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. Task 03.20 (Develop Optimization Criteria) and task 04.10 (Evaluate Component Reliability, Efficiency) of the previous report period have been nearly completed. Task 03.30 (Component Evaluation) and task 06.00 (Review of Business Factors) of the current report period are now complete. Task 04.20 (Redundancy, Reliability, and Backup) of the current report period is about 80% complete. Figure 1 shows the tasks of the current report period on a program schedule chart.

WORK STATUS

The sections which follow relate to the evaluation of component reliability and efficiency, development of and an optimization criteria and evaluation of effects of redundancy and back-up on overall system reliability.

EVALUATION OF COMPONENT RELIABILITY, EFFICIENCY

Through the use of questionnaires, direct contact, helium equipment user visits, and APCI in-house experience, a fairly good assessment of component efficiencies have been obtained. An accurate assessment of component reliability was considerably more difficult to obtain. The reliability figures which are being used to develop an optimization criteria for component selection are based in large part on APCI standard nitrogen plant experience and to somewhat lesser extent on the survey of helium users which was conducted by APCI.

DEVELOPMENT OF OPTIMIZATION CRITERIA, COMPONENT EVALUATION, AND EVALUATION OF RELIABILITY THROUGH REDUNDANCY AND BACK-UP

All three major tasks have been listed in the above heading because, after giving these tasks considerable thought, it becomes apparent that all three are closely interrelated so that one cannot be evaluated without evaluating the effects on the other two.

Development of a component optimization criteria must take into account component reliability, efficiency, capital cost, maintenance costs and the cost of utilities. In order to be effective the optimization criteria must then provide a measure of how all of these component parameters influence the total system reliability and the capital plus operating cost. In the final analysis the optimum component is that which permits the total system to reach the required level of system reliability at the lowest capital plus operating

cost. Evaluation of a component in this light, requires that a reliability analysis of the entire network of components, which is to make up the complete superconducting power transmission line, be performed. This analysis yields an overall system reliability for a specific assemblage of components. Given these components and their associated efficiencies, capital costs, maintenance intervals, mean time between failures, and the cost of labor and utilities one is then in a position to put a price tag (depreciated capital plus operating costs) on the computed level of total system reliability. It may well occur that the computed level of reliability does not measure up to the required level (this level must be set by the electric utilities); this would then imply that for the specific components used, the level of reliability sought can only be achieved through the use of redundancy or back-up. At this point in the analysis it would make sense to follow through with the computations to the point where the required degree of back-up for the critical system components would be determined.

While one would like to carry out this analysis for all types of components and possible system configurations, this is not practical within the scope of the present investigation. For this reason, one must work within the framework of a specific system design - we have chosen to look at the BNL basic system which was set up to satisfy the requirements of the LILCO plan 3A study.

To review, the requirements of that system were:

- Two separate cables each rated at 4800 MVA and 345 KV

- Heat load per cable at superconductor: 3600 watts
- Temperature of central cable: $6.75^{\circ} - 8.75^{\circ}\text{K}$
- Load on shield per cable: 11,200 watts at $75^{\circ} - 100^{\circ}\text{K}$
- Mass flow in central circuit per cable: 312 g/sec.
- Mass flow at helium in shield circuit per cable: 80 g/sec.
- Distance between refrigeration stations: 12 Km
- Total length of line: 68 Km (assume six refrigeration stations)

Reliability Network Model

In order to illustrate the manner in which the reliability portion of the aforementioned analysis is implemented, one simple system will be looked at and the reliability of the overall system computed.

It will be assumed that each refrigeration section will consist of two large screw compressors with their associated oil separation systems (see Figure 2); one compressor would be operating at full capacity and would be capable of providing enough helium for both cables along a 12 Km section of the line. In other words, one compressor, with a 50% isothermal efficiency, would require about 2526 Kw of input power. The second screw compressor would only operate in the event of failure or scheduled maintenance of the first unit. Both compressors would be connected to a common manifold so that either of the compressors could service either of the two cold boxes which are described below.

