^a STP = 70°F, 1 atm.

Table 3-B. Calculated fractionator bottom information

Experiment number	Calculated flow rates (scfm) ^a		Measured concentrations						Calculated concentrations			
	Stream 10	Stream 11	Stream 1		Stream 10		Stream 11		Stream 1		Stream 10	
			O ₂	Kr	O ₂	Kr	O ₂	Kr	O ₂	Kr	O ₂	Kr
			(%)	(ppb)	(%)	(ppb)	(%)	(ppb)	(%)	(ppb)	(%)	(ppb)
1206	51.79	3.98	0.0030	0.74	0.0030	1.53	0.0040	10.74	0.00022	1.15	0.0081	1.89
1214	50.57	2.76	0.020	1.19	0.039	2.03	0.39	15.46	0.021	1.66	0.041	2.41
1222	51.08	3.26	0.0068	1.08	0.0089	1.89	0.045	14.19	0.0025	1.52	0.0052	2.33
1230	51.37	3.55	0.0055	0.89	0.0059	1.72	0.014	12.33	0.00075	1.33	0.0016	2.09
1246	51.60	3.84	0.00020	0.72	0.00070	1.47	0.0017	10.13	0.000094	1.09	0.00021	1.76
1254	51.65	3.94	0.00	0.56	0.00030	1.08	0.0035	7.74	0.00019	0.83	0.00045	1.36
1262	51.34	3.65	0.00	0.61	0.00	1.12	0.0041	8.10	0.00023	0.87	0.00050	1.39
1270	51.09	3.38	0.00040	0.53	0.0022	1.15	0.023	8.22	0.0013	0.89	0.0027	1.37
1278	50.88	3.17	0.011	0.69	0.028	1.16	0.42	8.45	0.023	0.91	0.048	1.38
1286	51.29	3.58	0.00060	0.40	0.00060	0.73	0.0077	5.32	0.00043	0.57	0.0093	0.90
1302	45.63	3.27	0.00	0.52	0.00020	0.98	0.0024	6.76	0.00013	0.73	0.0030	1.16
1310	45.43	3.10	0.00020	0.49	0.00060	0.93	0.0093	6.88	0.00052	0.74	0.0011	1.16
1318	45.26	2.93	0.00060	0.51	0.0022	0.94	0.024	6.85	0.0014	0.74	0.0029	1.14
1326	44.99	2.60	0.0032	0.58	0.0075	0.94	0.095	7.20	0.0053	0.78	0.010	1.15
1359	50.12	2.67	0.025	0.37	0.051	0.59	0.72	4.56	0.040	0.50	0.076	0.07
1368	50.85	3.35	0.0013	0.27	0.0028	0.48	0.031	3.70	0.0017	0.40	0.0037	0.62
1376	50.97	3.52	0.00030	0.25	0.0019	0.42	0.028	3.13	0.0016	0.34	0.0034	0.53
1386	51.07	3.69	0.00010	0.21	0.00060	0.38	0.0094	2.68	0.00052	0.29	0.0012	0.46
1396	56.62	4.06	0.00	0.15	0.00030	0.28	0.0078	2.04	0.00043	0.22	0.00096	0.35
1404	54.27	3.93	0.00070	0.06	0.00030	0.11	0.0057	0.81	0.00032	0.09	0.00071	0.14
1425	54.06	3.65	0.00070	1.88	0.00060	3.27	0.0088	22.79	0.00049	2.45	0.0010	3.83
1433	53.86	3.51	0.00070	1.63	0.0018	3.19	0.020	22.47	0.0010	2.42	0.0023	3.72
1442	53.61	3.30	0.0050	1.82	0.013	3.11	0.14	23.31	0.0071	2.51	0.015	3.79
1450	54.32	3.88	0.000050	0.71	0.000050	1.51	0.00055	11.64	0.000027	1.12	0.22	2.78
1460	54.05	3.67	0.00020	0.90	0.00020	1.67	0.0013	12.89	0.000063	1.24	0.00015	2.03
1468	53.92	3.55	0.00020	0.84	0.00080	1.57	0.0019	12.25	0.000092	1.18	0.00021	1.91
1484	51.38	3.58	0.0019	0.82	0.0027	1.57	0.020	11.22	0.0011	1.20	0.0024	1.90
1485	51.33	3.52	0.0040	0.87	0.0043	1.56	0.037	11.31	0.0020	1.21	0.0044	1.90
1494	51.24	3.58	0.0009	0.64	0.0016	1.19	0.0086	8.68	0.00043	0.94	0.00094	1.48
1501	51.13	3.51	0.0035	0.57	0.0020	0.88	0.011	7.39	0.00061	0.80	0.0013	1.25
1510	50.80	3.65	0.0068	0.73	0.0081	1.30	0.076	8.58	0.0047	1.01	0.0098	1.55
1531	44.49	2.02	0.25	1.27	0.44	1.73	4.90	12.84	0.25	1.20	0.44	1.73
1539	44.97	2.50	0.27	1.48	0.53	1.67	3.60	12.25	0.21	1.45	0.38	2.05
1547	45.03	2.64	0.10	0.83	0.21	1.40	1.00	9.91	0.056	1.18	0.10	1.69
1560	45.24	2.78	0.091	0.75	0.16	1.20	2.10	8.38	0.13	1.00	0.25	1.45
1568	45.38	2.88	0.015	0.51	0.025	0.83	0.20	5.42	0.013	0.64	0.025	0.94

