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SUBJECT: PRELIMINARY ESTIMATE OF THE COST OF PRODUCTION OF
10% ISOTOPIC PURITY OXYGEN-17 BY CHEMICAL EXCHANGE

TO: J. S. Drury

FROM: B. B. Klima

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SUMMARY

An order of magnitude estimate was made to determine a minimum cost for 10% pure oxygen-17 when produced by a chemical exchange process. The calculations were based on separations factors of 1.03, 1.01 and 1.003. The cost of product was found to vary from \$23 per gram for the larger factor to \$165 per gram for the smaller.

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Introduction

The nuclear magnetic moment of the oxygen-17 isotope makes it particularly attractive for use as a tracer in certain research activities. Application as a tracer would be greatly increased if this isotope were available at the 10% purity level. The purpose of this report is to estimate a minimum order-of-magnitude cost of small amounts of oxygen-17 at this concentration by a chemical exchange method.

The chemical exchange method by which this enrichment is to be achieved is not known at the present time although research directed toward the development of such a system is now in progress.(1) The purpose of this estimate is served by making some general assumptions regarding the nature of the enrichment process which would lead to a minimum cost for a specified production rate and product purity. The chemical exchange system is assumed to be a gas-liquid countercurrent process, having certain designated single stage separation factors and which can be refluxed by the addition or removal of heat. The gaseous phase is assumed to be some oxygen containing gas which exchanges readily with an oxygen species contained in the liquid phase. Three different single stage separation factors were assumed for the separation of oxygen-16 and oxygen-17: 1.03, 1.01, and 1.003. The first of these is probably optimistic and should certainly lead to a minimum product cost. The last value mentioned is too low to be competitive with the separation attainable through the equilibrium distillation of water but it is nevertheless useful for the purpose of this estimate as it extends the range over which interpolation can be made of product cost versus magnitude of separation factor. The value of 1.01 is believed to be a more realistic estimate of the separation factor which may be attained in an actual system.

General Considerations

Chemical exchange as a means of separating oxygen isotopes has been under investigation by the Chemical Separation of Isotopes Section of the Chemistry Division for some time.(1) This investigation has included work on such chemical exchange systems as the exchange between gaseous

(1) J. S. Drury, et. al., "Chemical Separation of Isotopes Section Semiannual Progress Report for the Period Ending December 31, 1955," ORNL-2097, July 13, 1956, page 34.

Ibid., June 30, 1956," ORNL-2176, October 3, 1956, page 21.

carbon monoxide and an aqueous cuprous chloride carbon monoxide complex. In this system the reflux is accomplished at one end of the plant by heating to completely dissociate the complex and is accomplished at the other end of the plant by absorption of the gas at ambient temperatures to reform the complex. Similar gas-liquid systems are possible using other complexing agents with a variety of gaseous oxygen compounds. This estimate was made to be general in nature and while it uses some data which are based on the above system, it may be applied to any chemical exchange system wherein a gas and a liquid are contacted to isotopically enrich oxygen and in which the reflux at one end of the plant is accomplished by heat to dissociate the complex and the reflux at the other end of the plant is accomplished by an ambient temperature absorption to reform the complex.

The separation factor, alpha, is different for each specific isotope separation process and will change as the operating conditions vary for that process. At this time a specific process has not been designated. For this reason 1.03 was used as the separation factor for the oxygen-16 and oxygen-17 isotope exchange (2) to determine by which of three processes the lowest priced product could be made. Two additional estimates were made for that process using a separation factor (3) of 1.01 and 1.003.

Cascade Design

Mr. S. A. Levin, Chief of the Process Design and Analysis Department of the Operational Analysis Division of the Oak Ridge Gaseous Diffusion Plant, K-25, was asked to undertake the calculation of a cascade design suitable for the concentration of the oxygen-17 isotope to 10% purity. As a result of this effort, three cascades were designed (4) as shown in Figures 1, 2, and 3 (see Table 1.). Following is an excerpt from the letter (4) describing these cascades:

"It should be kept in mind that these designs are by no means the best which could possibly be obtained to perform the desired separation but are different approaches to the problem. An optimum design is obtainable only by considering the

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- (2) The separation factor for oxygen-16 and oxygen-18 is 1.06.
 - (3) Throughout the remainder of this report each time the separation factor is referred to, it applies to the oxygen-16 - oxygen-17 separation factor.
 - (4) M. Hanig, Cascade Design for O-17 Production, KOA-174, October 10, 1956.

costs involved in the interstage flow, plant length, and feed requirements of the various plant designs.

"The effect of the size of the stage separation factor was examined and it was found that reduction of the separation factor between adjacent isotopes from 1.03 to 1.015 resulted in a plant which required twice the interstage flow and twice the number of stages to meet the same production requirement with the same feed. It may be assumed that reduction of the separation factor to other values requires a similar increase equal to $(\alpha - 1) \text{ old} / (\alpha - 1) \text{ new}$, both in the interstage flow and in the number of stages in order to obtain the same production with the same feed." (4)

The first cascade (Figure 1) consists of four plants. The first plant product feeds the second plant. The second, third, and fourth plants are mirror images as far as the oxygen-16 and oxygen-18 contents of the waste and product streams are concerned. Thus there are four final product streams, two of which meet the oxygen-17 requirement, (W' and P'') one which should have a secondary product value due to its contents of highly enriched oxygen-18 (P') and one which contains virtually pure oxygen-16 (W'') which is presumed to be of little value.

The second cascade (Figure 2) evolved from the first cascade by feeding the bottoms from the second plant (W' - F'') back into the first plant as a secondary feed. This eliminates one plant and gives two product streams from the cascade, one meeting the oxygen-17 requirements (W') and the other highly enriched in oxygen-18 (P').

The third cascade (Figure 3) is a single, two section plant which produces product which meets the oxygen-17 requirement (M) and a secondary product highly enriched in oxygen-18 (P).

Process Considerations

Cascade Number 1: (Figure 1) Each of the four plants consists of a single packed exchange column, a recombiner refluxer in which the complex is formed by absorption, a decomposer refluxer in which the complex is thermally decomposed, reboilers, pumps, and heat exchangers. (For details see Appendix B.)

Cascade Number 2: (Figure 2) Using the separation factor of 1.03, each of the three plants consists of a single, packed exchange column with the same auxiliary equipment as the first cascade. The flows in the first plant of this cascade are smaller than for the first plant of the first cascade, however, the flow in the last two plants is greater than for the corresponding plants of the first cascade. There

See Table I for Key.

FIGURE 1 — OXYGEN 17 CASCADE NUMBER 1

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See Table I for Key

FIGURE 2 — OXYGEN 17 CASCADE NUMBER 2

See Table I for Key

FIGURE 3 - OXYGEN 17 CASCADE NUMBER 3

TABLE 1: KEY TO SYMBOLS ON FIGURES 1, 2, AND 3

F	=	Feed to cascade and first plant (grams oxygen per day).
F'	=	Feed to second plant (grams oxygen per day).
F''	=	Feed to third plant (grams oxygen per day).
F'''	=	Feed to fourth plant (grams oxygen per day).
F ^{ss}	=	Secondary feed to first plant (grams oxygen per day).
W	=	Waste oxygen 17 - oxygen 18 depleted stream from cascade and from first plant (grams oxygen per day).
W'	=	Waste oxygen 17 - oxygen 18 depleted stream from second plant (grams oxygen per day).
W''	=	Waste oxygen 17 - oxygen 18 depleted stream from third plant (grams oxygen per day).
W'''	=	Waste oxygen 17 - oxygen 18 depleted stream from fourth plant (grams oxygen per day).
P	=	oxygen 17 - oxygen 18 enriched stream from first plant (grams oxygen per day).
P'	=	oxygen 17 - oxygen 18 enriched stream from second plant (grams oxygen per day).
P''	=	oxygen 17 - oxygen 18 enriched stream from third plant (grams oxygen per day).
P'''	=	oxygen 17 - oxygen 18 enriched stream from fourth plant (grams oxygen per day).
M	=	oxygen 17 - oxygen 18 enriched stream from mid-point Cascade Number 3 (grams oxygen per day).
L	=	Interstage flow in plant (grams oxygen per day).
O ₁₆	=	Mol fraction of oxygen 16, stream analysis.
O ₁₇	=	Mol fraction of oxygen 17, stream analysis.
O ₁₈	=	Mol fraction of oxygen 18, stream analysis.
N _e	=	Enrichment stages.
N _s	=	Stripping stages.

is a considerable reduction in the total number of stages in this cascade over the requirement for the first cascade. (For details see Appendix C.)

Cascade Number 3: (Figure 3) This cascade consists of a single, two-section plant. Each of the sections of this plant, based on a separation factor of 1.03, consists of a single packed exchange column, and the same type of auxiliary equipment as is used in the other two cascades. The flows in this cascade are considerably greater than for the other two cascades, and the number of stages is considerably less. (For details see Appendix D.)

