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AN ASSESSMENT AND STUDY OF EXISTING CONCEPTS
AND METHODS OF CRYOGENIC REFRIGERATION
FOR SUPERCONDUCTING TRANSMISSION CABLES

PROGRESS REPORT

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INTRODUCTION

This report covers the progress made in a six task program as outlined in Table 1. All of task 01 and 02 are completed along with some of the sub-tasks in task 03. As shown in Figure 1, the current report period includes review of equipment versus requirements, development of an optimization criteria, and evaluation of component reliability and efficiency (sub-task 04.10).

WORK STATUS

The sections which follow relate to the results and findings of the helium refrigerator user visits, system and component manufacturers responses to questionnaires, telephone calls and visits, and the information obtained from a review of APCI standard N₂ plant experience.

ASSESSMENT OF OPERATING EXPERIENCE ON LARGE HELIUM REFRIGERATION EQUIPMENT

In order to develop an optimization criteria for the selection of system components, to be used on the superconducting power transmission line refrigeration system, which will insure a high degree of reliability and low maintenance requirements, it is imperative that one begin the design process by becoming thoroughly familiar with the many potential problems and failures which can effect the operation of a helium refrigeration plant. The best way of accomplishing this is to talk, first hand, with the people who operate and maintain large helium refrigeration systems and liquefiers. APCI visited users both in the U.S. and in Europe in order to find out about the problems experienced on refrigeration systems which represent a cross section of the major types of equipment presently available (oil lube turbo-expanders, externally pressurized bearing turbines, and self actuated gas bearing turbines). In addition to the APCI visits, information has been utilized from the Strobridge and Sindt report to NAL (January 1974), "Operating Experience - Helium Extraction and Liquefaction Expansion Devices". This report covers the operating experience on the turbo-expanders, reciprocating expanders, and compressors used on large helium extraction facility liquefiers. These units represent the largest helium liquefiers in the U.S. This information, together with the APCI visits and APCI N_2 plant experience (to be discussed in a later section), should provide a good data base from which to proceed with reliability and cost studies.

The installations visited, together with the information obtained by Strobridge and Sindt, are tabulated and summarized in Table 2. A couple of words of

caution are in order, for fear that one would try to obtain anything other than general types of information regarding failure modes and failure frequency rates from these visits: First, since accurate operating logs were not kept in most of these installations, information which appears in Table 2 was obtained largely through the operators attempts to mentally recall past incidents. While most of the failures which appear are probably fairly accurate, there are undoubtedly many failures which occurred but were not reported here. This is especially true of the less glamorous types of system shutdowns which were the result of power interruptions, cooling water problems, system leaks, etc. Also, many of these systems reported here were "one of a kind" type installations which inherently would have a higher incidence of failures than well established systems, such as in the case of the APCI standard N₂ plants where a large number of accumulated operating hours have provided a valuable amount of engineering feedback which aids in increasing the reliability of the system.

Of all the refrigerator users visited, the operating experiences on the CENG cold neutron source have been fairly well documented in one of the papers given at the recent 5th International Cryogenic Engineering Conference. This paper was entitled, "Cold and Ultra Cold Neutrons: a Test Facility for Cryogenic Engineering" by P. Agerson, J. M. Astruc, A. Lacaze and J. Verdier. If one counts the failures on this system; there have been 26 failures on the system in the past 12,700 hours - this works out to about 18 failures per year. It is interesting to compare this to the experience gained from reviewing the APCI N₂ plant operating reports. The Alcoa N₂ plant, which is to be

described in detail in a later section, averaged, over a total operating time of 720,000 hours, about 17.5 outages per year.

TURBINE EXPERIENCE

Much interesting information may be gleaned from this summary - but one thing which will be mentioned here is an extension of the Strobbridge attempts at coming up with a value representative of the mean turbo-expander operating hours per failure. In the summary of the mean turbo-expander operating hours per failure found in the user visits and the helium plant facility visits of Strobbridge, as given in Table 3, the same definition of expander failure has been used here as in the helium extraction plant reports. In this case, a failure refers to any incident in which the turbo-expander either stopped on its own or was stopped at an unscheduled time to perform a repair or replacement. Excluded from the failures given in Table 3 have been those which occurred during the initial phases of system start-up and run-in.

INFORMATION SUPPLIED BY MANUFACTURERS

Helium Refrigeration System Manufacturers

Questionnaires were sent out to major helium refrigerator manufacturers in order to ascertain their recommendations relative to the requirements of the superconducting power transmission line. The questionnaire encompassed both state-of-the-art refrigeration systems as well as recommendations on development required to bring the reliability and performance of the system components up to the level required by the power transmission lines.

In order to obtain a standard of comparison, the manufacturers were asked to comment on a system which would meet the requirements of BNL's Plan 3A study which was carried out with the Long Island Lighting Company. Briefly, the requirements were:

Allowable conductor temperature range	6.75K-8.75K
Load in cable due to electrical losses and heat leak	3.6 Kw @ 8K
Equivalent refrigeration at 8K required to cover heat shield losses	0.7 Kw
Total load at 8K	4.3 Kw
Helium pressure in cable	15 atm
Distance between stations	12 Km

The manufacturers were allowed the freedom of specifying either an integral helium refrigerator/line configuration or a refrigerator linked only thermally

to a closed, pumped, transmission line loop via a heat exchanger.

The manufacturers who responded were:

Airesearch Manufacturing Co.

British Oxygen Co., Ltd.

CTI Cryogenics

CVI

L'Air Liquide

Linde AG

Sulzer Bros., Ltd.

Union Carbide - Linde Div.

A summary of these manufacturers responses is given in Table 4..

Compressor Manuafcturers

Compressor manufacturers were solicited by means of a questionnaire in order to gain information relating to compressor operating characteristics, maintenance, reliability and possible trends in future development. Compressor types for which information was sought included dry lube reciprocating compressors, labyrinth seal dry lube reciprocating compressors, centrifugal compressors, regenerative compressors, and helical screw compressors. For each of these types of compressors, information was sought regarding the advantages of modifying the compression cycle through the use of oil injection, water injection, or possibly the increase in apparent gas molecular weight through the use of high molecular weight gases such as Freon-12.

In order to obtain some commonality in the size compressor for which information was sought, the manufacturer was asked to comment on two flow ranges for a specific set of operating pressures. These two flow ranges would roughly correspond to the size required if one large refrigerator were used at each refrigeration station or if the refrigerator manufacturer would resort to two half size refrigerators at each station. The flow ranges were:

Flow range #1: 5000-10,000 SCFM

Flow range #2: 2400-4500 SCFM

The other operating parameters were:

Pressure levels: 15 atm/3 atm absolute

Cooling : water cooling at 80°F

The compressor manufacturers who responded to our questionnaire together with the types of compressors they responded with are listed below:

<u>TYPE OF COMPRESSOR</u>	<u>MANUFACTURER</u>
Dry Helical Screw	Ingersoll-Rand Co.
Centrifugal	Elliot Co. Ingersoll-Rand Co.
Regenerative	Ingersoll-Rand Co.
Oil Lubricated Screw	Howden Godfrey Compressors, Ltd. Dunham/Bush Co.
Dry Labyrinth Seal Reciprocating	Sulzer Bros., Ltd.
Dry Reciprocating	Cooper Penjox Worthington

Due to the rather slow response of some other manufacturers, those names do not appear above, the information related to helium compressors will not be tabulated here.

Turbine Manufacturers

Information relating to the capacity size range available in present state-of-the-art helium turbine expanders is shown in Table 5. This information was gathered during personal visits to two major turbine manufacturers and is probably fairly representative of the size range covered by other manufacturers since the same scaling laws apply in all cases. Table 5 is broken up into three major bearing types; externally pressurized gas bearings, self actuating gas bearings, and oil lubricated bearings.

REVIEW OF APCI STANDARD NITROGEN PLANT EXPERIENCE

Air Products presently owns and operates on the order of thirty (30) APCI built standard nitrogen plants which produce between 20 and 120 tons/day of product nitrogen. Some of the compressors used in these installations are about the same size as might be used in the superconducting power transmission line refrigeration plants. The cumulative running time on these plants represents about 200 years of operating experience. These plants are all unattended but are monitored and serviced by a single operator who is usually within 100 miles of the plant.

Although one may argue against drawing too close a comparison between the operating characteristics of a standard nitrogen plant and a helium refrigeration plant of the type required for the superconducting power transmission line, there is enough similarity in the physical nature of the individual components (rotating compressors, turbo-expanders, platefin exchangers, and controls) to make it instructive to review the operating experiences on some of the plants to ascertain the major causes of plant shutdown. The failure modes experienced together with the techniques used in insuring high "on-stream factors" (percentage of available time a plant is actually generating nitrogen) can provide valuable insight into the design of helium plants for use on superconducting power transmission lines.

Both the nitrogen plants and the helium refrigeration plants should share the following design objectives:

1. Both systems strive for a high on-stream factor with virtually no interruption

of service to the customer. During the past two year period, APCI standard nitrogen plants have established an overall on-stream factor of 98.5%, that is, the production of nitrogen was interrupted during 1.5% of the contracted delivery period. Table 6 is a tally sheet showing the on-stream factors for APCI plants during the months of April, May, June, July, and August of 1975. APCI guarantees delivery of product 100% of the contracted time period on all its standard plants; this is made possible by the on-site storage of LIN and in some cases, the delivery of LIN from nearby liquefaction plants. During 1974 there were only two instances in which product was not delivered to the customer; one case involved a failure of the automatic switching system used to switch over to the backup liquid tank during a plant failure, and in another instance the automatic unit which notifies the district maintenance office that the plant had shut down failed to operate and the backup liquid supply was exhausted before it was realized that the plant had shut down.