^a STP = 70°F, 1 atm.

Table 9-A. Calculated stripper top information

Experiment number	Calculated flow rate (scfm) ^a		Measured concentration				Calculated concentration	
			Stream 12		Stream 13		Stream 13	
	Stream 13	Stream 12	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)
752	49.11	6.18	0.95	16.04	--	2.01	0.12	2.05
770	48.59	5.73	2.02	14.90	1.67	1.80	0.58	1.82
782	56.00	8.01	0.15	10.13	0.02	1.48	0.02	1.46
790	55.01	7.81	0.48	11.01	0.03	1.45	0.07	1.55
800	54.08	6.02	0.18	10.16	0.06	1.17	0.02	1.21
810	53.39	5.28	--	10.14	--	1.11	--	1.17
820	62.12	8.67	1.88	16.64	0.03	2.01	0.26	2.33
832	61.21	7.70	2.18	17.43	0.10	2.02	0.27	2.23
842	59.89	6.50	3.23	17.10	0.30	1.79	0.35	2.06
852	59.00	5.73	3.51	16.34	1.40	1.71	0.34	1.99
864	59.20	5.67	1.22	12.77	0.40	1.25	0.12	1.33
874	59.90	6.47	1.45	10.97	0.32	1.16	0.16	1.23
884	60.78	7.31	1.84	8.77	0.15	0.97	0.22	1.06
896	62.10	8.52	1.37	3.09	0.10	0.93	0.19	0.43
901	56.12	7.84	0.28	6.99	0.11	0.92	0.04	0.98
914	54.92	6.57	1.43	5.86	0.12	0.66	0.17	0.70
936	54.20	5.09	1.54	6.12	0.06	0.61	0.17	0.68
938	53.56	5.23	3.07	6.39	0.20	0.59	0.30	0.68
954	47.44	4.62	1.93	13.97	0.14	1.55	0.19	1.41
966	47.92	5.18	1.68	13.41	0.15	1.46	0.18	1.47
978	48.75	5.97	0.12	12.43	0.07	1.52	0.02	1.52
990	47.92	5.18	0.96	11.40	0.16	1.60	0.18	1.47
1002	51.08	8.25	0.21	8.49	0.14	1.41	0.03	1.37
1014	49.85	6.97	0.02	5.40	0.01	1.08	0.002	0.75
1030	51.12	8.23	0.60	2.71	0.10	0.59	0.11	0.44
1042	64.00	10.49	0.95	12.51	0.10	3.79	0.16	2.05
1056	55.07	7.13	2.87	29.21	0.15	3.59	0.37	3.83
1067	49.33	6.84	1.84	20.08	0.20	2.58	0.67	2.78
1078	49.06	6.32	2.79	15.29	0.16	2.02	0.36	1.97
1090	55.14	7.05	2.82	14.07	0.17	2.17	0.37	1.80
1100	62.29	8.08	2.41	12.03	0.15	1.50	0.31	1.56
1110	55.34	7.19	2.43	12.93	0.33	1.51	0.32	1.68
1120	54.67	6.68	1.66	10.47	0.32	1.36	0.21	1.28
1130	53.86	5.82	2.93	12.54	0.19	1.30	0.32	1.36
1140	54.28	6.09	1.71	9.82	0.21	1.03	0.19	1.10
1148	53.56	5.39	1.95	10.84	0.17	1.06	0.20	1.10
1158	59.67	6.10	2.41	9.50	0.30	0.90	0.25	0.98
1168	58.88	5.38	1.67	9.73	0.25	0.80	0.16	0.93
1170	47.14	4.27	1.89	9.97	0.07	0.98	0.17	0.91
1188	53.24	4.95	1.30	7.20	0.19	0.74	0.12	0.68
1200	52.68	4.90	0.16	23.10	0.20	2.62	0.76	2.83

