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DESIGN PARAMETER CALCULATIONS FOR A FILT
THEMAL DIFFUSION APPARATUS

AUTHOR

H. L. Brandt

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THERMAL DIFFUSION DEVELOPMENT
DESIGN PARAMETER CALCULATIONS FOR A PILOT
THERMAL DIFFUSION APPARATUS

By

H. L. Brandt
Chemical Engineering Development Operation
Chemical Development Operation
Chemical Research and Development Operation
HANFORD LABORATORIES OPERATION

June 15, 1959

HANFORD ATOMIC PRODUCTS OPERATION

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THERMAL DIFFUSION DEVELOPMENT
DESIGN PARAMETER CALCULATIONS FOR A PILOT
THERMAL DIFFUSION APPARATUS

INTRODUCTION

The Atomic Energy Commission has expressed interest in obtaining xenon with a composite neutron absorption cross section of less than one barn. This material may be obtainable from the off-gas of the Purex dissolver. A proposed gas purification facility⁽¹⁾ would process the Purex off-gas through two distillation steps for isolation of a "rough" cut of xenon isotopes containing principally Xe^{131} , Xe^{132} , Xe^{134} , Xe^{136} , and a small quantity of krypton. This material would become the feed stream for a thermal diffusion plant for xenon isotope separation. Thermal diffusion has been shown to be the most economical way to concentrate the two heavier xenon isotopes of low cross section and to reject the krypton along with the lighter xenon isotopes of high cross section⁽²⁾.

An adequate basis does not exist for designing large scale thermal diffusion plants of the size and type required to produce the desired 1700 grams of xenon per day. Even though the principle of thermal diffusion has been known for over fifty years, most of the isotopic separation experience has been with small quantities of gas, and has not included work on xenon mixtures.

The objective of the work herein reported was to provide the basis for (1) a scope design of pilot thermal diffusion equipment and (2) design of experiments to be made with this equipment. In the absence of experimental data, the pilot design was developed from theoretical considerations of the parameters considered important in thermal diffusion column operations. It was assumed that the pilot unit would have to provide information on the correlation of theory with practice as well as delineating the sensitivity of the separation efficiency of the column to change in dimensional and operational variables. The present study is limited to single-stage columns, that is, columns with only one continuous tube as an enriching section.

Calculations and graphs are given in sufficient detail in the text to permit ready duplication of results.

SUMMARY

Xenon isotopes contained in the product of the proposed Gas Purification Plant at Purex can be theoretically rearranged in a single stage concentric-tube-type thermal diffusion column. The heavier isotopic fraction will result in a mixture with a composite neutron absorption cross section of less than one barn. For a production rate of one gram per day, the column is required to

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have the extremely high hot wall temperature of 879 C and a cold wall temperature of 27 C. The enriching section of the column, when operating at 1.0 atmosphere of pressure, should be about 10.8 meters long and have an annular gap of 0.522 cm. At 0.4 atmospheres, it could be reduced in length to about 6 meters with an annular gap of 0.635 cm. The inside diameter of the outer tube is 4.68 cm. A scrubber that is approximately the same dimensions as the enriching section may be used to reduce the quantity of feed needed for a given quantity of product.

DISCUSSION

Theory - Thermal diffusion is the motion of the components of a mixture subjected to a temperature gradient. If the temperature gradient is made horizontal, two mechanisms become operative, as in the concentric-tube-type column discussed below:

1. A partial separation of the components due to mass difference and thermal diffusive forces
2. A convective flow of the lighter components up the surface of the hot inner tube and a corresponding convective flow of the heavier components down the surface of the cold outer tube.

Under proper conditions, material may be drawn off either end of the column with considerable increase in composition of the heavy species at the bottom and with similar increase in composition of the lighter species at the top.

A comprehensive treatment of this principle, including the derivation of the transport equation on which the present calculations are based, is given in the basic reference work of Jones and Furry⁽²⁾.

