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MERCURY SEPARATION FOR POWER REACTORS,

I - MERCURY ISOTOPE SEPARATION

by

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MERCURY SEPARATION FOR POWER REACTORS, I - MERCURY ISOTOPE SEPARATION

H. T. Hahn

Mercury possesses distinct advantage as a primary heat exchange medium in liquid metal fueled reactors by virtue of its relatively low boiling point and the existent technology for its use. However, certain isotopes of mercury possess unusually large neutron cross-sections.

The problem may be approached in two ways. One can either provide a method of separating the heavier, low-cross section isotopes (e.g. Hg-204 = 0.4 barns) or quantitatively remove the mercury from the liquid metal prior to recycling. This paper concerns the former, and evaluates the potential of several isotope separation processes.

A process is required which will produce ten kg. per day of mercury containing greater than 99 percent of mercury-204 at a cost of $250 per kg.[1] However, processes will be screened by an initial goal of one kg/day containing 90 to 98 percent. In all cases, the feed material is naturally occurring mercury with a concentration of 6.8 percent mercury-204. The situation with respect to the "waste stream" is unique in that the mercury may be returned to industry, somewhat lighter for its experience, but with essentially no change in value.

Summary and Conclusions

1. A survey is made of methods of isotope separation to determine whether any are potentially capable of producing ten kilograms per day of mercury containing 99 percent mercury-204 at a cost of $250. per kilogram or less. The methods examined are gas centrifugation, chemical exchange, liquid and gaseous thermal diffusion, photo-excitation, distillation-diffusion and barrier diffusion.

2. Only distillation-diffusion is found capable of producing the desired results. From the standpoint of plant cost the distillation-diffusion cascade is most promising since little mechanical equipment is required and the separating elements are easily constructed. Energy costs are sufficiently low that labor costs will probably be critical. A separation factor for mercury-204 of slightly less than 1.013 per stage has been calculated from the experimental data of W. O. Harkins. Recent barrier development may permit a diffusion rate greater than 50 cc/hr. per unit thereby reducing plant size.

3. A distillation-diffusion cascade can produce 99.5 percent mercury-204 at 10 kg/day for $250./kg if labor costs can be kept under $118./kg. In this case, the plant would contain 79,500 units. A waste stream of 1288 kg/day of mercury containing 6.08 percent 204 would be returned to industry.

4. The possibility of a process based solely upon gaseous diffusion cannot be discounted. However experimental data and barrier costs are lacking for this case. The experimental separation factor is estimated to be 1.003 per stage. Energy costs alone will be close to the limit set. Pumps replace the vaporization heaters of the combination process. The barrier area required will be about 18 times greater than the latter.

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[1] C. A. Rohrmann, private communication.

Gas Centrifugation

The requirements for a centrifugal process are calculated by the method of Cohen.[2] For convenience a glossary of terms is included at the conclusion of this document.

We first calculate a simple process separation factor α_s from the equation:

$$\alpha_s = \exp \frac{(M_2 - M_1)(\omega r_2)^2}{2RT} \qquad (1)$$

where M_1, and M_2 are the atomic weights of the light and heavy isotopes respectively.

ω is the angular velocity, $\sec^{-1}$.

r_2 is the radius at the periphery, cm.

R is the gas constant, 8.314×10^7 ergs/°K/mole.

T is the absolute temperature, °K.

A peripheral velocity of 3×10^4 cm/sec is probably close to the upper limit imposed by the tensile strength of the centrifuge bowl. The average molecular weight, excluding 204, is 200.3. The appropriate mass difference lies between two and six, the weighted difference being 3.7 mass units. Using the latter figure and a temperature of 469°K, $\alpha_s = 1.044$. Diatomicity in the vapor state would tend to reduce this value.

We now calculate the value of the separative work to be performed. The value function V, is defined as

$$V = (2N-1) \ln \frac{N(1-N_o)}{N_o(1-N)} + \frac{(N-N_o)(1-2N_o)}{N_o(1-N_o)}, \qquad (2)$$

where N refers to the atom fraction of desired isotope

and $N_o = 0.068$ for natural mercury.

