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ENGINEERING DEVELOPMENT OF
AN ABSORPTION PROCESS FOR THE
CONCENTRATION AND COLLECTION OF
KRYPTON AND XENON
SUMMARY OF PROGRESS THROUGH JULY 1, 1967

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NUCLEAR DIVISION

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UNION CARBIDE CORPORATION
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Oak Ridge Gaseous Diffusion Plant
Oak Ridge, Tennessee

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A B S T R A C T

Gas streams containing radioactive isotopes of the noble gases, krypton and xenon, must be safely processed to allow innocuous venting both in nuclear reactor accident situations and in future large-scale irradiated fuel reprocessing operations. One of the most direct methods for stripping krypton and xenon from contaminated air streams is selective absorption in a fluorocarbon solvent, such as refrigerant-12, and a development program has been recently initiated at the Oak Ridge Gaseous Diffusion Plant to provide engineering scale-up data for design of a plant using this technique. The scope of the work includes (a) the design, construction, and operation of a pilot plant system; (b) conceptual studies and equipment selection for a mobile gas absorption plant which could be transported to and installed at a reactor site following a release accident; and (c) process optimization studies. Progress in each of these areas is summarized. The pilot plant design is essentially complete, with procurement and construction of equipment scheduled to begin shortly. Conceptual designs for two versions of a mobile system, both variations of a reference flow sheet based on a minus 94°F absorption step, have been completed, and detailed cost estimates were prepared. The optimization studies are well under way, with a mathematical model of the process currently being constructed.

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TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	13
SUMMARY	14
PROJECT DEFINITION	15
PILOT PLANT STUDIES	16
Flow Sheet Development	19
Equipment Design	20
FEED GAS COOLERS	20
SOLVENT COOLERS	21
ABSORBER	21
FRACTIONATOR	22
STRIPPER	24
MECHANICAL EQUIPMENT	25
Gas Compressors	25
Solvent Pump	25
MISCELLANEOUS EQUIPMENT	25
Construction, Procurement, and Installation	25
Operation	25
MOBILE UNIT DESIGN	26
System Design Details	30
HEAD-END EQUIPMENT	30
Compressor	30
Air Purification System	32
PROCESS EQUIPMENT	33
Packed Columns	33

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TABLE OF CONTENTS (Continued)

	<u>Page</u>
Heat Exchangers	34
Solvent Pump	36
Miscellaneous Process Equipment	36
REFRIGERATION EQUIPMENT	36
Case 1 (No Mechanical Refrigeration)	36
Case 2 (Self-Contained Processing Unit)	36
Transportation	39
Utility Requirements	41
Capital Cost Estimate	41
OPTIMIZATION STUDIES	48
STATUS AND FUTURE PLANS	49
ACKNOWLEDGEMENTS	49
BIBLIOGRAPHY	51

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LIST OF TABLES

<u>Table</u>		<u>Page</u>
I	Estimated Pilot Plant Absorber Flooding Conditions	22
II	Estimated Pilot Plant Fractionator Minimum Column Diameters	23
III	Estimated Gas Stream Details for Mobile Unit Reference Flow Sheet	27
IV	Summary of Mobile Unit Heat Exchanger Loads	35
V	Summary of Mobile Unit Operating Utility Requirements	46
VI	Summary of Capital Costs	47

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WAS INTENTIONALLY
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LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Pilot Plant Reference Flow Diagram	18
2	Mobile Unit Reference Flow Diagram No. 1 - No Mechanical Refrigeration	28
3	Mobile Unit Reference Flow Diagram No. 2 - Self-Contained Processing Unit	29
4	Summary of Preliminary Vendor Quotations for Mobile Air Compressor Packages	31
5	Summary of Preliminary Vendor Quotations for Heat Exchanger Packages	37
6	Possible Equipment Arrangement for Mobile Unit Compressor Trailer	40
7	Possible Equipment Arrangement for Mobile Unit Process Equipment Trailer	42
8	Trailer-Mounted Brine System Equipment Arrangement . . .	43
9	Possible Equipment Arrangement for Mobile Unit Electrical Distribution and Instrumentation Trailer .	44
10	Tentative Mobile Unit Electrical Diagram	45

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ENGINEERING DEVELOPMENT OF AN ABSORPTION PROCESS
FOR THE CONCENTRATION AND COLLECTION OF KRYPTON AND XENON
SUMMARY OF PROGRESS THROUGH JULY 1, 1967

Radioactive isotopes of krypton and xenon are produced in significant quantities during irradiation of nuclear fuel. In the event of a reactor excursion causing cladding rupture or fuel meltdown, as well as during normal fuel reprocessing operations, these fission product gases are released to the surrounding containment. Because of this, the importance of noble gas handling is increasing with the growth of nuclear power. Not only must the possibility of exposure to radioactive krypton and xenon be evaluated in analyses of potential reactor hazards, but also the gaseous waste disposal problems of large fuel recovery plants must be dealt with satisfactorily. It is probable, then, that systems for processing gas streams containing these radioactive constituents will be required to allow innocuous venting both in reactor accident situations and in future spent fuel treatment operations.

Several methods for isolating krypton and xenon have been proposed in the past, and many of these have been demonstrated for specific applications. Some of the schemes which have received serious attention are mentioned in reviews by Browning⁽²⁾ and by Keilholtz⁽⁴⁾. In general, it is possible to categorize basic noble gas recovery operations either as (a) selective adsorption, using such sorbent materials as charcoal or molecular sieves; (b) cryogenic distillation; (c) preferential absorption in liquid solvents; or (d) special techniques, for example, trapping as clathrates or separation by selective permeation. Because krypton and xenon are essentially inert, suitable chemical means for collection are not available.

In view of revised performance requirements envisioned for noble gas collection systems designed for near-future power reactor applications, the Environmental and Sanitary Engineering Branch of the U. S. Atomic Energy Commission Division of Reactor Development and Technology is sponsoring engineering development projects at Oak Ridge aimed at evaluating two especially promising processes for controlling krypton and xenon release. The first technique, being investigated at the Oak Ridge National Laboratory, employs a unique silicone rubber membrane; the krypton and xenon selectively permeate this material and are concentrated after passage through cascaded membrane packages⁽¹⁾. A second method, the subject of this report, is being tested at the Oak Ridge Gaseous Diffusion Plant and is based on preferential absorption of the noble gases in a high capacity fluorocarbon solvent. In both projects, the primary emphasis is on determining scale-up data necessary to design a mobile gas cleaning system which can be transported to and installed at a reactor site following a release accident. The developed information, however, will be equally useful in designing units for fuel reprocessing situations.

The ORGDP program is divided into three areas; namely, pilot plant testing to collect engineering performance data; mobile unit design to investigate hardware availability, packaging, and cost; and optimization studies to

elucidate process operating conditions and equipment configurations which result in maximum reliability and minimum cost. Progress made in each of these areas during the first semiannual report period is discussed in turn following an outline of project ground rules.

SUMMARY

The purpose of the ORGDP noble gas collection program is the development on an engineering scale of an absorption process for the separation of radioactive krypton and xenon from a reactor environment following a nuclear incident. The scope of the work includes the design, construction, and operation of a pilot plant system which will be run to demonstrate feasibility and to obtain engineering data. Concurrently, conceptual design studies for a plant-size mobile absorption unit are being made. Also, process optimization studies are being initiated in order to generate conceptual plant data for a variety of processing conditions, so that pilot plant studies can be conducted in the most promising ranges and confident selection of the optimal plant configuration can be made.

The essential steps in this noble gas recovery process are absorption at a relatively low temperature and high pressure followed by a subsequent stripping operation conducted at a higher temperature and lower pressure. In some cases, an intermediate fractionation may be desirable for further concentration of the sorbed krypton and xenon.