The two parallel cold boxes are assumed to be sized so that either of the cold

boxes operating alone would have sufficient capacity to keep both 12 Km sections of cable cold. Under normal operation both units would be running in parallel, each at half capacity. This is done so that in the event of failure or scheduled shutdown of one of the units the other could take the full compressor flow immediately, and deliver full capacity in a very short period of time without having to wait for the unit to cooldown to the required operating temperature. One manner in which the cold boxes could be made to operate at full or half capacity would be to use two half size turbo-expanders at each point in the cold box where there presently exists only one turbo-expander.

Since two cables are used in parallel and each is sized to handle the full contingency requirements, for the purposes of computation of the system reliability one would treat this as two parallel operating cables each with sufficient capacity to take over full normal load for a period of time. Unfortunately nothing is known about the reliability of the cable/cryogenic envelope subsystem so it cannot be included in the reliability analysis presented here.

The reliability analysis used here may be implemented in a building block fashion in which the reliabilities of the individual components are combined in various ways to compute a reliability for each subsystem, and then the reliabilities of these minor subsystems are combined to yield the reliability of major subsystems which are in turn combined to yield the reliability of the entire system.

Let us start with a specific component - for instance, a temperature sensor. if this sensor is subject only to random or chance failures, the probability that the sensor will not fail in a specified interval of time, t , is given by the formula (1):

$$R(t) = e^{-\lambda t} \quad (1)$$

where λ is a constant which expresses the chance failure rate of that particular component.

As pointed out by Bazovsky (1), this formula is correct only for those components which have been adequately debugged and which have not as yet been subjected to appreciable wear. Note also that the time, t , used in the reliability formula must never exceed the useful life of the device.

In order to illustrate how components are combined to obtain the reliability of a subsystem, reference is made to the component reliability block chart displayed in Figure 3.

This figure displays the BNL cold box and displays all the major components in a "series" configuration (linked one to another). A "series" type block link implies that if anyone of the component blocks in the chain failures, then the entire subsystem itself will fail. If R_1 refers to the reliability of component 1 (heat exchangers) given by:

$$R_1 = e^{-\lambda_1 t} \quad (2)$$

and if R_2 refers to the reliability of component 2 (expander no. 1) given by

$$R_2 = e^{-\lambda_2 t} \quad (3)$$

etc., then for the series network shown in Figure 3, the overall subsystem reliability can be expressed as

$$R_{CB} = R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 \quad (4)$$

where R_{CB} represents the probability that a single cold box, made up of series components 1 through 6, will not fail during an interval of time, t . Examination of the probability of no failure in a single cold box for realistic run times, t , soon make it obvious that for realistically engineered components, one cold box at each refrigeration station is not sufficient to obtain any reasonable degree of overall system reliability. One is then faced with the alternative of providing either back-up components for each critical component within the cold box or, one must provide a duplicate back-up cold box. For this particular example, as already mentioned previously, we will consider the somewhat more practical approach of providing a duplicate cold box.

Once the reliability of each minor subsystem is evaluated, such as the reliability of a single compressor or single cold box, we must then compute the combined reliability of the single unit and its back-up. It is at this point that we will depart from the conventional manner in which reliability analysis is applied to such systems as aircraft, missiles, etc., in which the operating time interval, t , is equal to the time required for a specific mission. Aircraft mission type reliability is usually computed on the basis that if the prime component fails and the back-up unit must take over, it is

assumed that no maintenance is carried out on the failed unit during the remainder of the mission time. However, in the case of the superconducting power transmission line, this type of operation would be impractical. It is essential to the maintenance of a high level of total system reliability that as soon as a unit such as a cold box fails due to the failure of one of its series components, that measures be taken to repair or replace the malfunctioning unit as soon as possible. The need for this type of operation becomes evident when one examines the reliability equations and discovers that for the case of prompt repair or maintenance, the reliability of the prime component and its stand-by is no longer a function of the total system operating time, t , but is instead a function of the time, t' , required to repair or replace the first unit in the event of a chance failure. More specifically, the reliability of the prime unit and its standby becomes the reliability of the standby unit operating for a period of time, t' - herein lies the incentive for well planned and efficient unscheduled maintenance procedures. While t' is a very important time in the system reliability analysis it is not the only one. Besides the chance failure of the prime operating unit, another reason for the shutdown of this unit would be for scheduled preventative maintenance. The important time parameter for this case becomes the time required for scheduled maintenance, t'' . The reliability of the prime unit and its standby then becomes the reliability of the standby unit operating for a period of time, t'' - herein lies the incentive for well planned and efficient scheduled maintenance procedures. The manner in which the effects of t' and t'' are combined to arrive at an overall system reliability is illustrated via the example case discussed below.