A plot of value function per atom fraction versus the atom fraction for both the rectifying and stripping section is given in Figure 1. The value function is not limited to centrifugation, but is applicable to the separative work required of any process which produces product and waste of concentrations N_p and N_w from feed material of concentration N_o.

For the region of interest ($0.90 < N_p < 0.98$):

$V = 19.74\, N_p^{2.640}$, where N_p is the atom fraction in the product. (3)

This equation is valid within less than two percent.

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[2] K. Cohen, The Theory of Isotope Separation, NNES III-1B, McGraw-Hill (1951).

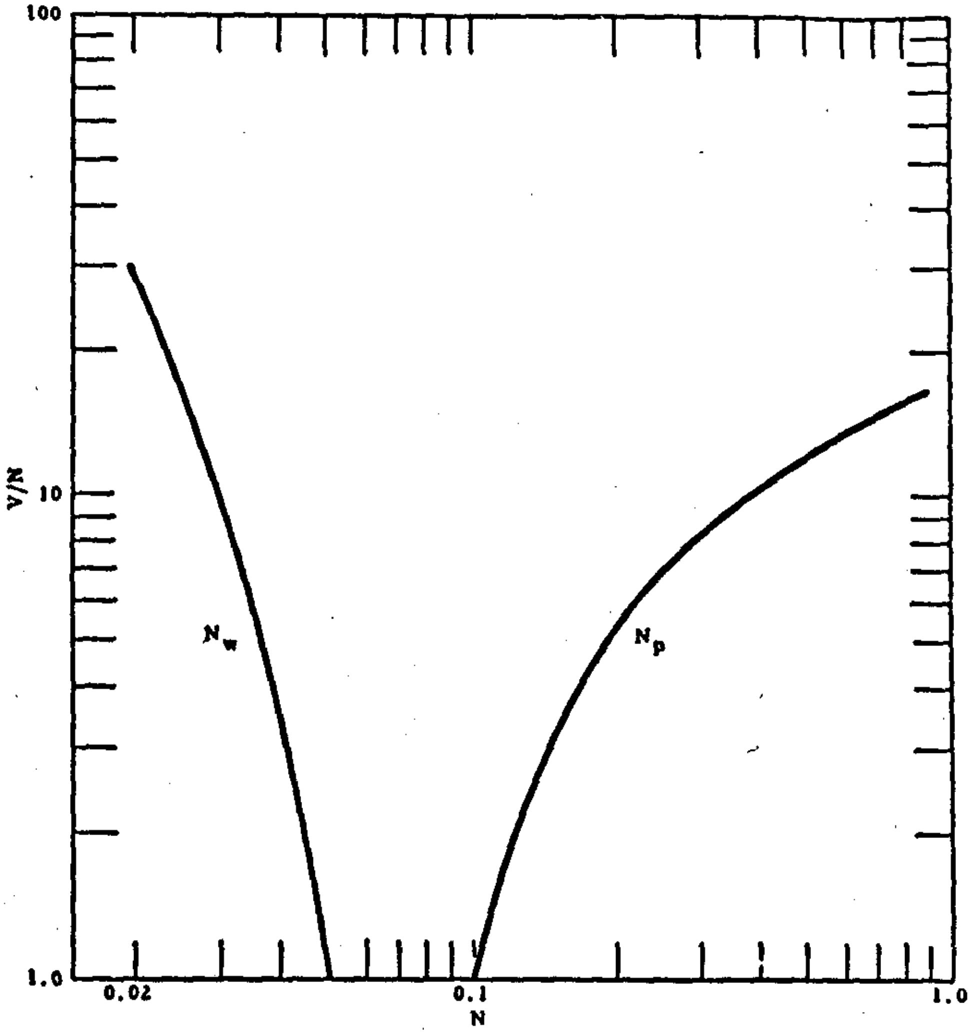

FIGURE 1
Value Function for H_c-204
(N_o = 0.068)

Since the tails from the first stage may be returned to industry, the separative work of only a single stage is involved. The contribution of the stripping section to the value function may therefore be neglected with less than one percent error.