During this report period, a considerable effort has been directed toward establishing a versatile pilot plant flow sheet and on designing the required process equipment items. Although the specific temperature-pressure conditions used in the design are absorption in refrigerant-12 solvent at minus 94°F and 14 atmospheres, fractionation at 32°F and 3 atmospheres, and stripping at 10°F and 2 atmospheres, all of the pilot plant units have been sized to accommodate a variety of temperatures, pressures, flows, and even a different solvent. A computer program, written to perform material balance calculations, has been used to furnish information for equipment sizing. The design of all pilot plant equipment, including feed gas coolers, solvent chillers, and absorber, fractionator, and stripper systems, is essentially complete, and most of the required fabrication drawings have been prepared.

The mobile unit design studies have centered around the development of preliminary equipment layouts and cost estimates for a portable plant-size system operating at the same conditions assumed for the pilot plant calculations. It was found, through numerous vendor contacts, that all required units, such as the compressor, heat exchangers, and, for one flow sheet version, a brine system, are commercially available in sizes which can be conveniently packaged in standard dimension trailers. Equipment layout drawings showing possible installation arrangements were prepared for a compressor trailer, a process trailer, a brine system trailer, and a control trailer.

Based largely on vendor quotes, the cost for the mobile plant has been estimated to be between \$630,000 and \$880,000, depending on whether liquid nitrogen or a mechanical system is used for low temperature refrigeration. Although these numbers represent cost limits for a plant processing 1600 scfm of gas and using the reference flow sheet, they are not presented as minimum costs for the absorption route itself, since it appears that both operation at higher temperatures and flow sheet simplification might result in substantial savings. These possibilities will be investigated thoroughly in the pilot plant and optimization study programs.

The optimization studies are well under way, with separate computer routines for calculating the performances of the flow sheet components currently being integrated into a mathematical model of the overall process. The effects on plant size and performance of varying temperatures, pressures, liquid-to-gas ratios, and numbers of stages, at selected processing times, are being established. Cost data will soon be incorporated into the computer programs.

PROJECT DEFINITION

The purpose of the ORGDP noble gas collection program is the development on an engineering scale of an absorption process for the separation of radioactive krypton and xenon from a reactor environment following a nuclear incident. The scope of the work includes the design, construction, and operation of a pilot plant system which will be run for a sufficient period of time to demonstrate feasibility and to provide engineering data. Concurrently, design studies for a plant-size mobile absorption unit are being made. Also, process optimization studies are being undertaken to generate conceptual plant data for a variety of processing conditions, so that pilot plant studies can be conducted in the most promising ranges. Pilot plant experience and results can then be applied to the final design of a mobile unit.

It should be emphasized that demonstration of the process should also allow its utilization at nuclear fuel reprocessing plants, where krypton and xenon are present in process vent gas streams. Although the optimization studies and design work are primarily focused on a mobile emergency unit, pilot plant testing will provide data equally useful in the design of reprocessing plant systems.

At the present time, the conceptual studies are being performed in accordance with the following assumed design criteria:

1. The nuclear reactor containment vessel volume is 3×10^6 cubic feet.
2. The required containment vessel krypton depletion factor is 100; i.e., 99% of the krypton must be removed.
3. The processing time allowed is one week. Actually, in the optimization studies, the processing time can be considered as a variable. The one-week value was chosen primarily for the initial design work.

4. The initial concentrations of krypton and xenon in the containment vessel are 100 and 650 ppm, respectively⁽⁶⁾.
5. The maximum volume available for krypton-xenon product storage is equivalent to 50,000 standard cubic feet. Thus, the maximum allowable product rate, for a one-week processing time, is about 5 scfm*.
6. The gas stream handled by the mobile unit has passed through a demister, iodine sorption traps, and particulate removal filters prior to entering the noble gas collection system.
7. The gas feed leaves the containment vessel at 80°F, 1 atmosphere, and 100% relative humidity.
8. The process equipment items are to be installed in trailers which are nominally 40 feet long and 8 feet wide, with about 8 feet of head room.
9. The amount of equipment setup work to be performed at the reactor site is to be limited to connecting the trailers to the reactor vessel, to each other, and to utility outlets.
10. Utilities, such as electricity and water, are available at the reactor site in the required quantities.

The above design assumptions are, in some cases, arbitrary and, in all cases, subject to change on the basis of pilot plant data, optimization study results, and AEC decisions concerning project ground rules.

PILOT PLANT STUDIES

K. E. Habiger and M. J. Stephenson

One of the most direct methods for stripping the noble gases, krypton and xenon, from contaminated air streams is selective absorption. The process can readily be made continuous, because the essential steps are conventional gas-liquid contacting operations. Several solvents, including carbon tetrachloride^(5,10,11), kerosene-base liquids^(7,8), liquid nitrogen⁽⁴⁾, nitrous oxide⁽⁹⁾, and dichlorodifluoromethane⁽⁹⁾, i.e., refrigerant-12, have been proposed. Because of solvent capacity and stability, as well as process safety, Steinberg has suggested the preferability of

* Initially, the krypton concentration is 300 cubic feet of krypton in the 3×10^6 cubic foot containment vessel. After processing, with 99% of the krypton removed from the reactor system, the product cylinders contain 297 cubic feet of krypton in a maximum of 50,000 cubic feet of stored gas. Thus, the minimum overall concentration factor needed for krypton is 59.4. Of course, to achieve this, single-pass concentration factors must be considerably larger, because of recycle of depleted gas.

fluorocarbon solvents and has collected solubility data for refrigerant-12⁽⁹⁾.

With refrigerant-12, krypton and xenon are markedly more soluble than argon, oxygen, and nitrogen, especially at temperatures below 0°F, and the separation factor between these two elements and the other gases increases considerably with decreasing temperature. Coupled with a direct pressure dependency for the solubilities, the temperature relationships allow a considerable latitude in the choice of processing conditions to achieve a given separation. Conceptually, then, an efficient absorption process can be devised from the solubility data by specifying an absorption step at some relatively low temperature and high pressure to maximize both absorption and separation, followed by a stripping operation conducted at a higher temperature and lower pressure to reclaim the noble gases as a product stream. Also, in some cases, an intermediate fractionating step may be desirable to allow further concentration of the krypton and xenon in the absorbed gas prior to recovery as product.

After tests with krypton-85 to establish radiation stability, a G-value for chlorine formation of 0.8 moles per 100 ev was estimated⁽⁹⁾. During processing, this would only result in ppm-range chlorine contamination of the product gas stream and would not represent serious solvent decomposition. In long-term product storage, however, the breakdown of the solvent collected (in low concentrations) with the product gases might be a significant factor requiring an additional product treatment step, so the problem is currently being looked at in more detail.

One version of the pilot plant flow diagram, based on the use of refrigerant-12 and temperature and pressure conditions suggested by the Brookhaven National Laboratory work⁽⁹⁾, is shown in figure 1. The feed gas is compressed to the absorber column operating pressure, 14 atmospheres, passed through a dessicant for moisture removal, and then cooled to minus 94°F, the absorption temperature. This stream is next introduced at the bottom of the packed column and is contacted with the downflowing liquid solvent. Gas leaving the top of the absorber, depleted in krypton and xenon, is used as a coolant for the incoming feed gas before being recycled or, perhaps, vented. Similarly, the liquid effluent from the bottom of the column, containing absorbed gas enriched in krypton and xenon, is first heated by the inlet solvent and is then fed, after some further warming, to a higher temperature, lower pressure (32°F, 3 atmospheres) fractionation system consisting of a flash unit, a packed column, a reboiler, and primary and secondary condensers. Use of cold exiting process streams to chill incoming feed streams allows a considerable reduction in refrigeration requirements and, consequently, in processing costs. In the fractionator, a portion of the absorbed nitrogen and oxygen is preferentially desorbed to concentrate the noble gases contained in the liquid further; the resulting gas stream, containing recycle krypton and xenon, in addition to argon, oxygen, and nitrogen, is returned to the bottom of the absorber. Liquid exiting from the fractionator is routed to a stripping system, again involving a flash unit, a packed column, a reboiler, and condensers. The stripper is operated at 10°F and 2 atmospheres, conditions at which essentially all remaining absorbed gas will be evolved as product.