Apparatus - In theory, the equipment required for a concentric-tube-type thermal diffusion column is simple. The main equipment consists of two coaxial tubes. The annular space between the tubes is the gas chamber in which the isotopic separation takes place. A schematic diagram of a thermal diffusion column is shown in Fig. 1. Note that the temperature gradient is unusually large in thermal diffusion -- amounting, in some cases, to as much as several hundred degrees Centigrade. The complications resulting from requirements of high temperature and precise symmetry will be discussed in Part III of this report on design.

Enricher - The enriching section concentrates the heavier species at the bottom of the column and the lighter species at the top. The heavier species, which may be removed from the column, is the product.

Scrubber - A scrubbing section, operating in the same sense, reworks the lighter material which is rejected by the enricher along with a portion of

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of the feed stream. The light stream rejected at the top of the scrubber is the raffinate or waste. The heavier stream, which tends to go to the bottom of the scrubber, flows to the enricher. A scrubber may be included in the thermal diffusion apparatus, if conservation of material is desired. The complete apparatus may be operated as a single tube, or the scrubber may be physically separated from the enricher.

Scope of Calculations - Calculations were limited to a single stage, concentric-tube-type column. The alternate hot central wire column would not be feasible to use for producing the anticipated plant requirement of 1700 grams of product per day.

Feed and Product Specifications - The composition of the column feed (Case II product) follows:

Composition of Column Feed

<u>Element</u>	<u>Wt Percent</u>	<u>Cross Section</u> (Barns)
Kr (mix. of Isotopes	1.0	
Xe 128, 129, 130	0.15	120
Xe 131	11.45	120
Xe 132	17.16	5.0
Xe 134	27.25	0.2
Xe 136	43.00	0.15

The concentration range of the product is limited by the requirement that the composite neutron absorption cross section be one barn or less. An "ideal" cascade study made at ORNL⁽²⁾ on this same feed was used as a guide to determine this range of concentration:

Composition of Column Products⁽²⁾

(wt percent)

<u>Component</u>	<u>First Case</u>			<u>Second Case</u>		
	<u>Feed</u>	<u>Product</u>	<u>Waste</u>	<u>Feed</u>	<u>Product</u>	<u>Waste</u>
Xe 131	12.13	0.68	18.54	12.13	0.68	34.71
Xe 132	17.69	3.18	25.28	17.69	4.29	44.12
Xe 134	27.53	24.17	29.41	27.53	32.28	18.17
Xe 136	42.65	71.97	26.23	42.65	62.75	3.00

The product draw-off rate is to be about one gram per day (1.16×10^{-5} grams/sec).

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Following is the basic method of calculation employed in this paper⁽³⁾:

1. Assume the column feed is a binary mixture with the key components Xe^{132} and Xe^{136}
2. Use the integrated transport equation for determination of the relationship between the dimensionless production parameter, n , and the dimensionless length parameter, y , under various assumed values of terminal xenon concentrations in the column.
3. Translate the length parameter into actual lengths for various selected values of the apparatus temperature, pressure, annulus width, and mean annulus circumference.
4. Translate the production parameter into actual production rates again for various selected values of apparatus temperature, pressure, annulus width, and mean annulus circumference.
5. Select, from graphical plots of the translations cited above, appropriate values of the parameters involved with proper regard for construction difficulty, size, and flexibility.

Binary Mixture - Reduction of the xenon feedstock to a binary base producer the following values:

Adjusted Mol Fractions of Assumed Binary Mixture

<u>Component</u>	<u>Feed</u>	<u>Product</u>	<u>Waste</u>
Xe 136	0.709	0.955*-0.930**	0.308
Xe 134	0.291	0.045	0.692

*Corresponds to first ORNL case

** Corresponds to second ORNL case

Arithmetic averages of the hot and cold gas temperatures were used to determine physical properties of the gas mixtures.