The total value ΔU to be produced is given by

$$\Delta U = V\ P \tag{4}$$

where P = 1 Kg Hg per day or 0.01157 gm Hg/sec.

$$\Delta U = 0.228\ N_p^{2.640} \text{ gm/sec.} \tag{5}$$

The maximum separative power of a centrifuge is given by

$$(\delta U)_{max} = \rho D \left[\frac{(M_2 - M_1)\quad (\omega r_2)^2}{2\ RT}\right]^2 \frac{\pi Z}{2} \tag{6}$$

where ρ is the density (gm/cm^3)

D is the diffusion constant (cm^2/sec)

and Z is the length of centrifuge (cm.)

The product of ρ and D is characteristic of the working medium and for gases it is proportional to the viscosity η.

We may write $\rho D = 1.4\ \eta$ with a probable error of less than seven percent. From viscosity data[3] for mercury we derive the equation,

$$\eta = \exp\left[\frac{-937}{T} - 5.896\right] \tag{7}$$

and therefore the ρD product may be expressed solely as a function of temperature by

$$\rho D = 1.4 \exp\left[\frac{-937}{T} - 5.896\right] \tag{8}$$

If we choose a centrifuge of 100 cm. length and 30,000 cm/sec peripheral velocity, and arbitrarily assign the minimum mass difference of two units, equation (6) becomes

$$(\delta U)_{max} = \frac{2.58 \times 10^4}{T^2} \quad \exp\left[-937/T - 5.896\right] \tag{9}$$

Differentiating we obtain,

$$\frac{d\ (\delta U)_{max}}{dT} = (937 - 2\ T) \quad \exp\left[-937/T - 5.896\right] \tag{10}$$

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[3] International Critical Tables, 1st ed, Vol V, p. 2.

and taking the non-zero solution we find the optimum temperature to be 469°K. It is interesting to note that this temperature of maximum separative power is dependent only upon the first coefficient obtained in the viscosity expression (7) and is independent of the centrifuge design. It is, of course, true that the design determines the efficiency or fraction of $(\delta U)_{max}$ attained.

Finally, for the total number of centrifuges (or other separative units) required,

$$X = \frac{\Delta U}{\delta U} \quad (11)$$

We have now reduced this value to a function of atom fraction N_p (Eqn. 5) and temperature T (Eqn. 9).

A nomograph is given (Figure II) to illustrate the interdependence of these variables. It is apparent that temperature is not an extremely critical variable in the range of interest.