Criteria: The criteria used in this estimate are presented in Appendix A. For cost estimating purposes the gas phase was assumed to be pure carbon monoxide and the liquid phase was assumed to be a 0.33 M carbon monoxide aqueous complex. The estimate is not highly sensitive to the carbon monoxide content of the aqueous phase. Most of the criteria, however, are based on data which is more general in nature and may therefore be applicable to many chemical exchange processes of this type.

Choice of Process for Scale-Up: The cost per gram of product oxygen is less using the first cascade. In addition the first cascade has an operational advantage over the second cascade in that there is no possibility of loss of enrichment by feed back (in the second cascade the bottoms from the second plant are fed back into the first plant). Therefore, the first cascade was the process which was chosen for scale-up.

Scale-Up: Estimates were made using separation factors of 1.01 and 1.003 based on Cascade Number 1. This was done by assuming that the feed, product, waste, and interplant flows were maintained the same. The interstage flows in each plant were increased three and tenfold respectively. The number of stages in each plant was increased three and tenfold respectively. (For details see Appendix E.)

Cost Estimating Procedures

Estimation of Costs: The cost of the product oxygen in each estimate was determined by laying out each cascade (using as a basis the Figures 1, 2, and 3) to include the required columns, pumps, tanks, and exchangers. These individual items of equipment were then sized, and the cost of each was estimated using the most recent information available. These equipment costs were then added to give the total cost of the installed process equipment. These costs were then factored to determine the total annual fixed and variable costs for each cascade. An amortization period of $6 \frac{2}{3}$ years was assumed for calculating depreciation. From the total annual costs the cost per gram of product oxygen was determined.

The size of the plants using separation factors of 1.01 and 1.003 was determined as outlined previously. The details of each cost estimate may be found in Appendices B, C, D, and E.

Minimum Product Cost

Estimates were made of the costs associated with each of the three cascades using a separation factor of 1.03 to determine the process which would produce ten grams of product per day (containing 10% oxygen ¹⁷) at a minimum cost. The details of the individual cost estimates may be found in Appendices B, C, and D. The cost of product oxygen based on carbon monoxide feed was found to be \$32 per gram using the process of the First Cascade, \$33 using the process of the Second Cascade, and \$131 using the process of the Third Cascade, see Table 2. These costs do not take into account any credit for either the waste or the secondary products.

Effect of Separation Factor on Cost of Product

Estimates (for details, see Appendix E) were made of the cost of product based on the first cascade process using three separation factors (1.03, 1.01, and 1.003). When the separation factor is decreased from 1.03 to 1.01, the cost of product oxygen based on carbon monoxide feed is increased to approximately \$49 per gram (see Figure 4 and Table 3). When the separation factor is decreased to 1.003, the cost of product increases to approximately \$174 per gram.

Total Plant Investment

The total plant investment based on a separation factor of 1.03 was found to be lowest, \$174,594, for Cascade Number 1, \$184,516 for Cascade Number 2 and \$236,133 for Cascade Number 3 (see Table 2).

Decreasing the separation factor to 1.01 increases the total plant investment required by a factor of 2.3 to a total of \$399,618 (see Table 3). Further decrease of the separation factor to 1.003 increases the investment requirement to \$1,914,693. For details see Appendices B, C, D, and E.

Effect of Plant Feed on Product Cost

The cost of product oxygen assuming zero cost of the feed and a separation factor of 1.03 was found to be \$23 per gram using the First Cascade, \$24 per gram using the Second Cascade and \$28 per gram using the Third Cascade (see Table 4). The cost of product oxygen assuming zero cost of the feed is \$41 per gram based on Cascade Number 1 if a separation

**TABLE 2 COSTS SUMMARY ASSUMING SEPARATION FACTOR OF 1.03
AND CARBON MONOXIDE FEED**

Code	Cost Designation	Cascade Number 1*	Cascade Number 2**	Cascade Number 3***
AA	Annual Fixed Cost	\$ 35,952	\$ 37,993	\$ 48,597
BB	Annual Variable Cost****	<u>80,532</u>	<u>82,193</u>	<u>430,145</u>
CC	Total Annual Operating Cost	\$116,484	\$120,186	\$478,742
DD	Cost Per Gram Product Oxygen*****	\$32	\$33	\$131
EE	Total Plant Investment	\$174,594	\$184,516	\$236,133

* For details see Appendix B.

** For details see Appendix C.

*** For details see Appendix D.

**** Includes cost of carbon monoxide feed.

***** Contains 10% oxygen 17.

**TABLE 3 COST SUMMARY ASSUMING THREE SEPARATION FACTORS
AND CARBON MONOXIDE FEED USING CASCADE NUMBER 1.**

Code	Cost Designation	1.03*	Separation Factor 1.01**	1.003**
AA	Annual Fixed Costs	\$ 35,952	\$ 82,263	\$393,886
BB	Annual Variable Costs***	<u>80,532</u>	<u>97,950</u>	<u>240,960</u>
CC	Total Annual Operating Cost	\$116,484	\$180,213	\$634,846
DD	Cost Per Gram Product Oxygen****	\$32	\$49	\$174
EE	Total Plant Investment	\$174,594	\$399,618	\$1,914,693

* For details see Appendix B.

** For details see Appendix E.

*** Includes cost of carbon monoxide feed.

**** Contains 10% oxygen 17.

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FIGURE 4 - EFFECT OF SEPARATION FACTOR ON PRODUCT COST

factor of 1.01 is assumed. The cost increases to \$165 per gram using a separation factor of 1.003, see Figure 4 and Table 5.

The quantity of feed chemical is dependent upon the number of stripping stages provided. If the cost of the required feed oxygen containing chemical were higher it might be found to be practical to provide additional stripping stages so that the quantity of feed would be reduced.

Another method of reducing the cost of the feed chemical would be integration of the oxygen-17 isotope separation plant into another type plant which would use the slightly depleted (in oxygen-17) waste stream so that at least partial credit for the cost of the feed could be applied against the feed costs.

Effect of Complexing Agent on Product Cost

The product and waste streams are removed from each cascade as gases, therefore, the cost of the complexing agent should have very little effect on the product cost. There will be a charge for complexing agent only as a depreciated inventory charge. The only possibility of the complexing agent seriously affecting the product cost would be due to destruction of the agent due to consumption in corrosion reactions, decomposition losses, poisoning or any other mechanism whereby the complexing agent would have to be periodically discarded and replaced.

**TABLE 4 COST SUMMARY ASSUMING SEPARATION FACTOR OF 1.03
AND ZERO COST FOR PLANT FEED**

Code	Cost Designation	Cascade Number 1*	Cascade Number 2**	Cascade Number 3***
AA	Annual Fixed Cost	\$ 35,952	\$ 37,993	\$ 48,597
BB	Annual Variable Cost****	<u>48,616</u>	<u>49,382</u>	<u>53,319</u>
CC	Total Annual Operating Cost	\$ 84,568	\$ 87,375	\$101,916
DD	Cost Per Gram Product Oxygen*****	\$23	\$24	\$28

* For details see Appendix B.
 ** For details see Appendix C.
 *** For details see Appendix D.
 **** Zero cost for plant feed assumed.
 ***** Contains 10% oxygen 17.

**TABLE 5 COSTS SUMMARY ASSUMING THREE SEPARATION FACTORS
AND ZERO COST FOR PLANT FEED USING CASCADE NUMBER 1**

Code	Cost Designation	1.03*	Separation factor 1.01**	1.003**
AA	Annual Fixed Cost	\$ 35,952	\$ 82,263	\$393,886
BB	Annual Variable Cost***	<u>48,616</u>	<u>66,034</u>	<u>209,044</u>
CC	Total Annual Operating Cost	\$ 84,568	\$148,297	\$602,930
DD	Product Oxygen Cost Per Gram*****	\$23	\$41	\$165

* For details see Appendix B.
 ** For details see Appendix E.
 *** Zero cost for plant feed assumed.
 ***** Contains 10% oxygen 17.

APPENDIX "A"Criteria

The following assumptions and bases were used in sizing and designing the equipment and in making the cost estimates.

Product purity: Product oxygen to contain 10 percent oxygen-17.

Production rate: Ten grams of product oxygen is to be produced per day.

Separation factor: The following oxygen-16 - oxygen-17 separation factors to be used: 1.030
1.010
1.003

Gas phase in exchange columns:

Gas containing 57.1% oxygen (pure CO) *

Liquid phase in exchange columns:

Liquid contains 9.24 gms oxygen per liter complex (0.33 molar CO complex). **
Liquid phase has properties of water.

Complex: Complexing agent not specified.
Heat of formation - 8K cal/mole.
Heat of decomposition - 8K cal/mole.

Reactions:

Exchange column:

Decomposer:

Recombiner:

* Based on carbon monoxide - copper chloride separation system.

Decomposer: 10 stages - packed, operating temperature, 212° F.

Recombiner: 10 stages, operating temperature, 77° F.

Cascade feed: Carbon monoxide - commercial in cylinders.
Price: \$20.00 per 100 cubic feet.

Operating labor and supervision:

One operator per shift, one supervisor per day.
Pay (including benefits) \$3.00 per hour. (The estimate using the separation factor of 1.003 was made assuming 2 operators per shift due to the increased size of the plant.)