PILOT PLANT FLOW SHEET VERSION #1

ABSORPTION AT -94°F , 14 ATM
 FRACTIONATION AT 32°F , 3 ATM
 STRIPPING AT 10°F , 2 ATM
 REFRIGERANT-12 SOLVENT
 (VERSION #1 CONDITIONS TAKEN FROM BNL-542)

Figure 1
 PILOT PLANT REFERENCE
 FLOW DIAGRAM

The solvent stream discharged from the reboiler is recycled through the solvent interchange cooler and a solvent chiller to the top of the absorber, thus completing the circuit.

Flow Sheet Development

During this report period, emphasis has been placed on establishing a versatile flow sheet and on designing the required pilot plant equipment items. Although the specific temperature-pressure conditions used in the design are those outlined by Steinberg⁽⁹⁾, all of the units have been sized to accommodate a variety of temperatures, pressures, flows, and even a different solvent. This latter fact is especially important, since operation with a higher temperature fluorocarbon solvent might be preferred over the use of refrigerant-12.

It should be noted that, in terms of equipment, the pilot plant flow sheet, figure 1, is probably more complex than required for either the mobile unit or a reprocessing plant system. To ensure the maximum yield of information from test results, however, it was considered desirable to have an equipment configuration which would allow performance testing of several equipment items which might be utilized in a plant-scale version. Thus, the pilot plant can be operated either with the fractionator flash unit, the fractionator column, the stripper flash unit, and the stripper column in series, or with any of these units bypassed completely. It is expected that test data may well show that some of the pilot plant units are not required for specific plant designs, thereby resulting in significant flow sheet simplifications for some larger scale applications.

As the first step in the development of the pilot plant flow sheet, a computer program was written to perform material balance calculations. Among the assumptions incorporated into the program are that the columns operate at constant temperature and pressure and that the use of Colburn's method⁽³⁾ for diffusional process analysis is valid since only dilute absorbed gas solutions are involved. In addition, it is assumed that the solvent stream entering the absorber column is pure.

Among the input parameters required for execution of the program are temperature, pressure, liquid-to-gas flow ratio, and the number of stages for each column, plus the absorber column gas flow rate and feed composition. The program then solves for the flows and concentrations corresponding to a mass-balanced process. At the present time, conditions suggested by Brookhaven National Laboratory experiments are being used as the basis for pilot plant design. Calculations have indicated, however, that the absorber column can be operated at a higher pressure and a correspondingly higher temperature with nearly the same results as for the reference low temperature case. Conversely, lowering the pressure would require an even lower temperature before comparable product specifications could be met. This pressure-temperature effect on krypton concentration suggests a set of optimum conditions where compressor and refrigerant loads are balanced such that the plant cost is minimized.

The pilot plant material balance code is now being used to investigate the effects of variation of operating conditions, as well as the effects of certain flow sheet modifications. For example, preliminary calculations have shown that the fractionator can be operated at about the same conditions as the stripper with essentially no change in performance. Also, calculations for the stripper flash unit have shown the flash curve to be extremely steep, suggesting control problems under some operating conditions.

Calculations have also been made to explore the possibility of replacing the stripper column with a simple vaporizer-condenser system. Instead of passing through a column, the liquid stream from the fractionator would be volatilized and then passed through a partial condenser. The results of preliminary calculations for such a system, however, have indicated that the dissolved gases may not be effectively stripped in this way, but the use of this system, or a similar one, as a possible flow sheet change is still being reviewed.

Equipment Design

The design of equipment for the pilot plant is essentially complete, and most of the required fabrication drawings have been prepared. Sizing of the pilot plant components was based on the criterion of processing 15 scfm of air at absorber pressures as high as 40 atmospheres. This flow rate and pressure are considered to be adequate for collecting mass transfer and throughput data needed for the confident engineering design of larger systems. Summaries of specific details for the various equipment items are given in the following sections.

FEED GAS COOLERS

Leaving the aftercooler of the booster compressor, the process air is expected to be at a temperature near 80°F. Before the gas can be fed to the absorber column, therefore, it must be cooled to minus 94°F, the operating temperature of the column. In order to reduce refrigeration costs, a two-step cooling procedure is incorporated into the pilot plant design. For most of the load, the otherwise wasted cooling capacity of the minus 94°F process air exiting from the absorber is utilized by passing it and the feed stream countercurrently through a heat exchanger. With a calculated heat transfer rate of 2,500 Btu/hr, this interchange accomplishes over 75% of the total required process gas cooling, and the feed temperature will be reduced from 80°F to around minus 55°F. Based on a calculated overall heat transfer coefficient of 3.7 Btu/hr-sq ft-°F, a heat transfer surface area of about 25 square feet is required for a nonfinned, one-pass, shell and tube heat exchanger.

The remainder of the process cooling will be done in the absorber gas chiller. This exchanger consists of three coils of 1-inch stainless steel tubing wound on a 9-3/4-inch radius, with the coils pitched 8 inches apart. The assembly will be immersed in a refrigerant bath maintained at about minus 110°F. The chiller is designed to remove 730 Btu/hr from the process

gas stream. With an overall heat transfer coefficient of 10 Btu/lb-sq ft-°F, 2.3 square feet of inside surface area is required.

SOLVENT COOLERS

The process flow sheet calls for the krypton and xenon rich refrigerant stream leaving the absorber to be warmed from minus 94°F to around minus 5°F or higher prior to flashing in the fractionator flash unit. On the other hand, the incoming refrigerant solvent, pumped from a storage tank maintained at 0°F, must be cooled to the column temperature. The purpose of the solvent interchanger is to facilitate an efficient transfer of heat between the two refrigerant streams. With the loaded solvent stream entering the interchanger at a temperature of minus 94°F and being warmed to minus 15°F, 19,900 Btu/hr must be transferred between the two fluids to cool the incoming refrigerant stream to approximately minus 80°F. Anticipating an overall heat transfer coefficient of 100 Btu/hr-sq ft-°F, 16.0 square feet of exchanger surface area will be required for a single pass shell and tube heat exchanger.

The solvent chiller completes the cooling of the pure refrigerant feed. This chiller consists of ten coils of 3/4-inch stainless steel tubing wound on a 3-5/8-inch radius, with coils spaced 2-3/4 inches apart. The coils are immersed in the same refrigerant bath used for the absorber gas chiller. Based on an overall heat transfer coefficient of 64 Btu/hr-sq ft-°F, an inside surface area of 2.34 square feet will be required to handle the 3,300 Btu/hr cooling load. At this rate, the solvent chiller handles less than 15% of the total solvent cooling load.

ABSORBER

The absorber column is a 3-inch-diameter stainless steel pipe, 10 feet high, with a 9-foot packed height. The initial packing tested will probably be metal Goodloe column packing*, although Pro-Pak† protruded metal distillation packing and ceramic Intalox saddles‡ may be used in later tests. There are three 3-foot sections of packing, with intermediate gas sample points provided between the segments.

Two items of major interest in the experimental program are, of course, the mass transfer efficiencies and pressure drop characteristics of the packings tested. Estimated flooding velocities for the packings considered for pilot plant testing are listed in table I for various temperatures and pressures. It can be seen that a wide range of processing conditions can probably be tolerated without flooding the column at the 15 scfm air flow.

* Product of the Packed Column Corporation, Springfield, New Jersey.

† Product of the Scientific Development Company, State College, Pa.

‡ Product of U. S. Stoneware, Inc., Akron, Ohio.

TABLE I
ESTIMATED PILOT PLANT ABSORBER FLOODING CONDITIONS

Temperature, °F	Pressure, atm	Estimated Flooding Flow*, scfm		
		Goodloe	3/8-Inch Intalox	Pro-Pak
- 94	14	29	19	17
- 94	40	35	24	21
- 50	20	29	20	17
- 10	30	30	21	18

* Flooding rates were predicted using standard correlations published by the Packed Column Corporation, U. S. Stoneware, Inc., and the Scientific Development Company. The L/G ratio assumed for these calculations was 15.