2. It would be economically advantageous if the helium refrigeration plants could be operated essentially unattended. All of the APCI standard nitrogen plants are designed to run unattended with the exception of a total of about 8 hours per week when an operator checks the plant. The unattended operation is made possible through the use of a "Telemergency" system (Eton Corp.) which automatically contacts the plant manager by phone if a failure occurs.
3. As will be the case for the design of the helium refrigeration stations, the nitrogen plant designer has had to confront the problem of increasing plant reliability through increased component reliability, preventive maintenance, fast change out of failed components, availability of spare parts, possible use of redundant componets, or some alternate means. It may prove to be instructive to review the approach taken by the nitrogen plant designer which

has led to the high percentages of "on-stream" time illustrated in Table 6; this review will be made in one of the sections which follow.

In order to understand the approach taken in the design and operation of standard nitrogen plants, which insures product delivery 100% of the contract time period, it is important to look at a typical standard plant layout along with some representative sampling of the failure modes experienced together with the time interval during which the plant is not in operation during the outage. This information, together with an understanding of the preventative plant maintenance schedule followed in the operation of the nitrogen plants suggests one avenue of approach which could possibly be taken in the design of the helium refrigeration plants for the superconductive power transmission lines.

Basic Nitrogen Plant Layout

Figure 2 shows a typical, somewhat simplified APCI standard nitrogen plant layout. For illustrative purposes this plant is assumed to produce high purity nitrogen at the rate of about 38,000 SCFM. This plant would require about a 650 BHP compressor to produce the stated product yield. The main air compressors (MAC) used are centrifugal, 3 or 4 stage (depending on plant design) compressors with a typical discharge pressure of about 110 psig. Cooling towers are used to reject waste heat. The air which enters the compressor passes first through the inlet air filter. Following the compressor aftercooler, the gas passes through the aftercooler separator where much of the moisture is removed from the air. The gas then passes through a section of line which has provision for heating the gas during a plant defrost and proceeds from here to an automatic four way switch valve which regu-

larly switches the high and low pressure flow circuits on the two main heat exchangers in order to flush out the ice and carbon dioxide on the low pressure exhaust phase of the cycle. The four way valve typically switches every five minutes.

The two main switching exchangers are fabricated from aluminum plate fin cores. After cooling down in the main switching heat exchangers, the gas enters the aluminum plate fin liquefier - subcooler and continues on to the high pressure section of the double rectification column where liquid air, which is not higher in O_2 concentration, is drained off the bottom of the column and is sent back to the liquefier-subcooler exchanger to help cool the incoming air. From there, the air passes through a hydrocarbon adsorber bed and is then sent into the low pressure half of the column. A mixture of gaseous N_2 and O_2 is removed from the top of the column. This gas then makes another circuit through the liquefier-subcooler and then splits into two streams. One stream goes directly to the turbo-expander while the other stream goes to the expander after first making a pass through the colder of the two switching heat exchangers. The turbo-expanders used in these plants are APCI built radial inflow, oil lubricated turbo expanders which are loaded with an integral turbo compressor. The turbine wheel for this size plant is four inches in diameter and the journal rotates at about 30,000 rpm. The pressure ratio across the turbine is typically about 3.3 with an inlet temperature of about 125°K. Typical isentropic efficiencies for these units are about 80%. From the expander the cold gas, now at about 98°K, is sent to the liquefier-subcooler once again, back through the switching exchangers, and is finally diverted by the four-way switching valve to a vent stack where it is returned to the atmosphere.

Cold product N_2 gas is taken from the top of the high pressure section of the column and is channeled through both the liquefier-subcooler exchanger and the switching heat exchangers before it is sent on its way to the customer. Liquid nitrogen is also tapped off the high pressure column and is piped to a liquid storage tank which, for the case of a 38,000 SCFH plant, would typically be about 10,000 gallons. It is the inventory of liquid in this tank which is used in case of a plant shutdown to insure continuity of N_2 supply to the customer. A simple calculation will show that the storage capacity of the storage tank, relative to the required customer demand of 38,000 SCFH, will allow the plant to be off-stream for about 25 hours. As will be shown later, this time interval is adequate to correct the source of the plant outage in a large percentage of the most common failure modes. This time interval is also adequate for most of the scheduled plant maintenance and plant defrosts.

The principal controls and instrumentation on the compressor, expander and associated lube oil systems and cooling systems are typical of the controls and instrumentation found on other low temperature systems. These include temperature and pressure sensors, speed indicators, electrical power instrumentation, and vibration sensors on both the compressor and expander. Many of these sensors, such as the vibration sensors, provide the operation with an early warning or possible impending failure on either the compressor or expander, which could be prevented by taking corrective measures during scheduled plant shutdown.

Other instrumentation include an Adelphi AI electrochemical cell analyzer used to measure the impurity level of O_2 present in the N_2 stream (typical impurity is on the order of 5-10 ppm O_2 or less). Gas samples may be taken from a number

of locations in the plant flow circuit. Exceeding a preset impurity level in the product stream automatically shuts down the plant and switches over to the LIN storage tanks. Also the rectification column liquid level is detected and controlled by two liquid level controllers used in conjunction with drain and vent valves. In the nitrogen plant outage case history which follows, LRC-2 refers to the high pressure column liquid level controller and LRC-3 refers to the low pressure column controller. As already discussed, exceeding a preset value for any of the plant parameters mentioned above, automatically shuts down the plant, switches over to the reserve liquid supply, and notifies the plant manager of a shutdown via telephone.

Review of Operating Experiences on a Few APCI Standard Nitrogen Plants

In order to gain insight into the operation of a standard nitrogen plant and the types of failures which cause interruption of service, a case history of the outages occurring during the life of one specific plant is presented. Following the case history, an outage chart representing an average of the outage experience on six random APCI plants is also presented; these outage charts merely attempt to categorize outages in specific groups and attaches percentages to these groups which represent the fraction of the total outage time which is taken up by each specific outage category. In addition to these outage charts, a tabulation is made which groups the outages in terms of the plant shutdown time interval experienced for all the outages. This type of tabulation is important in understanding the ability of these plants to guarantee product delivery 100% of the time.

Case History of Outages for A Specific Standard Nitrogen Plant

The plant which is to be examined is a 52,000 SCFH N₂ plant in Alcoa Tennessee. The plant outage reports which are listed cover the period of operation from 14 July 1970 to 29 July 1975. The reasons for the outages which are listed in Table 7 were copied directly from the monthly outage reports submitted by the plant managers to the APCI Operations Department; in some cases, clarifying remarks have been added. A pie chart summarizing the causes of the outages in the Alcoa plant in terms of failure categories is given in Figure 3. A word should be said at this point to clarify some of the categories which appear on the pie charts. Electrical problems refer to all outages of an electrical nature other than main power line interruptions and electrical malfunctions on instruments and process controls. This category would include such things as failures of power transformers, main motor controllers, and overloads in motors which cause plant shutdown. Miscellaneous maintenance refers to unscheduled maintenance outages which are of a general nature such as repairing leaks in piping, cleaning filters, etc. Cooling water interruptions include loss of cooling water, loss in cooling water pressure which would trigger an outage, or plugging of heat exchanger tubes because of mineral deposits or dirt. Scheduled maintenance refers to planned plant shutdowns designed to perform scheduled preventative maintenance tasks or planned shutdowns directed at correcting conditions which indicate deterioration of performance or potential failures in some of the components. The remaining categories are self-explanatory.

In order to obtain a more representative idea of the extent to which certain types of outages cause plant shutdown, an outage pie chart was generated which represents

the cumulative experiences of six randomly chosen nitrogen plants (including the Alcoa plant). This chart is shown in Figure 4. The total plant operating time represented by Figure 4 amount to about 259,000 hours (30 years). The overall on-stream record for these plants is 98.27%.

The first observation one is forced to make in reviewing Figure 4 is that it is the cumulative effects of mundane types of outages, such as scheduled maintenances, plant defrosts, power interruptions, electrical problems, cooling water problems, etc., which far outweigh the more "glamorous" types of failures such as catastrophic turbo-expander breakdowns and compressor failures, which contribute most to the down-time of the plant. It is interesting to note that the expander and compressor account for only 8.6% of the total down-time for the plants represented in Figure 4.

Because of the physical similarity of many of the components in a helium and nitrogen plant, it is tempting to assume that the same percentage breakdown of outages (with the obvious exclusion of the switch valve and distillation outages) will occur in the helium plant. Even if the percentage breakdowns of the individual outage categories relative to the plant total outage time are similar for both the helium and nitrogen plants, this gives us no assurance that the value of the outage time for each category of outage relative to the total operating plant time will be the same for both plants. For example, while 6% of the total outage time of the plant may be due to problems related to controls and instruments for both types of plants, this does not imply that if an equivalent of 1/4% of the nitrogen plant running time will be subject to outages due to instruments and controls that an equivalent of 1/4% of the helium plant running time will also

be subject to outages related to instruments and controls. While knowing this type of information would be very helpful in the design of a helium plant, just the knowledge of the relative contribution of each category of outage to the total plant outage time would be of great help in that it would tell us where to concentrate our efforts in order to significantly reduce the total outage of the plant. For example, the nitrogen plant data would suggest trying to improve the reliability of the cooling water system or the reliability of the controls and instrumentation rather than spending time and money in increasing the reliability of the turbo-expander. As another example, it would be better to concentrate on more efficient ways to defrost the plant rather than to attempt improving the compressor reliability.

