CRYOGENIC DIELECTRICS AND
SUPERCONDUCTING AND CRYOGENIC
MATERIALS TECHNOLOGY FOR
POWER TRANSMISSION

Semiannual Report — March 1, 1973

OAK RIDGE NATIONAL LABORATORY

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FOR POWER TRANSMISSION

Semiannual Report - March 1, 1973

Cryoelectrics Section
Engineering Sciences Group
Thermonuclear Division

MAY 1973

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TABLE OF CONTENTS

	<u>Page</u>
I. ABSTRACT	1
II. INTRODUCTION	5
III. NATIONAL AND SOCIETAL NEEDS	7
IV. PROGRAM ELEMENTS	17
A. Cryogenic Dielectrics	19
1. Introduction	19
2. Experimental Equipment	21
3. Experimental Program	23
a) Cryogenic Apparatus Design	25
b) Flashover Experiments	26
c) dc Breakdown	32
d) ac Breakdown	33
e) Partial Discharge	33
f) Impulse Testing	33
B. Superconducting Materials	34
1. Introduction	34
2. Work Completed Through February 1973	35
a) Niobium-Rare Earth Dispersion Studies	35
b) Alternating Current Loss Measuring Techniques	43
c) Expansion of Program to High T_c Materials Such as Nb_3Sn	49
3. Work Planned for the Remainder of FY 1973	50
a) Nb-Rare Earth Dispersions	50
b) Alternating Current Loss Measuring Techniques	51
c) Work on the High T_c Superconductors	51
References to Section IV.B	52
C. Dispersion Hardening of Aluminum	53
1. Introduction - Statement of Problem	53
2. Scope of Work	54
a) Hypothesis and Rationale	54
b) Program Plan	58
3. Progress	60
4. Expected Results (Second Quarter CY 1973)	61
5. Visits	64
References to Section IV.C	66

TABLE OF CONTENTS (continued)

	<u>Page</u>
APPENDIX A, Dielectric Strength of Liquids and Gases at Cryogenic Temperatures--A Literature Survey . .	69
APPENDIX B, Stabilized High Voltage dc Power Supplies of the Shielded Design, G. Reinhold et al., IEEE Trans. Nucl. Sci. <u>NS-12</u> , 293 (1965)	107
APPENDIX C, 600 kV Rectifier	113
APPENDIX D, Series Resonant ac Dielectric Test Equipment . .	121
APPENDIX E, Trip Report - DAT Superconducting Transmission Line Project, Brookhaven National Laboratory, January 17-19, 1973	127

I. ABSTRACT

Reduction in the cost of underground electrical transmission is recognized as a critically important task if the utility industry is to meet the nation's needs for electric energy without undue cost while preserving the amenities in and near load centers and power plants. Cryogenic and superconducting cables which operate at temperatures from 90 K down to 4 K are being developed with the expectation of power capabilities from four to ten times that of present-day cables and with substantial reductions in investment. The components for these cables which are under development are of necessity based upon present state-of-the-art materials, whether dielectrics for electrical insulation or metals for the superconductor or normal conducting substrate. The program at ORNL is designed to investigate the materials in a more general manner than can be undertaken in the cable development programs, and this will provide information needed to understand the phenomena occurring at low temperatures as well as to optimize the material selection according to differing criteria.

The dielectrics proposed for the developmental cables include vacuum, liquids, gases, and solids, yet the experimental investigations of dielectrics at low temperatures have been so few that the cable developments are proceeding with such meager understanding of the dielectric phenomena at low temperatures that otherwise very expertly proposed developments are in danger of failure. Similarly, the conductors, both superconducting and normal, are those materials which have been studied extensively for use in dc or slowly pulsed magnets or in microwave equipment such as

accelerators but which have not been optimized for power transmission whether ac or dc.

The dielectrics program is being conducted in the Thermonuclear Division and is directed initially to an investigation of the ac and dc dielectric properties of cryogenic fluids, particularly helium and nitrogen, as a first step toward increasing our understanding of low temperature dielectric phenomena. A literature search has revealed that low temperature dielectric investigations to date have been so limited in voltage, gap length, and test power that there is insufficient data or understanding for engineering design purposes.