FRACTIONATOR

The fractionator system consists of a flash unit and a packed column, with an associated reboiler and both primary and secondary condensers. The flash unit is a 6-inch-diameter stainless steel cyclone, approximately 30 inches high, equipped with a tangential gas inlet, a liquid drain, and a gas outlet pipe and mist shield. The design of this unit was based on limiting the peripheral gas velocity to 45 ft/sec under conditions where 100% of the liquid feed flashes.

The fractionator column design is identical to that used for the absorber, except that provisions have been made for feeding between packed sections, if desired. Table II presents column diameters estimated for operation of the column at 70% of the flooding rate with the same packings considered for the absorber. From these calculations, it appears that the 3-inch-diameter allowed should suffice for wide ranges of pilot plant test conditions.

TABLE II
ESTIMATED PILOT PLANT FRACTIONATOR MINIMUM COLUMN DIAMETERS

L/G Ratio	Temperature, °F	Pressure, atm	Estimated Minimum Column Diameter, inches*		
			Goodloe	3/8-Inch Intalox	Pro-Pak
100	32	3	1.9	3.5	2.6
100	32	6	1.8	2.4	2.5
100	10	2	2.1	2.7	2.9
150	32	3	1.8	2.3	2.5
50	32	3	2.1	2.8	2.9

* Values correspond to 70% of the estimated flooding flow, as predicted using correlations published by the Packed Column Corporation, U. S. Stoneware, Inc., and the Scientific Development Company. The liquid flow rate assumed in the calculations was approximately 1.43 gpm solvent fed to the fractionator system.

A reboiler is required at the bottom of the fractionator column to provide the heat necessary to generate a stripping vapor stream. An enthalpy balance around the fractionator column and reboiler, assuming no preheating of the feed, indicates a heating requirement of 9,500 Btu/hr, or about 2.8 kw. To allow operating flexibility, the reboiler will be equipped with a 5 kw electrical heater. The unit will be built from a 3-foot-long section of 8-inch stainless steel pipe.

Two condensers, a primary overhead condenser and a final condenser, are needed to remove solvent from the gas streams leaving the flash unit and the fractionator column. Without these condensers, over 30 lb/hr of refrigerant-12 would be vented, creating problems due to condensation in gas lines when the stream is recycled through the booster compressor and heat exchangers back to the absorber.

Most of the cooling load, as presently designed, falls on the mechanically refrigerated overhead condenser, with the low temperature final condenser relied on for as little cooling as possible. With the gas entering the overhead condenser at 32°F and leaving the unit at minus 40°F, 21.9 lb/hr of refrigerant-12 will be condensed. The cooling requirement here, 2,000 Btu/hr, represents over 70% of the total load. Most likely, the unit will be a shell and tube heat exchanger, and boiling refrigerant-22, with an operating temperature of minus 70°F, will be used as the coolant. An estimate of the surface area required for this service, assuming an overall heat transfer coefficient of 5 Btu/hr-sq ft-°F, is 6.9 square feet.

By further cooling the gas stream to minus 94°F, the fractionator final condenser removes an additional 8.2 lb/hr of refrigerant-12 from the gas stream leaving the fractionator. The cooling will be achieved through the use of a refrigerant bath similar to the one used to complete the cooling of the absorber gas and solvent streams. The calculated heat load on the final condenser is 810 Btu/hr. Based on an overall heat transfer coefficient of 3 Btu/lb-sq ft-°F, 7.4 square feet of condensing surface is required.

STRIPPER

In terms of required equipment items, the stripper system is identical to the fractionator. There are, however, a few important departures in design details.

While the stripper flash unit design is the same as that used for the fractionator, it appears that the packed column must be significantly larger in diameter than the fractionator column. For this reason, a 6-inch-diameter stainless steel pipe, 9 feet high, containing approximately 8 feet of packing in two sections will be used. With a liquid-to-gas ratio of 7, a temperature of 10°F, and a pressure of 2 atmospheres, it is estimated that column diameters of 4.0, 4.4, and 4.7 inches would be necessary for operation at 70% of flooding with Goodloe packing, 3/8-inch Intalox saddles, and Pro-Pak, respectively. Thus, the 6 inches provided should permit substantial variation of operating conditions.

The reboiler for the stripper will be the same size as that used for the fractionator. The nominal heat load is 12,600 Btu/hr, or 3.7 kw, with 5 kw actually supplied.

The stripper overhead condenser and final condenser serve the same purposes as the fractionator condensers; i.e., they remove most of the refrigerant-12 vapor from the krypton and xenon product stream leaving the stripper column and flash unit. As before, the bulk of the heat load falls on the mechanically refrigerated overhead condenser. In fact, because the amount of noncondensables is small, over 99% of the required load can be carried by the first unit. The product gas stream leaves the overhead condenser at about minus 30°F. With a calculated heat load of 17,000 Btu/hr, around 224 lb/hr of refrigerant will be condensed. Although the size is much larger, the basic design of the stripper overhead condenser will probably be the same as that used for the fractionator overhead condenser. Assuming an overall heat transfer coefficient of 5 Btu/hr-sq ft-°F, 31.8 square feet of condensing surface will be required.

The cooling load on the stripper final condenser is small, 14 Btu/hr, and only an additional 0.16 lb/hr of refrigerant-12 will be condensed at this point. With an overall heat transfer coefficient of 1 Btu/hr-sq ft-°F, less than 1 square foot of condenser surface area is required.

MECHANICAL EQUIPMENT

Gas Compressors

Requirements established for the pilot plant gas compressor package are as follows:

- a. Suction conditions - 1 atmosphere and 70°F
- b. Discharge conditions - approximately 40 atmospheres and 80°F
- c. Flow rate - 15 scfm (70°F, 1 atmosphere basis)

The package will also include a dessicant trap, an aftercooler, and a receiver so that dry, oil-free air can be supplied at a maximum temperature of 80°F and at pressures up to 600 psia.

Solvent Pump

The specifications for the solvent pump, which will be of the diaphragm metering type, include the following items:

- a. Suction temperature - 0°F
- b. Suction pressure - flooded
- c. Discharge pressure - 40 atmospheres
- d. Maximum flow rate - 2.5 gpm

MISCELLANEOUS EQUIPMENT

In addition to the equipment items just described, liquid and gas surge tanks will also be required. Also, a krypton-xenon supply station and a sampling system are being designed.

Construction, Procurement, and Installation

Construction of the pilot plant equipment will begin shortly, with installation expected to begin during the next report period. Requisitions for the equipment items which will be purchased, namely, the gas and liquid interchange coolers, the overhead condensers, the gas compressor, the solvent pump, and miscellaneous instrumentation, are being prepared and will be issued shortly.

Operation

Pilot plant operation should commence early in calendar year 1968 with shakedown tests.

MOBILE UNIT DESIGN

B. F. Crump and J. L. Hammontree

Based on system calculations made using the pilot plant flow sheet code, mobile unit design studies are being conducted by the ORGDP Plant Engineering Division. To date, these studies have centered around the development of preliminary equipment layouts and cost estimates for a transportable plant-size noble gas removal system operating at the conditions specified by Steinberg⁽⁹⁾. For this reference plant design, emphasis has been placed on determining costs and availability of commercial items suitable for trailer installation.

