2.74
10/15/80 T.S.

29. 1840

MLM-2774

Combined Electrolysis Catalytic Exchange (CECE)

Robert E. Ellis, Thomas K. Mills, and

Michael L. Rogers

cp

MASTER

September 30, 1980

MOUND FACILITY
Miamisburg, Ohio 45342

operated by
MONSANTO RESEARCH CORPORATION
a subsidiary of Monsanto Company

for the
U. S. DEPARTMENT OF ENERGY

Contract No. DE-AC04-76-DP00053

Monsanto

NOTICE

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes A02
Printed copy: _____
Microfiche copy: A01

MLM-2774
UC-70

Combined Electrolysis Catalytic Exchange (CECE)

Robert E. Ellis, Thomas K. Mills, and Michael L. Rogers

Issued: September 30, 1980

MOUND FACILITY
Miamisburg, Ohio 45342

operated by
MONSANTO RESEARCH CORPORATION
a subsidiary of Monsanto Company

for the
U. S. DEPARTMENT OF ENERGY

Contract No. DE-AC04-76-DP00053

Contents

Published by Information Services:
Marjorie F. Hauenstein, Editor

Abstract

Starting from an effort to control airborne emissions, the Mound tritium containment program has evolved to include development of the Combined Electrolysis Catalytic Exchange (CECE) process. This process separates tritiated aqueous streams into detritiated water and an enriched hydrogen stream that is suitable for use by other tritium recovery processes. Experimentation has shown that the process performs as predicted by bench-scale measurements, and that available process components exhibit acceptable resistance to damage by radiation from tritium exposure. Planned future efforts are concentrated on finalizing automatic control of the process and on developing feed treatment methods for the protection of process components.

Background

In 1972, Mound Facility initiated a program to demonstrate the operation of a tritium-handling laboratory capable of achieving zero release of tritium to the environment. In its early stages, this project focused on the development of advanced processes and techniques for the containment of airborne emissions. It soon became apparent, however, that the most promising technique for controlling airborne emissions -- oxidation followed by adsorption -- merely transformed gaseous tritium into the more hazardous aqueous form. Thus, the emphasis of the project shifted from gaseous emissions to liquid waste streams. Numerous approaches to the problem of detritiating these liquid streams were considered, including extractive distillation, electrolysis, and electrolysis with recombination. These methods, however, failed to demonstrate sufficient separation to form the basis for a workable process. After some preliminary investigations, development of the Combined Electrolysis Catalytic Exchange (CECE) process was begun in 1975. Since that time, the major focus of the program has been the demonstration of CECE as a practical approach to the problem posed by tritiated water streams.

Process description

The Combined Electrolysis Catalytic Exchange (CECE) process is based on the exchange reaction which occurs between molecular tritium and tritium oxide:

$$HT + H_2O \rightleftharpoons HTO + H_2$$

This is an equilibrium reaction that, at ambient temperatures, favors the formation of the tritiated oxide. At 25°C, the equilibrium coefficient for the reaction is approximately 7. Thus, when a tritiated gaseous hydrogen phase is brought into contact with a liquid water phase, there is a net transfer of tritium from the gas to the liquid phase. The rate of transfer is enhanced by the presence of a precious metal catalyst.

In the CECE process, as shown in Figure 1, a stream of tritiated water is fed to a column packed with catalyst. In the column, this feed stream mixes with a liquid reflux stream flowing countercurrent to a gaseous hydrogen stream. Tritium is

