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PRELIMINARY ESTIMATE OF THE COST
OF PRODUCING ENRICHED OXYGEN-18
WATER BY DISTILLATION

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PRELIMINARY ESTIMATE OF THE COST OF PRODUCING
ENRICHED OXYGEN-18 WATER BY DISTILLATION

J. S. Drury and B. B. Klima*

Chemistry Division

Date Issued: OCT 10 1958

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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*Chemical Technology Division

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PRELIMINARY ESTIMATE OF THE COST OF PRODUCING
ENRICHED OXYGEN-18 WATER BY DISTILLATION

Abstract

An order of magnitude estimate was made to determine the cost of producing oxygen-18 enriched water by the equilibrium distillation of water. Three isotopic purities and two production rates were considered. Costs varied from \$26 per gram for 3% oxygen-18 enriched water produced at a rate of 100 grams per day to \$225 per gram for 99% oxygen-18 water produced at a rate of one gram per day.

Introduction

For many years oxygen-18 enriched water has been produced in this country as an incidental by-product of the heavy water industry. The oxygen-18 content of this material has varied from slightly enriched to eight times normal abundance, depending on the particular enrichment process employed. Enrichment of large quantities of oxygen-18 to concentrations greater than 1-2% has not been undertaken in the United States. It is the purpose of this report to estimate the order of magnitude cost of producing enriched oxygen-18 water in this country.

The equilibrium distillation of water was the enrichment process chosen for consideration in this report. This method has several advantages over existing competitive processes. It utilizes a cheap, non-corrosive feed material, a relatively inexpensive refluxing mechanism, and a simple operational procedure. The major disadvantages of the method are its low separation factor and the associated long isotopic equilibrium time. Despite these shortcomings, the distillation method is considered to be the most attractive process for the production of multigram quantities of enriched oxygen-18 water at the present time.

Cascade Design

The enrichment of oxygen-18 in three isotopic purities and at two production rates was considered. The product purities chosen were 3%, 40%, and 99% oxygen-18. The production rates were 1 and 100 grams per day for the higher purities. For the 3% case, the smaller production rate was doubled.

Three basic cascades were designed for the lower production rate, one each for the low, intermediate, and high purity product. The cascade designed for product of intermediate purity was scaled up to allow a hundredfold increase in its production rate. Costs for the low and high purity cascades at the higher production rate were extrapolated from cost

data obtained from the other four cascades.

Oxygen-17 which has a normal abundance of 0.04% was neglected in the foregoing calculations. This simplification introduces no significant error into the calculation of the cascades for production of low and intermediate purity oxygen-18. However, in the case of the cascade producing high purity oxygen-18, an allowance must be made. The purity stated for the product of the latter cascade includes both oxygen-17 and oxygen-18. It is estimated that the product would contain 1-2% oxygen-17 with a corresponding decrease in the oxygen-18 content. Oxygen-17 of higher purity, perhaps up to 5% oxygen-17, would be available at an intermediate point in the cascade if desired. However, withdrawal of oxygen-17 at this point would reduce the oxygen-18 yield of the cascade.

Each cascade was designed as a series of columns of decreasing diameter in order to minimize holdup, equilibrium time and capital investment. The required taper was approximated first from plots of $V_{\min}/D$, minimum reflux ratio, vs. X_n , mole fraction of product in downflow at a given stage. Several variations of these preliminary configurations then were calculated to refine the design with respect to the length and width of each section. The cascades which evolved are thought to be reasonable, though not necessarily optimum, designs upon which cost estimates might be made. The criteria

used in designing the cascades are given in Appendix "A".

Cascade 1

The first cascade was designed to produce 99% oxygen-18 water at the rate of one gram per day. This cascade (Fig. 1) consists of three packed distillation columns with associated reboilers, condensers, pumps, storage vessels, vacuum system, and coolant towers. Feed is introduced as steam into the first column at a point about one-third column length from the top. The first column thus serves as both a stripper and an enricher. One half of the contained oxygen-18 is removed from the feed stream. Intercolumn transfer is accomplished by means of partial and total condensers, following the technique¹ used by Dostrovsky, et al, in the construction of the Weizmann Institute cascade. In this transfer method, the entire interstage flow from a particular column is condensed in a total condenser and the liquid is passed down the cascade to the reboiler of the next largest column. An equivalent amount of steam from the latter column is condensed in a partial condenser by the addition of precisely enough cooling water, and this condensate is fed by gravity into the former column. This technique eliminates the need for moving parts in the transfer process and, hence, is less prone to fail during the long periods of continuous operation required to enrich the heavy isotopes of oxygen.