The initial process gas flows and compositions for the reference flow sheet are listed in table III. These values were estimated using the pilot plant material balance computer code, assuming absorption at minus 94°F and 14 atmospheres, fractionation at 32°F and 3 atmospheres, and stripping at 10°F and 2 atmospheres. The 1410 scfm feed rate corresponds to about five total containment vessel recycles during the 1-week operating period. Calculations have indicated that, as the concentrations of krypton and xenon in the feed are lowered, the compositions and flow rates of the other streams are affected somewhat. The most noticeable change appears to be in the product stream, where there is a decrease in both flow rate and krypton concentration as the feed concentration diminishes; the net effect, however, considering the low feed concentration, is an increase in the overall ratio of product krypton concentration to feed concentration. To bracket the possible plant costs, two versions of the basic flow scheme, differing only in refrigeration recovery and supply methods, were considered. In the first version, outlined in figure 2, as much cooling value as possible was reclaimed from the absorber off-gas stream, and liquid nitrogen was relied on for all remaining refrigeration. Thus, in addition to electricity and cooling water, the mobile unit would, in this case, require a large supply of liquid nitrogen. The second version, detailed in figure 3, is a self-contained system which provides for all of the low-temperature refrigeration by first compressing more air than needed for the process, and then routing the excess, after some cooling, with the absorber off-gas through a turbine, where the temperature is lowered considerably by the nearly isentropic expansion. This low-temperature gas stream is then used as a process stream coolant. The remainder of the cooling load in this version is borne by an intermediate temperature-level brine system.

At this point, it should be noted that neither case described here represents an optimized version of the process. In fact, these designs and estimates were made prior to the completion of the optimization studies (which are described in the next chapter) only because it seemed timely to set forth some realistic numbers for comparison with estimated costs of other processes, as well as with costs which will be developed later as a part of the optimization work.

TABLE III
ESTIMATED GAS STREAM DETAILS
FOR MOBILE UNIT REFERENCE FLOW SHEET

Gas Stream	Initial Flow Rate, scfm*	Initial Composition, mole percent					
		Nitrogen	Oxygen	Argon	Xenon	Krypton	Refrigerant-12
Feed from Reactor	1410	78.1	20.9	0.9	650†	100†	0
Recycle to Absorber from Fractionator	190	57.7	35.9	2.1	0.2	0.5	4.0
Total Feed to Absorber	1600	75.7	22.7	1.04	810†	680†	0.5
Absorber Off-Gas	1408	77.5	20.7	0.9	0.2†	8†	0.9‡
Product	1.5 to 2.0	5.3	25.9	4.9	49.3	8.6	6.2§

* Refrigerant-free basis.

† These values are reported in ppm.

‡ Over 70% of the solvent in the absorber off-gas stream is removed by cooling either in an air chiller (case 1) or in an expansion turbine (case 2). This liquid is routed to the solvent pump inlet, and the gas is returned to the reactor.

§ Because of possible solvent deterioration due to irradiation during long-term product storage, this concentration may have to be reduced prior to collecting the product. Studies are under way to evaluate this problem.

Figure 2
MOBILE UNIT REFERENCE FLOW
DIAGRAM NO. 1 - NO MECHANICAL
REFRIGERATION

Figure 3
MOBILE UNIT REFERENCE FLOW
DIAGRAM NO. 2 - SELF-CONTAINED
PROCESSING UNIT

System Design Details

The mobile unit equipment can be conveniently subdivided into a head-end system, a processing system, a refrigeration system, and a control system. The division along these functional lines is also essentially the same as the physical division between the various trailer-mounted packages.

HEAD-END EQUIPMENT

The function of the head-end system is to supply a suitable gas feed to the processing equipment at a rate high enough to ensure adequate containment vessel decontamination in the allowed cleanup time. It is important that the system perform this function with a minimum of energy and refrigeration value loss, at the same time protecting the process from fouling with such extraneous materials as water vapor, carbon dioxide, and oil. The major equipment items in this portion of the plant are a compressor, with accessories, and an air purification system.

Compressor

In the plant version utilizing liquid nitrogen refrigerant, the required compressor capacity is simply the absorber feed gas flow, 1600 scfm. When an expansion turbine is employed to provide a low temperature coolant, a 2400 scfm machine is needed. Because the capacity of this second compressor was not established when vendor contacts were first begun, inquiries were made concerning a 4000 scfm unit, to be conservative. Specific criteria used in contacting compressor manufacturers include:

1. Capacity - 1600 scfm (case 1); 4000 scfm (case 2)
2. Suction conditions - 90°F, 1 atmosphere
3. Delivery conditions - 90°F, 14 atmospheres
4. Package size - less than 40 feet long, 8 feet wide, and 8 feet high
5. Vibration - negligible, to allow trailer mounting
6. Seal requirement - no leakage to atmosphere
7. Utilities available - electricity and 85°F cooling water

Ten vendors were contacted, and five evidenced a definite capability for supplying compressors for at least one of the two cases. Three manufacturers proposed package units employing a two-stage rotary screw compressor for both the low and high flow service. Each of these systems includes electric motor, speed increaser, inlet filter, silencers, intercooler, aftercooler, lubrication system, and special seal arrangement. Costs furnished by the three vendors for the 1600 scfm and 4000 scfm rotary screw compressors are plotted in figure 4. The prices were based on completely piped systems, factory mounted on structural steel base plates sized for convenient trailer installation. Typical power

Figure 4
SUMMARY OF PRELIMINARY
VENDOR QUOTATIONS FOR MOBILE AIR COMPRESSOR PACKAGES

requirements at the two flow levels were up to 700 and 1500 hp, respectively, with cooling water loads of about 60 and 100 gpm.

Two other firms expressed interest only in the higher capacity unit and supplied data for centrifugal compressor systems including speed increasers, intercoolers, surge controls, and lubrication systems mounted as before on steel base plates. The prices varied considerably, with only one of the bids competitive. The differences in quotations for comparable units probably reflect the extent to which "shelf items" must be altered to allow packaging in trailers.

Considering the proposals, it appears that a two-stage rotary screw compressor system would be best suited for the mobile unit application, at least for the reference flow sheet case. Relatively oil-free air delivery, small space requirements, low vibration while operating, and a probable lower cost give this system a distinct advantage over others considered. It is significant that all of the vendors contacted indicated that, because of machine vibration, a reciprocating compressor system would not be satisfactory for trailer mounting unless flow rates were substantially lower than those presently envisioned. A reciprocating compressor system satisfying all of the design conditions would be considerably larger, would probably require a thick concrete foundation, and could cost 15 to 20% more than a rotary screw system. If lower flow rates, corresponding to considerably longer processing times, were permitted, it appears that throughput requirements could perhaps be eased sufficiently for reciprocating compressors to become competitive.

It is also interesting to note that lower delivery pressures would probably have made a centrifugal compressor system more attractive. It was found that several very compact centrifugal units are commercially available with delivery pressures in the range of 80 to 130 psia. The flow rates for these systems typically vary from 1,500 to 10,000 scfm. For example, one such compressor, handling 3000 scfm at 130 psia, has overall dimensions of 5 feet by 5 feet by 6 feet. Another unit has a capacity of 2100 scfm at a pressure of 125 psia, with space requirements of 4-1/2 feet by 6-1/2 feet by 12-1/2 feet.

Air Purification System

A two-stage system for the removal of moisture, carbon dioxide, and oil from the process gas stream is used for the mobile unit. The first step involves cooling the compressed gas to effect condensation of a large amount of the contained water vapor, while the second operation is trapping on dessicant beds. Although there are other methods which can be employed for the removal of traces of contaminants from compressed air streams which are to be used in low-temperature processes, this scheme was chosen because of its mechanical simplicity.

First-Stage Process Gas Cooler. As mentioned above, the compressor package will include a water-cooled aftercooler designed to lower the temperature of the discharged air to about 90°F. Additionally, a second heat exchanger will be located immediately downstream of the aftercooler to

reduce the moisture content of the incoming process air stream by cooling it to about 37°F. The coolant for this exchanger is the process gas being returned from the absorber to the containment vessel. Depending on the process gas flow, the cooling load expected for this exchanger is between about 94,000 and 140,000 Btu/hr. Design details and costs for this and other exchangers are presented in later sections.