Production and Length Parameters - The first step in arriving at column dimensions is to establish the relationship between n (production parameter) and y (the length or enrichment factor). This interrelationship was determined from the general solution of the transport equation given below for the boundary conditions c_1 , the concentration of Xe^{136} at the beginning of the enriching section, and c_f its concentration at the end of the section. Under these restrictions the transport equation is:

$$\tanh 1/2 b'y = b'(c_f - c_1) / [c_f + c_1 - n(c_f - c_1) - 2 c_f c_1]$$

$$\text{where } b' = [(1 + n)^2 - 4 n c_f]^{1/2}$$

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Since the feed concentration of Xe^{136} c_f is fixed by the nature of this problem, corresponding values of y and n were calculated for three different feed concentrations, c_f values of Xe^{136} -- viz., 0.955, 0.930, and 0.910. (See Fig. 2.) The c_f of 0.910 was subsequently considered too low to use in these calculations. Note that at a given value of production (n) the length factor (y) increases as the enrichment desired is increased.

The actual column length and the actual production rate are related to their respective dimensionless parameters by the equations:

$$\begin{aligned} \sigma &= nH \text{ and} \\ L &= YK/H \end{aligned}$$

where

$$\begin{aligned} \sigma &= \text{rate of production} \\ H &= \text{thermal diffusion coefficient} \\ L &= \text{column length} \\ K &= \text{sum of convective, diffusive, and parasitic current coefficients.} \end{aligned}$$

Inspection of these equations has shown that values of the independent variables should be selected to produce high values of the thermal diffusion coefficient to obtain the desired large production rate in a short column. Simultaneously, a low value should be obtained for the over-all negative coefficient K .

Transport and Diffusion Coefficients - The transport and diffusion coefficients (shown below) are functions of the column geometry, the temperature, pressure, and physical properties of the gas.

<u>Nature of Transport</u>	<u>Symbol</u>	<u>Mathematical Expression</u>
Thermal Diffusion	H	$\frac{(2w)^3 e^2 \epsilon_{GB} (\Delta T/T)^2}{6! \eta}$
Convection	K_c	$\frac{(2w)^7 e^3 g^2 B (\Delta T/T)^2}{9! \eta^2 D}$
Mass Diffusion	K_d	$2w DB = 2w 6_f \eta / 5e$
Self Diffusion	D	$6_f(\sigma) \eta / 5e$
Parasitic Diffusion	K_p	(undetermined)

Certain restrictions are usually placed on relative values of the transport coefficients. A parasitic coefficient K_p is introduced to account for unavoidable irregularities and asymmetries in column fabrication. For design purposes, the parasitic coefficient is usually limited to 30 percent of the convection transport coefficient (K_c). This value, in turn, limits the ratio of the mean circumference of the gap (B) to the annular gap distance ($2w$) to about 20, since K_p/K_c is dependent on $(B/2)^2$. This ratio does not affect the theoretical column efficiency because it appears to the first power in all of the transport coefficients and thus cancels out in the calculations of the column efficiency and dimensions.

Another design limitation is lamellar flow requirement. The transport equation presumes the condition of non-turbulent, convective gas flow in the annular gap. In practice, this means that the Reynolds number (R) should be less than 10. A good practice is to limit K_c/K_d to about 10. This restriction causes the Reynolds number to be much less than 10 and, thus will quickly damp out turbulence caused from localized irregularity in the column walls.

Characteristic Time - The characteristic time (t_c) is that time required to approach operating conditions (i.e., when the specified draw-off rate will permit attainment of the desired enrichment,

$$t_c = c_f K / C_1 H^2$$

where

u is the mass of gas per length of column (grams/cm); e.g., the column operating at 0.4 atmosphere

$$2w = 0.635 \bar{T} \qquad = 726 \text{ K} \qquad B = 20 \text{ cm}$$

$$t_c = 30.8 \text{ hrs}$$

for 0.522 cm column at 1 atmosphere 726°K, $t_c = 39.4 \text{ hrs}$.