Cascade 1

See Table 1 for Key

Figure 1. Schematic Diagram of Cascade to Produce One Gram per Day of Water Enriched to 99% Oxygen-18

Cascade 2

The second cascade (Fig. 2) was designed to produce 40% oxygen-18 water at the rate of one gram per day. Except for size and product purity, this cascade is identical to Cascade 1.

Cascade 3

The third cascade (Fig. 3) was designed to produce water containing 3% oxygen-18. This cascade consists of two distillation columns and related equipment. Initially, this plant was sized for one gram of product per day, but this production rate led to such a small second stage distillation unit that the production rate was doubled to permit use of standard size components.

Cascade 5

This cascade (Fig. 4) was designed to produce 100 grams per day of water containing 40% oxygen-18. It is a direct scale-up of Cascade 2. The higher production rate of this plant requires the use of relatively large diameter distillation columns. The longer stage heights associated with these large units lead to extremely long distillation columns. In practice it would be desirable to use a series of shorter columns to minimize the pressure drop across each distillation unit, but, for purposes of this preliminary estimate, a cascade consisting of one stripping and three enriching columns was chosen.

Cascade 2

See Table 1 for Key

Figure 2. Schematic Diagram of Cascade to Produce One Gram per Day of Water Enriched to 40% Oxygen-18

Cascade 3

See Table 1 for Key

Figure 3. —Schematic Diagram of Cascade to Produce
Two Grams per Day of Water Enriched to 3% Oxygen-18

Cascade 5

See Table 1 for Key

Figure 4. Schematic Diagram of Cascade to Produce One Hundred Grams per Day of Water Enriched to 40% Oxygen-18

Table 1

- F = Feed to cascade (gram-moles of water per day)
- W = Oxygen-18 depleted waste stream (gram-moles water per day)
- D = Oxygen-18 enriched product stream (gram-moles of water per day)
- N_E = Number of enrichment stages in a distillation column
- N_S = Number of stripping stages in a distillation column
- V = Interstage flow in the enriching section of a distillation column (gram-moles of water per day)
- V' = Interstage flow in the stripping section of a distillation column (gram-moles of water per day)
- L = Length of distillation column (feet)
- D = Diameter of distillation column (inches)
- X_t = Mole fraction oxygen-18 in product stream from a distillation column
- X_F = Mole fraction oxygen-18 in liquid stream feeding cascade
- X_B = Mole fraction oxygen-18 in liquid waste stream

Cascades 4 and 6

These cascades were not considered in detail. The costs given for these plants were obtained by extrapolating plots of Cost vs. Product Purity for cascades 1, 2, 3, and 5.

Cost Estimating Procedures

The cost of oxygen-18 enriched water from each cascade was determined by itemizing, sizing and pricing the major pieces of equipment required by the flow sheet of each cascade. The sum of these costs was taken as the total cost of the installed process equipment. These costs then were factored² to obtain the total annual fixed and variable costs for each cascade. An amortization period of 6-2/3 years was assumed in calculating depreciation. Because of the preliminary nature of this estimate, no AEC overhead charges were included. From the production rate and total annual costs of each cascade, the cost per gram of oxygen-18 enriched water was determined. Details of the cost estimates are shown in the appendices.

Summary of Estimated Costs

The cost per gram of 99% oxygen-18 enriched water produced at a rate of one gram per day was estimated to be \$225. This corresponds to a total annual operating cost slightly greater than \$82,000. The total plant investment required for such a facility was calculated to be about \$140,000. Production of 99% oxygen-18 enriched water at a rate of 100 grams per day would reduce the cost of product to \$64 per gram. However, a total plant investment of approximately \$9,800,000 and an annual operating cost of about \$2,400,000 would be required.

Forty per cent oxygen-18 enriched water was estimated to cost about \$186 per gram when produced at the rate of one gram per day, and about ⁵²~~\$64~~ when produced at a rate of one hundred grams per day. A total plant investment of some \$86,000 would be needed for the smaller plant and about ^{6,127,053}~~\$9,800,000~~ for the larger facility. The total annual operating cost for these plants was calculated to be approximately \$68,000 and \$1,900,000.