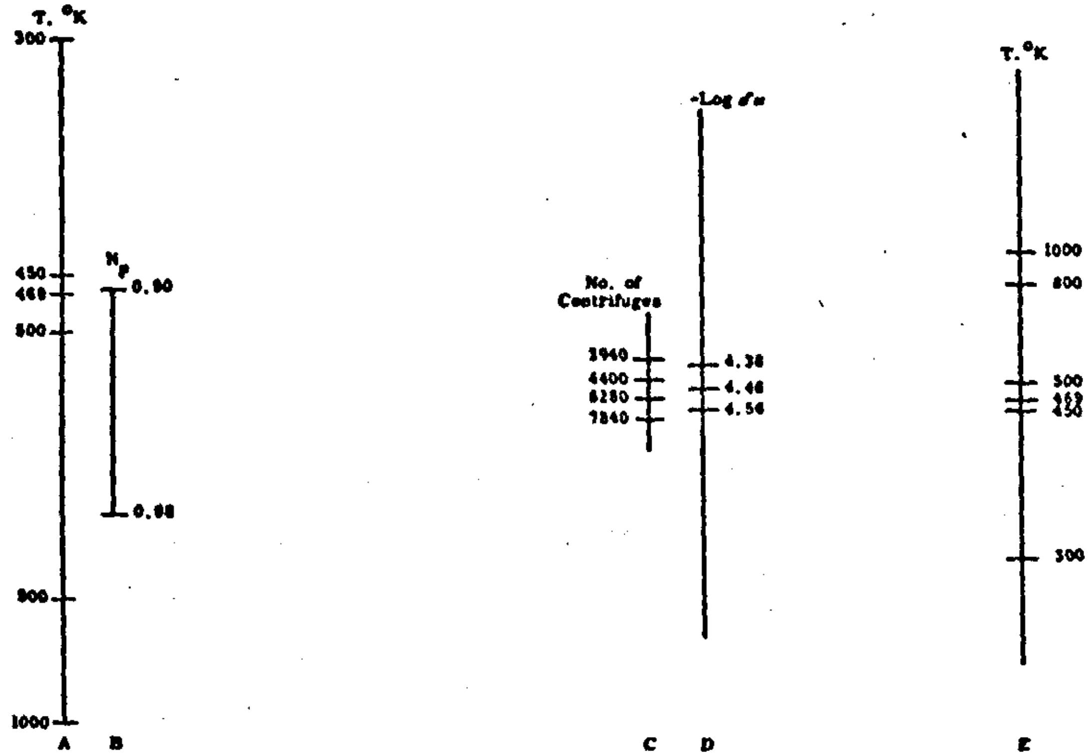

FIGURE 2
Centrifuges Required to Produce Mercury-204
A-D-E
B-C-D

Under the optimum conditions previously cited, to produce one kilogram per day of 90 percent mercury-204, 3940 centrifuges are required. If the weighted mass difference of 3.7 units is used, a factor of $(1.85)^2 = 3.42$ is gained. We then require 1150 centrifuges.

Based upon previous estimates[4] the operating cost of this plant is found to be in excess of \$13 per gram of mercury-204.

Chemical Exchange

To obtain a high separation factor in chemical exchange it is desirable that one of the exchanging species bond as little and as loosely as possible to its neighboring atoms while the other species forms many tight bonds. Obviously elemental mercury possesses the former quality, and in addition would probably exchange rapidly from its liquid state. A second species of mercury must be then found which forms many high frequency bonds, i.e. it possesses a large partition function.

A rapid method of estimating partition functions has been described[5] which employs the Bigeleisen equation:

$$f = 1 + \frac{\Delta M\ (n)\ (m)\ u_1^2}{24\ M_1 M_2} \qquad (12)$$

where ΔM is the mass difference between isotopes of mass M_1 and M_2,

n is the number of bonds formed with adjoining atom of mass m,

$u_1 = hc\nu_1/kT$,

and ν_1 is the symmetrical stretching frequency of the bond.

The maximum coordination number of mercury is four as evidenced in the divalent tetrachloromercurate ion. It has been shown[5] that chloride bonding generally produces lower-valued partition functions than bonds with oxygen and fluorine. However, neither a tetrafluoromercurate ion nor a peroxide is known.

The compound HgF_2 possesses the largest value estimated by this method. For HgF_2 and a weighted difference of 3.7 mass units, $f = 1.00155$. In combination with elemental mercury this also represents the simple process separation factor.

The large number of stages and rapid exchange required discourage further consideration of this method.

Liquid Thermal Diffusion

We first define the thermal diffusion column constants H and K according to Abelson[6] such that

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[4] NYO-3928 (Secret).

[5] H. T. Hahn, J. Chem. Physics 15, 261 (1947).

[6] P. W. Abelson, NNES IX-1, (Secret).

$$H = \frac{g\rho\Delta\rho b a^3}{720\,\eta}\, q\,\Delta T \tag{13}$$

$$K = \frac{g^2\rho(\Delta\rho)^2\, b a^7}{3.63 \times 10^5\,\eta^2 D} + \rho D\, ab \tag{14}$$

$$\alpha = \frac{H}{K} \tag{15}$$

where $g = 981$ cm sec^{-2}.

$\Delta\rho$ is the density difference (gm cm^{-3}) resulting from the temperature difference, ΔT (°K).

a is the annular spacing, cm.

b is the mean annular circumference, cm.

q is the thermal diffusion coefficient, deg^{-1}.

and other terms have been defined previously.

Combination and reduction produces

$$\alpha = \frac{1.36\,(\Delta\rho)\, a^2\, q(\Delta T)\eta D}{2.64\,(\Delta\rho)^2\, a^6 + \eta^2 D^2} \tag{16}$$

Density,[7] viscosity,[8] diffusion,[9] and thermal conductivity[10] data for mercury are approximated by

$$\Delta\rho = 0.0024\,\Delta T, \tag{17}$$

$$\eta D \sim 8 \times 10^{-10}\, T, \tag{18}$$

$$a = 0.0213\,\Delta T. \tag{19}$$

Substituting in (16)

$$\alpha = \frac{1.185 \times 10^{-15}\,\Delta T^4\ (T)\, q}{1.418 \times 10^{-15}\,\Delta T^6 + 6.4 \times 10^{-20}\, T^2} \tag{20}$$

and we now have α as a function of two temperature variables.