According to Jones and Furry⁽³⁾, the ratio $H^2/\mu K$ which is proportional to $1/w^2(1 + a/w^6)$ should be maximized when a minimum t_c is desired. The shortest characteristic time may be obtained when a minimum t_c is desired.

They point out, however, that the t_c does not change rapidly at this ratio; hence, K_c/K_d of 10, which has already been cited as a criterion for lamellar flow, adds only 25.3 percent more to t_c than when $K_c/K_d = 2$.

Summarizing, the total of the limitations suggests the desirability of coefficient ratios of $K_p/K_c/K_d = 0.3/1/0.1$. Thus, the total coefficient (K) is equal to $1.4 K_c$.

Effect of Temperature - Maximum thermal-to-transport-coefficient ratios may be obtained by the use of a large difference in temperature between hot and cold walls during column operation. The convection transport coefficient K_c decreases as the temperature increases because it is proportional to the fourth power of the density and is inversely proportional to the third power of the viscosity. The variation of thermal diffusion coefficient, H , is not as predictable as that of K_c as a result of the dependence on the temperature variation with viscosity. Even if the thermal diffusion constant, α , were increasing (it increases with temperature in most cases), the increase would be slow; and, as is the case with K_c , the increase of $(\Delta T/T)^2$ is not fast enough to prevent a decrease in the K_c/H ratio.

An experimental column of feasible dimensions, i.e., short length and large gas gap, may be used for the xenon system if a very large temperature gradient exists across the gap. The practical temperature limits are about 1152°K (due to construction limitations) for the hot wall and about 300°K for the cold wall.

Gap Dimension Limitation - The variation of column length (L) vs. production coefficient (n) with different temperatures has already been demonstrated. A choice of the annular gap width for a minimum length may now be made. (See Fig. 6.) Consideration must be given, however, to the practical lower gap limit, which is about 0.6 cm due to constructional difficulty.

Table 3 shows the transport coefficients for different gap width and column length values at a mean temperature of 726°K and a pressure of one atmosphere. Note the gap is 0.522 cm at 726°K and a production coefficient of 0.1. Here the K_c/K_d value is 19.7, which is above the desired ratio of 10. Greater gap widths would obviously produce even higher ratios.

TABLE I

TRANSPORT COEFFICIENTS vs. $2w$ and L
AVERAGE GAS TEMPERATURE = 726°K
PRESSURE = 1.0 atmosphere

Production Rate (n)	Gap Width (2w)(cm)	Length in Meters		H	K_c	K_d	K
		$c_F=0.955$	$c_F=0.930$				
0.025	.738	54.5	40.0	4.64×10^{-4}	8.31×10^{-1}	6.80×10^{-3}	1.09
0.05	.635	27.7	20.3	2.32×10^{-4}	2.08×10^{-1}	4.81×10^{-3}	2.75×10^{-1}
0.06	.592	16.7	18.6	1.93×10^{-4}	1.41×10^{-1}	4.37×10^{-3}	1.87×10^{-1}
0.07	.570	14.6	11.3	1.66×10^{-4}	1.04×10^{-1}	4.05×10^{-3}	1.76×10^{-1}
0.1	.522	14.8	10.17	1.16×10^{-4}	5.18×10^{-2}	3.40×10^{-3}	7.07×10^{-2}
0.2	.438	8.2	6.16	5.80×10^{-5}	1.28×10^{-2}	2.40×10^{-3}	1.90×10^{-2}
0.3	.398	5.84	5.08	3.87×10^{-5}	5.93×10^{-3}	1.98×10^{-3}	9.69×10^{-3}
0.4	.369	6.18	4.45	2.90×10^{-5}	3.22×10^{-3}	1.70×10^{-3}	5.89×10^{-3}
0.6	.332	6.49	4.38	1.93×10^{-5}	1.41×10^{-3}	1.38×10^{-3}	3.21×10^{-3}
0.7	.320	7.54	5.13	1.66×10^{-5}	1.04×10^{-3}	1.28×10^{-3}	2.63×10^{-3}
0.8	.310	18.54	6.46	1.45×10^{-5}	7.99×10^{-4}	1.20×10^{-3}	2.24×10^{-3}
2.9	.301	--	--	1.29×10^{-5}	6.33×10^{-4}	1.13×10^{-3}	1.95×10^{-3}