Three per cent oxygen-18 enriched water was estimated to cost \$70 per gram when produced at a rate of 2 grams per day, and \$26 per gram when produced at the rate of 100 grams per day. The total investments in these plants amounted to approximately \$37,000 and \$1,750,00. Total annual operating expenses were calculated to be about \$51,000 and \$950,000.

Additional cost data are summarized in Table 2. The costs presented here should be considered minimum costs, obtainable under favorable conditions, since the contingency factors contained in the estimates are modest for isotope separation processes. Several simplifications employed in the estimate, such as the use of a few long columns instead of several short ones, etc., also favor understating the cost of the final product.

Table 2

Summary of Estimated Costs for Producing
Water Enriched in O¹⁸

Cascade No.	1	2	3	4	5	6
Product Purity, % O ¹⁸	99	40	3	99	40	3
Production Rate, Gms Water per Day	1	1	2	100	100	100
Total Plant Investment, \$	139,198	85,747	36,742	9,800,000	6,127,053	1,750,000
Annual Fixed Cost, \$	28,238	17,394	7,327	1,676,000	1,293,933	350,000
Annual Variable Cost, \$	54,008	50,564	44,052	660,000	614,771	600,000
Total Annual Operating Cost, \$	82,246	67,958	51,379	2,336,000	1,908,704	950,000
Cost per Gram of O ¹⁸ Enriched Water, \$	225	186	70	64	52	26

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Appendix "A" - Design Criteria

The following data, assumptions, and conditions were used in the design of the various cascades described in this report.

Product purity: Three product purities were considered: 3%, 40%, and 99% oxygen-18. The presence of oxygen-17 in the feed was ignored.

Production rates: (1) 1 gram per day of 99% oxygen-18 water.
(2) 1 gram per day of 40% oxygen-18 water.
(3) 2 grams per day of 3% oxygen-18 water.
(4) 100 grams per day of 40% oxygen-18 water.

By extrapolating the costs estimated for the above cascades, cost estimates were made for the following cases:
(5) 100 grams per day of 99% oxygen-18 water.
(6) 100 grams per day of 3% oxygen-18 water.

Separation factor: The separation factor varies continuously in a distillation column because of the pressure drop across the column. An average value of 1.006 for oxygen-16 - oxygen-18 sepa-

ration was assumed in this report.

Operating pressure: An average distillation column pressure of 265 mm Hg was assumed.

Reflux ratio: The reflux ratio used in these calculations was 1.2 times the calculated minimum reflux ratio.

Distillation columns: The distillation columns were assumed to be constructed of copper pipe insulated for outdoor service.

Column packing: "Heli-Pak", a metal packing manufactured by Podbielniak, Inc., Chicago, 11, Illinois, was used in this estimate. The size of the packing varied with the diameter of the distillation columns as follows:

Column Diameter (inches)	Type No.	Size (inches)
0.5-0.75	3012	0.035 x 0.070 x 0.070
1 - 4	3013	0.050 x 0.100 x 0.100
larger	3008	0.092 x 0.175 x 0.175

"Octa-Pak", another packing manufactured by the same company, was considered for use in the larger columns. However, because of longer stage lengths, no economic advantage accrued

through its use and, for convenience, all columns were assumed to be filled with stainless steel "Heli-Pak".

HETP:

Varying height equivalents of a theoretical plate and holdups were assumed, depending on column diameter, packing size and flow rate:

<u>Column Diameter</u> <u>(inches)</u>	<u>HETP</u> <u>(inches)</u>
0.5	0.5
0.75	0.65
1.0	0.75
1.5	0.90
2.0-4.0	1.00
5.0-6.0	1.50
10-12	2.00
25	3.00

These estimates are assumed for column loadings of 10% to 15% of flooding and are optimistic, especially for the larger columns. Higher loadings reduce the required size of the distillation columns at the expense of stage length, and increase the over-all cost of the installation.

Waste stream:

The waste stream was stripped of one-half of the oxygen-18 initially contained in the feed.