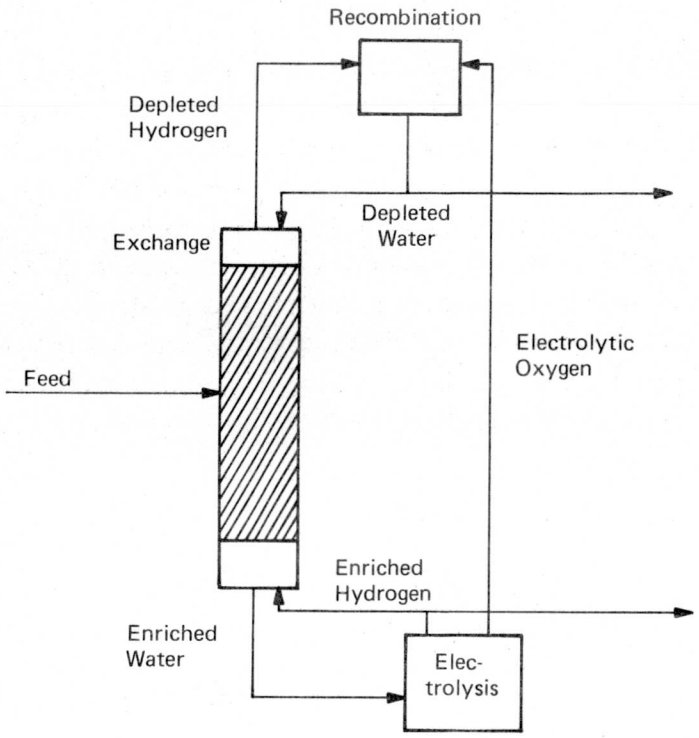


FIGURE 1 - Combined electrolysis catalytic exchange process schematic.

transferred from the gas to the liquid, so that as the streams leave the column, the liquid stream is enriched in tritium and the gas stream is depleted. Outside the column, the liquid is electrolyzed to provide the hydrogen stream for the exchange reaction and a product hydrogen stream enriched in tritium. At the opposite end of the column, the depleted hydrogen stream is recombined with oxygen from the electrolysis to form a detritiated water stream that provides liquid reflux to the column and the detritiated water product.

Introduction

The feasibility of the CECE process is dependent on two recently developed key technologies: Solid Polymer Electrolyte (SPE) electrolysis cells from General Electric Company (GE) and hydrophobic exchange catalyst developed at the Chalk River Nuclear Laboratory of Atomic Energy of Canada, Ltd. (AECL). The importance of the SPE electrolysis cells is in the fact that the electrolyte is held within the cell, rather than being dissolved in the process water. This eliminates many of the processing problems associated with earlier electrolysis cells. Additional advantages of the SPE cells over conventional electrolysis cells are greater operating efficiency and dramatically lower water holdup.

The hydrophobic exchange catalyst is perhaps the cornerstone of the CECE process. Catalysts that were available prior to its development were able to promote the exchange reaction in strictly vapor phase systems only and, even then, were extremely susceptible to loss of catalytic activity.

A process based on such catalysts would have been burdened with a requirement for large amounts of water evaporation and recondensation and would have required frequent catalyst regeneration or replacement. The AECL catalyst retains its activity in the presence of liquid water and over a longer period of time, thus allowing a simple, more economical process [1]. As used in the CECE, the catalyst consists of a mixture of alumina spheres treated with the platinum/carbon/Teflon active material and untreated spheres. The treated spheres are hydrophobic, and the untreated spheres are hydrophilic. Although the catalyst used in the CECE pilot studies at Mound was obtained directly from AECL, an equivalent catalyst is now available from Noranda, Ltd., and possibly from other catalyst manufacturers.

Development of the CECE process has focused on three major areas of investigation: (1) effects of tritium exposure on electrolysis cell operation, (2) effects of tritium exposure on the hydrophobic exchange catalyst, and (3) operation of a pilot CECE unit. The purpose of these studies has been to determine what limits -- if any -- are imposed on process operating parameters by component durability considerations and to provide parametric information that will serve as a basis for the design of production units.

Results and discussion

Electrolysis cell damage studies

Unlike conventional electrolysis cells in which the cell electrolyte is disssolved in the reactant water, the SPE cell has its electrolyte bound in a membrane between the two electrodes. It operates, then, by the migration of hydrogen ions through the membrane and the formation of molecular hydrogen at the cathode. Molecular oxygen is formed at the anode and leaves the cell with the excess water that is supplied to the cell for cooling. A small amount of water is carried through the cell membrane and removed with the gaseous hydrogen stream. Figure 2 is a schematic representation of this process.

The key structural feature of the SPE electrolysis cell is a membrane that separates the electrodes and within which the cell electrolyte resides. This membrane is composed of Nafion, a polymeric material that is susceptible to damage by radiation. Therefore, one of the interests of the CECE development effort has been to observe the effect of tritium exposure on cell operation and life expectancy.