During this first quarter, the program has been staffed, the objectives and plan have been reviewed, and the initial steps toward apparatus design have been taken. A 130 kV test set to determine the flashover characteristics of various insulators has been set up as has a conductive paper plotting table for voltage grading studies. An experimental site has been prepared adjacent to the 600 kV 60 mA dc power supply. The purchase of a 700 kV series resonant ac test set has been initiated and plans formulated for extending the dielectric investigations to include ac tests.

The materials programs being conducted in the Metals and Ceramics Division of the laboratory are directed toward 1) an understanding of the ac loss mechanism in high transition temperature superconductors, both pure metal (Nb) and alloy (Nb_3Sn) and 2) toward the improvement of mechanical strength of very high conductivity aluminum while preserving the high residual resistance ratio needed for use as a normal metal composite for a superconductor.

During this first quarter both of the conductor materials programs have been staffed, literature searches completed, experimental materials received, and characterization started. In the superconducting program, high purity samples of Nb (less than 200 ppm Ta) have been acquired, and an apparatus has been developed for levitation melting for the controlled random fine dispersions of insoluble rare earths in this pure Nb in order to study the effect of these dispersions on the magnetic hysteresis and ac losses. AC loss measurement techniques are being reviewed to select the most convenient method, and the preparation of high T_c alloy specimen has commenced. In the aluminum conductor program a specially prepared high purity ingot with residual resistance ratio of 13,000 has been acquired. Specimen from this ingot have been used to study heat treatment of the pure material. A zone refined master alloy with 1.1% gold has been prepared from which the test specimen for the study will be fabricated.

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II. INTRODUCTION

The cryogenic dielectrics, superconducting, and cryogenic materials program at ORNL was funded as of November 1, 1972, and work in the three areas commenced shortly after that. This report covers the period from November 1 through February 28. The information is an expanded version of that presented at the program review held at ORNL on February 8-9 and contains the background information needed to place these programs in context with the overall national needs as well as the programmatic results obtained during these first four months.

After a general comment on background information, progress in each of the program areas, Cryogenic Dielectrics, Superconducting Materials, and Dispersion Hardening of Aluminum, is presented in an independent report which provides the particular technical justification for that program area.

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III. NATIONAL AND SOCIETAL NEEDS.

Forecasts of electric energy demand in the U.S. indicate that the utilities will probably have to double the capacity of their systems each decade between now and the end of this century if they are to meet the demand. Much of the added generation capability will be supplied by nuclear power stations which will no doubt be large and may have to be located remotely from the loads which are generally in areas of high population density. The transmission routes connecting these large generating stations with their loads may of necessity traverse areas of scenic beauty and suburban housing areas where overhead lines will be undesirable and heavily populated urban areas where overhead lines are physically or economically impossible. Underground transmission will be required, yet today the cost of underground transmission is virtually prohibitive save in the aforementioned heavily populated urban areas.

Reduction in the cost of underground transmission is obviously of great importance if we are to preserve our amenities and continue to have low cost power. A utility industry task force on R & D goals* recognizes the task of providing substantially more economical underground transmission of large blocks of power as one of eleven "critically important" projects with the highest priority--"those projects having an indispensable effect on all goals, which by their nature must receive first attention."

* "The Electric Utilities Industry Research and Development Goals Through the Year 2000," Report of the R & D Goals Task Force to the Electric Research Council. The Electric Research Council, 90 Park Avenue, New York, New York 10016 (June 1971).

The economic impact of the successful development of lower cost underground transmission is readily discernible from the projected investment by the utilities in transmission facilities. The 22nd Annual Electric Industry Forecast by the McGraw Hill publication Electrical World (September 15, 1971) states that: "Transmission capacity must be expanded to carry the rapidly growing generation output, particularly as large power stations are built at acceptable sites remote from the loads they will serve. The recent development of 765 kV line designs, and research looking toward still higher voltages, will enable this power to be carried on few but higher-capacity lines. But the very fact that each line have such a high power rating will require extensive reinforcement and expansion of interconnections and underlying systems.