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With a gap of 0.522 cm, a column length of 14.8 meters would be needed for a product purity of $c_p = 0.955$ mol fraction and a column length of 10.8 meters for a product purity of $c_p = 0.930$ mol fraction. The draw-off rate increases initially with pressure, reaching its maximum value of 10.5 grams/sec. at 1.2 atmosphere. (See Fig. 7.)

Effect of Pressure - Decreasing the operating pressure of a thermal diffusion column reduces the convective to mass diffusion coefficient ratio (allowing the use of larger gaps) and decreases the thermal coefficient and the transport to thermal coefficient ratio; thus, reducing the production rate and the required column length. Table II shows the performance of a column with a gap of 0.635 cm. At 0.4 atmosphere an enricher length of only 5.4 meters is needed to get a c_p of 0.930 mol fraction and a draw-off rate of 1.16×10^{-6} grams/sec, or a column length of 7.5 meters is required to obtain a c_p of 0.955 mol fraction at $T = 726^\circ\text{K}$.

TABLE II

COLUMN PERFORMANCE AT AN AVERAGE CASE TEMPERATURE 726°K

Pressure (atmos)	Length Factor (y)	2w = 0.635 cm L = 15 meters			
		Production Factor (n) $c_p = 0.930$	Production Rate g/sec	Production Factor (n) $c_p = 0.955$	Production Rate g/sec
0.2	2.66	0.73	6.77×10^{-6}	0.24	2.23×10^{-6}
0.4	4.76	0.847	3.14×10^{-5}	0.695	2.58×10^{-5}
0.6	3.14	0.685	5.72×10^{-5}	0.420	3.51×10^{-5}
0.8	1.92	0.235	3.48×10^{-5}	--	--
1.0	--	--	--	--	--

A review at this point of the effect of significant variables will be helpful in placing thermal diffusion column operation in perspective. The separation of the xenon isotopes is enhanced by increasing the temperature of the hot wall, however the maximum operating temperature for the equipment is about 879°C . An operating pressure of 0.4 atmosphere permits the use of an annular gap of 0.635 cm. At this gap size, higher pressures introduce turbulence, whereas at lower pressures the rate of production is grossly reduced. The ratio of the coefficient due to convection to the coefficient due to thermal diffusion increases as the gap size increases. The mean gap circumference, B, is fixed after a gap dimension, 2w, is selected because the magnitude of the parasitic currents varies as $(E/w)^2$. About 20 appears to be the upper limit for B/2w in practice. For example, if 2w is 0.635 cm, then B is determinate at 12.7 cm.

Power Consumption - The cooling and heating requirements for a particular column can be meaningful only after the dimensions, operating conditions, and materials have been selected. The conductive heat loss may be calculated from the heat

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conductivity for a rare gas

$$\begin{aligned}\lambda &= 15 \eta_{R/4} M &= 2.363 \times 10^5 &\text{ cal/cm/6K sec at } 726^\circ\text{K} \\ Q &= T/2w &= 3.7 \times 10^2 &\text{ cal/cm}^2/\text{sec} \\ BQ &= 0.43 \text{ watts cm}\end{aligned}$$

The value given above is an example of the heat conducted by the gas; thus, for a six-meter column the conductive loss is 0.242 kw. The loss of heat by radiation becomes greater as the temperature is increased (varies as T according to the Stefan-Boltzman concept). The net quantity of energy transferred by radiation equals the energy emitted, less the energy absorbed. The rate of heat transferred from the hot to the cold tube is

$$q = A_2 \sigma e (T_2^4 - T_1^4)$$

Here σ is the Stefan-Boltzman constant, e is the emissivity, and A_2 is the radiating area of the hot tube. For a polished stainless steel, at this high temperature, the radiant heat loss becomes predominant. For example, in the 0.635 cm column, the radiant heat loss is 1.97 kw/m, or for a 6-meter column a total of 11.8 kw.