To make these observations, a test was conducted in which a cell was continuously exposed to significant tritium concentrations. The cell was operated for periods of 5 to 20 min at weekly intervals, and its performance was monitored until cell failure occurred. During the first phase of the test, the cell was exposed to water containing 1 Ci/ml of tritium. This continued for 29 weeks, during which no significant degradation of cell performance was observed. In the second phase of the test, the same cell was exposed to water containing a tritium concentration of 10 Ci/ml. This portion of the test was discontinued during its tenth week because of leakage from the oxygen to the hydrogen side of the cell. The cell membrane was then examined and found to be embrittled and dehydrated. The leak appeared to have been in or around the

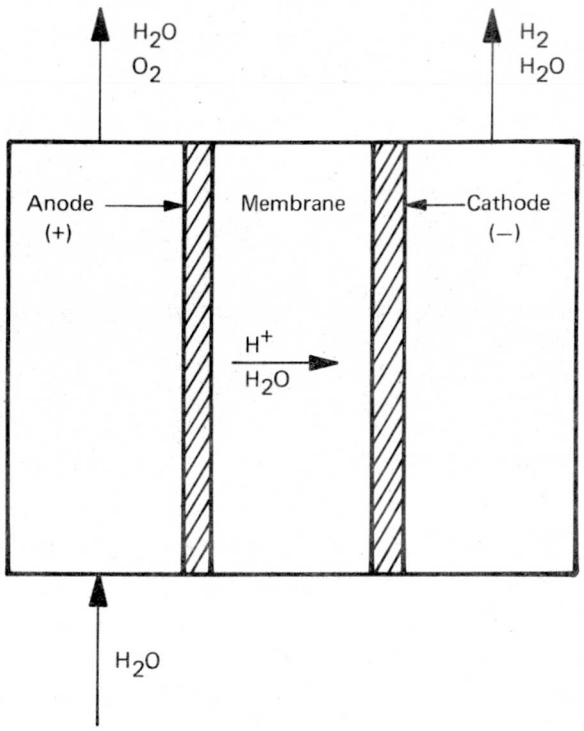


FIGURE 2 - Schematic of electrolysis cell operation.

seal area at the edges of the membrane, rather than in the active area. Also, there had been no apparent changes in the electrical operation of the cell prior to failure.

From this test, it was concluded that, while tritium exposure may have an adverse impact, cell longevity under process conditions is sufficient for CECE feasibility. Further, it would appear that some relatively slight changes in the cells, such as increasing the thickness of membrane support areas, might yield substantial improvement in the tolerance of the cells to tritium exposure.

Catalyst damage studies

Like the electrolysis cell membranes, the hydrophobic exchange catalyst used in the CECE process contains polymeric material that is susceptible to damage by radiation. For this reason, a test was conducted to determine the nature and extent of any effect of tritium exposure on the catalyst [2]. A sample of catalyst was placed in a closed vessel designed to simulate a packed exchange column, and exposed to water containing 320 Ci/ml of tritium. The exposure was continued for 124 days, after which the catalyst was rinsed with distilled water and dried. The catalyst was then returned to the Chalk River Nuclear Laboratory, where it was found that the catalyst pellets retained approximately 4 mCi/g of tritium, which appeared to be strongly bonded. Apart from some dusting, there appeared to be no physical damage to the catalyst, and it was determined by AECL that the catalyst had retained approximately 80% of its original activity.

Since the radiation dosage received by the catalyst during this test was equivalent to the dosage that would be received in several years of operation under anticipated CECE process conditions, it was concluded that tritium exposure has a very minor practical effect on the operation of the catalyst.

CECE pilot unit

To complete the demonstration of CECE as a feasible process for the recovery of tritium from aqueous streams, it was necessary to demonstrate the integration of the various process components into a functional process unit. For this purpose, construction of a CECE pilot plant was begun in early 1976. Refinement and modification of this pilot unit have continued to the present, along with experiments demonstrating the operation of the process.