^a
STP = 70°F, 1 atm.

Table 9-B. Calculated fractionator top information

Experiment number	Calculated flow rate (scfm) ^a		Measured concentration				Calculated concentration	
			Stream 12		Stream 13		Stream 13	
	Stream 13	Stream 12	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)	O ₂ (%)	Kr (ppb)
1206	51.79	3.98	3.45	22.04	0.26	2.40	0.27	2.76
1214	50.57	2.76	5.00	19.05	0.25	2.16	0.29	2.61
1222	51.08	3.26	4.70	18.94	0.28	2.10	0.30	2.64
1230	51.37	3.55	4.47	18.97	0.28	2.08	0.31	2.55
1246	51.60	3.84	3.89	17.90	0.14	1.96	0.29	2.34
1254	51.65	3.94	6.60	12.87	0.33	1.40	0.50	1.75
1262	51.34	3.65	5.92	11.80	0.27	1.30	0.42	1.65
1270	51.09	3.38	5.94	11.11	0.44	1.25	0.39	1.56
1278	50.88	3.17	6.59	10.42	0.50	1.19	0.43	1.50
1286	51.29	3.58	4.83	8.26	0.34	0.94	0.34	1.11
1302	45.63	3.27	4.35	10.51	0.23	1.17	0.31	1.43
1310	45.43	3.10	4.23	9.99	0.21	1.09	0.29	1.37
1318	45.26	2.93	5.50	9.10	0.18	1.04	0.36	1.28
1326	44.99	2.60	4.61	9.09	0.23	1.02	0.27	1.26
1359	50.12	2.67	5.50	5.23	0.22	0.61	0.34	0.33
1368	50.85	3.35	4.54	4.83	0.23	0.54	0.30	0.69
1376	50.97	3.52	7.00	3.98	0.29	0.45	0.48	0.59
1386	51.07	3.69	7.07	3.92	0.29	0.44	0.51	0.55
1396	56.62	4.06	3.64	3.12	0.25	0.36	0.26	0.43
1404	54.27	3.93	3.20	1.28	0.16	0.14	0.23	0.17
1425	54.06	3.65	5.56	33.29	0.18	3.67	0.38	4.54
1433	53.86	3.51	4.41	32.10	0.16	3.54	0.29	4.35
1442	53.61	3.30	5.46	28.05	0.21	3.29	0.34	4.08
1450	54.32	3.88	3.06	24.37	0.20	2.39	0.22	2.78
1460	54.05	3.67	2.70	24.40	0.21	2.37	0.18	2.81
1468	53.92	3.55	3.86	22.09	0.25	2.19	0.25	2.56
1484	51.38	3.58	7.45	14.50	0.32	1.63	0.52	2.13
1485	51.33	3.52	7.33	14.24	0.36	1.62	0.50	2.10
1494	51.24	3.58	4.77	12.48	0.27	1.38	0.33	1.74
1501	51.13	3.51	5.00	10.30	0.24	1.16	0.34	1.46
1510	50.80	3.65	7.53	10.78	0.31	1.36	0.55	1.71
1531	44.49	2.02	9.15	13.53	0.95	1.70	0.67	2.07
1539	44.97	2.50	8.64	13.09	0.83	1.64	0.68	2.10
1547	45.03	2.64	7.48	11.06	0.59	1.39	0.49	1.76
1560	45.24	2.78	8.16	9.75	0.49	1.22	0.62	1.53
1568	45.38	2.88	8.30	6.96	0.40	0.88	0.54	1.04