While one could probably develop an argument against drawing the type of analogy between the nitrogen and helium plant, the fact remains, that in the absence of any large body of well documented operating experience on large helium plants, the nitrogen plant analogy is the most logical place to begin.

In drawing any conclusions from the outage charts which have been presented, it is important to understand that while certain types of outages experienced by the N_2 plant do not apply to helium plants (switch valve and distillation column outages), by the same token, certain types of outages which would occur on a helium plant would not show up in a N_2 plant. The most obvious example of this would be outages due to failure of the vacuum pumps used to maintain the cold box vacuum or some other incident leading to loss of vacuum integrity. This is no problem on nitrogen plants since they use only rockwool in an inert N_2 atmosphere as insulation.

Another interesting bit of information which may be gleaned from the N_2 plant experiences is the time intervals during which the plant is not producing N_2 during each outage. A survey was made of the outage time intervals for the six plants used in this investigation, and the findings were arranged in a manner which would show the percentage of outages which fell within one of four outage time interval groups. These results are presented in Table 8. The significance of these results is that 94.6% of all the plant outages last less than 24 hours. Recall that the inventory of the liquid nitrogen tank shown in Figure 2 was such that the tank could supply the customers with product for a period of 25 hours. Thus, a large majority of the plant outages can be taken care of without having to call on external sources of liquid nitrogen. A summary of the outages which took more than 24 hours is given in Table 9. This table indicates that most of the outages in excess of 24 hours were due either to scheduled preventative maintenance or plant defrost. The remaining long outage times result from major breakdowns which require a considerable number of man-hours to correct, or else result from the fact that some of the failed components are not usually kept in the plant site parts inventory. The preventative maintenance outage times could be reduced by breaking up the scheduled tasks into smaller groups, in which no group would require greater than a 24 hour outage, or by bringing in a larger maintenance crew to perform the maintenance. This is not done at the present time because there is no economic justification for increasing the maintenance crew size or trying to break a large group of maintenance tasks into a number of shorter tasks. A typical price for trucked in liquid N_2 is about 14¢/100 ft³. This means that in order to supply a plant with 38,000 SCFH of nitrogen, the cost would amount to about \$53/hour. Thus, any corrective measures taken to reduce a 38,000 SCFM plant maintenance down-time must fall below \$53/hour to be considered - so far there has been no need to enlarge work crews or break

the tasks into smaller groups. It can easily be seen that if the N_2 which is produced were used in an installation as critical as a superconducting power transmission line there would be considerably more incentive to reduce these large outage periods.

While the LIN storage tank does a great deal to insure that N_2 is delivered 100% of the time, no realistic amount of storage capacity would prevent the service from being interrupted if the failure rates of the plant components were too high. The outstanding plant outage records owe much to the judicious selection of plant components together with the well thought out and executed preventative plant maintenance program and spare parts inventory control. Both the preventative plant maintenance program and the spare parts inventory for each nitrogen plant are controlled by the APCI computer. The computer keeps track of plant operating time and past maintenance performed at each plant. Cards are then sent out by the computer to individual plants in order to notify plant managers of the need to replace components, perform maintenance checks on specific components, or perform routine plant defrosts. In addition, as spare parts are used up by a specific plant, cards are sent back to APCI which notify the computer of the removal from the parts inventory of a specific item. The computer then notifies suppliers who in turn replace the specific item. All plant managers are required to acknowledge completion of each task the computer has requested them to carry out. Each month the compliance record for each of the APCI plants are tabulated and distributed within the company. This type of "score keeping" insures a high level of compliance to the maintenance tasks requested by the computer; as an example, the overall compliance rate for the month of March 1975 was 99.8%. It is these types of compliance rates which are

required to insure on-stream factors on the order of 98.5%

APCI Nitrogen Plant Turbo-Expander MTBF

Because the turbo-expanders used in the APCI plants are almost exclusively of APCI design, quite comprehensive records have been kept relative to turbine failures. Together with the total plant operating time this information allows one to make an estimate of the MTBF of the turbo-expander. Over a total accumulated operating time of a little over 200 years 20 "catastrophic" turbine failures have occurred. "Catastrophic" failure, as used here, refers to failures which occurred without prior warning and before any preventative maintenance could be performed to prevent total failure. If one assumes a 98% on-stream factor for the entire 200 year period, this translates to a MTBF of about 85,850 hours. This is quite an impressive record.

It should be noted, that when a failure does occur, the normal time which elapses from the time the plant shuts down to when it is back on stream with the new plug-in expander replacements, is typically between four and seven hours.

WORK PLAN FOR NEXT REPORT PERIOD

The next report period covers the initiation and/or completion of the following tasks:

- 03.20 Develop Optimization Criteria
- 03.30 Component Evaluation

- 04.10 Evaluate Component Reliability, Efficiency
- 04.20 Redundancy, Reliability, and Backup

- 06.00 Review of Business Factors

TABLE 1

STUDY OF EXISTING CONCEPTS AND METHODS OF CRYOGENIC
REFRIGERATION FOR SUPERCONDUCTING TRANSMISSION CABLES

TASK 01.00	TRANSMISSION LINE SURVEY
01.10	Literature Survey - Transmission Lines
01.20	Visit Program Centers (Transmission Lines)
TASK 02.00	REFRIGERATOR SURVEY
02.10	Literature Survey - Refrigerators
02.20	Contact Refrigerator Users APCI Operations Review Contact Refrigerator Manufacturers Contact Component Manufacturers
02.30	Evaluate Refrigerator Data
TASK 03.00	DEVELOPMENT PROGRAM
03.10	Review of Equipment Vs. Requirements
03.20	Develop Optimization Criteria
03.30	Component Evaluation
03.40	Recommend Development Programs
TASK 04.00	SYSTEM RELIABILITY
04.10	Evaluate Component Reliability, Efficiency
04.20	Redundancy, Reliability, and Backup
TASK 05.00	SELECT BEST CURRENT SYSTEM(S)
TASK 06.00	REVIEW OF BUSINESS FACTORS

TABLE 2

HELIUM AND HYDROGEN REFRIGERATOR/LIQUEFIER OPERATING EXPERIENCE

System User Location	Central Electrical Research Lab Leatherhead, England	Culham Laboratory Abingdon, England	International Research & Dev. LTD. Newcastle, England
System description and use	BOC system refrig/liquefier	BOC system used on superconducting levitron (supercritical)	BOC system used on Fawley pumping station project (see note #3)
Liquefaction/refrig. capacity (LL/hr/watts)	60 LL/hr or 220 watts @ 4.5°K	30 LL/hr or 90 watts @ 4.4°K circulate hel. @ 3°K & 2.5 atm	15 LL/hr w/o LIN 30 LL/hr w/ LIN
LIN precool - yes/no	Yes	Yes	Yes (later - see note #3)
System operating time (hrs)	12,000	17,500	5,500
Type of turbine used	BOC externally pres. gas bearing turbines	BOC externally Pres. gas bearing turbine	BOC externally pressure gas bearing turbine
Total no. of turbines	Two - one redundant or used during cooldown	One	Two and later only one
Type turbine loading	He brake compr.	He brake compr.	He brake compr.
Operating hrs. on turbine	6000 hr. old turbine 6000 hr. new turbine	17,500	5,500
Turbine turnaround time (hrs)	Four hours	--	--
Compressor type	Alley dry lube compr.	Broom Wado, V Machine (air compr.)	Broom Wado
No. of compressors	One	One	One
No. of stages	Two	Two	Two
Water cooled, yes/no	Yes	Yes	Yes
Flow (SCFM)	745	500	500
Pressure Ph/Pl (PSIA)	125/16	160/15	140/16
Power (Kw or H.P.)	200 H.P.	125 H.P.	85 KW
Compressor operating time (hrs)	18,000	17,500	5,500
H ₂ O cooling tower, Yes/no	Yes	--	--
Other Cooling	--	--	Pumped sea water
Heat exchanger type	Alum. plate fin	Alum. plate fin	Alum. plate fin
FAILURES			
No. of turbine failures	None	One	Two
Reasons for failure	Occasional partial build up of impurities on turbine, however, tip press. monitor provides warning	Failure due to reduced bearing gas pressure	-1 failure due to impurities buildup on turbine wheel -1 failure due to problem in gas bearing line piping
Seal gas or oil contamination of helium?	--	--	--
No. of compressor failures	4	3	1 major (numerous minor)
Reasons for failure	-(2) motor burn outs -initial numerous ring failures -moisture leak in aftercooler	-(1) motor burnout -(2) system shutdown due to excessive gland leakage on piston rod	-(1) due to leak in compr. cooler sea water entered helium -numerous ring wear problems -problems with oil separator thru glands
Any control failures?	34 control related failures	--	Initially had shutdowns due to control failures
Any vacuum system failures?	Five failures of vacuum pump	--	--
Any exchanger freezeup?	--	--	--
Other problems related to purity?	--	--	--
Cold box leaks?	Leak in heat exchanger transition joint	--	Initial cold box leak
Other failures?	-problems with H ₂ O circulating pump -(7) instrument air compr. failures -numerous power interruptions -ring dust problems	-(1) broke suction line on compr. allowing air in -(1) lack of feed gas allowed air to be sucked in -(1) shutdown due to power failure -(1) syst. trip due to electrical failure	--
MAINTENANCE			
Recommended compr. maintenance interval (hrs)	2000 hrs turnaround 2 days	3000 hrs turnaround 8 days	Not meaningful because of recurring problems 2500 hrs for most recent ring design
For dry lube no. hrs. on rings	3000 hrs.	--	--
No. of hrs. on valves	3000 hrs.	--	--
Other maintenance requirements	Intercooler tubes require descaling due to hard water	--	--
Turbo-expander maintenance interval (hrs)	None except for routine brg. gas & turbine inlet filter replacement	None	None