In its present configuration, the pilot unit contains a center-fed column array 15 m in length and 2.5 cm in diameter. The electrolysis section consists of four 8-cell electrolysis modules, each of which is capable of producing approximately 3 liters (STP) of hydrogen at a current consumption of 50 A. The recombiner section is composed of a temperature-controlled reaction vessel and a condenser for producing liquid water.

In experimental operation, the pilot CECE unit demonstrated good agreement with previous experimental results obtained in bench-scale work done by AECL [3]. A series of eight experiments, representing 600 hr of operation, was conducted for this purpose, as well as to show the effect of in situ catalyst regeneration by purging with hot nitrogen and oxygen. The regeneration is done to dry the catalyst and to remove any accumulation of NO or CO, since these substances are known to poison the exchange reaction. The results of these experiments are shown in Table 1 and plotted in Figure 3.

The first six columns in Table 1 identify the experiment and list the experimental conditions. The seventh column is the observed value of the mass transfer coefficient $(K_y a)_o$; a sample calculation for $(K_y a)_o$ is shown in Appendix A. The eighth column in Table 1 is the predicted value of the mass transfer coefficient $(K_y a)_p$. This predicted value is dependent upon the initial catalyst activity $K_y a^o$ and the conditions under which the experiment was performed. The initial catalyst activity was measured by Butler of AECL and for the particular batch of catalyst used in this system had a value of 0.95 ± 0.05 $m^3(STP)/m^3 sec$. This initial measurement was performed at a temperature of 298°K, a pressure of 1.0 atm, a superficial gas phase flowrate of 1.0 m/sec, and a liquid phase mass flux of 0.2 g/sec-cm^2. Any experimental conditions different from these can be corrected using the empirical relationship:

$$(K_y a)_p = K_y a^o (G)^{0.3} \left(\frac{L}{0.2}\right)^{0.1} (P)^{-0.4} \left[4.041 \times 10^5 \exp\left(\frac{-3848.9}{T}\right)\right]$$

where

$(K_y a)_p$ = predicted value for the mass transfer coefficient, $m^3(STP)/m^3$-sec

$K_y a^o$ = initial catalyst activity, $m^3(STP)/m^3$-sec, measured at conditions of G = 1.0 m/sec, L = 0.2 g/cm^2.sec, P = 1 atm, and T = 290°K (equal to 0.95 $\pm$ 0.05 for the catalyst in this system)

Table 1 - CATALYST ACTIVITY DATA

Experiment	T (°K)	P (atm)	G (m/sec)	L ($g/cm^2 sec$)	L/G (mole/mole)	$(K_y a)_o$	$(K_y a)_p$	$(K_y a)_o/(K_y a)_p$	$(K_y a)_c$
1	305	1.7	0.1650	0.0152	0.75	0.37	0.46	0.80	0.49
2	300	1.7	0.1622	0.0156	0.76	0.37	0.37	0.95	0.38
3A	300	1.7	0.1577	0.0102	0.52	0.30	0.36	0.83	0.32
3B	300	1.7	0.1597	0.0200	1.01	0.29	0.38	0.76	0.31
4	298	1.6	0.1685	0.0200	1.02	0.25	0.36	0.69	0.26
6	301	1.6	0.1688	0.0203	1.03	0.29	0.42	0.69	0.33
7A	299	1.7	0.1566	0.0152	0.80	0.35	0.35	1.00	0.35
7B	299	1.7	0.1578	0.0102	0.51	0.51	0.34	1.50	0.51

T - absolute temperature in degrees Kelvin

P - absolute pressure in atmosphere

G - superficial column gas velocity meters/sec

L - column liquid flux

$$\frac{\text{grams } H_2O}{\text{sec-cm}^2 \text{ column cross-section}}$$

L/G - liquid to gas molar ratio in column

$(K_y a)_o$ - observed value of mass transfer coefficient

$(K_y a)_p$ - predicted value of mass transfer coefficient

$(K_y a)_c$ - corrected value of mass transfer coefficient (T=298°K, P=1.65 atm, G=0.1659 m/sec)