^a STP = 70°F, 1 atm.

Table 10. Absorber mass transfer information

Experiment number	Pressure (psig)	Average column temperature (°C)	L/V (mole/mole)	Absorption factor (L/VK)	HTU	Column DF	Overall DF
669	358.7	-15.6	9.7	1.39	3.37	657	2068
675	356.0	-16.1	8.0	1.14	3.48	27	54
680	349.0	-16.0	10.1	1.41	3.39	631	1795
690 ^a	344.6	-17.3	9.7	1.35	3.33	355	1305
700 ^b	363.0	-13.4	7.4	1.07	3.43	18	39
710 ^b	387.5	-11.3	7.9	1.22	3.40	91	300
720 ^b	364.5	-13.3	9.7	1.41	3.31	2291	10528
730 ^b	312.0	-18.5	8.7	1.10	3.43	30	57
740 ^b	310.2	-18.0	10.3	1.30	3.30	1534	5247

^aLiquid scrub entry point lowered.

^bFeed gas not precooled.

Table 11. Stripper mass transfer data

Experiment number	Column pressure (psig)	Average column temperature (°C)	L/V (mole/mole)	Stripping factor (VK/L)	Relative standard deviation of stream 11 count rate	HTU (ft)	Column DF	Overall DF
752	278.0	-18.7	7.9	1.19	0.005	0.82	26	65
770	278.6	-18.6	8.5	1.11	0.0059	0.87	14	33
782	278.6	-18.7	7.0	1.34	0.013	0.99	40	126
790	278.4	-19.3	7.1	1.32	0.022	0.71	105	287
800	279.7	-19.3	9.0	1.03	0.0033	1.06	7	18
810	279.7	-19.3	10.1	0.92	0.0035	1.67	3	7
820	279.7	-19.2	7.2	1.29	0.0109	0.74	83	196
832	279.7	-19.0	8.0	1.16	0.0070	0.86	22	50
842	279.7	-19.1	9.2	1.01	0.0031	1.56	4	9
852	279.7	-19.5	10.3	0.90	0.0030	0.29	2	4
864	249.7	-23.1	10.4	1.00	0.0041	1.13	5	14
874	249.7	-22.9	9.3	1.12	0.0068	0.99	13	35
884	252.7	-22.6	8.3	1.24	0.014	0.60	112	325
896	249.7	-22.3	7.3	1.42	0.070	0.81	132	980
901	249.7	-22.5	7.2	1.44	0.087	0.66	428	1489
914	249.7	-22.5	8.4	1.24	0.043	0.62	106	294
926	249.7	-22.5	9.3	1.12	0.0081	0.84	17	45
938	249.7	-22.5	10.2	1.02	0.0037	1.35	5	13
954	249.7	-23.0	10.3	1.01	0.0064	0.50	14	41
966	249.7	-23.1	9.3	1.12	0.0092	0.67	26	80
978	249.7	-23.1	8.2	1.27	0.0290	0.60	154	529
990	249.7	-22.9	9.3	1.12	0.14	0.67	26	80
1002	249.7	-23.0	6.2	1.68	24.67	0.05	∞	∞
1014	224.6	-26.0	7.2	1.60	4.8	0.42	53868	315125
1030	250.0	-22.7	6.2	1.68	11.6	0.47	29609	161486
1042	249.8	-22.5	6.1	1.70	1.16	0.53	12566	104109
1056	279.7	-19.2	7.7	1.21	0.0080	0.72	45	116