Dessicant Traps. Only one manufacturer was contacted regarding the design of dessicant traps for the mobile unit application, and this vendor recommended the use of molecular sieve beds. For a system handling 1600 scfm of air saturated at about 35°F, a 2-foot-inside-diameter by 7-foot-high trap, filled with 1500 pounds of sorbent, was specified. It was stated that this system would reduce the dew point of the gas to less than minus 160°F, while lowering carbon dioxide and oil contents to 1 ppm or below. For continuous processing, a dual trap system is necessary, with an 8-hour cycle time for each trap. The beds can be regenerated in place by heating at 450°F for 5 hours followed by 3 hours' cooling, using a small portion of the dry returning process gas stream as the regenerating gas.

PROCESS EQUIPMENT

Packed Columns

Three packed columns are required for the reference flow sheet cases; the functions of the absorber, fractionator, and stripper have already been discussed in the previous chapter. Based on absorption at minus 94°F and 14 atmospheres, fractionation at 32°F and 3 atmospheres, and stripping at 10°F and 2 atmospheres, diameters tentatively predicted for the columns are:

1. Absorber - 25 inches
2. Fractionator - 21 inches
3. Stripper - 48 inches

These estimates were arrived at using 70% of the flooding velocity calculated for Goodloe column packing. The packing height allowed in each column is only 5 feet due to the limited headroom.

The choice of packing material for the mobile unit columns must, in any final design, be arrived at on the basis of both economic considerations and physical limitations. A low-cost, high capacity packing has the advantage of relatively small required column diameters, but, because of fairly large stage heights common with most of these materials, use of this type of packing would probably necessitate having multiple columns,

operated in series, to achieve the desired number of stages*. On the other hand, high efficiency packings are usually more expensive and are also characterized by relatively low throughputs, resulting in large diameter columns. Goodloe packing was tentatively chosen for these initial estimates because it appears to be a relatively high efficiency, yet low-cost, material, with an intermediate capacity. As mentioned earlier, an important aspect of the pilot plant testing program will be clarification of the packing selection problem by providing actual stage height and throughput data.

Due to the rather low processing temperatures, especially in the absorber, the material of construction for the columns was chosen to be stainless steel 304L. This conservative selection should allow meeting pressure vessel standards readily, because of the comparative ease of achieving good welds; however, when a final plant design is begun, the possibility of using other less expensive materials, such as weldable aluminum alloys, will be investigated.

Heat Exchangers

Several heat exchanger manufacturers were asked to supply performance information and cost data for compact exchangers, and two of the vendors who responded specified especially interesting variations of the same basic design for each mobile unit heat transfer application. These units are built from corrugated aluminum sheets which are sandwiched between two flat aluminum plates and sealed at the sides with aluminum strips, thereby providing numerous fluid flow passages. This configuration can be repeated by layering in a variety of fashions, with the result that heat exchangers can be readily tailored to meet specific requirements. In fact, these units can be designed to have any of several flow patterns and can be employed as gas coolers, liquid coolers, or condensers. Also, more than one exchanger can be housed in a single package. Because of the very large specific heat transfer surface areas possible (up to about 500 square feet per cubic foot), the close approach temperatures permitted, and the low costs, compact heat exchangers of this type have been used widely in aircraft, in military vehicles, and in other systems with stringent space and weight requirements.

Since the mobile unit will not be operated for sustained periods, aluminum appears satisfactory as a heat exchanger construction material. For longer term operation, this material might still suffice, although tests would be required to establish limits on the amount of chlorine which could be tolerated in the process gas streams. Furthermore, the brazed construction normally used seems adequate for safe operation at the process temperatures and pressures assumed for the reference plant design.

Heat loads for the required exchangers are listed in table IV. Each of the coolers is of the compact design just described, and total installed

* Of course, the situation would be different in reprocessing plant systems, because overall column heights in that case are not limited to a few feet.

TABLE IV
SUMMARY OF MOBILE UNIT HEAT EXCHANGER LOADS

<u>Coolers</u>	<u>Cooling Load, Btu/hr</u>	
	<u>Case 1*</u>	<u>Case 2†</u>
First-Stage Air Interchanger	94,000	140,000
Second-Stage Air Interchanger	230,000	350,000
Air Chiller	60,000	not required
Solvent Interchanger	2,000,000	2,000,000
Solvent Chiller	82,000	82,000
Fractionator Overhead Condenser	190,000	190,000
Fractionator Final Condenser	100,000	100,000
Stripper Overhead Condenser	1,600,000	1,600,000
Stripper Final Condenser	2,000	2,000
<u>Heaters</u>	<u>Heat Load, kw</u>	
	<u>Case 1*</u>	<u>Case 2†</u>
Fractionator Reboiler	275‡	275‡
Stripper Reboiler	350	350

* In case 1, the process gas flow is 1600 scfm, and a liquid nitrogen cooling system is employed.

† In case 2, the process plus excess gas flow is 2400 scfm, and an expansion turbine system is utilized for low temperature refrigeration.

‡ A portion of this load may be borne by feed stream preheaters.

costs based on estimates furnished by two firms which build these units, as well as layout drawings indicating approximate package sizes, are presented in later sections. The estimated purchase prices (excluding indirect costs and installation charges) are plotted versus surface area in figure 5. The two heaters, i.e., the fractionator and stripper reboilers, are fired by electrical immersion heaters inserted into shells which are integrally associated with the bottoms of the packed columns.

Solvent Pump

Three pump manufacturers were contacted regarding the solvent pump; specifications included a maximum capacity of 175 gpm and a discharge pressure of 210 psia. Since the estimated price was relatively low, it was decided to install a spare to ensure continuous operation. The specific pumps selected are line-mounted, 3550 rpm, centrifugal units, with carbon seals.

Miscellaneous Process Equipment

Other process equipment items required for the mobile unit include a small (2 scfm) product compressor and product storage cylinders. The actual details of product handling and packaging have not yet been considered in the present studies.

REFRIGERATION EQUIPMENT

Case 1 (No Mechanical Refrigeration)

In deciding on the first version of the reference flow sheet, figure 2, the goal was presentation of a plant case having a minimum capital investment for the assumed processing conditions. Hence, although as much cooling value as possible is recovered from cold process streams by routing them through heat interchangers, no mechanical refrigeration equipment is included in the plant design, and liquid nitrogen is relied on for all remaining cooling. As a result, several tons of liquid nitrogen are needed each day the mobile unit is operated, with a total estimated daily cost of about \$7500. After being used as the coolant, the nitrogen is vented to the atmosphere.

The principal objection to the total use of liquid nitrogen arises because this scheme requires that an additional plant input be provided in order for the unit to be operated continuously. Contacts with two of the largest companies engaged in liquid nitrogen manufacture have indicated that tonnage quantities can indeed be delivered throughout the United States on rather short notice (and on proper authority) to meet emergency needs. On balance, however, such large nitrogen loads, especially continuing for several days, may well be considered to constitute an undesirable logistics problem, in spite of the low capital investment.

Case 2 (Self-Contained Processing Unit)

The second version of the reference flow sheet, figure 3, illustrates the case where the capital investment for the mobile plant is a maximum for

DWG. NO. G-67-558

Figure 5
SUMMARY OF PRELIMINARY
VENDOR QUOTATIONS FOR HEAT EXCHANGER PACKAGES

the basic operating parameters but where there are no service ties except for electricity and water. In addition to the 1600 scfm process gas flow, the compressor is sized to deliver another 800 scfm which bypasses the absorber column and is subsequently blended with the absorber off-gas. This stream is then fed through an expansion turbine, lowering the temperature to about minus 200°F. This cold gas is then split into two streams which are routed separately to the solvent chiller and to the final condenser package*. Upon leaving these units, the coolant gas streams are again blended and passed to the second stage air interchanger, entering that equipment item at approximately minus 125°F. In this exchanger, the coolant flows countercurrent to the incoming process gas stream and exits the unit at a temperature near 30°F. The 30°F stream is, in turn, used as coolant in the first stage air intercooler before it is finally returned to the reactor containment vessel.

The air expansion cooling technique accomplishes all of the low temperature refrigeration needed for mobile unit operation. The most sizable cooling loads, i.e., the intermediate temperature level fractionator and stripper condenser loads cannot, however, be satisfied practically using this scheme, so that a 150-ton brine system is also provided. Data for the expansion turbine and for the brine unit are given in the following sections.