Holdup:

In the case of the smaller columns, hold-up was taken from data supplied by the manufacturer of the packing. These data were extrapolated roughly to obtain estimates of holdup for the larger columns.

Column Diameter (inches)	Holdup (ml/ft of packed column)
0.5	8.6
0.75	16 (est.)
1.0	28.3
1.5	40 (est.)
2.0	60.6
3.0	100 (est.)
4.0	200 "
5.0	312 "
12.0	1800 "
25.0	7940 "

Equilibrium time:

After the required flow rates were established and the cascade equipment was sized, upper and lower limits were placed upon the estimated equilibrium time of each cascade. The cost of operating the plant the minimum time necessary to reach equilibrium was determined and used as the basis of the pre-operational expense.

Cooling water:

Experience³ with the Weizmann Institute cascade has shown the need to cool heat exchangers with treated water to

avoid buildup of deposits and fouling of heat exchange surfaces during the long periods of continuous operation required by oxygen-18 enrichment plants. The use of treated water is assumed in this cost estimate. For economy, this treated water was assumed to be cycled through a cooling tower and reused. A suitable cooling tower was provided for each cascade.

Building:

It was assumed that the various plants would be constructed outdoors. Only office and changehouse space for the operating and supervisory personnel was provided. For the gram-a-day plants, provision was made for one supervisor and four operators. One supervisor and eight operators were allowed in the larger plants.

Scale-up of Cascade 2: To obtain estimates of the cost of producing oxygen-18 enriched water at a higher rate, cascade 2 was resized to permit a hundredfold increase in flow. The same cascade configuration was used as in the one gram per day case.

The larger equipment then was priced and factored as before. The direct operating labor required was assumed to be doubled.

Appendix "B" - Cost Estimating Criteria

The various procedures used in determining the reported costs are given below.

- Equipment cost: The major pieces of equipment in each cascade first were itemized, then sized, and the installed cost of each item determined. Ten per cent of the installed cost was added in the case of items requiring insulation. Process piping costs were estimated as 60% of the installed equipment cost. Instrumentation was taken as 15% of the installed equipment cost and the cost of service facilities was assumed to be 50% of the installed equipment cost.
- Building cost: Four hundred and six hundred square feet of space were allowed for office and changehouse facilities for the small and large production rate plants. A cost of \$14.78 per square foot was assumed for these buildings.
- Total plant investment: The cost of the total physical plant was taken as the sum of the costs of the installed process equipment, pro-

cess piping, instrumentation, and the process building. The total plant investment was determined by adding charges to the physical plant cost for engineering, site development, pre-operational expenses and contingencies. The cost of engineering was taken as 40% of the cost of the total physical plant. Site development charges were estimated at 10% of the total physical plant cost. The pre-operational expenses shown are estimates of the cost of leak testing, equipment shake-down, operator training, and other start-up costs incurred prior to routine operation. This item also includes the minimum estimated cost of operating the plant until isotopic equilibrium is achieved. The contingency factor used was 30% of the total physical plant cost.

Annual fixed cost:

The fixed cost associated with the construction of these plants was defined as the sum of depreciation charges, investment costs and overhead. De-

preciation was calculated at the standard AEC rate of 15% per year. Investment costs were calculated as 3% of the total plant investment. Overhead was defined as the sum of the costs of maintenance, labor, and supplies plus 60% of the cost of direct operating labor and supervision. However, for convenience, the overhead on direct labor and supervision was tabulated under Annual Variable Costs.

Annual variable cost: The annual variable cost was defined as the cost of direct operating labor and supervision (including overhead), utilities, maintenance labor and supplies, isotopic and chemical analyses, storage and miscellaneous. The working force for the small (1 gram per day) plants was assumed to consist of 1 operator per shift plus 1 supervisor per day. The large (100 grams per day) plants were assumed to have 2 operators per shift and 1 supervisor per day. Labor charges of \$3.00 and \$4.85 per hour, including overhead,

were assumed for operators and supervisors, respectively. Utilities, maintenance labor, and storage costs each were taken as 5% of the cost of the total physical plant. The cost of maintenance supplies was estimated at 0.5% of the cost of the total physical plant. Analytical costs were based upon a minimum sampling program--one isotopic analysis per distillation column per day at \$10.00 per sample.

Total annual operating cost:

The total annual variable and fixed costs were added to give the total annual operating cost.