SCRUBBER DESIGN

A sample calculation for a scrubber to match an enricher 12 meters in length with an annular gap of 0.592 cm and operating at an average gas temperature of 726°K is given. A material balance yields

$$\sigma_s = \sigma c_f c_i / c_i - c_s = 6.06 \times 10^{-6} \text{ grams/sec}$$

Assuming the Xe^{132} to be the product and treating the scrubber for the lighter isotope, n is calculated to be 0.1044, y equals 1.82 at $c_f = 0.692$. The length of the scrubber is 11.1 meters; and the ratio length of enricher to length of scrubber is 1.07.

At subatmospheric pressure, scrubber lengths have been calculated in the same manner as above to match a column with an annular gap 0.635 cm for the conditions given.

At P atmos	Production Rate	Production Rate
	$c_f = 0.930$ enricher grams/sec	$c_f = 0.955$ enricher grams/s
.2	3.72×10^{-6}	1.227×10^{-5}
.4	1.73×10^{-5}	1.42×10^{-5}
.6	3.15×10^{-5}	1.93×10^{-5}
.8	1.92×10^{-5}	

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$$C_F = 0.930$$

<u>Pressure</u>	<u>Production Factor (n)</u>	<u>Enrichment Factor (y)</u>	<u>Length (meters) (L)</u>	<u>Production Rate σ_s</u>	<u>L_F/L_S</u>
0.2	0.401	2.93	1.66×10^1	3.72×10^{-6}	0.639
0.4	0.467	4.00	1.26×10^1	1.73×10^{-5}	0.551
0.6	0.377	3.78	3.47×10^1	3.15×10^{-5}	0.539
0.8	0.130	1.87	8.78×10^1	1.92×10^{-5}	0.686

$$C_F = 0.955$$

<u>Pressure</u>	<u>Production Rate σ_s</u>	<u>H</u>	<u>Production Factor (n)</u>	<u>Enrichment Factor (y)</u>	<u>Length (meters) (L)</u>	<u>L_F/L_S</u>
0.2	1.228×10^{-6}	9.28×10^{-6}	0.1323	1.87	1.05×10^{-1}	1.50
0.4	1.42×10^{-5}	3.71×10^{-5}	0.383	2.80	0.883×10^{-1}	1.10
0.6	1.42×10^{-5}	8.34×10^{-5}	0.231	2.12	1.81×10^{-1}	1.03

CONCLUSIONS

A single stage thermal diffusion column must operate near the upper limit of its separations capacity to rearrange the isotopes of xenon as specified, if the product from the Case II Facility is used as feed. A temperature of about 879 C is needed for the surface of the hot wall in order to produce a sufficient quantity (about one gram per day) for pilot plant studies. A relatively long column is needed to obtain the required nonturbulent convective gas flow and a minimum 1/4-inch annular gap required for construction purposes.

At an operating pressure of 0.4 atmosphere, a shorter column with a larger gap may be used:

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Product Concentration* of Xe-136(mol fraction)	Enricher Length (meters)	Wall Temperature °C		Pressure Atmos.	Annular Gap (cm)	Outer Tube ID (cm)
		Cold	Hot			
0.930	10.8	27	879	1.0	0.522	3.94
0.930	5.4	27	879	0.4	0.635	4.68
0.955	14.8	27	879	1.0	0.522	3.84
0.955	7.5	27	879	0.4	0.635	4.68

A scrubber may be used to reduce the quantity of feed required for a given product. It would have the same cross section and about the same length as the corresponding enriching section.

*Computed as a binary mixture of Xe^{136} - Xe^{132} .