Expansion Turbine Details. One manufacturer was contacted for design information for expansion turbines which might be suited for the mobile plant application. When the inquiry was made, it was thought that two turbines might be required, so conditions were outlined as follows:

Turbine No. 1: Air flow - 6,300 lb/hr
 Inlet conditions - minus 90°F, 200 psia
 Outlet conditions - minus 202°F, 40 psia

Turbine No. 2: Air flow - 11,500 lb/hr
 Inlet conditions - minus 75°F, 200 psia
 Outlet conditions - minus 209°F, 30 psia

The vendor proposed two turbine systems, each equipped with compressor loader, lubrication system, seal gas system, and various controls. The utility requirements for each system included 5 to 25 scfm of nitrogen seal gas, 5 gpm cooling water for the lubrication system, and electricity for the 5 hp oil pump motor. Both units were capable of being operated with liquid loadings up to 10%. Later studies have shown that both systems are not required, however, and that the smaller unit alone should be adequate, thus reducing the low temperature refrigeration cost accordingly.

Brine System Details. Four manufacturers were contacted to obtain information about possible brine refrigeration systems for the mobile unit. The capacity specified was 150 tons refrigeration, i.e., 1,800,000 Btu/hr

* The fractionator and stripper final condensers are housed in a common heat exchanger package.

heat removal capacity. Two temperature levels were investigated, minus 15°F and minus 40°F.

All four vendors expressed an interest in the minus 15°F system. One of the preliminary quotations was made after only a cursory review of specifications and was not competitive. The three remaining estimates, however, were each near \$100,000, plus or minus 15% depending on whether the equipment is supplied unmounted, skid-mounted, or installed in trailers. Two of the firms also quoted on the minus 40°F system. Again, one of the bids was not competitive, but the other estimate indicated that the lower temperature unit would cost approximately 20% more than the minus 15°F system.

Transportation

For the initial studies, the mobile unit trailer size was fixed at that of a standard van type trailer, with nominal outside dimensions of 8 feet in width by 40 feet long by 13-1/2 feet high (from the road) and an inside height of 8 feet. Using such trailers, the mobile unit could easily be hauled over the road, although special permits would be necessary in most states because the compressor and brine system trailers would weigh 55,000 to 60,000 pounds. The trailers could also be shipped on railroad flatcars. In considering air transportation, however, no presently built commercial aircraft capable of carrying this size trailer has yet been found, and information on the availability of large military transports is now being gathered. Based on dimensional specifications for the mobile unit equipment packages, however, it appears that smaller trailers, specially designed for air transportation*, could be employed without seriously affecting the hardware choices.

Three firms were contacted for preliminary quotations on standard dimension trailers, and the costs estimated were about \$5,000 in each case. Additional charges, as noted in a later section, are expected for some of the trailers because of modifications which will be necessary. For example, a portion of the floor in the process trailer will be lowered to accommodate the fractionator and stripper reboilers, and the compressor trailer will be sealed. It is assumed that cabs for the trailers will be readily available for emergency service from any of several government installations or private agencies, so costs for these items were not considered.

Depending on the choice of refrigeration method, either three or four trailers are required to house the present versions of the mobile system. Figure 6 illustrates a possible trailer layout for the head-end equipment, which includes the compressor package, the first-stage gas interchanger,

* Dimensions found for one type of air-transportable trailer are a length of 40 feet, a width of 7-1/2 feet, and a height of 7 feet. Airplane loading is accomplished by retracting the wheels into storage compartments located inside the trailer.

- (201) AIR COMPRESSOR FIRST STAGE SILENCER
- (202) AIR COMPRESSOR SECOND STAGE SILENCER
- (203) AIR COMPRESSOR INTERSTAGE SEPARATOR
- (204) AIR COMPRESSOR DISCHARGE SEPARATOR
- (205) FIRST STAGE AIR INTERCHANGER SEPARATOR
- (301) AIR COMPRESSOR INTERCOOLER
- (302) AIR COMPRESSOR AFTERCOOLER
- (303) FIRST STAGE AIR INTERCHANGER
- (310) SIEVE REGENERATOR
- (501) AIR COMPRESSOR SPEED INCREASER
- (502) FIRST STAGE AIR COMPRESSOR
- (503) SECOND STAGE AIR COMPRESSOR
- (506) COMPRESSOR TRAILER
- (601) MOLECULAR SIEVE BED A
- (602) MOLECULAR SIEVE BED B
- (701) 700HP 4160V ELECTRIC MOTOR
- (709) SIEVE REGENERATOR HEATER
- (901) LUBE OIL CONSOLE

Figure 6
POSSIBLE EQUIPMENT ARRANGEMENT
FOR MOBILE UNIT COMPRESSOR
TRAILER

and the dessicant traps. The process equipment, including all columns, heat exchangers, and an expansion turbine, if used, can also be installed in a single trailer, as shown in figure 7. A trailer-mounted brine system, used in one version of the reference flow sheet, is outlined in figure 8. It should be noted that these drawings are intended to show only the essential equipment arrangements and are not piping diagrams.

The final trailer, to serve as an electrical distribution and process control center, is shown in figure 9. Liquid nitrogen tank cars and a supply header (perhaps mounted in another trailer) would, of course, be needed instead of the brine trailer for the plant using this cooling technique. Additionally, a smaller trailer might be desired for housing operating personnel but is not included as a part of the present system.

Utility Requirements

The operating electrical power and cooling water requirements for the mobile unit are listed in table V. Depending on the method used for refrigeration, between about 1.3 and 1.9 mw and from 65 to 940 gpm will be needed during operation. A one-line electrical diagram showing installed electrical capacity and switching arrangements for the various equipment items is shown in figure 10.

Capital Cost Estimate

The capital cost estimate for the reference flow sheet mobile unit design is given in table VI. The total costs expected for the liquid nitrogen cooled (case 1) and mechanically refrigerated (case 2) versions, including equipment purchase, installation, piping, insulation, instrumentation, electrical distribution, indirect charges, and a contingency, are about \$630,000 and \$880,000, respectively. These numbers represent limits for systems operated at the assumed processing conditions, and other flow sheet versions at the same temperatures and pressures with different refrigeration system combinations, e.g., use of some liquid nitrogen and some brine, appear to be of intermediate cost.

The cost estimates were based almost entirely on manufacturers' quotations or catalogue prices. In fact, all of the equipment items selected for the mobile application were essentially standard vendor units, presently available, so that no significant cost or performance extrapolation was required.

The total capital cost for the system employing liquid nitrogen is naturally much lower than the cost for the self-contained plant, since the liquid nitrogen charges are primarily operating costs which would be incurred only if the mobile unit is operated. Any choice between the two systems, however, would have to be made weighing the desirability of depending on sustained deliveries of large quantities of this coolant.