Cost per gram of oxygen-18 enriched water:

The total annual operating cost was divided by the annual product yield to obtain the cost per gram of product.

Extrapolated estimates for cascades 4 and 6:

Cascades 4 and 6 were not studied in detail. Instead, estimates of the reported costs were made by plotting the various costs of cascades 1, 2, 3, and 5 as a function of product purity. Costs for cascade 3 were

adjusted to the one gram per day production rate by use of the 0.6 factor.⁴ The respective costs for cascades 4 and 6 then were obtained by passing a curve through the data point calculated for cascade 5 and parallel to the curve drawn through the one-gram-per-day points calculated for cascades 1, 2, and 3. This method yields only rough approximations at best, but the resulting precision was deemed sufficient for the purpose of this report. Except for annual variable costs, which were sensitive to production rates and insensitive to product purities, the data obtained by this method were surprisingly consistent. Some adjustments were made in the data for cascade 6 to obtain internal consistency.

Appendix "C" - Flow Diagrams and Equipment Lists

Simplified flow diagrams depicting the major pieces of equipment of each cascade are shown on the following pages. For convenience, the cooling system and spare items are not shown on the flow sheets. However, all major items appear in the tabulated equipment list immediately following each flow sheet. Prices were obtained from the manufacturer or from Chilton² and were corrected to the 1958 cost level.

Cascade No. 1

Figure C-1. Simplified Equipment Diagram of Cascade
to Produce 1 Gram per Day of 99% Oxygen-18 Water

Table C-1. Cost of Installed Equipment

Cascade No. 1

Item No.	Type	Number*	Installed Equipment Cost each	Total
B-1	Boiler, 3KW	1	\$ 421	\$ 421
B-2	Boiler, 0.5KW	1	138	138
B-3	Boiler, 0.5KW	1	138	138
B-4	Standby Steam Supply, 13 lbs/hr.	1	575	575
C-1	Condenser, 0.240 sq. ft.	1	66	66
C-2	Condenser, 0.122 sq. ft.	1	66	66
C-3	Condenser, 0.030 sq. ft.	1	66	66
C-4	Condenser, 0.009 sq. ft.	1	66	66
C-5	Condenser, 0.002 sq. ft.	1	66	66
E-1	Distillation Column, 75 ft., 4 in. Ø	1	3,218	3,218
	Packing			12,745
E-2	Distillation Column, 58 ft., 1.5 in. Ø	1	1,021	1,021
	Packing		1,623	1,623
E-3	Distillation Column, 62 ft., 0.5 in. Ø	1	409	409
	Packing		272	272
H-1	Heater, 0.5KW	1	138	138
P-1	Waste pump, 3.5 cc/min	2	250	500
P-2	Feed pump, 3.5 cc/min	1	250	250
T-1	Waste storage, 35 liter	1	153	153
T-2	Feed tank, 35 liter	1	153	153
	Cooling tower, 12,210 BTU/hr	1	1,000	1,000
				<u>\$23,084</u>

*Includes spares where necessary.

Cascade No. 2

Figure C-2. Simplified Equipment Diagram of Cascade
to Produce 1 Gram per Day of 40% Oxygen-18 Water

Table C-2. Cost of Installed Equipment

Cascade No. 2

Item No.	Type	Number*	Installed Equipment Cost	
			each	Total
B-1	Boiler, 1.5KW	1	\$ 273	\$ 273
B-2	Boiler, 0.5 KW	1	138	138
B-3	Boiler, 0.5KW	1	138	138
B-4	Standby Steam Supply, 13 lbs/hr			575
C-1	Condenser, 0.100 sq. ft.	1	66	66
C-2	Condenser, 0.080 sq. ft.	1	66	66
C-3	Condenser, 0.020 sq. ft.	1	66	66
C-4	Condenser, 0.014 sq. ft.	1	66	66
C-5	Condenser, 0.003 sq. ft.	1	66	66
E-1	Distillation Column, 67 ft., 3 in. Ø	1	2,211	2,211
	Packing		6,389	6,389
E-2	Distillation Column, 36 ft., 1.2 in. Ø	1	554	554
	Packing		448	448
E-3	Distillation Column 29 ft., 0.5 in. Ø	1	191	191
	Packing		128	128
H-1	Heater, 0.5KW	1	138	138
P-1	Waste pump, 1.4 cc/min.	2	250	500
P-2	Feed pump, 1.4 cc/min	1	250	250
T-1	Waste storage, 14 liters	1	126	126
T-2	Feed tank, 14 liters	1	126	126
	Cooling tower, 5,760 BTU/hr.	1	700	700
				<u>\$13,215</u>

*Includes spares where necessary.