Column's maximum height: 100 feet

Packing characteristics for exchange columns:

<u>Column Diameter Inches</u>	<u>HETS* Inches</u>
1	1
4	1 1/2
6	1 1/2
10	2

Product and waste streams:

All product and waste streams are removed as gases.
(This permits continuous recirculation of the complexing agent without losses.)

Complexing agent:

No make up is assumed for the complexing agent since it will not be withdrawn in any product, waste or feed streams. No cost is assumed or assigned to the complexing agent since its only contribution to the cost of the plant will be as depreciated inventory charge. The only possibility for an appreciable complexing agent requirement or charge would be the following:

- Appreciable vapor pressure of complexing agent.
- Poisoning of complexing agent.
- Deterioration of complexing agent.

* These stage heights are assumed based on low column loading (10 - 30% of flooding). These loadings give optimum stage efficiencies. When there are many stages required it is especially desirable to operate at optimum efficiency (low HETS). At higher loadings it is possible to decrease the size of the column, however, the increased HETS increases the cost of the column considerably.

APPENDIX "B" - FIRST CASCADEProcess Description

General: Cascade number one is composed of four plants. It has two equal size streams which meet the isotopic requirement of 10% oxygen-17, one from the third plant, W'', which is rich in oxygen-18 (85%), and one from the fourth plant, P''', which is rich in oxygen-16 (85%). There is one stream from the third plant, P'', which contains approximately 8.8 grams per day of oxygen which is almost pure oxygen-18 (99%), and should be a valuable secondary product. There is one additional stream from the fourth plant, W''', which contains approximately 8.8 grams of oxygen per day which is essentially pure oxygen-16 in which the oxygen-17 isotope is enriched to approximately 1% or about 25 times normal abundance and which might therefore be a valuable secondary product. The waste stream, W, for the cascade is withdrawn from the first plant, and is approximately 99.6% of the cascade feed. The oxygen containing gas which is fed to the first plant is assumed to be isotopically normal (0.037% oxygen-17 - see Figure 1 in the body of the report).

First Plant: The feed for the cascade, F, is assumed to be gaseous carbon monoxide which is metered into the plant from cylinders. The feed enters the exchange column, C-1 (see Figure B-1), and joins the gaseous interstage flow which is rising through the packed column. As the gaseous phase leaves the top of the column the flow is split. A small stream, 6% of the interstage flow, is pumped out, P-24, as the plant waste stream, W. The bulk of the gaseous flow is complexed in the recombiner refluxer, RF-51, by being contacted with the aqueous complexing agent at ambient temperatures. The refluxer must be cooled due to the heat of formation of the complex. The complexed carbon monoxide is pumped, P-22, into the exchange column and flows counter current to the gaseous phase. The complexed carbon monoxide flows from the bottom of the exchange column into the decomposer refluxer which consists of a reboiler, RB-41, and a packed decomposer, RF-52. Vapor is generated in the reboiler which heats up the incoming complexed carbon monoxide and dissociates the complex. The carbon monoxide gas leaving the refluxer is cooled, HE-11, and reintroduced into the exchange column. A small stream, 0.02% of the interstage flow, is pumped out P-25, as enriched feed to the second plant, P, F'. A receiver is not supplied for the waste stream since it is assumed that this stream could be vented through a catalytic-type vent. The carbon monoxide free complexing solution is cooled, HE-12, and then pumped, P-21, to the top of the exchange column for re-use.

Second Plant: The second plant is identical in process to the first plant and the purposes of the equipment are the same. The stream, P', F'', from this plant serves as feed to the third plant, and the stream W', F''', from the second plant serves as feed to the fourth plant.

Third Plant: The third plant is identical in process to the first plant and the purposes of the equipment are the same. Two additional items of equipment which are used in this plant are the product receiver tanks T-61 and T-62. These are used to store product gases W''' and P''' which are respectively half of the primary cascade product and, possibly, a valuable secondary product.

Fourth Plant: The fourth plant is identical in process to the first plant and the purposes of the equipment are the same. Two additional items of equipment which are used in this plant are the product receiver tanks T-64 and T-63. These are used to store product gases P''' and W''' which are respectively half of the primary cascade product and a second secondary product.

Equipment Cost

The individual items of equipment, see Figure B-1 and Table B.1 were sized and the installed cost of each item was determined. Where it was deemed necessary spares are included. The total cost of the installed process equipment was found to be \$17,905 based on the use of the separation factor of 1.03, see Table B.1.

Total Plant Investment

Based on the cost of the installed process equipment and the cost of the process building a cost for the total physical plant was determined, see Table B.2. To this cost was added charges for engineering, site development, pre-operational expenses and contingency to determine the total plant investment required. The factors used in this extrapolation are noted in Table B.2. The total plant investment required was found to be \$174,594 based on the use of the separation factor of 1.03.

Annual Fixed Costs

The annual fixed costs include depreciation, investment cost, labor overhead and maintenance overhead. Three of these items were determined by factoring other costs, see Table B.3. The cost of labor overhead was assumed to be included in item "R" (Table B.4) since one supervisor was allocated to the operation. Additional supervision might be necessary for a plant producing more than the 10 grams of product oxygen per day assumed for these estimates. The annual fixed charges were found to be \$35,952 based on the use of a separation factor of 1.03.

Annual Variable Costs

The annual variable costs include raw materials, operating labor and supervision, utilities, maintenance labor, supplies, analysis, storage, etc., see Table B.4. These are obtained

by factoring other costs except for raw material which is calculated assuming carbon monoxide as the cascade feed and operating labor and supervision which is assumed to be one man per shift and one supervisor per day.

The annual variable costs, assuming carbon monoxide feed, amounted to \$80,532 and \$48,616 if the feed was assumed to have zero cost. This last figure will more easily permit the substitution of other feed material costs into the estimate.

Product Cost

Adding the annual fixed costs and variable costs gives the total annual operating cost of \$116,484 assuming a feed of carbon monoxide and \$84,568 assuming the feed has zero cost, see Table B.5. The product oxygen was found to cost \$32 per gram assuming carbon monoxide feed and \$23 per gram assuming zero feed cost.

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FIGURE B1 - CASCADE NUMBER 1, EQUIPMENT DIAGRAM

**TABLE B.1 COST OF INSTALLED PROCESS EQUIPMENT, CASCADE Number 1,
USING A SEPARATION FACTOR OF 1.03.**

Item No.	Type	Number*	Installed Equipment Cost	
			Each	Total
C-1	Exchange Column - 1st Plant, 35'4" glass pipe. Packed.	1	\$224	\$224
C-2	Exchange Column - 2nd Plant, 50'1" glass pipe. Packed	1	112	112
C-3	Exchange Column - 4th Plant, 17'1" glass pipe. Packed	1	447	447
C-4	Exchange Column - 3rd Plant, 17'1" glass pipe. Packed	1	447	447
HE-11	Gas Cooler - 1st Plant, 5.3 sq. ft.	1	197	197
HE-12	Recycle Liquid Cooler - 1st Plant, 178.6 sq. ft.	1	23500	23500
HE-13	Gas Cooler - 2nd Plant, 0.02 sq. ft.	1	20	20
HE-14	Recycle Liquid Cooler - 2nd Plant, 0.56 sq. ft.	1	98	98
HE-15	Gas Cooler - 4th Plant, 0.01 sq. ft.	1	20	20
HE-16	Recycle Liquid Cooler - 4th Plant, 0.30 sq. ft.	1	98	98
HE-17	Gas Cooler - 3rd Plant, 0.01 sq. ft.	1	20	20
HE-18	Recycle Liquid Cooler - 3rd Plant, 0.34 sq. ft.	1	98	98
P-21	Recycle Liquid Pump - 1st Plant, 5 gpm	2	508	1016
P-22	Complex Pump - 1st Plant, 5 gpm	1	508	508
P-24	Waste Gas Pump - 1st Plant, 0.6 cfm	1	508	508
P-25	Product Pump - 1st Plant - feeds 2nd Plant, 0.001 cfm	2	250	500
P-26	Recycle Liquid Pump - 2nd Plant, 0.02 gpm	1	250	250
P-27	Complex Pump - 2nd Plant, 0.02 gpm	2	250	500
P-28	Pump - 2nd Plant - feeds 3rd Plant, 0.001 cfm	1	250	250
P-29	Pump - 2nd Plant - feeds 4th Plant, 0.001 cfm	2	250	500
P-30	Recycle Liquid Pump - 4th Plant, 0.01 gpm	1	250	250
P-31	Complex Pump - 4th Plant, 0.01 gpm	2	250	500
P-32	By-product Gas Pump 4th Plant, 0.001 cfm	2	250	500
P-33	Product Gas Pump - 4th Plant, 0.001 cfm	1	235	235
P-34	Recycle Liquid Pump - 3rd Plant, 0.01 gpm	2	250	500
P-35	Complex Pump - 3rd Plant, 0.01 gpm	1	250	250

TABLE B.1 (continued)