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[7] International Critical Tables, 1st Ed., Vol II, p. 458.
[8] Ibid., Vol. V, p. 7.
[9] J. Chem. Phys 20, 1956-70 (1952).
[10] Chemical Engineers Handbook, John H. Perry, ed., 2nd Ed., p. 949.

We maximize α by differentiating with respect to ΔT at constant T, and obtain

$$\Delta T_{(\alpha \, \mathrm{Max})} = 0.2075 \, T^{1/3} \qquad (21)$$

The temperature of 400°K is chosen as easily obtainable, and we must then have $\Delta T = 1.53$°K and $a = 0.0326$ cm. Columns with this annular spacing have been fabricated in the Hanford Laboratories.[11] From (13) and (20) we calculate $\alpha = 17.9\, q$ and $H = 2.83 \times 10^{-3}\, q$.

The total number of columns χ required in an ideal cascade is given by

$$\chi = \frac{4\,P\,V}{\alpha\, L_1 H_1} \qquad (22)$$

where the subscripts refer to an individual column and V is defined by (2).

For enrichment of one kilogram of mercury to 90 percent mercury-204, $V = 15.2$. Since the stripped mercury may be returned to industry we need not be concerned with holdup and may choose long columns, e.g. 40 feet. For this length we find the number of columns required is $1.14 \times 10^{-2}/q^2$. The value of q must be determined experimentally, but is probably no greater than 10^{-4}. The number of columns is therefore prohibitively high.

Thermal Diffusion in Mercury Vapor

Some experimental data is available[12] for the separation of mercury isotopes by gaseous thermal diffusion. The separation was made in a tube 220 cm. long and 0.7 cm. in diameter, with an axially located tungsten wire at 1800 C. An insulated outer tube maintained the working tube above 350 C. Mercury at the lower end was heated by a constant d.c. source; at the upper end the mercury vapor diffused through an argon cushion. A withdrawal rate of 0.25 gm. per hour produced a difference in atomic weight of 0.05 percent[*] between light and naturally occurring mercury after 60 hours.

The magnitude of separation and rate of production are too small to be useful for the present requirement.

Photo-Excitation

A method of separating mercury isotopes by a photochemical process has been described.[13] The method makes use of a monoisotopic resonance lamp as the source of

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11. HW-39477, H. T. Hahn, Interim Report on the Separation of Isotopes by Liquid Thermal Diffusion, October, 1955.
12. Naturwissenschaften 27, 554 (1939).
13. J. Chem. Phys. 21, 1702-6 (1953).

[*] This percentage appears in Chemical Abstracts; however the original note contains the value "0,5 0/00". It is possible that this rather unique terminology is a typographical error, in which case the separation would be of interest indeed. An attempt will be made to correspond with one of the authors, Harteck.

light. In this particular case a mercury-198 lamp was used to excite the mercury-198 atoms in the naturally occurring mixture of isotopes. The activated mercury atoms reacted with water vapor to produce enriched mercuric oxide. A separation factor of 1.5 was obtained. No production rate or yield is given.

The separation is based upon the fact that the hyperfine structure of the 2537 Å line in mercury reveals a 198 component somewhat removed from the other isotopes. Unfortunately the 199 a, 201 a and 204 components of this radiation are superimposed, so that it would be useless for the separation of mercury-204. However, other mercury lines do possess isolated 204-components as shown in Table I, compiled from reference 14.