Lets look at the reliability of the two cold boxes running in parallel at one half full capacity:

Assume that one cold box is referred to as cold box A and the other cold box B.

It is obvious that with two units operating simultaneously either A or B may fail. If B fails first, the probability of failure of the remaining unit, $Q_{A\lambda}$, during the maintenance of unit B in the interval t'_B is given by

$$Q_{A\lambda} = 1 - e^{-\lambda_A t'_B} \quad (5)$$

Note by definition, the probability of failure, $Q_{A\lambda}$, is equal to one minus the probability of no failure, that is

$$Q_{A\lambda} = 1 - P_{A\lambda} \quad (6)$$

In equation (5), t'_B is the time required to repair cold box B after a chance or random failure and λ_A is the failure rate of A.

If unit A fails, then the probability of failure of the remaining unit during the time required to repair A (t'_A) is given by,

$$Q_{B\lambda} = 1 - e^{-\lambda_B t'_A} \quad (7)$$

Since it is convenient to express the failure rates in terms of failures per year instead of the usual use of failures per hour, the following substitutions can be made:

$$\lambda'_B = 8760 \cdot \lambda_B \quad (8)$$

$$\lambda'_A = 8760 \cdot \lambda_A \quad (9)$$

packages (Q'_C) illustrated in Figure 2. The probability of failure of such a full capacity unit running with an inactive standby becomes:

$$Q'_C = 3 - e^{-\lambda'_C t'_C / 8760} - e^{-\lambda'_C \xi'_{CA} t'_C / 8760} - e^{-\lambda'_C \xi'_{BC} t'_C / 8760} \quad (16)$$

It can be shown if one accounts for the fact that compressor B runs only if A is off due to chance failure or scheduled maintenance, then the number of scheduled maintenances required on unit B, based on that required for A, is given by

$$\xi'_{BC} = \xi'_{CA} \frac{(\lambda'_C t'_C + \xi'_{CA} t'_C)}{8760} \quad (17)$$

One can now use equation (16) to generate curves of Q'_C versus λ'_C for the screw compressor combination for various values of ξ'_{CA} . Such a plot is shown in Figure 4. Figure 4 was generated with a mean-time to repair during a scheduled maintenance of $t'' = 10$ hours; this value is based on a 20 man-hour maintenance time quoted by Howden Godfrey Ltd. for their screw compressors (assuming two men in maintenance crew). Also assumed in Figure 4 was a mean-time to repair during a chance failure of $t'' = 24$ hours. Figure 4 shows probabilities of a failure during a year for various combinations of ξ'_{CA} and λ'_C ; however, based on some numbers supplied by Howden Godfrey Ltd. and Dunham-Bush in response to our questionnaire, a reasonable choice for ξ'_{CA} and λ'_C would be

$$\lambda'_C = 0.175 \text{ failure /year} \\ \text{(based on a MTBF of 50,000 hours)}$$

$$\xi'_{CA} = 0.29 \text{ scheduled maintenances/year} \\ \text{(this includes oil separator)}$$

Note that these values for λ'_C and ξ'_{CA} place the probability of failure of the screw compressor pair, over a period of one year, down to a valuable of about 1.5×10^{-4} or 0.015%.

Figure 5 illustrates the probability of failure of the cold box pair as a function of λ'_{CB} and ξ'_{CB} . For this plot it was assumed that $t' = 24$ hours and that $t'' = 24$ hours.