Item No.	Type	Number *	Installed Equipment Cost	
			Each	Total
P-36	Product Gas Pump - 3rd Plant, 0.001 cfm	2	\$235	\$ 470
P-37	By-product Gas Pump- 3rd Plant, 0.001 cfm	1	250	250
RB-41	Reboiler - 1st Plant, 162 sq. ft.	1	2339	2339
RB-42	Reboiler - 2nd Plant, 500 watts	1	125	125
RB-43	Reboiler - 4th Plant, 500 watts	1	125	125
RB-44	Reboiler - 3rd Plant, 500 watts	1	125	125
RF-51	Recombiner ----- 1st Plant, 22.6 sq. ft.	1	425	425
RF-52	Decomposer - 1st Plant 10" diam. x 2ft. Packed	1	120	120
RF-53	Recombiner ----- 2nd Plant, 0.09 sq. ft.	1	45	45
RF-54	Decomposer ----- 2nd Plant, 1" diam. x 10". Packed	1	5	5
RF-55	Recombiner ----- 4th Plant, 0.05 sq. ft.	1	20	20
RF-56	Decomposer ----- 4th Plant, 1" diam. x 10". Packed	1	5	5
RF-57	Recombiner ----- 3rd Plant, 0.05 sq. ft.	1	20	20
RF-58	Decomposer ----- 3rd Plant, 1" diam. x 10". Packed.	1	5	5
T-61	Tank - Product ----- 5 gal SS. Tank	2	126	252
T-62	Tank - By product ----- 5 gal SS. Tank	2	126	252
T-63	Tank - By product ----- 5 gal SS. Tank	2	126	252
T-64	Tank - Product - 17 5 gal SS. Tank	2	126	252
	Packing - 4.6 cu. ft.		700	3220
Total Installed Process Equipment				\$17,905

* Includes spares where necessary.

TABLE B.2 TOTAL PLANT INVESTMENT BASED ON CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.03

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
A	Installed Process Equipment Cost	*	\$17,905
B	Process Piping	60% A	10,743
C	Instrumentation	15% A	2,686
D	Process Building	75,300 cu ft	42,000
E	Service Facilities	50% A	<u>8,953</u>
F	Total Physical Plant		\$82,287
G	Engineering	40% F	32,915
H	Site Development	10% A	1,791
I	Pre-operational Expense	40% F	32,915
J	Contingency	30% F	<u>24,686</u>
K	Total Plant Investment		\$174,594

* See Table B.1.

TABLE B.3 ANNUAL FIXED COST FOR CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.03

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
L	Depreciation	15% K	\$26,189
M	Investment Costs	3% K	5,238
N	Labor Overhead	*	---
O	Maintenance Overhead	"T + U"	<u>4,525</u>
P	Annual Fixed Cost		\$35,952

* Included in Code "R", Table B.4.

TABLE B.4 ANNUAL VARIABLE COST FOR CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.03

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
Q	Raw Material	*	\$31,916
R	Direct Operating Labor and Supervision	**	35,040
S	Utilities	6% F	4,937
T	Maintenance Labor	5% F	4,114
U	Maintenance Supplies	0.5% F	411
V	Misc., Analysis, Storage, etc.	5% F	4,114
W	Annual Variable Cost		\$80,532
X	Annual Variable Cost Using Zero Raw Material Cost	(W - Q)	\$48,616

* 11,317 pounds carbon monoxide per year

** one operator per shift plus one supervisor per day

TABLE B.5 PRODUCT OXYGEN COST FOR CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.03 AND ASSUMING NO CREDIT
ALLOWANCE FOR WASTE OR SECONDARY PRODUCTS

<u>Code</u>	<u>Cost Designation</u>	<u>Cost Assuming CO Feed</u>	<u>Cost Assuming Zero Cost Feed</u>
AA	Annual Fixed Cost *	\$35,952	\$35,952
BB	Annual Variable Cost **	80,532	48,616
CC	Total Annual Operating Cost	\$116,484	\$84,568
DD	Operating Cost Per Day	\$319	\$231
EE	Product Oxygen Cost Per Gram (10% oxygen-17)	\$32	\$23

* See Table B.3.

** See Table B.4.

APPENDIX "C" - SECOND CASCADE

Process Description

General: Cascade number two is composed of three plants. It has one stream from the third plant, W'', which meets the isotopic requirement of 10% oxygen-17, which contains approximately equal concentrations of oxygen-18 (40%), and oxygen-16 (50%). There is one stream from the third plant, P'', which contains approximately 10.2 grams per day of oxygen which is almost pure oxygen-18 (99.9%), and should be a valuable secondary product. The waste stream, W, for the cascade is withdrawn from the first plant, and is approximately 99.8% of the cascade feed. The oxygen containing gas which is fed to the first plant is assumed to be isotopically normal (0.037% oxygen-17 - see Figure 2 in the body of the report).

First Plant: The feed for the cascade, F, is assumed to be gaseous carbon monoxide which is metered into the plant from cylinders. The feed enters the exchange column, C-1 (see Figure C-1), and joins the gaseous interstage flow which is rising through the packed column. As the gaseous phase leaves the top of the column the flow is split. A small stream, 6.5% of the inter-stage flow, is pumped out, P-24, as the plant waste stream, W. The bulk of the gaseous flow is complexed in the recombiner refluxer, RF-51, by being contacted with the aqueous complexing agent at ambient temperatures. The refluxer must be cooled due to the heat of formation of the complex. The complexed carbon monoxide is pumped, P-22, into the exchange column and flows counter current to the gaseous phase. The complexed carbon monoxide flows from the bottom of the exchange column into the decomposer refluxer which consists of a reboiler, RB-41, and a packed decomposer, RF-52. The vapor generated in the reboiler, heats up the incoming complexed carbon monoxide and dissociates the complex. The carbon monoxide gas leaving the refluxer is cooled, HE-11, and reintroduced into the exchange column. A small stream, 0.1% of the interstage flow, is pumped out, P-25, as enriched feed to the second plant, P, F'. A receiver is not supplied for the waste stream since it is assumed that this stream could be vented through a catalytic-type vent. The carbon monoxide complex-free complexing agent solution is cooled, HE-12, and then pumped, P-21, to the top of the exchange column for re-use. This plant has a secondary feed, W', F''', which is pumped from the second plant.

Second Plant: The second plant is identical in process to the first plant and the purposes of the equipment are the same. The stream, P', F'', from this plant serves as feed to the third plant. The stream W', F''', from the second plant serves as a secondary feed to the first plant.

Third Plant: The third plant is identical in process to the first plant and the purposes of the equipment are the same. Two additional items of equipment which are used in this plant

are the product receiver tanks T.61 and T.62. These are used to store product gases W' and P' which are respectively the primary cascade product and a secondary product.

Equipment Cost

The size and cost of the individual items of equipment were determined as in Appendix B. See Figure C.1 and Table C.1 for details. The total cost of the installed process equipment was found to be \$19,962.

Total Plant Investment

The total plant investment was determined as in Appendix B. The total plant investment required was \$184,516 (Table C.2).

Annual Fixed Costs

The annual fixed costs were calculated as in Appendix B. The annual fixed charges were \$37,993 (Table C.3).

Annual Variable Costs

The annual variable costs, assuming carbon monoxide feed, amounted to \$82,193 and \$49,382 if the feed was assumed to have zero cost. Table C.4 contains a detailed account of these costs. The assumptions used for calculating these costs are presented in Appendix B.

Product Cost

Adding the annual fixed costs and variable costs gives the total annual operating cost of \$120,186 assuming a feed of carbon monoxide and \$87,375 assuming the feed has zero cost, see Table C.5. The product oxygen was found to cost \$33 per gram assuming carbon monoxide feed and \$24 per gram assuming zero feed cost.

FIGURE C1- CASCADE NUMBER 2, EQUIPMENT DIAGRAM

TABLE C.1 COST OF INSTALLED PROCESS EQUIPMENT, CASCADE NUMBER 2

USING A SEPARATION FACTOR OF 1.03.