Cascade No. 3.

Figure C-3. Simplified Equipment Diagram of Cascade
to Produce 2 Grams per day of 3% Oxygen-18 Water

Table C-3. Cost of Installed Equipment

Cascade No. 3

Item No.	Type	Number*	Installed Equipment Cost	
			each	Total
B-1	Boiler, 0.5 KW	1	\$ 138	\$ 138
B-2	Boiler, 0.5KW	1	138	138
B-3	Standby Steam Supply, 13 lbs/hr			575
C-1	Condenser, 0.02 sq. ft.	1	66	66
C-2	Condenser, 0.01 sq. ft.	1	66	66
C-3	Condenser, 0.003 sq. ft.	1	66	66
E-1	Distillation Column, 33 ft., 1 in. Ø	1	399	399
	Packing		411	411
E-2	Distillation Column, 16 ft., 0.5 in. Ø	1	106	106
	Packing		71	71
H-1	Heater, 0.5 KW	1	138	138
P-1	Waste pump, 13.3 cc/hr	2	250	500
P-2	Feed pump, 13.3 cc/hr	1	250	250
T-1	Waste storage, 2 liters	1	108	108
T-2	Feed tank, 2 liters	1	108	108
				<u>\$3,140</u>

*Includes spares where necessary.

Cascade No. 5

Figure C-4. Simplified Equipment Diagram of Cascade to Produce 100 Grams per day of 40% Oxygen-18 Water

Table C-4. Cost of Installed Equipment

Cascade No. 5

Item No.	Type	Number*	Installed Equipment Cost	
			each	Total
B-1	Boiler, 6.9 sq. ft.	1	\$ 105	\$ 105
B-2	Boiler, 6.6 sq. ft.	1	105	105
B-3	Boiler, 1.45 sq. ft.	1	53	53
B-4	Boiler, 0.24 sq. ft.	1	48	48
B-5	Standby Steam Supply, 616 lb/hr			3,150
C-1	Condenser, 9.66 sq. ft.	1	143	143
C-2	Condenser, 36.8 sq. ft.	1	314	314
C-3	Condenser, 9.2 sq. ft.	1	143	143
C-4	Condenser, 8.1 sq. ft.	1	128	128
C-5	Condenser, 2.0 sq. ft.	1	60	60
C-6	Condenser, 1.4 sq. ft.	1	53	53
C-7	Condenser, 0.34 sq. ft.	1	53	53
E-1	Distillation Column 68 ft., 25 in. Ø Packing	1	11,276	11,276 450,177
E-2	Distillation Column 120 ft., 25 in. Ø Packing	1	21,710	21,710 860,633
E-3	Distillation Column 94 ft., 12 in. Ø Packing	1	7,990	7,990 143,375
E-4	Distillation Column 87 ft., 5 in Ø Packing	1	4,089	4,089 22,996
H-1	Heater, 0.27 sq. ft.	1	193	193
P-1	Waste pump, 140 cc/min.	2	675	1,350
P-2	Feed pump, 140 cc/min.	1	675	675
P-3	Product pump, 4.7 cc/hr.	2	250	500
T-1	Waste storage, 60 gal.	2	318	636
T-2	Feed tank, 60 gal.	2	318	636
T-3	Product receiver, 0.2 liter	2	40	80
	Cooling tower, 575,600 BTU/hr.	1	9,335	9,335
				<u>\$1,540,006</u>

* Includes spares where necessary.

Appendix "D" - Tabulated Costs

Herein are presented the various charges which contribute to the total plant investment, annual fixed cost, annual variable cost, total annual operating cost, and cost per gram of product.