TABLE 2

HELIUM AND HYDROGEN REFRIGERATOR/LIQUEFIER OPERATING EXPERIENCE

System User Location	CENTER FOR NUCLEAR STUDIES (CEMO) Grenoble, France		
System description and use	L'Air Liquide refrigeration sys. on cold neutron source	L'Air Liquide liquefier	L'Air Liquide refrigerator
Liquefaction/refrig. capacity (LL/hr/watts)	7. Kw @ 18-28°K (1 turb.) 14. Kw @ 10-20°K (2 turb.)	25 LL/hr (old turbine) 50 LL/hr (new turbine)	100 watts @ 4.2°K
LIN precool - yes/no	No	Yes	Yes
System operating time (hrs)	12,700	19,800	15,000
Type of turbine used	Two L'Air Liquide externally pressurized gas brg.	L'Air Liquide externally pressurized gas brg. turbo-exp.	L'Air Liquide externally pressurized gas brg. turbo-exp.
Total no. of turbines	Two in parallel	One	One
Type turbine loading	He compressor brake loop	He compressor brake loop	He compressor brake loop
Operating time on turbines	12,700	15,000 hrs old turbine 4,800 hrs. new turbine	15,000
Turbine turnaround time (hrs)	Four	--	--
Compressor type	Sulzer labyrinth seal	Sulzer labyrinth seal	Sulzer labyrinth seal
No. of compressors	Two	One	One
No. of stages	Two	Two	Two
Water cooled yes/no	Yes	Yes	Yes
Flow (SCFM)	2130/compr.	--	--
Pressure Ph/P1 (PSIA)	210/40	220/15	220/15
Power (Kw or H.P.)	350 Kw/compr.	--	--
Compr. operating time (hrs)	13,300 hrs #1 compr. 12,700 hrs #2 compr.	19,800	15,000
H ₂ O cooling tower hrs/no	--	--	--
Other cooling	--	--	--
Heat exchanger type	Alum. plate fin	--	--
FAILURES			
No. of turbine failures	Two	None	None
Reasons for failures	-Bearing failure due to improper regulator setting on bearing -Same failure as above, occurred 10 min. after above failure	No major failures	Although actual failure did not occur, turbine was changed after 13,000 hrs. due to blade erosion
Seal gas or oil contamination of helium?	--	--	--
No. of compressor failures	None	One	None
Reasons for failure	No major failures other than problems with piston rod gland leakage, valves, etc.	Had to replace cylinder lining after 16,000 hr. due to excessive clearance	--
Any control failures?	Six failures due to defective or bad settings on control sys.	--	--
Any vacuum system failures?	--	--	--
Any exchanger freezeup?	--	--	--
Other problems related to purity?	Have had to shut system down 6-7 times due to build-up of impurities on turbine blade	--	--
Cold box leaks?	--	--	--
Other failures?	-one shutdown due to cooling water problem -pipe broke on compressor due to vibration -two air compr. failures -seven electrical power failures	--	--
MAINTENANCE			
Recommended compressor maintenance interval (hrs)	8000 hrs. (1 wk turnaround)	8000 hrs.	8000 hrs.
For dry lube no. hrs. on rings	--	--	--
No. of hrs. on valves	--	--	--
Other maintenance requirements	None	None	None
Turbo expander maintenance interval (hrs)	Occasionally clean out water side of helium turbine brake loop exchanger	--	--

TABLE 2

HELIUM AND HYDROGEN REFRIGERATOR/LIQUEFIER OPERATING EXPERIENCE

System User Location	Argonne National Lab. Argonne, Ill	CERN Geneva, Switzerland	
System description and use	Airco/BOC liquefier	Sulzer refrigerator on BEBC bubble chamber (see note #1)	Sulzer refrigerator on OMEGA magnet system (supercritical He)
Liquifaction/refrig. capacity (LL/hr/watts)	100 LL/hr w/wet exp. 70 LL/hr w/o wet exp.	1.5 Kw @ 4.2°K (with two compressors on main loop)	-- --
LIN precool - yes/no	yes	no (use turbine precool loop)	-- --
System operating time (hrs)	4200	8000	12,000
Type turbine used	One (1) BOC externally pressurized gas bearing	Sulzer oil lube - each/ with own lube oil system	Sulzer oil lube
Total no. of turbines	one	four-main loop one-precool loop	two --
Type turbine loading	He brake compressor	oil brake	oil brake
Operating hrs. on turbine	-3000 hrs. old turbine -1200 hrs. new turbine	each of 4 - 8000 hrs 1 precool - 8000 hrs	-- --
Turbine turnaround (hrs)	one hour	one hour (2 men)	-- --
Compressor type	PA. dry lube	Sulzer labyrinth seal in parallel on main circuit	Sulzer labyrinth seal
No. of compressors	one	two	-- --
No. of stages	three	three	-- --
Water cooled yes/no	yes	yes	-- --
Flow (SCFM)	950	4810/compr.	-- --
Pressure Ph/P1 (PSIA)	205/15	265/21	-- --
Power (Kw or H.P.)	230 Kw	700 Kw/compr.	-- --
Compr. operating time (hrs)	4200	8000	12000
H ₂ O cooling tower, yes/no	yes	yes	-- --
Other cooling	--	--	--
Heat exchanger type	alum. plate fin	Alum. plate fin all but coil tube between main loop and H ₂ circuit	--
FAILURES			
No. of turbine failures	-3 (old turbine) -1 (new turbine)	-Two on He pre-cool circuit -None on four main loop	None
Reasons for failure	-3 ice formation (old) -high axial thrust loads on old required frequent disassembly and bearing dressing -1 ice formation (new)	Both failures occurred within recent months within hours of each other - reason as yet unknown	--
Seal gas or oil contamination of helium?	--	--	--
No. of compressor failures	Five	Four	Two
Reasons for failure	-casting leak allowed water into compr. heat exchanger -one main brg. failure -about 3 times over 3 years have had valve or valve spg failures	-leak of cooling H ₂ O after- cooler due to water acidity -replacement st. stl exchanger leaked -broken valve plates -excessive leakage thru stuffing box	Piston seized on two occasions
Any control failures?	--	Initially had some control problems	--
Any vacuum system failures?	Once got vacuum oil on superinsulation	--	--
Any exchanger freezeup?	plugged 3 times due to back-streaming from dewar	--	--
Other problems related to purity?	Dust from rings effected check valves and relief valves	On few occasions had build up of impurities on turbine wheel due to aftercooler leak	--
Cold box leaks?	--	Few leaks at start	--
Other failures?	-loss of cooling H ₂ O on diffusion pump due to fouling -many problems with cooling water tower -power transformer failure	Problems with main switches on compressor	--
MAINTENANCE			
Recommended maintenance interval (hrs)	wait for problems to develop	-major overhaul every 8800 hrs. -- -turnaround in 165 min. hrs.	--
For dry lube no. hrs. on rings	Initially had prbs. now get 3000 hrs. on rings	--	--
No. of hrs. on valves:	Changed valve and springs 3 times in 3 years	--	--
Other maintenance requirements	--	Check valves and stuffing boxes every 2000 hours	--
Turbo-Exp. maintenance interval (hrs.)	Mono	Routinely check lube oil system	--