Table 11 (cont'd)

Experiment number	Column pressure (psig)	Average column temperature (°C)	L/V (mole/mole)	Stripping factor (VK/L)	Relative standard deviation of stream 11 count rate	HTU (ft)	Column DF	Overall DF
1067	279.6	-19.3	7.2	1.29	0.104	0.42	1225	2802
1078	249.2	-22.7	7.7	1.35	5.1	0.03	∞	∞
1090	249.2	-22.7	7.8	1.33	0.22	0.34	9555	29262
1100	249.2	-22.8	7.7	1.35	0.051	0.63	243	689
1110	249.5	-22.7	7.7	1.35	0.066	0.58	364	1024
1120	235.2	-24.8	8.2	1.34	0.16	0.49	875	3023
1130	234.9	-24.7	9.2	1.21	0.017	0.59	80	238
1140	220.7	-26.4	8.9	1.31	0.15	0.44	1118	3862
1148	220.5	-26.6	9.9	1.18	0.018	0.56	76	235
1158	220.5	-28.1	9.8	1.19	0.017	0.62	63	194
1168	220.5	-26.5	10.9	1.07	0.0076	0.74	14	41
1178	220.2	-26.4	11.0	1.06	0.0143	0.37	44	138
1188	220.5	-26.5	10.7	1.09	0.014	0.59	24	78
1200	279.8	-19.4	10.7	0.88	0.004	0.34	2	4

Table 12. Fractionator mass transfer data

Experiment number	Column pressure (psig)	Average column temperature (°C)	L/V (mole/mole)	Stripping factor (VK/L)	HTU (ft)	Column DF	Overall column DF
1206	280.5	-19.5	13.0	1.39	0.59	540	1731
1214	280.6	-20.4	18.3	1.00	0.89	7	18
1222	280.5	-19.9	15.7	1.16	0.59	57	148
1230	281.0	-19.9	14.5	1.26	0.55	193	521
1246	281.5	-19.5	13.5	1.34	0.46	1381	3943
1254	281.0	-19.9	13.1	1.39	0.51	1111	2814
1262	281.5	-20.1	14.1	1.29	0.44	840	2327
1270	281.5	-20.2	15.1	1.20	0.50	144	356
1278	281.5	-20.5	16.1	1.14	1.31	9	22
1286	281.0	-19.6	14.3	1.27	0.49	365	861
1302	281.5	-19.7	14.0	1.30	0.43	1033	3258
1310	281.5	-19.8	14.7	1.23	0.48	263	853
1318	282.0	-19.8	15.4	1.18	0.47	124	324
1326	281.5	-20.2	17.3	1.05	0.44	27	91
1359	280.5	-21.0	18.8	0.98	1.52	4	11
1368	281.0	-20.1	15.2	1.20	0.58	81	248
1376	281.0	-20.5	14.5	1.26	0.59	141	385
1386	280.5	-20.2	13.8	1.32	0.53	425	1284
1396	281.0	-19.8	13.9	1.30	0.56	270	1226
1404	281.0	-19.3	13.8	1.32	0.55	323	1186
1425	281.0	-20.0	14.8	1.23	0.44	380	987
1433	281.0	-20.1	15.3	1.19	0.50	126	411
1442	281.0	-20.5	16.2	1.12	0.72	23	82
1450	250.5	-23.4	14.0	1.49	0.50	3437	15956
1460	250.5	-22.4	14.7	1.40	0.51	1200	5546
1468	251.0	-23.0	15.2	1.34	0.48	1190	5138
1484	279.5	-20.7	14.4	1.28	0.56	216	597
1485	280.0	-20.9	14.6	1.26	0.62	113	320
1494	281.5	-20.0	14.3	1.27	0.49	351	1232
1501	281.0	-20.4	14.6	1.25	0.50	261	952
1510	308.0	-17.9	13.9	1.18	0.62	56	146
1531	310.5	-20.8	22.0	0.75	8.20	2	3
1539	310.6	-20.5	18.0	0.92	6.52	1	4
1547	311.0	-19.2	17.1	0.96	1.24	4	10
1560	311.0	-19.0	16.3	1.01	3.85	2	4
1568	311.5	-17.2	15.8	1.02	0.39	21	83