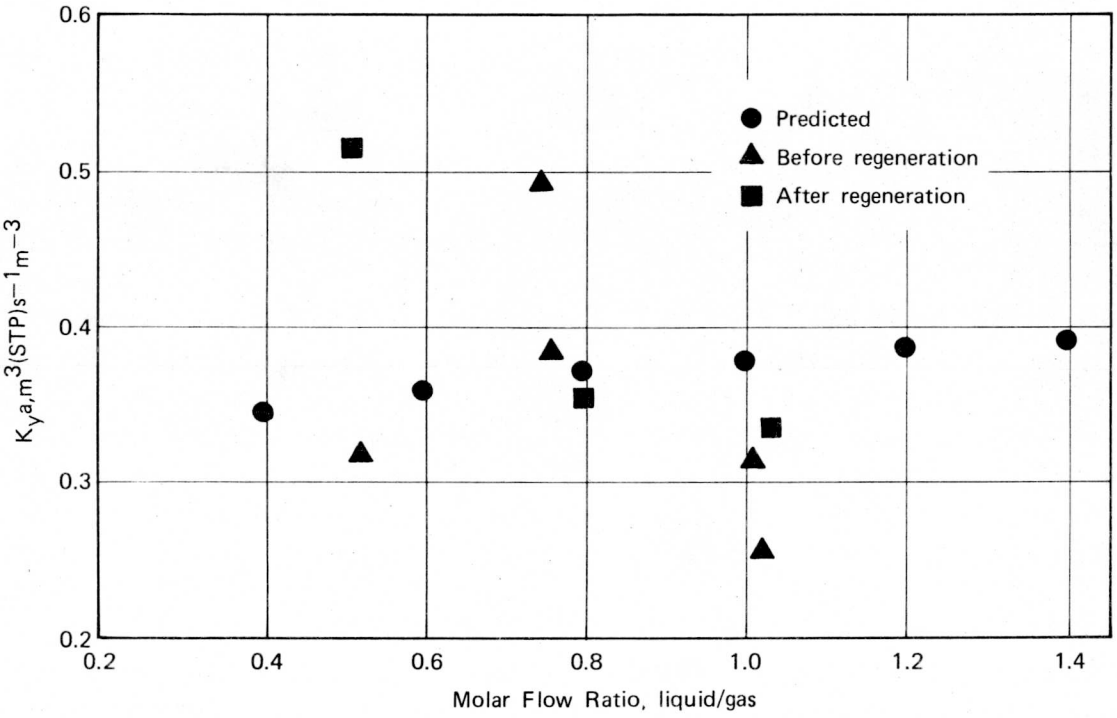


FIGURE 3 - Observed catalyst activity as a function of molar flow ratio. Data corrected to 25°C, 1.65 atm; gas velocity = 0.1659 m/sec.

G = superficial gas velocity, m/sec

L = superficial liquid flow (mass flux) g/cm^2-sec

P = pressure, atm

T = temperature, °K

A ratio of the observed value $(K_ya)_o$ and the predicted value $(K_ya)_p$ is shown in column nine. Observed values of the mass transfer coefficient, $(K_ya)_o$, can be corrected to common conditions of temperature, pressure, and gas velocity while varying the liquid flowrate using the similar equation:

$$(K_ta)_c = (K_ya)_o \left(\frac{G}{0.1659}\right)^{0.3} \left(\frac{P}{1.65}\right)^{0.4} \left[4.041 \times 10^5 \exp\left(\frac{-3848.9}{T}\right)\right]$$

where

$(K_ya)_c$ = the corrected value of the mass transfer coefficient, $m^3(STP)/m^3$-sec. Corrected to superficial gas velocity, G = 0.1659 m/sec; pressure P = 1.65 atm; and temperature T = 298°K.

Calculated values of $(K_ya)_c$ are given in column 10 of Table 1.

Figure 3 shows the observed catalyst activity as a function of molar flow ratio. The data shown in Figure 3 range from 31% under to 50% over the values predicted. However, as shown, most are within 20% of the predicted values, indicating good agreement with the earlier results.

The construction and operation of the CECE pilot unit have provided significant insight into the hardware requirements of the process. For applications sized similarly to the pilot unit, this experience will be of particular importance in the areas of recombiner design, instrumentation and control, pump selection, and containment.