TABLE 2

HELIUM AND HYDROGEN REFRIGERATOR/LIQUEFIER OPERATING EXPERIENCE

System User Location	Brookhaven National Lab. Upton, N.Y.	McGill University Magnet Lab Montreal, Canada	Brookhaven National Lab. Upton, N.Y.
System description and use	CTI/Sulzer H ₂ refrigerator used on bubble chamber	Canadian L'Air Liquide/Sulzer refrigerator cooling super-critical pumped loop	CTI/Sulzer refrigerator on cold neutron moderator (super-critical)
Liquefaction/refrig. capacity (LL/hr/watts)	7.8 Kw @ 23°K	4.0 Kw @ 10°K	5. Kw @ 14-17°K
LIN precool - yes/no	yes	--	no
System operating time (hrs)	12,000	15,600	2-3 wks intermittent operation
Type of turbine used	Sulzer oil-lube turbo-Exp.	Sulzer oil lube turbo-exp. in series	Sulzer oil lube turbines
Total no. of turbines	Two	Two	Two
Type turbine loading	Oil brake	Air compressor brake loop	Oil brake
Operating hrs. on turbine	12,000	15,600	--
Turbine turnaround time (hrs)	--	--	--
Compressor type	Norwalk dry lube comp.	Sulzer labyrinth seal comp.	--
No. of compressors	Two plus one standby	-one (1) 500 HP main refrig -one (1) 40 HP on secondary loop	--
No. of stages	Two	Two	--
Water cooled yes/no	Yes	Yes	--
Flow (SCFM)	1100/unit	--	2480
Pressure Ph/Pl (PSIA)	175/25	165/18 (large unit)	215/48
Power (Kw or H.P.)	--	500 HP 40 HP	482 HP
Compr. operating time (hrs)	--	15600 hr on 500 HP unit	--
H ₂ O cooling tower, yes/no	--	Yes	--
Other cooling	--	--	--
Heat exchanger type	--	Alum. plate fin	Alum. plate fin
FAILURES			
No. of turbine failures	One	None	--
Reasons for failure	Main lube oil pump bearing failure (turbine not damaged)	--	--
Seal gas or oil contamination of helium?	--	Poor seal gas cleanup got oil into system on one occasion	--
No. of compressor failures	Many during system startup	None	Two
Reasons for failure	Most initial failures, including poor ring wear, due to shaft misalignment	--	Due to operator error oil from lube oil system got into heat exchangers and as result lost two turbines
Any control failures?	--	Have had failures on small air compr. used for controls	--
Any vacuum system failures?	--	--	--
Any exchanger freezeup?	--	--	--
Other problems related to purity?	--	--	--
Cold box leaks?	--	--	--
Other failures?	Pumped turbine lube oil into heat exchanger (operator error)	-bugs collect in cooling system in summer and plug circuit -main circuit BOC failure	-drier on clean-up package imploded and sent debris into heat exchanger
MAINTENANCE			
Recommended compr. maintenance interval (hrs)	At convenient times during interval less than 3000 hrs	Once a year during summer months	--
For dry lube no. hrs. on rings	3000 hrs.	--	--
No. of hrs. on valves	No problems other than occasional hangup due to dirt	40 HP compr. has had two valve failures	--
Other maintenance requirements?	--	Change compr. oil, check valves, replace gaskets	--
Turbo-exp. maintenance interval (hrs)	None	None	None

TABLE 2

HELIUM AND HYDROGEN REFRIGERATOR/LIQUEFIER OPERATING EXPERIENCE

System User Location	Phillips Greenwood Plant (Note 5) Elkhart, Kansas		Cities Service Jayhawk Helium Plant (Note 5) Santanta, Kansas	
System description and use	Helium Liquefaction process is a Claude Cycle system with two turbines in series		Helium Liquefaction	
			Old Liquefier	New Liquefier
Liquifaction/refrig. capacity (LL/hr/watts)	He Liquifaction 630 LL/hr		818 LL/hr design 727 LL/hr nominal	818 LL/hr
LIH precool - yes/no	Yes		Yes	Yes
System operating time (hrs)	8 years		5 years	1.5 years
Type of turbine used	Oil lubricated turbo-expander		Oil lube turbo expander	Oil lube turbo expander
Total no. of turbines	Two		Two (in series)	Two
Type turbine loading	Oil brake		Oil brake	Oil brake
Operating hrs. on turbine	--		--	--
Turbine turnaround time (hrs)	--		--	--
Compressor type	Dry lube gas mtr. dr. 4 cyc.	Dry lube gas mtr. dr. 2 cyc.	Drylube steam turbine drive compressor	Drylube nat. gas motor drive
No. of compressors	One	One	One	One
No. of stages	--	--	Four	Five
Water cooled yes/no	--	--	--	--
Flow (SCFH)	--	--	--	--
Pressure Ph/Pl (PSIA)	165/17	165/17	--	290/15.5
Power (Kw or H.P.)	550 H.P.	600 H.P.	1200 H.P.	800
Compressor operating time (hrs)	--	--	--	--
H ₂ O cooling tower, yes/no	--	--	--	--
Other cooling	--	--	--	--
Heat exchanger type	Plate fin		Plate fin	Plate fin
FAILURES				
No. of turbine failures	Three in two years		One per year	Three in 1.5 years
Reasons for failure	-During initial plant startup had problems with wheel erosion due to dirt or solid neon -Initially had short life on bearings and seals		--Frequent bearing failures - Initially (unit sensitive to change in process cond.) --Difficulties starting and stopping --How about one failure/yr.	- Failure at startup due to prior freezeup - Bearing failure due to electrical power loss
Seal gas or oil contamination of helium?	--		--	--
No. of compressor failures	?		?	--
Reasons for failure	-Initial problems finding correct ring material		-Corrosion of intercooler baffles due to poor water quality -90 day ring replacements required	-No major problems
Any control failures?	--		--	--
Any vacuum system failures?	--		--	--
Any exchanger freezeup?	--		--	--
Other problems related to purity?	--		--	--
Cold box leaks?	Had initial problems		Numerous problems	--
Other failures?	--		Initially had problems with flow distribution in heat exchangers	--
MAINTENANCE				
Recommended compressor maintenance interval (hrs)	Annual overhaul		--	Check compressor rings each 90 days
For dry lube no. hrs. on rings	Rings changed at annual overhaul		Refion ring replacement every 2200 hrs. (2 day turnaround)	--
No. of hrs. on valves	--		--	--
Other maintenance requirements?	Pistons rotated 1/2 turn each 6 months		--	--
Turbo-expander maintenance interval (hrs)	None		None	None

TABLE 2

HELIUM AND HYDROGEN REFRIGERATOR/LIQUEFIER OPERATING EXPERIENCE

System User Location	Kansas Refined He Co. Otis, Kansas	Lawrence Livermore Lab. Livermore, Cal.	Gesellschaft für Kernforschung (GFK) Karlsruhe, Germany
System Description and use	Helium liquefaction	Airco/BOC liquefier	Linde AG refrigeration system used on multiple experiments (note 2)
Liquefaction/refrig. capacity (LL/hr/watts)	-880 LL/hr -1090 LL/hr with wet exp.	60 LL/hr	380 watts @ 1.8°K or 115 LL/hr
LIN precool - yes/no	yes	yes	no
System operating time (hrs)	7.5 yrs	19,000	15,000
Type of turbine used	Oil lubricated turbo-exp.	One (1) BOC externally pressurized gas brg.	Two Linde AG oil lube turbo expanders in series
Total no. of turbines	Two (in series)	One	Two
Type turbine loading	Oil brake	He brake compr.	Oil brake
Operating hrs. on turbine	--	19,000	15,000
Turbine turnaround (hrs)	--	1/2 hour	--
Compressor type	Dry lubricated with nat. gas motor drive	Rix dry lube comp. (rebuilt air compr)	Linde AG dry lube, vertical with "Gefangener" piston rings
No. of compressors	Two	One	--
No. of stages	Four	Two	Three
Water cooled yes/no	--	yes	yes
Flow (SCFM)	--	850	1950
Pressure Ph/P1 (PSIA)	225/19	190/16	295/16
Power (Kw or H.P.)	500 H.P.	250 H.P.	540 Kw
Compr. operating time (hrs)	--	19,000	15,000
H ₂ O cooling tower, yes/no	--	--	Yes
Other cooling	--	--	--
Heat exchanger type	Plate-fin	Alum. plate fin	Coiled tube
FAILURES			
No. of turbine failures	10 in 7.5 yrs.	No major failures during last 13,000 hrs.	Two
Reasons for failure	-most failures due to contaminants in process stream -remaining due to oil pump failures -most of above problems corrected	-initially got only about 20 stop/start cycles out of bearings --after initial problems solved ran OK -examined after about 13,000 hrs and found no signs of wear	-oil bearing problem due to overspeed run -oil bearing problem due to dirt
Seal gas or oil contamination of helium?	--	--	--
No. of compressor failures	--	3	2
Reasons for failure	--	-2nd stage bearing due to lack of lubrication -main bearing failure -few failures due to valve spring breakage	-number of shutdowns due to excessive stuffing box leakage
Any control failures?	--	--	Minor control failures
Any vacuum system failures?	--	--	-2 breakdowns of vacuum pumps used for 1.8°K operation
Any exchanger freezeup?	--	--	--
Other problems related to purity?	--	--	--
Cold box leaks?	--	--	--
Other failures?	--	--	--
	-many problems resulted from migration of ring wear particles - added (3) sets of filters to correct this	--	-poor water quality causes problems with cooling loop, exchanger plugging and corrosion -two breaks in water line to compr. due to vibration
MAINTENANCE			
Recommended compressor maint. interval (hrs)	-check compr. piston & rider rings - 90 days -change interstage & final filters - 30-60 days	2-3000 hours	Check every 8000 hours
For dry lube no. hrs. on rings	6600 hrs.	6000 hrs - rings rotated every 2000 hrs	Some rings have lasted 15,000 hours
No. of hrs. on valves	--	--	Check every 8000 hours
Other maintenance requirements	--	Valves and valve springs checked every 2000 hrs.	Change or check stuffing box every 4000 hrs (some leak after 1-2K hrs)
Turbo-Exp. maintenance interval (hrs)	None	None	None