Table 13. Values used in Figure 15

Experiment number	Experimental HTU (ft)	$\frac{1.798L^{2.877}}{v^{2.138}K^{3.643}}$
		(ft)
752	0.823	0.769
770	0.875	0.884
790	0.713	0.676
820	0.743	0.747
832	0.858	0.923
874	0.989	0.851
926	0.842	0.792
966	0.672	0.721
978	0.600	0.559
1056	0.723	0.803
1130	0.586	0.620
1148	0.556	0.594
1158	0.620	0.622
1168	0.743	0.783

Table 14. Values used in Figure 18

Experiment number	Experimental HTU (ft)	$\frac{0.013L^{1.78}}{v^{0.850}K^{0.764}}$
		(ft)
1206	0.59	0.50
1222	0.59	0.57
1230	0.55	0.54
1246	0.46	0.51
1254	0.51	0.50
1270	0.50	0.56
1286	0.49	0.54
1302	0.43	0.47
1310	0.48	0.49
1318	0.47	0.51
1368	0.58	0.56
1386	0.53	0.52
1396	0.56	0.57
1404	0.55	0.55
1425	0.44	0.57
1433	0.50	0.59
1442	0.72	0.62
1450	0.50	0.50
1460	0.51	0.52
1484	0.56	0.53
1485	0.62	0.54
1494	0.49	0.53
1501	0.50	0.54

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APPENDIX A: CHRONOLOGY OF CAMPAIGN III

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APPENDIX A: CHRONOLOGY OF CAMPAIGN III

1975

6/30- The system facility was being prepared for Campaign III.

9/5 This preparation included (1) servicing all heavy equipment, (2) repair of sampling system, (3) calibration of recorders, controllers, etc., (4) preparing and installing new stripper column, and (5) purging system of N_2 and refrigerant 12 and charging system with CO_2 .

9/8 Started the system for the purpose of tuning the refrigeration controls.

9/9 Continued refrigeration adjustments.

9/10 Attempted absorber flooding studies. Column floods at flow rates much less than those in previous studies.

9/11 Reran dry packing ΔP measurements across absorber - no change.

9/12 Again attempted absorber flooding studies.

9/15 Reviewed x rays of absorber column taken 5/24/75.

9/16 X-rayed absorber column.

9/17 X rays showed substantial distortion. Absorber column was removed from system for repacking.

9/25 Started stripper flooding studies.

9/26 Problems with refrigeration unit A. Leak in heat exchanger tubing was discovered.

9/30 Completed installation of absorber column.

10/2 Stripper flooding studies.

10/3 Stripper flooding studies.

10/6- Refrigeration unit A was shut down. Had difficulty in locating problem. Finally discovered stem on king valve was broken

10/17 in closed position. Valve stem was replaced.

10/20 Recharged system with CO_2 and calibrated liquid level indicators.

10/21 Stripper flooding studies.

10/22 Stripper flooding studies.

10/23 Stripper flooding studies.