TABLE I

FINE STRUCTURE OF MERCURY LINES

Isotopic Shift, cm^{-1}

Isotopic Component	2537 Å	6716 Å	6234 Å	6072 Å
198	+0.161	-0.233	-0.070	-0.241
199 a	-0.333	-0.195	-0.268	-0.867
199 b	+0.132	-	-0.118	-0.799
199 c	+0.394	-	+0.117	-0.465
199 f	-	-	-	+0.270
200	0	-0.118	-0.040	-0.120
201 a	-0.333	-0.274	-0.185	-0.630
201 b	+0.394	-	+0.201	-0.465
202	-0.178	0	0	0
204	-0.333	+0.122	+0.020	+0.118

In both the 6072 Å and 6716 Å radiations of mercury the 204-component is separated from its nearest neighbor by 0.12 cm^{-1}. (The nearest neighbor in both lines is fortunately the 202-component). This may be compared to a major component proximity of 0.16 cm^{-1} for the 198-separation previously cited.

However, two factors will restrict the applicability of this information. Firstly, the intensity of both the 6072 and 6716 Å lines is less than the 2537 Å line by a

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14. Zeits.f. Physik. 72, 423-441 (1931).

factor greater than ten. Of greater importance is the fact that both the longer radiations arise from transitions between excited states. It would therefore be necessary to excite the subject mercury atoms to the 6s7s $^1S_0$ and 6s7s $^3S_1$ states prior to irradiation. Other atoms would be excited to the intermediate 6s6p levels also. A reaction requiring 220 Kcal/mole must now be provided to return the 6s7s atoms to the ground state without affecting the lower excited states. Thus, considerable research may be required with no assurance that the yields will be sufficiently high.

No data were found on the hyperfine structure of mercury radiation in the vacuum ultraviolet range. Here, too, laboratory research would be required before a complete evaluation could be made.

Distillation-Diffusion

Processes based upon the relative rates of molecular diffusion or of evaporation would yield rates inversely proportional to the square roots of the masses. For a mixture of mercury isotopes, Harkins[15] gives an equimolar effective mass difference of three units, and for mercury 201-204 this ratio would then be 1.007.

A series of experiments involving a combination of diffusion and distillation[16-17] is appropriate to this discussion.

In each stage mercury vapor was distilled at about 5 mm pressure from a flask with wide vertical neck into a vertical Pyrex tube containing a filter paper membrane. The height of the tube was about seven feet; the length of diffusion element was one meter; the diameter was 30 mm. The barrier was surrounded by a water jacket. After diffusion through the barrier the mercury condensed on the wall of the jacket and was collected at the base of the annulus. The paper barrier was relatively short-lived and eight hours was required to replace it. A diffusion rate of 50 cc per hour was found optimum, with each stage initially containing 50 cc. Higher rates shortened the life of the membrane. The rate of evaporation was 450 cc per hour. A cut of 50 percent was made at each stage.

Mass changes were determined by density measurements, and composition changes by the equations of Harkins.[15] The heavy fraction gained 0.1 unit after 25 operations, while the light fraction lost 0.08 unit after 20 operations. From an original concentration of 6.45 percent (lower than the modern value), the corresponding mercury-204 end concentrations were 7.45 and 5.73 percent respectively. From this data a separation factor of 1.0128 per stage is calculated for mercury-204 relative to the other isotopes.

The chief objection to the distillation-diffusion batch separations conducted by Harkins was the need for frequent replacement of the paper diffusion barriers. Development of the art of barrier manufacture has progressed rapidly as a result of experience gained in separating uranium isotopes by the gaseous diffusion of uranium hexafluoride. Creation of a suitable permanent barrier material should therefore present no problem at this time.* Increased area or permeability will

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15. J. Amer. Chem. Soc. 51, 56 (1922).
16. J. Amer. Chem. Soc. 45, 1592, (1923).
17. Phil. Mag. 6 (7), 601-31 (1928).

* Steel, ceramics, or graphite have good corrosion resistance to mercury at these temperatures.

increase the throughput per unit. Unit cost per element may be anticipated to be low since the elements require neither mechanical parts nor close tolerances.

We now combine each of the separate distillation-condensation operations into a stripping plant, arranging the cascade so that only material of identical composition is combined after 50 percent cuts. These characteristics closely approximate those of an ideal cascade.

The separative power of a single unit under these conditions is[2]

$$\delta U = \frac{G}{2} (\alpha_{o} - 1)^2 \qquad (23)$$

were G is the rate of feed to the unit.