TABLE 2

HELIUM AND HYDROGEN REFRIGERATOR/LIQUEFIER OPERATING EXPERIENCE

System User Location	Keyes Helium Plant (see note 5) Keyes, Oklahoma	SIN- Swiss Institute of Nuclear Studies Villigen, Switzerland
System description and use	Helium extraction facility. Equipment used with N_2 to provide refrig. for crude helium (70%) liquefaction and phase separation	Sulzer refrigeration system used for Muon channel cooling (supercritical)
Liquefaction/refrig. capacity (LL/hr/watts)	--	Total requirements equivalent to 250 watts @ 4.3°K (see note 4)
LIN precool - yes/no	Yes	No
System operating time, (hrs)	13 yrs.	11,000
Type of turbine used	Oil lubricated N_2 expansion turbine 2 turbines in series	Sulzer self actuating gas bearing turbines
Total no. of turbines	Six (2 per cold box)	Two in series
Type turbine loading	Air blower	He compr. brake loop
Operating hrs. on turbine	--	11,000
Turbine turnaround (hrs)	--	Three hours
Compressor type	Oil lube, N_2 compr. with natural gas motor drive	Oil lube, Crude He compr. with gas motor drive
No. of compressors	Three	Three
No. of stages	Three	Three
Water cooled, yes/no	-	-
Flow (SCFM)	-	-
Pressure Ph/P1 (PSIA)	615/18	2715/65
Power (Kw or H.P.)	2500 H.P.	240 H.P.
Compr. operating time (hrs)	-	-
Cooling tower, - yes/no	-	-
Other cooling	-	-
Heat exchanger type	-	-
		Alum. plate fin
FAILURES		
No. of turbine failures	(1) failure/yr with four operating	One
Reasons for failure	-most failures involve bearing and seal destruction -other failures have been caused by operator error -some problems caused by pressure surges in process streams	Bearing failure due to dirt
Seal gas or oil contamination of helium?	-	-
No. of compressor failures	None	None
Reasons for failure	Both N_2 compr. and crude He compr. relatively trouble free	-
Any control failures?	-	(1) failure due to a pneumatic control
Any vacuum system failures?	Insulation is rock wool with N_2 purge	-
Any exchanger freezeup?	-	-
Other problems related to purity?	-	-
Cold box leaks?	-	-
Other failures?	-	-
MAINTENANCE		
Recommended compr. maintenance interval (hrs)	Annual overhaul of compr/ cylinders when motors serviced	5000 hrs.
For dry lube no. hrs. on rings	-	-
No. of hrs. on valves	-	-
Other maintenance requirements	-	None
Turbo-expander maintenance interval (hrs)	-	-

NOTES

- #1. Total system consists of three (3) refrigeration circuits which are thermally linked through specific common heat exchangers
 - (a) Main helium circuit produces supercritical helium and consists of two large Sulzer labyrinth seal compressors and a small auxiliary labyrinth seal compressor. Also has oil lubricated turbines (4) which appear as two parallel turbine sets which follow each other in series.
 - (b) 60°K precooling circuit consisting of a Sulzer compressor and single turbine.
 - (c) H₂ circuit, with a Sulzer compressor, linked to main helium circuit through a single heat exchanger. Produces liquid H₂ with J-T.
- #2. Experiments served by this refrigerator plus a 300 watt @ 1.8°K Messer-Griesheim system include:
 - (a) He II cooled LINAC Experiment.
 - (b) Superconducting energy storage experiment.
 - (c) R.F. Particle Separator.
 - (d) 2000 liter helium dewar used if liquefying helium.
- #3. System originally designed as two turbine Claude Cycle, later replaced warm turbine with LIN heat exchanger.
- #4. System must simultaneously provide:
 - 90 watts at 4.3°K and 10 atm
 - 0.4 gls gas at 4.3°K (lead cooling)
 - 1200 watts at 92°K and 10 atm (shield cooling)
 - 10 LL/hr liquid
- #5. Information taken from T. R. Strobridge and C. F. Sindt report "OPERATING EXPERIENCE - HELIUM EXTRACTION AND LIQUEFACTION EXPANSION DEVICES", prepared for National Accelerator Laboratory, January 1974. Only turbo machinery included here and compressors pertinent to present study. For reciprocating expander experience and other details see this report.

TABLE 3

MEAN TURBO-EXPANDER OPERATING HOURS PER FAILURE

<u>TYPE OF TURBINES</u>	<u>HELIUM SYSTEM USER</u>	<u>NUMBER OF TURBINES</u>	<u>TOTAL ACCUMULATED TURBINE HOURS</u>	<u>NUMBER OF FAILURES</u>
Oil lubricated	(CERN) (BEBC)	4 + 1	40,000	2
	CERN (Omega magnet)	2	24,000	0
	BNL (H ₂ turbo-expanders on bubble chamber)	2	24,000	1
	McGill Univ. Magnet Lab.	2	31,200	0
	GFK	2	30,000	2
	TOTALS:		149,200	5

Mean turbo-expander operating time per failure = 29,840 hours

Oil lubricated (from Strobridge, Sindt report for NAL, JAN 1974)	Phillips Greenwood Plant	2	(3 failures in 2 years) 35,040	3
	Cities Service Jayhawk Plant			
	(old system)	2	(1 failure/yr) 17,520	1
	(new system)	2	(3 failures/1.5 yrs) 26,280	3
	Kansas Refined Helium Co.	2	(10 failures/7.5 Yrs) 131,400	10
	TOTALS:		210,240	17

Mean turbo-expander operating time per failure = 12,367 hours.

Grand total for all oil lubricated turbo-expanders:	359,440	22
---	---------	----

Mean oil lube turbo-expander operating hours per failure = 16,340

Externally pressurized gas bearing expansion turbines	CERL	2 on sys. but 1 is redundant	12,000	0
	Culham Lab.	1	17,500	1
	IRD	2	11,000	2
	CENG			
	(cold neutron source)	2	25,400	2
	(liquefier)	1	19,800	0
	(100 watt refrigerator)	1	15,000	0
	Argonne Nat'l. Lab.	1		
	(old turbine)		3,000	3
	(new turbine)		1,200	1
	Lawrence Livermore Lab.	1	13,000	0
	TOTALS:		117,900	9

Mean ext. pressure gas bearing turbo-expander operating hours per failure = 13,100 hrs.

Self-actuating gas bearing turbo-expander	SIN	2	22,000	1
---	-----	---	--------	---

Mean operating hours per turbine for self actuating gas bearing unit = 22,000 hours

TABLE 4

HELIUM REFRIGERATOR STATE-OF-THE-ART AND FUTURE TRENDS

MANUFACTURING RECOMMENDATIONS

1 *

2

RESPONDENTS;

3

4

5

6

7

8

GENERAL SPECIFICATIONS

Type of cable refrigeration system
(a) Integral refrig/cable flow loop
(b) Separate cable pumped loop

Type of compressor recommended

Modifications to compression cycle

Compressor Efficiency

Type of Expander

Expander loading Mechanism

Type of Heat Exchangers

For Separate Pumped Loop Design
Choice - Type of Circulating Pump

Purifier Recommendation

Estimated capital cost per
system if (10) units purchased

Estimated Operator Time
(man-hr/day)

(a)

Requires
study(a) or
(b) ?

(a)

(b)

(a)

(a)

(a)

Helical screw

Helical screw

Helical screw

Recip. dry lube

Labyrinth dry
seal recip.
or dry helical
screwHelical Screw
or CentrifugalLabyrinth dry seal
Seal

Centrifugal

Optimize oil
injection and
pressure ratio
for helium

Oil injection

Oil lube screw com-
pressor state-of-
art adequateSpecific vertical
compr. of this
type has been built
and are satisfactory.
Precautions needed
for sealingLow compression
ratios to limit
temperature rise
other than that
no special
featureScrew: oil free
Centrifugal:
no modificationsPresent state
adequateFreon mixed
system75-80%
Isentropic50%
Isothermal70%
Isentropic80%
Isentropic55%
Isothermal40%
Isothermal55%
Isothermal70%
IsentropicTurbo, dynamic
gas bearingsTurbo, static
gas bearingsTurbo, dynamic
gas bearingsTurbo, dynamic
gas bearingsTurbo, static
gas bearingsTurbo, oil
lubricated brgs.Turbo, oil or
dynamic gas brgs.Turbo, static or
dynamic brgs.Gas compr. or
Alternator

Gas compressor

Gas compressor

Gas compr. or
Alternator

Gas compressor

Gas Compr. or
AlternatorGas Compr. or
Alternator

Oil Loaded

Stainless
steel plateAluminum
plate fin

Aluminum

Aluminum

Aluminum

Aluminum or
St. Stl. plateAluminum or
SST Plate

Aluminum

Centri.

--

Centri.

--

Centri.