- NOTE: (1) Michels, L. R., & J. M. Gerhart. Process Study - Gas Purification Facilities at Purex. December 31, 1958. HW-58400. (Secret).
- (2) Blumkin, C., Separation of the Isotopes of Xenon. KOA. 459. Undated.
- (3) Jones, R. C., & W. H. Furry. The Separation of Isotopes by Thermal Diffusion. Review of Modern Physics 18. April 1946

HL Brandt:pc

TABLE OF NOMENCLATURE

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B	= mean circumference (cm) = $\pi(r_1 + r_2)$
$\bar{c}$	= $1 - c$
c_1	= fractional molar concentration of
c_2	= fractional molar concentration of $c_1 + c_2 = 1$
c_i	= initial concentration of c
c_f	= final concentration of c
D	= coefficient of self-diffusion (cm^2/sec)
D_t	= coefficient of thermal diffusion (cm^2/sec)
D_{12}	= coefficient of ordinary diffusion (cm^2/sec)
g	= acceleration of gravity cm/sec^2
H	= transport coefficient due to convection ($\text{g-cm}/\text{sec}$)
H_p	= transport coefficient of thermal diffusion (parasitic)
K^p	= $K_c + K_d + K_p$
K_c	= transport coefficient due to convection ($\text{g-cm}/\text{sec}$)
K_d	= transport coefficient due to diffusion ($\text{g-cm}/\text{sec}$)
K_p	= transport coefficient due to convection (parasitic)
L	= length of column (cm) or (m) as indicated
M	= molecular weight
n	= σ/H (dimensionless)
P	= pressure (atmospheres)
q	= separation factor
Q	= conductive heat flow (quantity/unit area/unit time)
r_1	= radius of outer tube (cm)
r_2	= radius of inner tube (cm)
R	= Reynolds number
R	= gas constant (1.9864 calories/ $^{\circ}\text{C}/\text{mole}$)
t	= time (sec)
t_c	= characteristic time for the approach to an operating condition
T	= absolute temperature ($^{\circ}\text{K}$)
T_1	= temperature of cold wall (outer tube)
T_2	= temperature of hot wall (inner tube)
$\bar{T}$	= $1/2 (T_1 + T_2)$
ΔT	= $T_2 - T_1$
W	= $1/2(r_1^2 - r_2^2)$ (cm)
$2w$	= $r_1 - r_2$ = annular gap
γ	= HL/K (dimensionless)
α	= thermal diffusion constant
η	= viscosity (poises)
μ	= g ⁴ xenon gas/cm of column
δ	= force index (see appendix)
ρ	= density g/cm^3
σ	= flow of gas through column (g/sec)

The subscript (s) pertains to the scrubbing section.

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LENGTH FACTOR VS. PRODUCTION FACTOR

$$\tanh \frac{1}{2} b' y = \frac{b'(cf - ci)}{cf + ci - n(cf - ci) - 2cf ci}$$

$$b' = \frac{[(1+n)^2 - 4ncf]^{\frac{1}{2}}}{cf}$$

ci = 0.709 curve (1) cf = 0.955
 curve (2) cf = 0.930
 curve (3) cf = 0.910

↑
Y

0.0

0.2

0.4

0.6

0.8

1.0

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FIGURE 2

ENRICHER LENGTH vs. PRODUCTION FACTOR

(At various temperatures)

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FIGURE 3

ERICHSEN LENGTH vs. PRODUCTION FACTOR
at $\bar{T} = 600^\circ\text{K}$

FIGURE 4

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ENRICHMENT LENGTH vs. PRODUCTION FACTOR

at $\bar{T} = 726^\circ K$

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NW-60333 Part I of IV

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INCH OF INCH

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NW-60333 Part I

LENGTH FACTOR VS. PRODUCTION FACTOR FOR SCRUBBER

Y VS. n FOR SCRUBBER

$X = 132$ $C_i = 0.291$
 $C_f = 0.692$

0.8

0.6

0.4

0.2

n

Y

DATE

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10 / 31 / 94

END