APPENDIX A (cont'd)

1975

10/24 Stripper flooding studies.
10/27 Absorber flooding studies.
10/28 Absorber flooding studies.
10/29 Absorber flooding studies.
10/30 Absorber flooding studies.
10/31 Absorber flooding studies.
11/3 Experiments 669 and 675.
11/4 Experiments 680 and 690.
11/5 Experiment 700.
11/6 Experiments 710 and 720.
11/7 Experiments 730 and 740.
11/10 Adjustments on main stripper condenser necessary.
11/11 Experiment 752.
11/12 Experiment 760.
11/13 Experiment 770.
11/14 Experiments 782 and 790.
11/17 Experiment 800.
11/18 Experiment 810.
11/19 Experiment 820.
11/20 Burned filament in mass spectrometer. Teledyne O₂ analyzer was calibrated.
11/31 Experiment 832.
11/24 Experiment 842.
11/25 Experiment 852.
11/26 Attempt to reduce stripper pressure from 20 to 18 atm cause refrigeration problems.
11/27 Continued refrigeration adjustments.
11/30 Continued refrigeration adjustments.
12/1 Experiment 864.
12/2 Experiment 874.
12/3 Experiment 884.

APPENDIX A (cont'd)

1975

12/4 Experiment 896.
12/5 Experiment 901.
12/8 Experiment 914.
12/9 Experiment 926.
12/10 Experiment 938.
12/11 Checked, repaired, and calibrated temperature indicator
No. 4.
12/12 Replaced existing thermocouples at top and bottom of absorber
column with calibrated thermocouples.
12/15 Experiment 954.
12/16 Experiment 966.
12/17 Experiment 978.
12/18 Experiment 990.
12/19 Experiment 1002.
12/22 Experiment 1014.
12/23 Shut down for holidays and vacations.

1976

1/5 Charged system with CO₂ and O₂ and adjusted refrigeration units.
1/6 Continued refrigeration adjustments.
1/7 Continued refrigeration adjustments
1/8 Mass spectrometer was down due to ion pump failure.
1/9 Mass spectrometer was still down.
1/12 Refrigeration unit A shut down due to low oil.
1/13 Refrigeration unit A shut down due to low oil again.
1/14 Experiment 1030.
1/15 Experiment 1042.
1/16 Adjusted refrigeration unit.
1/17 Continued adjustments on refrigeration units.
1/20 Attempted experiment but it was aborted due to failure to
oxygen analysis instruments.

APPENDIX A (cont'd)

1976

1/21 Lost solvent flow due to low level in solvent tank.

1/22 Experiment 1056.

1/23 Refrigeration unit B not working; recharged unit with R-502.

1/26 Adjusted refrigeration controls.

1/27 Experiment 1067.

1/28 Experiment 1078.

1/29 Experiment 1090.

2/2 Experiment 1100.

2/3 Experiment 1110.

2/4 Attempted to reduce stripper pressure to 16 atm. The resulting solvent tank pressure was inadequate for satisfactory solvent pump operation.

2/5 Experiment 1120.

2/6 Experiment 1130.

2/9 Experiment 1140.

2/10 Experiment 1148.

2/11 Experiment 1158.

2/12 Experiment 1168.

2/13 Experiment 1178.

2/17 Experiment 1188.

2/18 Attempted refrigeration adjustments to operate stripper at 16 atm.

2/19 Continued adjustments.

2/20 Continued adjustments - Adjustments proved too time consuming to be practical.

2/23 Replaced existing thermocouples in stripper reboiler with calibrated thermocouples.

2/24 Experiment 1200.

2/25 Experiment 1201.

2/26 Malfunction of "Bias Tank" H₂O temperature controller. System was repaired.