--

--

--

Molecular/sieve
charcoalLIN cooled,
switched,
charcoal
adsorbersDual, full flow
drier and dual
low temperature
adsorber system
(fully automatic)H.P. charcoal
adsorption refrig.
with LIN for feed
gas, if impure or
held in bag stor-
age, Cleanup
purifier integral
with cycle also
needed.Double integrated
purifier coded by
helium circuit of
refrigerator
(adsorption)Adsorption
Molecular sieveLIN cooled
adsorbers

Adsorption

\$2.3 x 10⁶\$1.3 x 10⁶\$3.3 x 10⁶\$1.5 x 10⁶\$1 x 10⁶\$10 x 10⁶ ?\$1.8 x 10⁶

--

Four

One

--

Four

One

Eight

One

One

TABLE 4

HELIUM REFRIGERATOR STATE-OF-THE-ART AND FUTURE TRENDS

RESPONDENTS

RELIABILITY AND MAINTENANCE

	1 *	2	3	4	5	6	7	8
Est. man-hrs. scheduled maint./yr for entire refrigerator	120-160	--	240	200	300	200	--	500
Which components require most maintenance	Oil clean up	Compressor.	Controls and monitoring system	Compressor	Compressor	Compressor and purifier	Compressor	Compressor
Maintenance interval for compressor (hrs)	10-20,000 depending on desired confidence to achieve MTBF	8800 inspection	8800	2000	4000	8000	6-8000	26,000
Maintenance interval for expanders (hrs)	100,000 hrs. depending on MTBF confidence required	inspection occasionally	8800 inspection	2000 inspection	--	20,000	Inspection	8800
Most frequent failure on system	Monitoring and control equip.	Compressor and controls	Electrical power loss	Compressor seal leakage or low temp. freezeup	Compressor controls	Contamination	Contamination	Control system
MTBF for compressor (hrs)	75-150,000	50,000	20,000	--	5-10,000	20,000	--	50,000
MTBF for expander (hrs)	500,000	20,000 ?	20,000	--	--	40,000	20,000	12,000
For compressor, how would you handle increasing reliability of existing system (a) component redundancy (b) increase component reliability	(a) and (b)	(a)	(a)	(a)	(b)	(a) and (b)	Chose compr. with enough safety margin	(a) and (b)
For expander, how would you handle increasing reliability of existing system (a) component redundancy (b) increase component reliability	(b)	(a)	(b)	(a)	(a)	(a) and (b)	--	(a)
What other system components would require redundancy	-oil clean-up -monitoring/ control syst.	Electronic components, controls, etc.	Critical controls	--	Some controls	Instrumentation and controls	--	Complete cold box and machinery
FUTURE DEVELOPMENTS								
Level of development effort required in areas which follow in order to increase reliability of state-of-the-art system	-modest dev. effort -optimize compr. for helium compression	-major devel. -to use multi-stage centrifugal	-modest devel. -hydrocarbon detection alarm	Present devel. O.K.	Modest devel.	Major devel. -long life and maint. interval	Major devel. -turbo or screw compressor	Modest devel. -leakage and efficiency
COMPRESSOR								

TABLE 4

HELIUM REFRIGERATOR STATE-OF-THE-ART AND FUTURE TRENDS

RESPONDENTS

MANUFACTURING RECOMMENDATIONS

	1 *	2	3	4	5	6	7	8
EXPANDER	-Major devel. -minimize elements, process gas bearings	-Modest devel. -cannot easily preclude oil lube or dynamic gas brgs. (need study)	-Modest devel. -expand current designs into larger sizes	Present state-of-art O.K.	Present state-of-art O.K.	Major devel. -expander loading	Present state-of-art O.K.	-Modest devel. -bearings
CIRCULATING PUMP	-Modest devel.	-Modest devel.	-Major devel. -centrifugal pump with 70% adiab. efficiency	Major devel.	Major devel.	--	--	--
CONTROLS	-Modest devel. -integration of controls	-Modest devel. -automatic control of total system	-Present state-of art O.K.	-Modest devel.	-Modest devel.	-Modest devel. -reliability	Present state-of-art O.K.	Present state-of-art O.K.
HELIUM PURIFIER	Modest devel.	-Present state O.K. -address prob. of initial clean-up	-Modest devel. -automatic control of total system	-Present state O.K.	Modest devel.	-Present state O.K.	Modest devel.	-Present state O.K.
OIL CLEAN-UP PACKAGE (if oil lube compr. used)	-Modest devel. -definition of allowable levels of contamination	Present state O.K. -must design for each specific application	-Modest devel. -instrumentation for oil detection	-Modest devel.	--	--	--	-Present state O.K.
OTHER POTENTIAL PROBLEMS	Reliability of control and monitoring equipment	-Problems of response of refrig. to changes in line conditions -may require special damping	--	--	--	Helium storage, nitrogen pumps, reliability of power supply	--	--
OTHER COMMENTS	--	--	Suggest devel. of centrifugal compr. with at least 70% adiab. efficiency	Room for improvement in heat exchanger types	--	--	--	--

NOTES * - Respondent answered questionnaire in terms of projected equipment which should meet system requirements consistent with transmission line development time frame.

TABLE 5

TURBO-EXPANDER SIZE RANGE SUMMARY FOR PRESENT STATE-OF-THE-ART EQUIPMENT

TYPE OF TURBO-EXPANDER AND MANUFACTURER SUPPLYING INFORMATION	LOWER PRACTICAL LIMIT FOR CAPACITY RANGE watts @ 4.2 or LL/hr	ISENTROPIC EFFICIENCY AT LOWER RANGE	UPPER PRACTICAL LIMIT FOR CAPACITY RANGE watts @ 4.2 of LL/hr	ISENTROPIC EFFICIENCY AT UPPER RANGE
Externally pressurized gas bearing turbo- expander (BOC)	(w/LIN precool) 8 LL/hr	60%	(w/LIN precool) 1000 LL/hr or 2.5 Kw @ 4.2°K 5 Kw @ 4.2°K with 2 turbines in parallel	80%
Self-actuated gas bearing turbine (Sulzer Bros. Ltd.)	(w/o LIN precool) 40 watts @ 4.2°K	60%	(w/o LIN precool) 3000 watts @ 4.2 (two turbines in series) > 3000 watts @ 4.2 °K (one turbine in series with two parallel turbines) (w/LIN precool) 6000 watts @ 4.2°K (3 turbine configuration given above)	80%
Oil Lube turbines (Sulzer Bros. Ltd.)	(w/o LIN precool) 1000 watts @ 4.2°K	65%	150 Kw @ 4.2°K (this is economic limit for turbine loading device)	80%

TABLE 6

PERCENT ON STREAM AVAILABILITY OF STANDARD NITROGEN PLANTS
DURING THE MONTHS OF APRIL-AUGUST, 1975

	<u>APRIL</u>	<u>MAY</u>	<u>JUNE</u>	<u>JULY</u>	<u>AUGUST</u>
1. Addyston	99.68	100	99.55	83.92	100
2. Alcoa	98.61	96.24	99.62	97.72	100
3. Allentown	97.50	98.19	99.20	92.57	99.87
4. Apple Grove	100	98.66	99.44	100	99.13
5. Crystal City	97.78	100	100	100	97.92
6. Cuyahoga	90.66	99.60	100	100	100
7. Findlay	98.13	99.73	99.27	86.24	96.77
8. Fishkill No. 1	100	99.66	98.89	85.35	100
9. Greenville, S.C.	100	98.92	97.26	100	99.90
10. Hennepin	100	100	100	100	84.71
11. Kenova	99.17	100	99.20	99.19	98.39
12. LaPlace No. 1	100	99.40	82.88	99.82	100
13. LaPlace No. 2	100	99.06	100	99.10	98.55
14. Laurinburg	99.15	99.54	99.06	99.29	99.42
15. Leechburg No. 1	97.93	87.97	78.68	0	
16. Leechburg No. 2	89.39	11.62	97.57	100	
17. Lowland No. 1	98.02	99.63	100	100	99.87
18. Lowland No. 2	100	100	99.31	100	100
19. Meadville No. 1	100	100	98.68	98.83	93.48
20. Meadville No. 2	100	100	99.40	99.31	99.42
21. Mesa No. 1	0	0	0	0	0
22. Mesa No. 2	100	99.19	99.79	99.73	100
23. Mt. Holly Springs	100	89.45	96.46	93.88	100
24. Norco	79.51	98.99	99.53	99.09	100
25. Ottawa	100	100	100	100	100
26. Rocky Flats No. 1	0	0	0	0	0
27. Rocky Flats No. 2	98.89	99.66	98.09	100	98.32
28. Sunnyvale	94.42	99.66	100	98.06	96.92
29. Tulsa	99.50	100	100	99.80	98.79
30. Wichita Falls	100	99.73	99.27	100	99.06
31. Mountain View No. 2	100	98.58	99.53	95.97	98.60
32. Decatur	92.64	95.70	98.30	93.24	100
33. Palestine	-	-	-	-	0
34. Davenport	-	-	100	99.23	98.72
35. Fishkill No. 2	-	-	100	99.26	100

TABLE 7

STANDARD NITROGEN PLANT
ALCOA, TENN.