"Undergrounding must be anticipated for some circuits, and a few high voltage dc links may be built for long cable runs in metropolitan areas. But on the whole it seems proper to project transmission additions through 1990 on the basis of recent practice. Hence, expenditures for transmission will slightly exceed \$76-billion in the coming two decades." However, the survey states "underground transmission is slated for an upturn in the years ahead, but not quite so much as was anticipated a few years ago. Some 116 miles of cable circuit were energized in 1970, but only 79 miles are scheduled for 1971. A sharp increase is scheduled for 1972, however, and 1436 miles are slated for the six years through 1977." Nevertheless, the present day and projected contribution of underground cables to the "wheeling" of power is minimal as indicated by the following statistics from the survey. During the period 1970-1977, 38,484 gigawatt miles of overhead transmission lines and 147 gigawatt miles of underground cable are scheduled for installation,

representing a capital expenditure (including substations) of $\$2109 \times 10^6$. The average cost per gigawatt mile is \$54,600. Since the cost of underground cable circuits is from 10 to 20 times that of overhead, the respective average (using a factor of 15 for the underground cost) costs are about \$51,800 and \$775,000 per gigawatt mile. The relatively few miles of underground cable are a reflection of the high cost of these installations, and a substantial increase in underground cable mileage without an undue increase in the capital investment can occur only when the relative cost of underground lines is reduced. The successful reduction in cost of underground cables cannot be expected to reduce the overall investment in transmission, but it will provide the incentive for more underground transmission and thus make the required expansion of electric utilities more acceptable to the public.

The above data on transmission expenditures comes from responses to a McGraw Hill survey by 175 investor-owned utilities, 37 municipals and cooperatives, eight state agencies, and seven federal agencies who collectively represent 90% of the generation capacity of the U.S. and serve 83% of the electrical customers. Thus, research which may affect the results of this survey will touch on a substantial part of the utility industry and through them almost everyone in the nation.

The high relative cost of underground electric power transmission is directly related to the underground environment and the required physical properties and construction of the electric cable. The cost of trenching and/or tunneling is much greater per unit distance than the comparable above-ground construction, and the confined space of the trench or tunnel places such stringent requirements on the cable components that the power capability of cables is much lower than the

capability of overhead lines with the same voltage and conductor cross section. Quite obviously the cost of underground power transmission can be reduced by reducing the effective cost of the civil engineering works such as tunneling and by increasing the power transmission capability and thus the cost effectiveness of the cable itself. This proposal is concerned with research directed in the long term toward the latter objective of increasing the cost effectiveness of cables. The problem can best be presented by reviewing the physical phenomena occurring in overhead and underground transmission lines.

Normal electric conductors are, by virtue of their inherent resistivity, heaters and the heat produced by passage of electricity must be dissipated to the atmosphere. With overhead lines this dissipation occurs directly, but unfortunately the underground environment presents a high degree of thermal isolation, and the conductor current density must be greatly reduced, as compared to overhead lines, in order to prevent overheating and consequent degradation of the cable materials.

Even overhead lines have a current density restriction, for the heating of the conductors causes them to lengthen and thus droop closer to the ground between supports and, equally important, the heating represents a power loss to the utility. To avoid the increase in loss at high currents, the transmission engineer employs increasing voltage to achieve increased transmitted power since the power transmitted is proportional to the voltage current product. With a fixed efficiency (i.e. fixed ratio of conductor loss to power transmitted), the power transmission capability increases as the square of voltage so the gain with increasing voltage is great indeed. To accommodate the higher

voltage the conductors are spaced farther apart, the supporting towers are made higher, and the effective radius of the conductors is increased by using several small conductors in parallel, at the same potential, all these changes costing much less than duplicating lower voltage lines. While the losses attributable to the insulation (air and the solid supports) increase the voltage, they do not become dominant even at voltages as high as 1000 kV, although the control of the effects of voltage such as radio interference and corona discharge are the paramount problems of high voltage overhead lines.

In contrast, the underground cable is severely limited by the properties of the dielectric which must control the voltage in a much smaller space than overhead lines unless a large diameter tunnel is available for the underground run. Indeed, in some power plant installations, totally enclosed underground air dielectric transmission lines (not cables) have been used where the tunnel was available from the construction phase of the project. Unless there are very dramatic reductions in the cost of underground tunnels or conduits, however, the undergrounding of air dielectric systems cannot be considered a viable approach to the problem. One promising form of cable does utilize a gas dielectric, SF_6 , in place of air in order to reduce the dimensions of the cable to manageable proportions. These cables, while having a substantially higher capability than conventional wrapped dielectric cables, suffer from a similar thermal limitation since the cable losses must be dissipated to the earth. The present practice of using a very dense dielectric wrapping on the conductor, capable of supporting a very high voltage in a small diameter, in order to achieve a small conduit