Table D-1. Total Plant Investment
Cascade 1

Code	Cost Designation	Factor ²	Cost
A	Installed Process Equipment Cost		\$ 23,084
B	Process Piping	60% A	13,850
C	Instrumentation	15% A	3,463
D	Process Building		5,912
E	Service Facilities	50% A	11,542
F	Total Physical Plant		<u>\$ 57,851</u>
G	Engineering	40% F	23,140
H	Site Development	10% A	2,308
I	Pre-Operational Expense		38,544
J	Contingency	30% F	17,355
K	Total Plant Investment		<u>\$139,198</u>

Table D-2. Annual Fixed Cost
Cascade 1

Code	Cost Designation	Factor ²	Cost
L	Depreciation	15% K	\$ 20,880
M	Investment Costs	3% K	4,176
N	Labor Overhead	See Code "R"	
O	Maintenance Overhead	"T" + "U"	<u>3,182</u>
P	Annual Fixed Cost		<u>\$ 28,238</u>

Table D-3. Annual Variable Cost

Cascade 1

Code	Cost Designation	Factor ²	Cost
Q	Analyses		\$ 10,000
R	Direct Operating Labor and Supervision		35,040
S	Utilities	5% F	2,893
T	Maintenance Labor	5% F	2,893
U	Maintenance Supplies	0.5% F	289
V	Miscellaneous, Storage, etc.	5% F	2,893
W	Annual Variable Cost		\$ 54,008

Table D-4. Cost Summary

Cascade 1

Code	Cost Designation	Cost
AA	Total Plant Investment	\$139,198
BB	Annual Fixed Cost	28,238
CC	Annual Variable Cost	54,008
DD	Total Annual Operating Cost	82,246
EE	Cost per Gram of Oxygen-18 Enriched Water	225

Table D-5. Total Plant Investment
Cascade 2

Code	Cost Designation	Factor ²	Cost
A	Installed Process Equipment Cost		\$ 13,215
B	Process Piping	60% A	7,929
C	Instrumentation	15% A	1,982
D	Process Building		5,912
E	Service Facilities	50% A	6,608
F	Total Physical Plant		<u>35,646</u>
G	Engineering	40% F	14,258
H	Site Development	10% A	1,322
I	Pre-Operational Expense		23,827
J	Contingency	30% F	10,694
K	Total Plant Investment		<u>\$ 85,747</u>

Table D-6. Annual Fixed Cost
Cascade 2

Code	Cost Designation	Factor ²	Cost
L	Depreciation	15% K	\$ 12,862
M	Investment Costs	3% K	2,572
N	Labor Overhead	See Code "R"	
O	Maintenance Overhead	"T" + "U"	<u>1,960</u>
P	Annual Fixed Cost		<u>\$ 17,394</u>

Table D-7. Annual Variable Cost

Cascade 2

Code	Cost Designation	Factor ²	Cost
Q	Analyses		\$ 10,000
R	Direct Operating Labor and Supervision		35,040
S	Utilities	5% F	1,782
T	Maintenance Labor	5% F	1,782
U	Maintenance Supplies	0.5% F	178
V	Miscellaneous, Storage, etc.	5% F	1,782
W	Annual Variable Cost		\$ 50,564

Table D-8. Cost Summary

Cascade 2

Code	Cost Designation	Cost
AA	Total Plant Investment	\$ 85,747
BB	Annual Fixed Cost	17,394
CC	Annual Variable Cost	50,564
DD	Total Annual Operating Cost	67,958
EE	Cost per Gram of Oxygen-18 Enriched Water	186

Table D-9. Total Plant Investment
Cascade 3

Code	Cost Designation	Factor ²	Cost
A	Installed Process Equipment Cost		\$ 3,140
B	Process Piping	60% A	1,884
C	Instrumentation	15% A	471
D	Process Building		5,912
E	Service Facilities	50% A	1,570
F	Total Physical Plant		<u>12,977</u>
G	Engineering	40% F	5,191
H	Site Development	10% A	314
I	Pre-Operational Expense		14,367
J	Contingency	30% F	<u>3,893</u>
K	Total Plant Investment		\$ 36,742

Table D-10. Annual Fixed Cost
Cascade 3

Code	Cost Designation	Factor ²	Cost
L	Depreciation	15% K	\$ 5,511
M	Investment Costs	3% K	1,102
N	Labor Overhead	See Code "R"	
O	Maintenance Overhead	"T" + "U"	<u>714</u>
P	Annual Fixed Cost		\$ 7,327