<u>Date of Outage</u>	<u>Duration of Outage (Hrs)</u>	<u>Reason for Outage</u>
29 Jul 75	5.0	Repair LRC-3-RC (low pressure rectification column liquid level controller)
22 Jul 75	2.5	Flooded reboiler
19 Jul 75	1.0	Flooded reboiler
14 Jul 75	2.5	Flooded reboiler
8 Jul 75	4.0	Flooded reboiler. H ₂ O pump stopped
3 Jul 75	2.0	Low-high pressure column level
28 Jun 75	1.0	Low pressure column upper liquid level line plug
20 Jun 75	1.75	Low pressure column upper liquid level line plug
29 May 75	8.5	Low purity. Worked on FRC-6-V1 and V2 (flow control valves)
26 Ma6 75	0.5	Low purity, low pressure
25 May 75	0.5	Low purity, low pressure
24 May 75	0.75	Low purity, low pressure
14 May 75	1.0	Change switch valve actuator
14 May 75	1.0	Low pressure loss of purity
11 May 75	0.75	Low purity
7 May 75	9.5	Remove and repair switch valve
5 May 75	0.75	Loss of purity
30 Apr 75	10.0	Low column and exchanger pressure
13 Mar 75	64.25	Scheduled plant defrost - 24 months

<u>Date of Outage</u>	<u>Duration of Outage (Hrs)</u>	<u>Reason for Outage</u>
14 Jan 75	5.50	Low flow to turbo-expander (changed inlet filter)
18 Nov 74	1.25	Power failure
21 July 74	17.5	Main breaker failure
4 July 74	5.50	Changed switch valve and work on "A" cooling fan
30 Jun 74	1.0	O ₂ Analyzer malfunction
26 Jun 74	9.0	Scheduled defrost and minor maintenance
9 Jun 74	4.5	Switch valve malfunction
26 Nov 73	3.0	Earth quake
12 Nov 73	1.50	O ₂ analyzer malfunction
2 Nov 73	3.50	Low level on H.P. column
29 Oct 73	0.75	Customer power failure
25 Oct 73	4.50	Plant maintenance (replaced switch valve, air inlet filters, etc.)
23 Oct 73	1.75	Customer power outage
22 Oct 73	6.0	Liquefier defrost
19 May 73	7.0	FRC-6-V2 venting low purity had closed FRC-6-V1
4 Apr 73	2.0	Voltage dip - thunder storm
1 Apr 73	1.25	O ₂ analyzer malfunction
27 Mar 73	80.5	Plant maintenance and defrost
10 Mar 73	1.0	O ₂ analyzer problem
8 Mar 73	21.25	Switch valve failure
2 Mar 73	2.25	Warning light
19 Jan 73	3.0	Warning light
18 Jan 73	3.50	Warning light

<u>Date of Outage</u>	<u>Duration of Outage (Hrs)</u>	<u>Reason for Outage</u>
12 Jan 73	1.25	Alarm (analyzer malfunction)
13 Jan 73	2.50	Cooling water make-up valve malfunction
19 Dec 72	2.25	High level in H.P. column
12 Nov 72	1.0	Blip on O ₂ analyzer
16 Oct 72	3.5]	Power interruption
30 Sep 72	3.75	?
4 Sep 72	2.5	Cooling water tower problem
22 Jun 72	0.50	Install pilot valve in compressor control panel
13 Jun 72	9.0	Electric and plant maintenance
18 May 72	2.5	Change switch valve
8 May 72	9.0	Low level in high pressure column
7 May 72	2.75	Low level in H.P. column
8 Mar 72	2.5	Low level in H.P. column
16 Jan 72	4.9	Float valve on cooling water make-up valve frozen
4 Jan 72	69.25	Plant defrost
17 Nov 71	8.5	Pressure drop across liquefier - H.P. liquid level low
23 Aug 71	2.0	High oil temperature on air compressor caused by automatic valve failure in water line from cooler
14 Jul 71	2.5	Thunder storm
28 Jun 71	2.4	Thunder storm (voltage drop)
27 May 71	5.4	Liquefier defrost
8 May 71	4.25	Electrical repair by customer

<u>Date of Outage</u>	<u>Duration of Outage (Hrs)</u>	<u>Reason for Outage</u>
27 Feb 71	3.75	Restriction in H.P. column upper liquid level line causing a low level shutdown
18 Jan 71	Alarm	Low purity scam flashing
8 Dec 70	3.0	LRC2RC malfunctioned and held LRC2V wide open causing low liquid level shutdown in H.P. column
7 Dec 70	2.0	LRC3V malfunctioned and lost liquid level in reboiler causing low product purity
30 Nov 70	4.50	Low cooling water pressure due to cooling water pressure switch frozen with ice
22 Nov 70	3.75	Electrical equipment malfunction
22 Nov 70	4.75	Electrical equipment malfunction
28 Nov 70	3.5	Upper liquid level line restriction - low level in H.P. column
27 Oct 70	7.75	Liquefier defrost
27 Oct 70	6.0	?
20 Oct 70	5.5	Electrical power turned off by customer (did not notify plant)
11 Oct 70	7.25	Low water in cooling tower reservoir, low water pressure
28 Sep 70	1.33	O ₂ analyzer malfunction
26 Sep 70	2.0	High level in H.P. column - purity 9 ppm due to flooding column - caused by LRC-2 line restriction purity 76 ppm
25 Sep 70	2.33	High level in H.P. column - purity 9 ppm due to flooding column - caused by LRC-2 line restriction purity 87 ppm
22 Sep 70	9.5	To install larger 3rd stage impellor on Elliot compressor
12 Sep 70	5.7	Electrical equipment malfunction

<u>Date of Outage</u>	<u>Duration of Outage (Hrs)</u>	<u>Reason for Outage</u>
7 Sep 70	3.25	Low level - H.P. column
2 Sep 70	34.00	New transformer installed. New 3rd stage wheel installed. Checked 2nd stage and 1st stage.
10 Aug 70 thru 20 Aug 70	70.00	Expander warning flashing and series rectifier failure, also a transformer replacement
1 Aug 70	3.25	Voltage dip due to thunder storm
1 Aug 70	64.00	Rectifier in motor control malfunction (installed new 800 amp breaker and rectifier)
25 Jul 70	2.0	Alcoa power outage
5 Aug 70	13.00	Electrical malfunction (rectifier). (took time to defrost)
14 Jul 70	4.0	Had to reset (electrical device wires) to start plant
14 Jul 70	3.5	Had to reset (electrical device wires) to start plant
14 Jul 70	3.9	Vibration switch malfunction
TOTAL	<u>719.96 hours</u>	
AVAILABLE	44,124 hours	
% ON STREAM	98.37	
TOTAL OUTAGES	89	
OUTAGES/YR.	17.5	

TABLE 8

OUTAGE TIME INTERVAL BREAKDOWNS FOR SIX
RANDOMLY SELECTED STANDARD NITROGEN PLANTS

DURATIONS OF OUTAGE (Hrs.)	PERCENTAGES OF OUTAGES FALLING INTO THIS GROUP %
0-6	73.8
6-24	20.8
24-72	4.3
> 72	1.1

TABLE 9

SUMMARY OF OUTAGES LONGER THAN 24 HOURS
SIX APCI STANDARD N₂ PLANTS, UNATTENDED

<u>PLANT</u>	<u>DATE</u>	<u>HOURS</u>	<u>REASON FOR OUTAGE</u>
<u>Addyston</u>			
11,160 hrs	12 Aug 74	54.6	NCD
65 t/d	12 Jul 75	112.5	NCD
<u>Alcoa</u>			
44,124 hrs	1 Aug 70	64	Motor control rectifier failure
45 t/d	10-20 Aug 70	70 tot.	Series of expander alarms (no failures) and several rectifier failures
	2 Sep 70	34	Replace transformer and 3rd stage compressor wheel
	4 Jan 72	69.25	PM
	27 Mar 73	80.5	PM
	13 Mar 75	64.25	PM
<u>Allentown</u>			
71,040 hrs	10 Jan 68	32.5	Automatic shutdown, Unknown cause
52 t/d	16 Jul 68	58.75	PM
	28 Apr 71	43.0	PM
	11 Nov 71	67.33	Compressor motor failure
	3 Feb 72	36.5	PM
	5 Dec 72	42.33	Install experimental switch valve
	24 Jul 73	40.75	PM
	15 Jul 74	38.5	PM
	23 Jul 74	55.25	PM
	21 Feb 75	55.0	High acetylene, defrost
<u>Apple Grove</u>			
64,920 hrs.	23 Feb 68	266.5	Main air compressor motor failure
61 t/d	10 Jun 68	47.5	Switch valve failure
	10 Oct 69	79.0	PM
	29 Jun 70	57.5	Plugged intercooler on main compressor
	9 Nov 70	62.5	PM
	10 Dec 72	34.0	Bearing failure on cooling system
	2 Apr 74	27.5	PM
<u>East Fishkill</u>			
49,056 hrs	8 May 73	43.0	PM
35 t/d	25 Jul 75	109	PM
<u>Rocky Flats</u>			
18,696 hrs	20 Jun 73	42.5	Problems with compressor motor and coupling clearance
61 t/d			

NCD No customer demand

PM Preventive maintenance (scheduled)

Capacity is tons/day of gas

Power $\approx$ 20 HP / (t/d)

FIGURE 1
PROGRAM SCHEDULE BY TASK

SHADING SHOWS PERCENT OF WORK COMPLETED

FIGURE 2

SIMPLIFIED APCI, STANDARD NITROGEN PLANT 38,000 SCFH

FIGURE 3

STANDARD NITROGEN PLANT
PERCENTAGE BREAKDOWN OF SOURCES OF PLANT OUTAGE
ALCOA PLANT

TOTAL PLANT ON STREAM TIME: 44,124 HRS.
TOTAL OUTAGE TIME: 719.9 HRS.
% OF AVAILABLE TIME ON STREAM: 98.37 %

FIGURE 4

STANDARD NITROGEN PLANT

AVERAGE PERCENTAGE BREAKDOWN OF SOURCES OF PLANT OUTAGE FOR SIX RANDOM PLANTS

TOTAL PLANT ON STREAM TIME: 258,996 HRS.
 TOTAL OUTAGE TIME 4,465 HRS.
 % OF AVAILABLE TIME ON STREAM: 98.27%