Item No.	Type	Number*	Installed Equipment Cost	
			Each	Total
C-1	Exchange Column - 1st Plant, 35'4" glass pipe. Packed.	1	\$ 224	\$ 224
C-2	Exchange Column - 2nd Plant, 15'1" glass pipe. Packed	1	34	34
C-3	Exchange Column - 3rd Plant, 17'1" glass pipe. Packed	1	47	47
HE-11	Gas Cooler - 1st Plant, 4.8 sq ft	1	197	197
HE-12	Recycle Liquid Cooler - 1st Plant, 163 sq ft	1	2350	2350
HE-13	Gas Cooler - 2nd Plant, 0.23 sq ft	1	98	98
HE-14	Recycle Liquid Cooler - 2nd Plant, 7.6 sq ft	1	197	197
HE-15	Gas Cooler - 3rd Plant, 0.07 sq ft	1	98	98
HE-16	Recycle Liquid Cooler - 3rd Plant, 2.3 sq ft	1	98	98
P-21	Recycle Liquid Pump - 1st Plant, 5 gpm	2	508	1016
P-22	Complex Pump - 1st Plant, 5 gpm	1	508	508
P-24	Waste Gas Pump - 1st Plant, 0.6 cfm	1	508	508
P-25	Product Pump - 1st Plant - feeds 2nd Plant 0.004 cfm	4	250	1000
P-26	Recycle Liquid Pump - 2nd Plant, 0.2 gpm	1	675	675
P-27	Complex Pump - 2nd Plant, 0.2 gpm	2	675	1350
P-28	Pump - 2nd Plant - feeds 1st Plant, 0.004 cfm	4	250	1000
P-29	Pump - 2nd Plant - feeds 3rd Plant, 0.001 cfm	2	250	500
P-30	Recycle Liquid Pump - 3rd Plant, 0.06 gpm	1	675	675
P-31	Complex Pump - 3rd Plant, 0.06 gpm	2	675	1350
P-32	By-product Gas Pump - 3rd Plant, 0.001 cfm	2	250	500
P-33	Product Gas Pump - 3rd Plant, 0.001 cfm	1	250	250

Table C.1 (continued)

Item No.	Type	Number*	Installed Equipment Cost	
			Each	Total
RB-41	Reboiler - 1st Plant, 162 sq ft	1	\$2339	\$2339
RB-42	Reboiler - 2nd Plant, 6.5 sq ft	1	2287	2287
RB-43	Reboiler - 3rd Plant, 1.5 kw	1	248	248
RF-51	Recombiner - 1st Plant, 19.4 sq ft	1	425	425
RF-52	Decomposer - 1st Plant 10" diam. x 2 ft. Packed	1	120	120
RF-53	Recombiner - 2nd Plant, 1.0 sq ft	1	98	98
RF-54	Decomposer - 2nd Plant, 4" diam. x 15". Packed.	1	13	13
RF-55	Recombiner - 3rd Plant, 0.3 sq ft	1	98	98
RF-56	Decomposer - 3rd Plant, 1" diam. x 10". Packed	1	5	5
T-61	Tank - Product 5 gal SS. Tank	2	126	252
T-62	Tank - By-product 5 gal SS. Tank	2	126	252
	Packing - 4.5 cu ft		700	3150

Total Installed Process Equipment \$19,962

* Includes spares where necessary.

TABLE C.2 TOTAL PLANT INVESTMENT BASED ON CASCADE NUMBER 2

USING A SEPARATION FACTOR OF 1.03

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
A	Installed Process Equipment Cost	*	\$19,962
B	Process Piping	60% A	11,977
C	Instrumentation	15% A	2,994
D	Process Building	75,300 cu ft	42,000
E	Service Facilities	50% A	<u>9,981</u>
F	Total Physical Plant		\$86,914
G	Engineering	40% F	34,766
H	Site Development	10% A	1,996
I	Pre-operational Expense	40% F	34,766
J	Contingency	30% F	<u>26,074</u>
K	Total Plant Investment		\$184,516

* See Table C.1.

TABLE C.3 ANNUAL FIXED COST FOR CASCADE NUMBER 2

USING A SEPARATION FACTOR OF 1.03

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
L	Depreciation	15% K	\$27,677
M	Investment Costs	3% K	5,535
N	Labor Overhead	*	---
O	Maintenance Overhead	"T + U"	<u>4,781</u>
P	Annual Fixed Cost		\$37,993

* Included in Code "R", Table C.4.

TABLE C.4 ANNUAL VARIABLE COST FOR CASCADE NUMBER 2
USING A SEPARATION FACTOR OF 1.03

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
Q	Raw Material	*	\$32,811
R	Direct Operating Labor and Supervision	**	35,040
S	Utilities	5% F	5,215
T	Maintenance Labor	5% F	4,346
U	Maintenance Supplies	0.5% F	435
V	Misc., Analysis, Storage, etc.	5% F	4,346
W	Annual Variable Cost		\$82,193
X	Annual Variable Cost Using Zero Raw Material Cost	(W - Q)	\$49,382

* 11,635 pounds carbon monoxide per year

** one operator per shift plus one supervisor per day

TABLE C.5 PRODUCT OXYGEN COST FOR CASCADE NUMBER 2 USING
A SEPARATION FACTOR OF 1.03 AND ASSUMING NO CREDIT
ALLOWANCE FOR WASTE OR SECONDARY PRODUCTS

<u>Code</u>	<u>Cost Designation</u>	<u>Cost Assuming CO Feed</u>	<u>Cost Assuming Zero Cost Feed</u>
AA	Annual Fixed Cost*	\$37,993	\$37,993
BB	Annual Variable Cost **	82,193	49,382
CC	Total Annual Operating Cost	\$120,186	\$87,375
DD	Operating Cost Per Day	\$329	\$239
EE	Product oxygen Cost Per Gram (10% oxygen-17)	\$33	\$24

* See Table C.3.

** See Table C.4.

APPENDIX "D" - THIRD CASCADE

Process Description

General: Cascade number three is composed of one two-section plant. It has one stream, M, which meets the isotopic requirement of 10% oxygen-17. There is one stream, P, from the second section of the plant which contains approximately 49 grams per day of oxygen which is almost pure oxygen-18 (99.5%) and should be a valuable secondary product. The waste stream, W, for the cascade is withdrawn from the first section of the plant and is approximately 99.9% of the cascade feed. The oxygen containing gas which is fed to the first plant is assumed to be isotopically normal (0.037% oxygen-17 - see Figure 3 in the body of the report).

First Section of the Plant: The feed for the cascade, F, is assumed to be gaseous carbon monoxide which is metered into the plant from cylinders. The feed enters the exchange column, C-1 (see Figure D-1), and joins the gaseous interstage flow which is rising through the packed column. As the gaseous phase leaves the top of the column the flow is split. The plant waste stream, W, 19% of the inter-stage flow, is pumped out, P-24 and the remainder of the gaseous flow is complexed in the recombiner refluxer RF-51, by being contacted with the aqueous complexing agent at ambient temperatures. The refluxer must be cooled due to the heat of formation of the complex. The complexed carbon monoxide is pumped, P-22, into the exchange column and flows counter current to the gaseous phase. The complexed carbon monoxide flows from the bottom of the exchange column into a hold-up tank, T-63, prior to splitting the flow. Two percent of the complex is pumped, P-28, to the top of the second section of the plant and the remainder is pumped, P-27, to the decomposer refluxer for the first section of the plant. The decomposer refluxer consists of a reboiler, RB-41, and a packed decomposer, RF-52. Vapor is generated in the reboiler which heats up the incoming complexed carbon monoxide and dissociates the complex. The carbon monoxide gas leaving the refluxer is cooled, HE-11, and reintroduced into the exchange column. A small stream, 0.002% of the interstage flow, is pumped out, P-25, as product, M, and is stored in Tank T-61. A receiver is not supplied for the waste stream since it is assumed that this stream could be vented through a catalytic-type vent. The carbon monoxide complex-free complexing agent solution is cooled, HE-12, and then pumped, P-21, to the top of the first section of the exchange column for re-use.

Second Section of the Plant: The complex is received at the top of the exchange column, C-2, from pump, P-28, and flows counter current to the gaseous phase. The complexed carbon monoxide flows from the bottom of the exchange column into the decomposer refluxer which consists of a reboiler, RB-42, and a packed decomposer, RF-53. Vapor is generated in the reboiler which heats up the incoming complexed carbon monoxide and dissociates the complex. The carbon monoxide gas leaving the refluxer is cooled, HE-13, and

re-introduced into the exchange column. A small stream, 0.5% of the interstage flow, is pumped out, P-30, as a valuable secondary product, P, into tank T-62, for storage. The gaseous phase leaving the top of the column C-2, is returned to the bottom of the first section exchange column, C-1, by pump, P-29.

Equipment Cost

The size and cost of the individual items of equipment were determined as in Appendix B. See Figure D-1 and Table D.1 for details. The total cost of the installed process equipment was found to be \$35,012.

Total Plant Investment

The total plant investment was determined as in Appendix B. The total plant investment required was \$236,133 (Table D.2).

Annual Fixed Costs

The annual fixed costs were calculated as in Appendix B. The annual fixed charges were \$48,597 (Table D.3).

Annual Variable Costs

The annual variable costs, assuming carbon monoxide feed, amounted to \$430,145 and \$53,319 if the feed was assumed to have zero cost. Table D.4 contains a detailed account of these costs. The assumptions used for calculating these costs are presented in Appendix B.

Product Cost

Adding the annual fixed costs and variable costs gives the total annual operating cost of \$478,742 assuming a feed of carbon monoxide and \$101,916 assuming the feed has zero cost, see Table D.5. The product oxygen was found to cost \$131 per gram assuming carbon monoxide feed and \$28 per gram assuming zero feed cost.