Depending on the failure rates and scheduled maintenance rates, figure 4 and 5 now permit us to determine the probability of failure of one of a possible six similar helium refrigeration stations situated along the 68 Km cable route.

Once the probability of failure of a particular station is known, the failure rate of the entire system can be obtained in the following manner.

If the probability of no failure of the parallel compressor set during the course of one year is R'_C , and the probability of no failure occurring in the parallel cold box set during the course of one year is R'_{CB} , then the probability of no failure occurring at the station during the year R'_S , is:

$$R'_S = R'_{CB} R'_C \quad (18)$$

In terms of the probability of failure of the station, Q'_S

$$Q'_S = 1 - (1 - Q'_{CB})(1 - Q'_C) \quad (19)$$

Once the reliability of each station is known, the reliability of the entire cable refrigeration system, consisting of n stations, becomes:

$$R'_{TOT} = R'_S{}^n = (R'_{CB} \cdot R'_C)^n \quad (20)$$

or, in terms of the probability of failure,

$$Q'_{TOT} = 1 - [(1 - Q'_{CB})(1 - Q'_C)]^n \quad (21)$$

Q'_{TOT} could now be compared with the maximum probability of failure of the cable system required by the electric utility company. Unfortunately no such clear cut maximum value appears to exist. Estimates have ranged from one days outage every twenty years to 0.031 outages per year per cable mile with an average outage duration of 336 hours. In terms of Plan 3A, the latter outage failure rate works out to 1.3175 failures per year per cable. These figures obviously represent quite a wide latitude in system reliability. It is obviously very important that a serious effort be made to get the utilities to define a reasonably concrete level of system reliability.

If one were to assume that the failure rate most accurately describing the requirements of the utilities would be one days outage in twenty years and if only one outage occurred which lasted one day (as opposed to a number of outages in twenty years which add up to one day), then the equivalent reliability for a one year period would be:

As equations (5) and (7) now stand, they express the probability of failure of the second unit during one chance failure of the first. It would be more meaningful to compute the probability of failure of the parallel cold box combination during the course of one year - this would then involve the repeated chance failures of both units A and B during the course of one year; to be more specific, λ'_B failures of B and λ'_A failures of A during the year. The manner in which to compute the overall probability of failure of repeated events is discussed on page 102 of reference (2) under the heading of repeated Bernoulli trials. Apply this analysis to the present case one obtains:

For the repeated failure of unit B at the rate of λ'_B failure per year, the probability of failure of A during one year becomes:

$$Q'_{A\lambda} = 1 - (e^{-\lambda'_A t'_B / 8760})^{\lambda'_B} \quad (10)$$

For the repeated failure of unit A at the rate of λ'_A failures per year, the probability of failure of B during one year becomes,

$$Q'_{B\lambda} = 1 - (e^{-\lambda'_B t'_A / 8760})^{\lambda'_A} \quad (11)$$

Over the course of one year, failure can therefore occur either through failure of unit A or unit B. These two events are mutually exclusive, therefore, the probability of failure of the station through either failure of A or B during one year becomes the sum of equation (10) and (11):

$$Q'_\lambda = 2 - e^{-\lambda'_A \lambda'_B t'_B / 8760} - e^{-\lambda'_A \lambda'_B t'_A / 8760} \quad (12)$$

A similar analysis must now be carried out for failures which can occur during the scheduled maintenance of either A or B. If ξ'_A is the number of scheduled maintenances per year done on unit A and ξ'_B is the number of scheduled maintenances performed on unit B then the probability of failure of either A or B during the course of a year resulting from the scheduled maintenance of either A or B becomes

$$Q'_{\xi} = 2 - e^{-\lambda'_A \xi'_B t_B'' / 8760} - e^{-\lambda'_B \xi'_A t_A'' / 8760} \quad (13)$$

Finally the probability of the cold box combination failure during the course of one year due to either chance failure of one of the components or scheduled maintenance becomes

$$Q'_{CB} = 4 - e^{-\lambda'_A \lambda'_B t_B' / 8760} - e^{-\lambda'_A \lambda'_B t_A' / 8760} - e^{-\lambda'_A \xi'_B t_B'' / 8760} - e^{-\lambda'_B \xi'_A t_A'' / 8760} \quad (14)$$