diameter leads to a very temperature sensitive cable and in addition to very high dielectric losses at higher voltages. In fact, the combination of these two factors causes the cable ratings to be barely proportional to the operating voltage rather than to the square of the voltage as in the case of overhead. Thus, there is not the same gain in power capability of cables with increasing voltage as there is with overhead lines. Nevertheless, the power density in terms of cable diameter does increase, and there is some economic gain in increasing voltage. Furthermore, since cables must be integrated into the electrical network, the systems designer needs cables with voltage and power capability to match overhead lines. At present this is possible only at transmission voltages of 138 kV or below, for at higher voltages the current (power) rating of cables is less than that of comparable voltage overhead lines. Consequently, when called to use underground cables to extend an overhead line with voltage greater than 138 kV or to dip such a line under a river or other obstacle, the system designer must employ multiple cables at considerably higher cost than overhead lines.

The problem of increasing current rating of cables to match overhead lines can, in principle, be solved by directly cooling the conductor to remove the heat and thus prevent deterioration of the dielectric wrapping. The gain is limited, however, by the permissible low operating temperatures of the cable components, by the dielectric losses in the insulation which are proportional to the square of voltage and do not decrease with temperature, and by the cost of refrigeration. The operating temperature limit can, however, be lowered substantially by changing the cable components and construction methods. One such proposed cable employs vacuum for the electrical insulation, thus eliminating the gas or wrapped dielectric.

Studies of low temperature cables by various groups have indicated an economic gain for operation of resistive conductors at liquid nitrogen and liquid hydrogen temperatures (77 K and 20 K, respectively) and superconductors at liquid helium temperatures, 4 K. These studies have been quite specific with regard to materials and cable design in order to make the economic estimates and are based on such materials property data as are available in the literature or as developed in the restricted scope of the programs. In the particular case of dielectrics at low temperatures, the available literature data is sparse, limited to relatively low voltages and short gaps, and the values used in these studies may prove to be incorrect. Since insulation (and thus dielectrics) is an essential part of all electrical equipment, it is of vital importance to have highly reliable and comprehensive dielectric property data. A major part of the ORNL program is to investigate dielectrics at liquid nitrogen and helium temperatures in order to provide a rational basis for the design of cryoelectric equipment. The measurements will extend to large gap lengths to test the total voltage effect and to ensure that the data will be applicable to full size equipment. In addition to ac and dc breakdown and partial discharge measurements, a high power dc test set will be employed in order to accumulate data on possible electrode deterioration with successive breakdowns. The choice of superconductor and the normal conductor employed as a substrate for study in cable design programs has perforce been restricted to those materials developed for other purposes such as conductors for high field dc or slowly pulsed magnets and microwave resonators for accelerators. The superconductor studies of the ORNL program will consider candidate superconductors, whether pure metal, alloy, or intermetallic compound on the basis of improving its suitability for power

transmission. For example, the inclusion of finely dispersed rare earth elements in high purity niobium may provide sufficient flux pinning in the bulk material to accommodate the high currents experienced under fault conditions while preserving a low loss surface for normal load operation. On the other hand, the inclusion of insoluble atoms in otherwise very high purity aluminum may provide the mechanical strength needed to use the very low resistance aluminum as a fault current conductor. Both of these materials programs are related to the basic metallurgical research conducted in the laboratory.

In the previously referenced report on R & D goals for the utility industry in the Transmission and Distribution Research Section, a specific goal under the broad classification of Bulk Power Transmission (one of five) is to "Develop new and improve existing underground transmission systems.... Bring into commercial use one or more systems with the potential of carrying from four to ten times the load of present-day cables at substantial savings in investment. These are needed to meet future requirements, such as high capacity dc cables and three phase gas insulated cables by the late 1970's, cryogenic cables by the mid 1980's, and superconducting cables by the 1990's." Another item in the broad classification of goals is Test Facilities under which a specific goal is to "Expand test facilities for HV and EHV cables and provide for testing dc as well as ac cables." The ORNL program is directed toward a partial fulfillment of these two specific goals of the electric utility industry in the realm of Transmission and Distribution.