- (101) ABSORBER
- (102) FRACTIONATOR
- (103) STRIPPER
- (207) FRACTIONATOR OVERHEAD SEPARATOR
- (208) STRIPPER OVERHEAD SEPARATOR
- (209) FRACTIONATOR FINAL SEPARATOR
- (210) STRIPPER FINAL SEPARATOR
- (211) TURBO-EXPANDER DISCHARGE SEPARATOR
- (304) SECOND-STAGE AIR INTERCHANGER
- (308) FRACTIONATOR REBOILER
- (309) STRIPPER REBOILER
- (311) SOLVENT INTERCHANGER
- (312) SOLVENT CHILLER
- (313) FRACTIONATOR OVERHEAD CONDENSER
- (314) STRIPPER OVERHEAD CONDENSER
- (315) DUPLEX FINAL CONDENSER
- (402) SOLVENT (R-12) STORAGE TANK
- (506) TURBO-EXPANDER
- (507A) SOLVENT PUMP
- (507B) SPARE SOLVENT PUMP
- (510) PROCESS TRAILER
- (710) FRACTIONATOR REBOILER HEATER
- (711) STRIPPER REBOILER HEATER

Figure 7
POSSIBLE EQUIPMENT ARRANGEMENT
FOR MOBILE UNIT PROCESS
EQUIPMENT TRAILER

- (206A) REFRIGERATION SYSTEM PURGE TANK
- (206B) REFRIGERATION SYSTEM PURGE TANK
- (305) WATER COOLED REFRIGERANT CONDENSER
- (306) REFRIGERANT COMPRESSOR INTERCOOLER
- (307) BRINE COOLER
- (401) BRINE (R-11) STORAGE TANK
- (504) TWO STAGE CENTRIFUGAL REFRIGERANT-12 COMPRESSOR
- (505A) BRINE CIRCULATING PUMP
- (505B) SPARE BRINE CIRCULATING PUMP
- (509) REFRIGERATION TRAILER
- (702) 500 HP 4160V ELECTRIC MOTOR

Figure 8
TRAILER-MOUNTED BRINE SYSTEM
EQUIPMENT ARRANGEMENT

Figure 9
POSSIBLE EQUIPMENT ARRANGEMENT
FOR MOBILE UNIT ELECTRICAL
DISTRIBUTION AND
INSTRUMENTATION TRAILER

Figure 10
TENTATIVE MOBILE UNIT
ELECTRICAL DIAGRAM

TABLE V

SUMMARY OF MOBILE UNIT OPERATING UTILITY REQUIREMENTS

Equipment Item	Electrical Power, kw		Cooling Water, gpm	
	Version 1	Version 2	Version 1	Version 2
Compressor	520	750	60	90
Lube Oil System	5	5	5	5
Expansion Turbine Lube System	-	5	-	5
Solvent Pump	30	30		
Brine System	-	370	-	840
Fractionator Reboiler	275	275		
Stripper Reboiler	350	350		
Dessicent Trap Regenerator	30	30		
Compressor Trailer Air Conditioning	30	30		
Control Systems	25	25		
Product Compressor (Allowance)	<u>25</u>	<u>25</u>	—	—
Total	1,290	1,895	65	940

TABLE VI

SUMMARY OF CAPITAL COSTS

Item	Cost*, \$	
	Case 1†	Case 2‡
<u>Head-End Trailer</u>		
Trailer, modified	12,000	12,000
Compressor Package	138,000	164,000
First-Stage Gas Cooler	15,000	21,000
Dessicant System, complete	<u>24,000</u>	<u>24,000</u>
Subtotal	189,000	221,000
<u>Process Trailer</u>		
Trailer, modified	13,000	13,000
Absorber	15,000	15,000
Fractionator, with exchangers	42,000	42,000
Stripper, with exchangers	65,000	65,000
Second-Stage Gas Cooler	15,000	21,000
Air Chiller	8,000	-
Solvent Chiller	7,000	7,000
Solvent Pumps	7,000	7,000
Surge Tanks	4,000	4,000
Expansion Turbine	-	<u>47,000</u>
Subtotal	176,000	221,000
<u>Brine System Trailer</u>	-	220,000
<u>Liquid Nitrogen Supply System</u>	55,000	-
<u>Control Trailer</u>		
Trailer, modified	22,000	22,000
Instrumentation	80,000	80,000
Electrical Supply	<u>83,000</u>	<u>91,000</u>
Subtotal	185,000	193,000
<u>Miscellaneous</u>	<u>25,000</u>	<u>25,000</u>
TOTAL COST	630,000	880,000

* Costs for individual items are total costs including not only purchase price, but also costs for installation, piping, and insulation, as well as indirect charges and a contingency.

† In case 1, the process gas flow is 1600 scfm, and a liquid nitrogen cooling system is employed.

‡ In case 2, the process plus excess gas flow is 2400 scfm, and an expansion turbine system is utilized for low temperature refrigeration.

It should be emphasized that the \$630,000 to \$880,000 cost range, while felt to be accurate for the operating conditions selected, probably does not represent the lowest cost for a noble gas removal system employing the absorption route. Refrigeration costs, varying from about 10 to 30% of the total cost, indicate that considerable savings might be realized by operating the plant at higher temperatures and pressures, perhaps using a different fluorocarbon solvent. Furthermore, such flow sheet simplifications as the elimination of a column or of one or more heat exchangers, perhaps possible at other processing conditions, would also reduce the total cost significantly. Of course, a change in project ground rules, e.g., extension of the allowed processing time or consideration of reactor site installed units, would also alter the cost picture. In any event, the coordinated pilot plant testing and optimization study programs are expected to point toward flow sheets resulting in plant costs lower than indicated here.

OPTIMIZATION STUDIES

S. C. Jacobs

Optimization studies are being conducted by the ORGDP Operations Analysis Division to indicate the best operating conditions and simplest flow schemes, considering both cost and reliability, for the noble gas absorption process. The ultimate goal is to incorporate cost data with process equipment performance data to obtain an optimal plant design. At present, separate computer routines for calculating the performances of the various flow sheet components are being integrated into a mathematical model of the overall process.

The flow sheet used as a basis for the computer studies is essentially identical to the pilot plant flow sheet, figure 1. The gas from the containment vessel is compressed and pumped through a low temperature sorber column where the krypton and xenon are selectively absorbed in the liquid, and depleted gas is returned to the containment vessel. The rich liquid is then flashed to the pressure of the fractionator and the flashed vapor, mixed with the vapor stream leaving the fractionator, is condensed. The condensate enters the top of the fractionator as a liquid feed, while the noncondensables, containing nitrogen, oxygen, argon, and recycle krypton and xenon, are routed to the absorber feed compressor.

Several alternative operating schemes are being considered. For example, as assumed for the reference mobile unit design, the liquid emerging from the fractionator reboiler can be fed to the top of a third column in which the absorbed gases are stripped from the liquid. The vapor leaving the top of the stripper column is condensed and refluxed, with the noncondensables removed as a product gas stream. The liquid from the stripper reboiler, containing a negligible amount of dissolved gas, is then recycled to the absorber.

Calculations presently being made are aimed at showing material flows and column sizes for a coupled absorber-fractionator system, sized for a specified processing time, where the operating parameters, with refrigerant-12

as the solvent, are varied as follows:

Absorber: Number of stages - 5 to 20
 Temperature - minus 80 to plus 70°F
 Pressure - 5 to 20 atmospheres
 Liquid-to-gas ratio - 2.5 to 10 (mole basis)

Fractionator: Number of stages 5 to 20
 Temperature - 50°F
 Pressure - 4 atmospheres
 Liquid-to-gas ratio - 50 to 200

A stripper column computing routine is being added, but the range of conditions for this unit have not yet been established. Future calculations will probably also include consideration of other solvents, but with different temperature-pressure ranges.

With an increase in pressure, the operating temperature can also be increased accordingly, thus requiring less refrigeration. The column diameter is dependent on the liquid-to-gas ratio. With pressure and temperature remaining constant, increasing this number at a fixed gas throughput, as in the absorber, corresponds to an increased diameter whereas increasing the liquid-to-gas ratio at a fixed liquid rate, as in the fractionator, results in a decreased diameter. The final parameter currently being considered, the number of stages, establishes the absorption or stripping efficiency of the columns at the assumed operating conditions.

It is expected that, after determining the relationships of costs to pressure, temperature, liquid-to-gas ratio, and number of stages in the present calculations, trends can be noted and the range of interest can be narrowed. Then, linear programming techniques may be applied, if necessary, inside this range to establish conditions for a truly minimum cost plant.

STATUS AND FUTURE PLANS

Design of the pilot plant is practically complete, and it is expected that construction, procurement, and installation of the various equipment items can be finished within the next six months. Work on the mobile unit will proceed at a decreased level of effort, pending collection of pilot plant data, and will be largely concerned with supplying cost data for the optimization work. The optimization studies, in turn, will be directed during the next report period to mobile unit cost evaluation and to suggesting promising testing ranges for the pilot plant experiments.

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