In the recombiner, work done at Chalk River by J. P. Butler has shown that the use of high temperature burners leads to the formation of nitrogen compounds that when present in the reflux stream, poison the exchange catalyst. The recombiner used in the CECE pilot unit at Mound uses a catalytic bed that operates at temperatures ~100°C and is sealed to prevent the entry of materials other than the oxygen and hydrogen feeds. It has operated successfully without any indication of the problem experienced with the higher temperature recombiners.

Instrumentation for the pilot unit has presented a challenge because of the numerical values of some process variables. Temperature, pressure, and level sensors are readily available, but online composition measurement has not been achieved because the available instruments are not sufficiently sensitive to monitor the low tritium concentrations, on the order of 10 μCi/ml, in the "cold" water product stream. Types of flowmeters and sources from which they are available are limited, particularly for the 1-10 ml/min liquid streams in the process. Oscillating ball type flowmeters from Fischer & Porter Company are currently being used successfully; however, an earlier attempt to use instruments based on hot-wire anemometry failed to produce acceptable results. Gas flows, which are in the range of 1-10 liter/min, are measured by turbine meters which are available from Flow Technology, Inc.

The control valves used in the CECE pilot unit are NUPRO bellows seal metering valves, modified in-house for control by computer-driven stepping motors. This approach was taken to obtain valves capable of regulating the small flows in the process while being sufficiently compact to be used inside the glovebox which contains the pilot unit. Performance has been acceptable, except that, in their present form, these valves are not compatible with standard, commercially available process controllers.

Because of the small flows within the process, the availability of process pumps is also somwhat limited. The pilot unit has been operated using gear pumps from Micropump Corp. and piston-type pumps from Fluid Metering, Inc. Although both types are usable, each has certain limitations. The gear pumps used in the pilot unit seemed to require excessive maintenance. The piston-type pumps impose a pulsation on process flows, as well as greatly reducing the effectiveness of the control valves.

The containment approach used for the CECE pilot unit was to enclose the majority of process components in gloveboxes under a recirculated helium atmosphere. The exchange columns, which were too large to fit within the gloveboxes, were mounted remotely and were contained -- along with their associated piping -- within vacuum jackets. Maintenance of the remotely mounted columns has proven to be quite difficult, thus favoring the installation of the entire process in a single, larger enclosure.

Conclusions

From the results of the CECE pilot unit operating experiments, it is concluded that CECE is a workable process for the detritiation of aqueous streams. Based on the observed data, it has been determined that, in a column 30 m in length, a feed stream containing 1000 Ci/liter of tritium could be separated into an aqueous overhead stream containing less than 0.02 μCi/liter, which is the current EPA standard for potable water, and an enriched gaseous hydrogen stream containing approximately 8000 Ci/m^3 (STP). Thus, reasonably sized process components are expected to provide good separation (see Appendix B for sample calculations). Also, it is concluded that process components are available that are able to survive and operate in the CECE process environment. Although there appears to be some potential for improvement in electrolysis cell longevity, it has been shown that both the cells and the polymeric component of the catalyst are able to perform adequately when exposed to tritium radiation.

Future work

Additional work is now in progress which will complete the demonstration of CECE feasibility for detritiation of aqueous streams. This work includes further development of the ability of the pilot unit to operate continuously under automatic control, thus reducing the labor cost for operation of the process. Also, further effort is being applied to the definition and development of feed pre-processing steps for the protection of the catalyst and electrolysis cell membranes.

References

1. J. P. Butler, "Hydrogen Isotopes Separation by Catalyzed Exchange Between Hydrogen and Liquid Water," presented at the symposium on Separation Science and Technology for Energy Applications, Gatlinburg, TN, October 30 - November 2, 1979.
2. J. P. Butler, F. W. Molson, and W. E. Tadlock, Effect of Tritium β-radiation on Pt-C-Teflon Catalyst, MLM-2620 (June 1979), p. 10.
3. J. P. Butler, J. H. Rolston and W. H. Stevens, "Novel Catalysts for Isotopic Exchange Between Hydrogen and Liquid Water," to be published in Separation Science and Technology, 1980.