FIGURE DI-CASCADE NUMBER 3, EQUIPMENT DIAGRAM

TABLE D.1 COST OF INSTALLED PROCESS EQUIPMENT, CASCADE NUMBER 3

USING A SEPARATION FACTOR OF 1.03

Item No.	Type	Number*	Installed Equipment Cost	
			Each	Total
C-1	Exchange Column - 1st Section, 30'6" glass pipe. Packed.	1	\$ 518	\$ 518
C-2	Exchange Column - 2nd Section, 13'1" glass pipe. Packed.	1	36	36
HE-11	Gas Cooler - 1st Section, 19 sq. ft.	1	620	620
HE-12	Recycle Liquid Cooler - 1st Section, 650 Sq. ft.	1	4800	4800
HE-13	Gas Cooler - 2nd Section, 0.4 sq. ft.	1	98	98
HE-14	Recycle Liquid Cooler - 2nd Section, 13 sq. ft.	1	287	287
P-21	Recycle Liquid Pump - 1st Section, 20 gpm	2	825	1650
P-22	Complex Pump from Recombiner Refluxer, 20 gpm	1	825	825
P-24	Waste Gas Pump, 6 cfm	2	1000	2000
P-25	Product Pump, 0.001 cfm	2	250	500
P-26	Recycle Liquid Pump - 2nd Section, 0.3 gpm	1	675	675
P-27	Complex Pump to Decomposer, 20 gpm	2	825	1650
P-28	Complex Pump to 2nd Section, 0.3 gpm	2	675	1350
P-29	Intersection Gas Pump, 0.1 cfm	2	508	1016
P-30	By-product Gas Pump, 0.001 cfm	2	250	500

TABLE D.1 (continued)

<u>Item No.</u>	<u>Type</u>	<u>Number</u> *	<u>Installed Equipment Cost</u>	
			<u>Each</u>	<u>Total</u>
RB-41	Reboiler - 1st Section, 552 sq. ft.	1	\$4470	\$4470
RB-42	Reboiler - 2nd Section, 11 sq. ft.	1	400	400
RF-51	Recombiner, 77 sq. ft.	1	1300	1300
RF-52	Decomposer - 1st Section, 20" diam. x 40". Packed.	1	2000	2000
RF-53	Decomposer - 2nd Section, 4" diam. x 15". Packed	1	13	13
T-61	Tank - Product, 5 gal SS. Tank	2	126	252
T-62	Tank - By-product, 20 gal SS. Tank	2	195	390
T-63	Tank - Complex Storage, 200 gal SS. Tank	1	562	562
	Packing - 13.0 cu. ft.		700	9100
Total Installed Process Equipment				\$ 35,012

* Includes spares where necessary.

TABLE D.2 TOTAL PLANT INVESTMENT BASED ON CASCADE NUMBER 3
USING A SEPARATION FACTOR OF 1.03

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
A	Installed Process Equipment Cost	*	\$ 35,012
B	Process Piping	60% A	21,007
C	Instrumentation	15% A	5,252
D	Process Building	51,750 cu. ft.	32,000
E	Service Facilities	50% A	17,506
F	Total Physical Plant		\$110,777
G	Engineering	40% F	44,311
H	Site Development	10% A	3,501
I	Pre-operational Expense	40% F	44,311
J	Contingency	30% F	33,233
K	Total Plant Investment		\$236,133

* See Table D.1.

TABLE D.3 ANNUAL FIXED COST FOR CASCADE NUMBER 3
USING A SEPARATION FACTOR OF 1.03

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
L	Depreciation	15% K	\$35,420
M	Investment Costs	3% K	7,084
N	Labor Overhead	*	----
O	Maintenance Overhead	"T + U"	6,093
P	Annual Fixed Cost		\$48,597

* Included in Code "R", Table D.4.

TABLE D.4 ANNUAL VARIABLE COST FOR CASCADE NUMBER 3USING A SEPARATION FACTOR OF 1.03

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
Q	Raw Material	*	\$376,826
R	Direct Operating Labor and Supervision	**	35,040
S	Utilities	6% F	6,647
T	Maintenance Labor	5% F	5,539
U	Maintenance Supplies	0.5% F	554
V	Misc., Analysis, Storage, etc.	5% F	5,539
W	Annual Variable Cost		\$430,145
X	Annual Variable Cost Using Zero Raw Material Cost	(W - Q)	\$53,319

* 133,625 pounds carbon monoxide per year

** one operator per shift plus one supervisor per day

TABLE D.5 PRODUCT OXYGEN COST FOR CASCADE NUMBER 3USING A SEPARATION FACTOR OF 1.03 AND ASSUMING NO CREDITALLOWANCE FOR WASTE OR SECONDARY PRODUCTS

<u>Code</u>	<u>Cost Designation</u>	<u>Cost Assuming CO Feed</u>	<u>Cost Assuming Zero Cost Feed</u>
AA	Annual Fixed Cost*	\$ 48,597	\$ 48,597
BB	Annual Variable Cost**	430,145	53,319
CC	Total Annual Operating Cost	\$478,742	\$101,916
DD	Operating Cost Per Day	\$1312	\$279
EE	Product Oxygen Cost Per Gram (10% oxygen-17)	\$131	\$28

* See Table D.3.

** See Table D.4.

APPENDIX "E" - SCALE UP OF FIRST CASCADE

General

Estimates were made of Cascade Number 1 using separation factors of 1.01 and 1.003. The following assumptions were made:

1. The feed, waste, product and inter-plant streams are to remain constant (10 grams of product oxygen containing 10% oxygen-17).
2. Interstage flows in each plant will be increased three-fold for the 1.01 cascade variation and ten-fold for the 1.003 cascade variation. See Table E.1.
3. The number of stages will be increased three-fold for the 1.01 cascade variation and ten-fold for the 1.003 cascade variation, see Table E.1.

Using these criteria the plant flows were calculated, the equipment designed, cost of the individual items of equipment were determined and the plant and product costs were calculated.

Process Description

General: Cascade Number 1 is composed of four plants. It has two equal size streams which meet the isotopic requirement of 10% oxygen-17, one from the third plant, W'', which is rich in oxygen-18 (85%), and one from the fourth plant, P'', which is rich in oxygen-16 (85%). There is one stream from the third plant, P'', which is almost pure oxygen-18 (99%), and should be a valuable secondary product. There is one additional stream from the fourth plant, W'', which is essentially pure oxygen-16 in which the oxygen-17 isotope is enriched to approximately 1% or about 25 times normal abundance, and which might therefore be a valuable secondary product. The waste stream, W, for the cascade is withdrawn from the first plant and is approximately 99.6% of the cascade feed. The oxygen containing gas which is fed to the first plant is assumed to be isotopically normal (0.037% oxygen-17 - see Figure 1 in the body of the report).

The cascade using the 1.01 separation factor has two exchange columns in the first and second plant, see Figure E.1. The cascade using the 1.003 separation factor has five exchange columns in the first and second plants and two exchange columns in the third and fourth plants. Since the equipment diagram for this cascade is very similar to Figure E.1 another was not made for the 1.003 cascade. Since the process is identical in the two cascades the following description while applicable to both, specifically describes the 1.01 cascade shown in Figure 1, Figure E.1, and Table E.1.

First Plant: The feed for the cascade, F, is assumed to be gaseous carbon monoxide which is metered into the plant from cylinders. The feed enters the exchange column, C-1B (see Figure E-1), and joins the gaseous interstage flow which is rising through

the packed column. As the gaseous phase leaves the top of the column the flow is split. A small stream, 2% of the interstage flow, is pumped out, P-24, as the plant waste stream, W. The bulk of the gaseous flow is complexed in the recombiner refluxer, RF-51, by being contacted with the aqueous complexing agent at ambient temperatures. The refluxer must be cooled due to the heat of formation of the complex. The complexed carbon monoxide is pumped, P-22, into the exchange column, C-1B, and flows counter current to the gaseous phase. The complex is transferred from the bottom of the first column, C-1B, to the top of the second column, C-1A, using pump P-23. The complexed carbon monoxide flows from the bottom of the exchange column, C-1A, into the decomposer refluxer which consists of a reboiler, RB-41, and a packed decomposer, RF-52. Vapor is generated in the reboiler which heats up the incoming complexed carbon monoxide and dissociates the complex. The dissociated carbon monoxide gas leaving the refluxer is cooled, HE-11, and reintroduced into the exchange column C-1A. A small stream, 0.007% of the interstage flow is pumped out, P-25, as enriched feed to the second plant, P, F'. A receiver is not supplied for the waste stream since it is assumed that this stream could be vented through a catalytic-type vent. The carbon monoxide free complexing solution is cooled, HE-12, and then pumped, P-21, to the top of the exchange column for re-use.

Second Plant: The second plant is identical in process to the first plant and the purposes of the equipment are the same. The stream, P', F'', from this plant serves as feed to the third plant, and the stream W', F''', from the second plant serves as feed to the fourth plant.

Third Plant: The third plant is identical in process to the first plant and the purposes of the equipment are the same. Two additional items of equipment which are used in this plant are the product receiver tanks T.64 and T.63. These are used to store product gases P''' and W''' which are respectively half of the primary cascade product and a valuable secondary product.

Fourth Plant: The fourth plant is identical in process to the first plant and the purposes of the equipment are the same. Two additional items of equipment which are used in this plant are the product receiver tanks T.61 and T.62. These are used to store product gases W'' and P'' which are respectively half of the primary cascade product and a second secondary product.