Table D-11. Annual Variable Cost
Cascade 3

Code	Cost Designation	Factor ²	Cost
Q	Analyses		\$ 7,000
R	Direct Operating Labor and Supervision		35,040
S	Utilities	5% F	649
T	Maintenance Labor	5% F	649
U	Maintenance Supplies	0.5% F	65
V	Miscellaneous, Storage, etc.	5% F	649
W	Annual Variable Cost		\$ 44,052

Table D-12. Cost Summary
Cascade 3

Code	Cost Designation	Cost
AA	Total Plant Investment	\$ 36,742
BB	Annual Fixed Cost	7,327
CC	Annual Variable Cost	44,052
DD	Total Annual Operating Cost	51,379
EE	Cost per Gram of Oxygen-18 Enriched Water	70

Table D-13. Cost Summary

Cascade 4

Code	Cost Designation	Cost
AA	Total Plant Investment	\$ 9,800,000
BB	Annual Fixed Cost	1,676,000
CC	Annual Variable Cost	660,000
DD	Total Annual Operating Cost	2,336,000
EE	Cost per Gram of Oxygen-18 Enriched Water	64

Table D-14. Total Plant Investment

Cascade 5

Code	Cost Designation	Factor ²	Cost
A	Installed Process Equipment Cost		\$ 1,540,006
B	Process Piping	60% A	924,004
C	Instrumentation	15% A	231,001
D	Process Building		8,868
E	Service Facilities	50% A	770,003
F	Total Physical Plant		\$ 3,473,882
G	Engineering	40% F	1,389,553
H	Site Development	10% A	154,001
I	Pre-Operational Expense		67,452
J	Contingency	30% F	1,042,165
K	Total Plant Investment		\$ 6,127,053

Table D-15. Annual Fixed Cost

Cascade 5

Code	Cost Designation	Factor ²	Cost
L	Depreciation	15% K	\$ 919,058
M	Investment Costs	3% K	183,812
N	Labor Overhead	See Code "R"	
O	Maintenance Overhead	"T" + "U"	<u>191,063</u>
P	Annual Fixed Cost		\$1,293,933

Table D-16. Annual Variable Cost

Cascade 5

Code	Cost Designation	Factor ²	Cost
Q	Analyses		\$ 15,000
R	Direct Operating Labor and Supervision		61,320
S	Utilities	5% F	173,694
T	Maintenance Labor	5% F	173,694
U	Maintenance Supplies	0.5% F	17,369
V	Miscellaneous, Storage, etc.	5% F	<u>173,694</u>
W	Annual Variable Cost		\$ 614,771

Table D-17. Cost Summary

Cascade 5

Code	Cost Designation	Cost
AA	Total Plant Investment	\$ 6,127,053
BB	Annual Fixed Cost	1,293,933
CC	Annual Variable Cost	614,771
DD	Total Annual Operating Cost	1,908,704
EE	Cost per Gram of Oxygen-18 Enriched Water	52

Table D-18. Cost Summary

Cascade 6

Code	Cost Designation	Cost
AA	Total Plant Investment	\$ 1,750,000
BB	Annual Fixed Cost	350,000
CC	Annual Variable Cost	600,000
DD	Total Annual Operating Cost	950,000
EE	Cost per Gram of Oxygen-18 Enriched Water	26

Appendix "E" - Variation of Cascade Costs
with Product Purity and Production Rate

In this section are presented graphs depicting the variation of the various cascade costs with product purity and production rate. In each case, the cost associated with the 100 gram per day, 40% oxygen-18 cascade has been extrapolated by the method of parallel curves to furnish order of magnitude estimates of cost for the large scale production of 3% and 99% oxygen-18 enriched water. This approximate method yields self consistent data for the 100 gram per day, 99% oxygen-18 case. It is not quite so exact for the 100 gram per day, 3% oxygen-18 case.

Figure E-1. Variation of Total Plant Investment
with Product Purity and Production Rate

Figure E-2. Variation of Annual Fixed Cost with Product Purity and Production Rate

Figure E-3. Variation of Annual Variable Cost
with Product Purity and Production Rate

Figure E-4. Variation of Annual Operating Cost with Product Purity and Production Rate

Figure E-5. Variation of Product Cost
with Product Purity and Production Rate

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