Appendix A

Example Calculation of $(K_y a)_o$ from Experimental Data

Column cross section	=	4.91 cm^2
Column height	=	7.5 m
Temperature	=	25°C
Pressure	=	1.65 atm
Feedwater concentration	=	10.44 Ci/liter
Electrolysis cell voltage	=	16.8 V
Electrolysis cell current	=	120A
Water feed rate	=	5.9 ml/min
Outlet gas concentration	=	2.47 μCi/liter (converted to water equivalent)
Outlet water concentration	=	0.91 mCi/liter
Water density	=	0.997 g/ml at 25°C
Gas density	=	4.46×10^{-5} gmol/cm^3 at STP
		6.75×10^{-5} gmol/cm^3 at 25°C, 1.65 atm

Equilibrium relationship:

$$y^* = \left(\frac{1}{7.0}\right)x$$

where y^* = equilibrium gas mole fraction

x = liquid mole fraction

A. Calculate molar liquid to gas (L/G) ratio:

$$L = \left(5.9 \frac{ml}{min}\right)\left(0.997 \frac{g}{ml}\right)\left(\frac{1}{18} \frac{mole}{g}\right)\left(\frac{1}{4.91\ cm^2}\right) = 6.66 \times 10^{-2} \frac{mole}{cm^2 min}$$

$$G = \left(120A\right)\left(16.8V\right)\left(\frac{1.6202^{-4}\ mole}{min \cdot V \cdot A}\right)\left(\frac{1}{4.91\ cm^2}\right) = 6.65 \times 10^{-2} \frac{mole}{cm^2 min}$$

$$L/G = \left(6.66 \times 10^{-2} \frac{mole}{cm^2 min}\right)\left(\frac{1}{6.66 \times 10^{-2}} \frac{cm^2 min}{mole}\right) = 1.002$$

B. Calculate superficial gas velocities:

$$\left(6.65 \times 10^{-2} \frac{mole}{cm^2 min}\right)\left(\frac{1}{4.46 \times 10^{-5}} \frac{cm^3}{mole}\right)\left(\frac{1m}{100cm}\right)\left(\frac{1\ min}{60\ sec}\right) = 0.248 \frac{m}{sec} \text{ at STP}$$

$$\left(6.65 \times 10^{-2} \frac{mole}{cm^2 min}\right)\left(\frac{1}{6.75 \times 10^{-5}} \frac{cm^3}{mole}\right)\left(\frac{1m}{100cm}\right)\left(\frac{1\ min}{60\ sec}\right) = 0.164 \frac{m}{sec} \text{ at } 25°C, 1.65 \text{ atm}$$

C. Calculate "cold" end mole fractions:

$$y_1 = \left(2.47 \frac{\mu Ci}{liter}\right)\left(3.45 \times 10^{-11} \frac{mole}{\mu Ci}\right)\left(\frac{1\ \ell}{997\ g}\right)\left(18 \frac{g}{mole}\right) = 1.54 \times 10^{-12}$$

$$x_1 = \left(10.44 \frac{\mu Ci}{liter}\right)\left(3.45 \times 10^{-11} \frac{mole}{\mu Ci}\right)\left(\frac{1\ \ell}{997\ g}\right)\left(18 \frac{g}{mole}\right) = 6.50 \times 10^{-12}$$

D. Calculate "hot" end mole fractions:

$$x_0 = \left(910 \frac{\mu Ci}{liter}\right)\left(3.45 \times 10^{-11} \frac{mole}{\mu Ci}\right)\left(\frac{1\ \ell}{997\ g}\right)\left(18 \frac{g}{mole}\right) = 5.67 \times 10^{-10}$$

$$y_0 = \left(\frac{L}{G}\right)\left(x_0 - x_1\right) + y_1 = 5.63 \times 10^{-10}$$

E. Calculate equilibrium mole fractions:

$$y_0^* = \left(\frac{1}{7.0}\right)\left(5.67 \times 10^{-10}\right) = 8.10 \times 10^{-11}$$

$$y_1^* = \left(\frac{1}{7.0}\right)\left(6.51 \times 10^{-12}\right) = 9.30 \times 10^{-13}$$