Equipment Cost

The individual items of equipment, see Figure E.1 and Tables E.2 and E.3, were sized and the installed cost of each item was determined. The total cost of the installed process equipment was found to be \$51,485 based on the use of the separation factor of 1.01, and \$345,470 based on the use of the separation factor of 1.003, see Tables E.2 and E.3.

Total Plant Investment

Based on the cost of the installed process equipment and the cost of the process building a cost for the total physical plant was determined, see Tables E.4 and E.5. To this cost was added charges for engineering, site development, pre-operational expenses and contingency to determine the total plant investment required. The factors used in this extrapolation are noted in Tables E.4 and E.5. The total plant investment required was found to be \$399,618 based on the use of the separation factor of 1.01 and \$1,914,693 based on the use of the separation factor of 1.003.

Annual Fixed Costs

The annual fixed costs include depreciation, investment cost, labor overhead and maintenance overhead. Three of these items were determined by factoring other costs, see Tables E.6 and E.7. The cost of labor overhead was assumed to be included in item "R" (Tables E.8 and E.9) since one supervisor was allocated to the operation. Additional supervision might be necessary for a plant producing more than the 10 grams of product oxygen per day assumed for these estimates. The annual fixed charges were found to be \$82,263 based on the use of a separation factor of 1.01 and \$393,886 based on the use of a separation factor of 1.003.

Annual Variable Costs

The annual variable costs include raw materials, operating labor and supervision, utilities, maintenance labor, supplies, analytical storage, etc., see Tables E.8 and E.9. These are obtained by factoring other costs except for raw material which is calculated assuming carbon monoxide as the cascade feed, and operating labor and supervision which are assumed to be one man per shift and one supervisor per day for the estimate using the separation factor of 1.01 and two men per shift and one supervisor per day for the other estimate.

The annual variable costs, assuming carbon monoxide feed and a separation factor of 1.01, amounted to \$97,950 and \$66,034 if the feed was assumed to have zero cost.

This cost is increased, using the separation factor of 1.003 to \$240,960 assuming carbon monoxide feed, and \$209,044 assuming zero cost feed.

Product Cost

Adding the annual fixed costs and variable costs using the separation factor of 1.01 gives the total annual operating cost of \$180,213 assuming a feed of carbon monoxide, and \$148,297 assuming the feed has zero cost, see Table E.10. This cost increased to \$634,846 and \$602,930 respectively using a separation factor of 1.003, and Table E.11.

The product oxygen was found to cost \$49 per gram assuming carbon monoxide feed and \$41 per gram assuming zero feed cost at 1.01 separation factor and \$174 per gram and \$165 per gram respectively using a separation factor of 1.003.

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FIGURE E1 - SCALE UP CASCADE NUMBER 1, SEPARATION FACTOR 1.01, EQUIPMENT DIAGRAM

TABLE E.1 PLANT CHARACTERISTICS OF CASCADE NUMBER 1

USING SEPARATION FACTORS OF 1.01 AND 1.003

Oxygen 16 - Oxygen 17 Separation Factor Alpha	Stripping Stages N_s^*	Interstage Flow L^* (gm. oxygen per day)	Enrichment Stages N_e^*
FIRST PLANT			
1.01	180	414,600	660
1.003	600	1,382,000	2200
SECOND PLANT			
1.01	825	1,425	825
1.003	22750	4,750	2750
THIRD PLANT			
1.01	216	828	384
1.003	720	2,760	1280
FOURTH PLANT			
1.01	384	828	216
1.003	1280	2,760	720

* See Figure 1.

TABLE E.2 COST OF INSTALLED PROCESS EQUIPMENT, CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.01

Item No.	Type	Number	Installed Equipment Cost	
			Each	Total
C-1	Exchange Column - 1st Plant, 55'6" glass pipe. Packed	2	\$4510	\$9020
C-2	Exchange Column - 2nd Plant, 70'1" glass pipe. Packed.	2	157	314
C-3	Exchange Column - 4th Plant, 50'1" glass pipe. Packed.	1	112	112
C-4	Exchange Column - 3rd Plant, 50'1" glass pipe. Packed	1	112	112
HE-11	Gas Cooler - 1st Plant, 16 sq. ft.	1	192	192
HE-12	Recycle Liquid Cooler - 1st Plant, 526 sq. ft.	1	2760	2760
HE-13	Gas Cooler - 2nd Plant, 0.06 sq. ft.	1	98	98
HE-14	Recycle Liquid Cooler - 2nd Plant, 2.1 sq. ft.	1	90	90
HE-15	Gas Cooler - 4th Plant, 0.04 sq. ft.	1	98	98
HE-16	Recycle Liquid Cooler - 4th Plant, 1.2 sq. ft.	1	66	66
HE-17	Gas Cooler - 3rd Plant, 0.04 sq. ft.	1	98	98
HE-18	Recycle Liquid Cooler - 3rd Plant, 1.2 sq. ft.	1	66	66
P-21	Recycle Liquid Pump - 1st Plant, 20gpm	2	625	1250
P-22	Complex Pump - 1st Plant, 20 gpm	1	625	625
P-23	Complex Inter-column Pump - 1st Plant, 20gpm	2	625	1250
P-24	Waste Gas Pump - 1st Plant, 0.6 cfm	2	508	1016
P-25	Product Pump - 1st Plant - feeds 2nd Plant, 0.001 cfm	2	250	500
P-26	Recycle Liquid Pump - 2nd Plant, 0.1 gpm	1	675	675
P-27	Complex Pump - 2nd Plant, 0.1 gpm	2	675	1350
P-28	Pump - 2nd Plant - feeds 3rd Plant, 0.001 cfm	1	250	250
P-29	Pump - 2nd Plant - feeds 4th Plant, 0.001 cfm	2	250	500
P-30	Recycle Liquid Pump - 4th Plant 0.03 gpm	1	250	250

Table E.2 (continued)

Item No.	Type	Number*	Installed Equipment Cost	
			Each	Total
P-31	Complex Pump - 4th Plant, 0.03 gpm	2	\$ 250	\$ 500
P-32	By-product Gas Pump 4th Plant, 0.001 cfm	2	250	500
P-33	Product Gas Pump - 4th Plant, 0.001 cfm	1	235	235
P-34	Recycle Liquid Pump - 3rd Plant, 0.03 gpm	2	250	500
P-35	Complex Pump - 3rd Plant, 0.03 gpm	1	250	250
P-36	Product Gas Pump - 3rd Plant, 0.001 cfm	2	235	470
P-37	By-product Gas Pump - 3rd Plant, 0.001 cfm	1	250	250
P-38	Complex Intercolumn Pump 2nd Plant, 0.1 gpm	2	675	1350
RB-41	Reboiler - 1st Plant, 500 sq. ft.	1	5040	5040
RB-42	Reboiler - 2nd Plant, 2.0 sq. ft.	1	150	150
RB-43	Reboiler - 4th Plant, 1.5 sq. ft.	1	150	150
RB-44	Reboiler - 3rd Plant, 1.5 sq. ft.	1	150	150
RF-51	Recombiner- 1st Plant, 68 sq. ft.	1	560	560
RF-52	Decomposer - 1st Plant 16" diam. x 30". Packed.	1	450	450
RF-53	Recombiner - 2nd Plant, 0.3 sq. ft.	1	150	150
RF-54	Decomposer - 2nd Plant, 2" diam. x 10". Packed	1	10	10
RF-55	Recombiner - 4th Plant, 0.2 sq. ft.	1	150	150
RF-56	Decomposer - 4th Plant, 1" diam. x 10". Packed	1	5	5
RF-57	Recombiner - 3rd Plant, 0.2 sq. ft.	1	150	150
RF-58	Decomposer - 3rd Plant, 1" diam. x 10". Packed	1	5	5
T-61	Tank - Product 5 gal SS. Tank	2	126	252
T-62	Tank - By-product 5 gal SS. Tank	2	126	252
T-63	Tank - Byproduct 5 gal SS. Tank	2	126	252
T-64	Tank - Product - 17 5 gal SS. Tank	2	126	252
	Packing - 26.8 cu. ft.		700	18,760

Total Installed Process Equipment \$ 51,485

* Includes spares where necessary.