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APPENDIX A (cont'd)

1976

2/27	Experiment 1206.
3/1	Experiment 1214.
3/2	Experiment 1222.
3/3	Experiment 1230.
3/4	Experiment 1238.
3/5	Experiment 1246.
3/8	Refrigeration adjustments required.
3/9	Experiment 1254.
3/10	Experiment 1262.
3/11	Experiment 1270.
3/12	Experiment 1278.
3/15	Adjustments in refrigeration required.
3/16	Experiment 1286.
3/17	Added CO ₂ , O ₂ , and ⁸⁵ Kr to system. Recharged Weber (Pump-head cooler) unit.
3/18	Adjustments in refrigeration required.
3/19	Experiment 1297.
3/22	Experiment 1302.
3/23	Experiment 1310.
3/24	Experiment 1318.
3/25	Experiment 1326.
3/26	Experiment 1334.
3/29	Experiment 1342.
3/30	Experiment 1350.
3/31	Adjustments in refrigeration required.
4/1	Continued refrigeration adjustments.
4/2	Continued refrigeration adjustments.
4/5	Experiment 1359.
4/6	Experiment 1368.
4/7	Experiment 1376.
4/8	Adjustments in refrigeration required.

APPENDIX A (cont'd)

1976

4/9 Experiment 1386.
 4/12 Experiment 1396.
 4/13 Adjustments in refrigeration required.
 4/14 Adjustments in refrigeration required.
 4/15 Adjustments in refrigeration required.
 4/19 Adjustments in refrigeration required.
 4/20 Experiment 1404.
 4/21 Experiment 1425.
 4/22 Experiment 1433.
 4/23 Experiment 1442.
 4/26 Adjustments in refrigeration required.
 4/27 Experiment 1450.
 4/28 Experiment 1460.
 4/29 Experiment 1468.
 4/30 Experiment 1476.
 5/3 Adjustments in refrigeration required.
 5/4 Experiments 1484 and 1485.
 5/5 Experiment 1494.
 5/6 Experiment 1501.
 5/7 Experiment 1510.
 5/10 Adjustments in refrigeration required.
 5/11 Adjustments in refrigeration required.
 5/12 Adjustments in refrigeration required.
 5/13 Adjustments in refrigeration required.
 5/14 Absorber experiment to pinch O_2 for verification of equilibrium data.
 5/17- Same as 5/14.
 5/18
 5/19 Added ^{85}Kr and minor refrigeration adjustments.
 5/20 Experiment 1531.
 5/21 Experiment 1539.
 5/24 Recharged refrigeration units with refrigerant.

APPENDIX A (cont'd)

1976

5/26 Experiment 1547.
5/27 Experiment 1555.
5/28 Experiment 1560.
6/1 Adjustments in refrigeration required.
6/2 Adjustments in refrigeration required.
6/3 Power failure of mass spectrometer.
6/4 Experiment 1568.
6/7 Adjustment in refrigeration required.
6/8 Tested mass spectrometer.
6/9 Absorber flooding studies.
6/10 Absorber flooding studies.
6/11 Absorber flooding studies.
6/21 Calibration check of stripper reboiler volt and amp meters.
Stripper flooding studies.
6/23 Stripper flooding studies.
6/24 X rays of stripper and absorber columns. No distortions found.

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APPENDIX B: EQUIPMENT PERFORMANCE THROUGH CAMPAIGN III

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APPENDIX B: EQUIPMENT PERFORMANCE THROUGH CAMPAIGN III

Gas Compressor - Main compressor has 2856 hr, whereas the auxiliary compressor has 392 operating hr. No problems were encountered with this equipment.

Liquid CO₂ Pumps - has 3005 operating hr. Early in Campaign II, the cast iron diaphragm backup plate on the oil side essentially disintegrated. The backup plate was replaced with stainless steel, and no further problems of this type have been encountered. During operation, check valves and air bleed valves were replaced. The oil refill valve did not operate properly; the supplied oil with a pour point of -30°F was changed to one with a pour point of -40°F. Gasification of liquid CO₂ occurs if the pump heads are not maintained at a temperature < -40°C and at a suction pressure of not less than ~240 psig. The pump has proven to be unreliable at flow rates < 0.4 ppm.

Refrigeration Units - Unit A has 16,863 operation hr and Unit B has 17,770. A heat exchanger tube in Unit A ruptured and was valved out of the system. A solid-state module controller failed in Unit A and was replaced. Refrigeration leaks occur in both units and require constant monitoring and/or maintenance.

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