F. Calculate number of transfer units:

$$N_{OG} = \frac{(y_0 - y_1)}{\left[\frac{(y-y^*)_0 - (y-y^*)_1}{\ell n \frac{(y-y^*)_0}{(y-y^*)_1}}\right]}$$

$$N_{OG} = 7.78$$

G. Calculate height of transfer unit:

$$H_{OG} = \frac{Z}{N_{OG}} = \frac{750\ cm}{7.78} = 96.4\ cm$$

where Z = column length

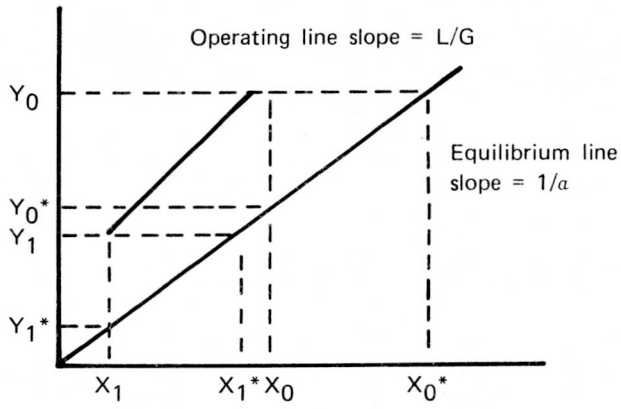
H. Calculate transfer coefficient:

$$K_y a = \left(\frac{G}{H_{OG}}\right) = \left(6.65\text{x}10^{-2}\ \frac{\text{mole}}{\text{cm}^2\text{min}}\right)\left(\frac{1}{96.38\ \text{cm}}\right)$$

$$= 6.90\text{x}10^{-4}\ \frac{\text{mole}}{\text{cm}^3\text{min}}$$

$$\left(6.90\text{x}10^{-4}\ \frac{\text{mole}}{\text{cm}^3\text{min}}\right)\left(\frac{1}{4.46\text{x}10^{-5}}\ \frac{\text{cm}^3}{\text{mole (STP)}}\right)\left(\frac{1\ \text{min}}{60\ \text{sec}}\right)\left(1\ \frac{\text{m}^3\text{cm}^3}{\text{m}^3\text{cm}^3}\right)$$

$$= 0.258\ \frac{\text{m}^3\text{(STP)}}{\text{m}^3\text{sec}}$$



For further information on this type of calculation, see Bennett, C.O. and J. E. Myers, Momentum, Heat, and Mass Transfer, 2nd Ed., McGraw-Hill, New York, 1974, p. 529.

Appendix B

Example calculation of column length from specified outlet concentrations

feedwater concentration	=	100 μCi/liter
mole fraction	=	0.622×10^{-10}
outlet water concentration	=	100 mCi/liter
mole fraction	=	0.622×10^{-7}

equilibrium relationship:

$$y^* = \left(\frac{1}{7.0}\right) x$$

Column is assumed to be operating at conditions of temperature, pressure, and liquid and gas velocities such that

$$H_{OG} = 1.0 \text{ m}$$

A. Calculate number of transfer units:

$$N_{OG} = \frac{y_0 - y_1}{\left[\frac{(y-y^*)_0 - (y-y^*)_1}{\ell n \frac{(y-y^*)_0}{(y-y^*)_1}}\right]}$$

$$N_{OG} = 9.08$$

B. Calculate column length:

$$Z = H_{OG} N_{OG} = (9.08)\ (1.0 \text{ m}) = 9.08 \text{ m}$$

Distribution

EXTERNAL

TIC-4500, UC-70 (267)
R. A. Brown, Exxon Nuclear Idaho Co., Inc.
R. K. Flitcraft, Monsanto Research Corporation
H. N Hill, DOE, Dayton Area Office
R. Y. Lowrey, DOE, Albuquerque Operations Office
Monsanto Technical Report Library, R2C, St. Louis

INTERNAL

W. T. Cave
R. E. Ellis
K. V. Gilbert
C. W. Huntington
C. J. Kershner
B. R. Kokenge
P. H. Lamberger
J. R. McClain
M. L. Rogers (50)

Library (15)
Publications