With a diffusion rate of 50 cc per hour per unit, $G = 1360$ gms/hr or 0.378 gm/sec. The separation factor is 1.0128. The value produced per unit is

$$\delta U = 3.10 \times 10^{-5} \text{ gm/sec.}$$

In order to produce one kilogram per day of mercury containing 90 percent mercury-204 a total value gain of 0.176 gm/sec is required (from Eqn. 5). The number of units necessary is therefore $0.176/3.1 \times 10^{-5} = 5678$ units.

The overall $\alpha = N_p/1-N_p \big/ N_o/1-N_o = 123$, and the number of stages is

$$S = \frac{\log 123}{\log 1.0128} = 378 \qquad (24)$$

The power requirements of vaporization are $5678\,(680)(71)(1.1 \times 10^{-6}) = 302$ Kw. If a loss in condensation of 200°C is assumed, an additional 29 Kw is required for reheating. At a power cost of \$0.005/Kwh, the minimum operating cost would be

$$\frac{0.005(331)(24)}{1000} = \$0.040 \text{ per gm mercury.}$$

To this point we have neglected the stripping section. From the data of Harkins $x_o - x_w = 0.0036$ per stage. The effect of varying the waste concentration is shown in Table II for a plant producing one kg. per day of 90 percent mercury-204 from a feed containing 6.8 percent.

TABLE II

STRIPPING SECTION

Stripping Stages	Total Stages	Total Units	Feed Kg/day	$\bar{X}_v$	U Kg/day	Kv	Power Cost $/Kg
1	378	5678	2312	0.06764	15.232	330	40
2	379	5700	1157	0.06728	15.270	331	40
3	380	5710	771	0.06692	15.299	331	40
5	381	5742	463	0.0662	15.376	333	40
10	383	5813	232	0.0644	15.572	338	41
20	388	5974	117	0.0608	16.000	347	42

It is possible to avoid all but one stripping stage. To do so requires a relatively large feed rate, as may be seen in Table II. For comparison the 1956 production rate of mercury in this country was 2282 Kg/day. Addition of 20 stripping stages reduces the feed requirement to less than ten percent of this amount with a five percent increase in unit power cost.

Obviously the process has greater capabilities than one Kg/day of 90 percent mercury-204, and still remain with $0.25 per gram.

We now estimate the total cost as follows:

$$X = \frac{\Delta U}{\delta U} = \frac{\Delta U}{2.68 \times 10^3 \text{ Kg/day}} \tag{25}$$

The heating requirement at five mils/Kwh = (0.0580) No. of units, X

Assuming 95 percent of the energy costs are in heating and vaporizing mercury,

$$\text{Heating cost} = \frac{(X)(0.0580)(.005)(24)}{.95\,P} = 0.00733 \left\{\frac{X}{P}\right\} \frac{\text{dollars}}{\text{Kg.}}$$

The cost of a unit is a matter of conjecture, but $25 per unit does not seem unreasonable. When amortized over ten years,

$$\text{Equipment cost} = \frac{(X)}{(P)}\frac{25}{3650} = 0.00685 \frac{(X)}{(P)} \frac{\text{dollars}}{\text{Kg.}}$$

With this type unit the plant should be essentially free of maintenance. With instrumentation, let's assume the manpower cost per 3000 units at an optimistic $25. per shift:

$$\text{Manpower cost} = \frac{3(25)X}{(P)\ 3000} = 0.0250 \frac{(X)}{(P)} \frac{\text{dollars}}{\text{Kg.}}$$

The labor cost is thus more than three times the energy or equipment costs.

Summing:

$$\text{Total cost} = 0.03918 \left(\frac{X}{P}\right) \text{ dollars/Kg mercury} \qquad (26)$$

For the entire range, from (25):

$$\text{Total cost} = 14.6 \ \frac{\Delta U}{P} \qquad (27)$$

At $P = 10$ Kg/day, $N_p = 0.995$, $N_w = 0.0608$, W is found to be 1238 Kg/day. For this case the feed constitutes 57 percent of the national production. The value to be produced is 213 Kg/day, the number of units required is 79,500, and the total cost from Eqn. (27) is \$311/Kg.