For identical units,

$$\begin{aligned} \xi'_B &= \xi'_A = \xi' \\ \lambda'_A &= \lambda'_B = \lambda' \\ t'_A &= t'_B = t' \\ t''_B &= t''_A = t'' \end{aligned}$$

Therefore, equation (14) reduces to:

$$Q'_{CB} = 2(1 - e^{-\lambda'^2 t_{CB}' / 8760}) + 2(1 - e^{-\lambda' \xi' t_{CB}'' / 8760}) \quad (15)$$

A similar procedure must be followed to compute the probability of failure, during one year, of the parallel set of screw compressors and oil clean-up

$$R'_s = e^{-\lambda_s t}$$

where $\lambda_s = \frac{1}{(20 \text{ yrs})(8760 \text{ HRS/YR})} = 5.708 \times 10^{-6} \frac{\text{FAILURE}}{\text{YR}}$

$$R'_s = e^{-(5.708 \times 10^{-6})(8760)}$$

$$R'_s = 95.12\%$$

or the probability of failure in one year becomes

$$Q'_s = 4.88\%$$

Figure 6 gives the permissible or maximum probability of failure allowed for the cold box given a specific probability of failure for the screw compressor set. This plot is a graph of

$$Q'_{CB} = 1 - \frac{(1 - 0.0488)^{1/6}}{(1 - Q'_c)}$$

which sets as an upper limit, a probability of failure of the total system of 4.88%. Thus, if a realistic probability of failure for the screw compressor set is 1.5×10^{-4} then the maximum possible probability of failure for the cold box set would be about 8×10^{-3} . If one now refers to Figure 5 and attempts to locate $Q'_{CB} = 8 \times 10^{-3}$ it becomes readily apparent that in order to achieve this low probability of failure with only two parallel cold boxes it would be necessary to have extremely high reliability components in each cold box - reliable enough so that the failure and maintenance rate per year for each cold box should be below one per year. In light of our own standard nitrogen plant experience it is obvious that this would be extremely

difficult if not impossible to achieve. One is now forced to look at systems with more redundancy or stand-by capability or even the use of some sort of thermal capacitance such as a large reservoir of liquid helium to hold the system over until repairs are made. It is the exploration of these alternate schemes which we are presently concentrating on from both a reliability and cost standpoint, and which will be reported in our final report.

REVIEW OF BUSINESS FACTORS

The business factors which might have in some way influenced the design of the refrigeration systems used on the superconducting power transmission line have been reviewed and the results of this review will be presented in the final report. The only comment which might be made at this point is that it has been found that, generally speaking, business factors will not influence the design of the systems proposed for the superconducting power transmission line.

BIBLIOGRAPHY

1. Bazovsky, Igor - Reliability Theory and Practice, Prentice-Hall Inc., 1961.
2. Parzen, Emanuel, Modern Probability Theory and Its Applications, John Wiley and Sons, Inc., 1960.

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

FIGURE 1
PROGRAM SCHEDULE BY TASK

SHADING SHOWS PERCENT OF WORK COMPLETED

FIGURE 2 RELIABILITY BLOCK NETWORK FOR SIMPLE SUPER-
CONDUCTING POWER TRANSMISSION LINE REFRIGERATION STATION

FIGURE 3 - RELIABILITY BLOCK DIAGRAM FOR COLD BOX COMPONENTS

FIGURE 4 - SCREW COMPRESSOR PROBABILITY OF FAILURE
FOR ONE OPERATING FULL CAPACITY AND
ONE IN STANDBY

FIGURE 5 - COLD BOX PROBABILITY OF FAILURE - TWO UNITS
RUNNING IN PARALLEL AT HALF CAPACITY

FIGURE 6 - PERMISSIBLE LEVELS OF Q'_{CB} AND Q'_C IN ORDER TO HAVE TOTAL SYSTEM PROBABILITY OF FAILURE SATISFY THE CONDITION THAT $Q'_{TOT} \leq 4.88\%$