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TABLE E.3 COST OF INSTALLED PROCESS EQUIPMENT, CASCADE NUMBER 1

USING A SEPARATION FACTOR OF 1.003

Item No.	Type	Number*	Installed Equipment Cost	
			Each	Total
C-1	Exchange Column - 1st Plant, 95'10" SS pipe. Packed.	5	\$19,950	\$99,750
C-2	Exchange Column - 2nd Plant, 95'1" glass pipe. Packed.	5	213	1,065
C-3	Exchange Column - 4th Plant, 85'1" glass pipe. Packed.	2	190	380
C-4	Exchange Column - 3rd Plant, 85'1" glass pipe. Packed.	2	190	380
HE-11	Gas Cooler - 1st Plant, 53 sq. ft.	1	320	320
HE-12	Recycle Liquid Cooler - 1st Plant, 1,786 sq. ft.	1	8,000	8,000
HE-13	Gas Cooler - 2nd Plant, 0.2 sq. ft.	1	98	98
HE-14	Recycle Liquid Cooler - 2nd Plant, 5.7 sq. ft.	1	90	90
HE-15	Gas Cooler - 4th Plant, 0.1 sq. ft.	1	98	98
HE-16	Recycle Liquid Cooler - 4th Plant, 3.2 sq. ft.	1	66	66
HE-17	Gas Cooler - 3rd Plant, 0.1 sq. ft.	1	98	98
HE-18	Recycle Liquid Cooler - 3rd Plant, 3.5 sq. ft.	1	66	66
P-21	Recycle Liquid Pump - 1st Plant, 50 gpm	2	825	1,650
P-22	Complex Pump - 1st Plant, 50 gpm	1	825	825
P-23	Complex Intercolumn Pump - 1st Plant, 50 gpm	6	825	4,950
P-24	Waste Gas Pump - 1st Plant, 0.6 cfm	2	508	1,016
P-25	Product Pump - 1st Plant - feeds 2nd Plant 0.001 cfm	2	250	500
P-26	Recycle Liquid Pump - 2nd Plant, 0.2 gpm	1	690	690
P-27	Complex Pump - 2nd Plant, 0.2 gpm	2	690	1,380
P-28	Pump - 2nd Plant, feeds 3rd Plant, 0.001 cfm	1	250	250
P-29	Pump - 2nd Plant - feeds 4th Plant, 0.001 cfm	2	250	500
P-30	Recycle Liquid Pump - 4th Plant, 0.1 gpm	1	670	670
P-31	Complex Pump - 4th Plant, 0.1 gpm	2	670	1,340
P-32	By-product Gas Pump - 4th Plant, 0.001 cfm	2	250	500
P-33	Product Gas Pump - 4th Plant, 0.001 cfm	1	235	235
P-34	Recycle Liquid Pump - 3rd Plant, 0.1 gpm	1	670	670
P-35	Complex Pump - 3rd Plant, 0.1 gpm	2	670	1,340

TABLE E.3 (continued)

Item No.	Type	Number*	Installed Equipment Cost	
			Each	Total
P-36	Product Gas Pump - 3rd Plant, 0.001 cfm	2	\$ 235	\$ 470
P-37	By-product Gas Pump - 3rd Plant, 0.001 cfm	1	250	250
P-38	Complex Intercolumn Pump - 2nd Plant, 0.2gpm	6	690	4,140
P-39	Complex Intercolumn Pump - 3rd Plant, 0.1 gpm	2	670	1,340
P-40	Complex Intercolumn Pump - 4th Plant, 0.1 gpm	2	670	1,340
RB-41	Reboiler - 1st Plant, 1620 sq. ft.	1	8,820	8,820
RB-42	Reboiler - 2nd Plant, 6.2 sq. ft.	1	335	335
RB-43	Reboiler - 4th Plant, 3.4 sq. ft.	1	335	335
RB-44	Reboiler - 3rd Plant, 3.8 sq. ft.	1	335	335
RF-51	Recombiner - 1st Plant, 226 sq. ft.	1	1,540	1,540
RF-52	Decomposer - 1st Plant, 30" diam. x 40". Packed.	1	1,100	1,100
RF-53	Recombiner - 2nd Plant, 0.9 sq. ft.	1	335	335
RF-54	Decomposer - 2nd Plant, 3" diam. x 10". Packed.	1	15	15
RF-55	Recombiner - 4th Plant, 0.5 sq. ft.	1	335	335
RF-56	Decomposer - 4th Plant, 2" diam. x 10". Packed	1	10	10
RF-57	Recombiner - 3rd Plant, 0.5 sq. ft.	1	335	335
RF-58	Decomposer - 3rd Plant, 2" diam. x 10". Packed.	1	10	10
T-61	Tank - Product 5 gal SS. Tank	2	126	252
T-62	Tank - By-product 5 gal SS. Tank	2	126	252
T-63	Tank - By-product 5 gal SS. Tank	2	126	252
T-64	Tank - Product 5 gal SS. Tank	2	126	252
	Packing - 280.7 cu. ft.		700	196,490
Total Installed Process Equipment				\$345,470

* Includes spares where necessary.

TABLE E.4 TOTAL PLANT INVESTMENT BASED ON CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.01

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
A	Installed Process Equipment Cost	*	\$ 51,485
B	Process Piping	60% A	30,891
C	Instrumentation	15% A	7,723
D	Process Building	178,500 cu. ft.	72,000
E	Service Facilities	50% A	<u>25,743</u>
F	Total Physical Plant		\$187,842
G	Engineering	40% F	75,137
H	Site Development	10% A	5,149
I	Pre-operational Expense	40% F	75,137
J	Contingency	30% F	<u>56,353</u>
K	Total Plant Investment		\$399,618

* See Table E.2.

TABLE E.5 TOTAL PLANT INVESTMENT BASED ON CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.003

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
A	Installed Process Equipment Cost	*	\$345,470
B	Process Piping	60% A	207,282
C	Instrumentation	15% A	51,821
D	Process Building	334,000 cu. ft.	118,000
E	Service Facilities	50% A	<u>172,735</u>
F	Total Physical Plant		\$895,308
G	Engineering	40% F	358,123
H	Site Development	10% A	34,547
I	Pre-operational Expense	40% F	358,123
J	Contingency	30% F	<u>268,592</u>
K	Total Plant Investment		\$1,914,693

* See Table E.3.

TABLE E.6 ANNUAL FIXED COST FOR CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.01

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
L	Depreciation	15% K	\$59,943
M	Investment Costs	3% K	11,989
N	Labor Overhead	*	----
O	Maintenance Overhead	"T + U"	<u>110,331</u>
P	Annual Fixed Cost		\$82,263

* Included in Code "R", Table E.8.

TABLE E.7 ANNUAL FIXED COST FOR CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.003

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
L	Depreciation	15% K	\$287,204
M	Investment Costs	3% K	57,441
N	Labor Overhead	*	----
O	Maintenance Overhead	"T + U"	<u>49,241</u>
P	Annual Fixed Cost		\$393,886

* Included in Code "R", Table E.9.

TABLE E.8 ANNUAL VARIABLE COST FOR CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.01

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
Q	Raw Material	*	\$31,916
R	Direct Operating Labor and Supervision	**	35,040
S	Utilities	6% F	11,271
T	Maintenance Labor	5% F	9,392
U	Maintenance Supplies	0.5% F	939
V	Misc., Analytical, Storage, etc.	5% F	<u>99,392</u>
W	Annual Variable Cost		\$97,950
X	Annual Variable Cost Using Zero Raw Material Cost	(W - Q)	\$66,034

* 11,317 pounds carbon monoxide per year

** one operator per shift plus one supervisor per day

TABLE E.9 ANNUAL VARIABLE COST FOR CASCADE NUMBER 1
USING A SEPARATION FACTOR OF 1.003

<u>Code</u>	<u>Cost Designation</u>	<u>Factor</u>	<u>Cost</u>
Q	Raw Material	*	\$31,916
R	Direct Operating Labor and Supervision	**	61,320
S	Utilities	6% F	53,718
T	Maintenance Labor	5% F	44,765
U	Maintenance Supplies	0.5% F	4,476
V	Misc., Analytical, Storage, etc.	5% F	<u>44,765</u>
W	Annual Variable Cost		\$240,960
X	Annual Variable Cost Using Zero Raw Material Cost	(W - Q)	\$209,044

* 11,317 pounds carbon monoxide per year

** two operators per shift plus one supervisor per day

TABLE E.10 PRODUCT OXYGEN COST FOR CASCADE NUMBER 1USING A SEPARATION FACTOR OF 1.01AND ASSUMING NO CREDIT ALLOWANCE FOR WASTE OR SECONDARY PRODUCTS

<u>Code</u>	<u>Cost Designation</u>	<u>Cost Assuming CO Feed</u>	<u>Cost Assuming Zero Cost Feed</u>
AA	Annual Fixed Cost*	\$82,263	\$82,263
BB	Annual Variable Cost**	97,950	66,034
CC	Total Annual Operating Cost	\$180,213	\$148,297
DD	Operating Cost Per Day (10% oxygen-17)	\$494	\$406
EE	Product Oxygen Cost Per Gram (10% oxygen-17)	\$49	\$41

* See Table E.6.

** See Table E.8.

TABLE E.11 PRODUCT OXYGEN COST FOR CASCADE NUMBER 1USING A SEPARATION FACTOR OF 1.003AND ASSUMING NO CREDIT ALLOWANCE FOR WASTE OR SECONDARY PRODUCTS

<u>Code</u>	<u>Cost Designation</u>	<u>Cost Assuming CO Feed</u>	<u>Cost Assuming Zero Cost Feed</u>
AA	Annual Fixed Cost *	\$393,886	\$393,886
BB	Annual Variable Cost **	240,960	209,044
CC	Total Annual Operating Cost	\$634,846	\$602,930
DD	Operating Cost Per Day	\$1739	\$1652
EE	Product Oxygen Cost Per Gram (10% oxygen-17)	\$174	\$165

* See Table E.7.

** See Table E.9.

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