To illustrate the importance of labor cost still further, let's assume the plant may be so automated that one man can tend 4500 units. This reduces Eqn. (27) to

$$\text{Total Cost} = 11.5 \ \frac{\Delta U}{P} \qquad (28)$$

and the product cost to \$245/Kg mercury.

A distillation-diffusion process therefore appears feasible when based solely upon the experimental data of W. D. Harkins. One envisions a cascade of stills possessing permanent diffusion barriers, so arranged that following a pre-set distillation period the heaters are deenergized and valves actuated, releasing the diffusate to the following light-component stage. The valves close, the heaters are energized, and the cycle repeated ad infinitum. It is also apparent that the throughput of a unit could be increased above that of the Harkins units by the proper combination of area and permeability of barriers.

Gaseous Diffusion

The possibility of a process based solely upon gaseous diffusion cannot be discounted. However, it is probable that the effective separation factor will be less than the theoretical vlaue of 1.007, thereby considerably increasing the throughput requirement (i.e. barrier area).

Pumping costs represent a considerable fraction of the operating cost of a diffusion plant. We may approximate the cost of pumping as follows. Assume an effective separation factor of 1.003 and an operating pressure ratio across the barrier of five.

The isothermal work of compression at 500°K is

$$w = R\,T \ln \frac{P_2}{P_1} = (1.987)\,(500)\,(2.303)\,(0.699) = 1600 \text{ cal/mole} \qquad (30)$$

The total flow is given by,

$$\frac{\alpha + 1}{(\alpha - 1)^2} \Delta u = \frac{2.00}{9 \times 10^{-6}} (0.176) = 3.91 \times 10^{4} \text{ gm/sec} \qquad (31)$$

The flow through the barriers is one-half this, or 1.174×10^6 gm/min.

The power requirements are then:

$$\frac{1600}{201} \frac{\text{cal}}{\text{gm}} \left(1.174 \times 10^6 \frac{\text{gm}}{\text{min}}\right) (6.98 \times 10^{-5}) = 652 \text{ Kw}$$

If the pumping costs are assumed to be 75 percent of operating cost, the latter, at five mils/kwh. would be

$$\frac{652}{0.75} (0.005) \frac{(24)}{1000} = \$0.11/\text{gm mercury}$$

Hanthorn[18] has estimated, by a somewhat different approach, the total cost for 99.5 percent mercury-204 to be $0.49 per gram. For corresponding product concentration our estimate would be $0.17 per gram, excluding plant and labor costs. Considering the approximations involved in both calculations the estimates do not differ greatly. A barrier area about 18 times greater than the corresponding distillation-diffusion and considerably more pumps would be required. It is concluded that the gains to be made by combining two separative processes in one high throughput operation place the distillation-diffusion process in the most favorable economic position of all the isotope separations schemes considered in this document.

H T Hahn

H. T. Hahn:dp

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[18] H. Hanthorn, private communication.

GLOSSARY

a , Annular spacing, cm.

b , Mean annular circumference, cm.

D , Diffusion constant, cm^2/sec.

g , Gravity acceleration, cm/sec^2.

G , Rate of feed to unit.

h , Planck's constant.

k , Boltzmann's constant.

L , Length of column, cm.

M_1, Atomic weight of light isotope.

M_2, Atomic weight of heavy isotope.

n , Number of bonds formed.

N , Atom fraction of desired isotope.

N_o, Atom fraction in original material.

N_p, Atom fraction in product.

P , Product rate.

q , Thermal diffusion coefficient, deg^{-1}.

R , Gas constant, appropriate units.

r_2, Peripheral radius, cm.

S , Number of stages.

T , Absolute temperature, °K.

ΔT , Temperature difference.

$(\delta U)_{max}$, Maximum separative power of a single unit.

ΔU , Total value to be produced = VP.

V , Value function, value per mole.

Z , Length of centrifuge, cm.

α = H/K, column constant ratio.

α_s, Simple process separation factor.

γ_1, Symmetrical stretching frequency.

η, Viscosity, poise.

ρ, Density, gm/cm^3.

$\Delta\rho$, Density difference.

X, Number of separative units.

ω, Angular velocity, Sec^{-1}.