In discussing Fundamental Research, the task force refers to Dielectric Phenomena in Materials and states: "The behavior of dielectric

materials generally plays a key role in determining the rating of a piece of equipment. For example, as discussed in the preceding section, the required thickness of ground insulation severely limits the operating voltage of a turbine generator. Similarly, an underground transmission cable has a voltage rating set by the electrical strength of its insulation and a current rating limited in part by the losses in its insulation and by the ability of the insulation to transfer heat to the surrounding medium.

"Thus we need to do fundamental research on dielectric behavior of materials to learn more about why dielectrics break down electrically, why they have dielectric losses, and how to control their dielectric constants more effectively. Successful results should lead to more reliable, less expensive equipment."

Further under Equipment Needs (for Fundamental Research), the task force states: "To do effective research, the best equipment must be available to the researcher. In many cases the equipment exists and can be acquired; in other cases, research must be done to develop the equipment necessary to perform the desired research. An example of this occurred during the development of the vacuum circuit breaker when it was found necessary to work at vacuums well beyond the capability of existing vacuum gauges. Another research effort was necessary to develop a new vacuum gauge capable of the necessary measurements.

"In most cases of fundamental research, complicated and expensive instrumentation is required along with technicians qualified to operate it. As in developing research scientists and engineers, it takes a lot of time to develop sophisticated instruments and to train people to operate

them. Thus, research facilities and personnel training must be planned for well in advance of the time results are required."

The ORNL program is also directed toward a partial fulfillment of these two specific goals of the utility industry in the realm of Fundamental Research. Thus, the program is directed toward problems recognized in the industry, and the results of the program can provide a needed input into the direction of research activities on behalf of utility problems.

Future development and application of cryoresistive and superconducting cables and other cryoelectrical equipment will require accessory apparatus compatible with the cryogenic equipment and possibly operating in a cryogenic environment. Thus later activities may very well be concerned with other questions such as:

1. the transfer of high power, both ac and dc into and out of cryogenic environments;
2. overvoltage protection and surge divertors operating at cryogenic temperatures to provide the protection needed for system operation of cryogenic equipment; and
3. the handling of large transient voltages and currents at low temperatures which may provide the key to the economic use of large superconducting inductors for energy storage as well as lead to the possibility of cryogenic circuit breakers, both ac and dc.

IV. PROGRAM REPORTS

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A. CRYOGENIC DIELECTRICS

1. Introduction

The dielectric strength of liquid and low temperature gaseous helium, hydrogen, and nitrogen is of great importance for application in electric power engineering (superconducting and cryoresistive electric power transmission and electric machinery, superconducting magnets and energy storage, etc.). A literature search (Appendix A) has confirmed that the dielectric strength data available at this time are severely limited in voltage, gap length, and test power and thus are not sufficient for engineering design purposes. Therefore, appropriately planned and executed investigations on this subject are very necessary for the successful development of cryoelectric equipment. This situation is also recognized by other groups whose primary aim is equipment design, and they are undertaking the limited dielectric testing needed to give them an initial solution to the insulation problem. In contrast, the ORNL program is directed to a more general objective of providing information needed to understand the phenomena and to optimize the dielectric design. We expect to obtain sufficient statistically evaluated data that we can corroborate existing empirical laws relating to dielectrics or if needed establish new laws which can be used for scaling experimental results and designing experiments.

The experiments will be primarily with liquid and low temperature gaseous helium and nitrogen. Investigations with hydrogen are likewise of interest for cryogenic applications, however, since special safety measures would be necessary, we will not complicate our present program by including hydrogen. Studies of breakdown, flashover, and partial

discharges with solids in vacuum, gas, and liquid at low temperatures will be included in the full program. Solids of interest include those useful as mechanical support members such as ceramics, filled epoxies, and other polymers and films and fibrous papers and mats which can be used as wrapped insulations. The initial tests will be with dc up to 600 kV and ac up to 700 kV rms. The extension of the dc voltage to 1000 kV and addition of appropriate impulse testing will be accomplished as soon as practical.

The first effort will be to obtain dielectric strength data with dc high voltage since for even a semi-quantitative understanding of the basic physics phenomena (which should be the starting point for an intelligent search for practical design data) the dc performance is of greatest importance. Tests will be made to elucidate the effect of variables such as purity of the gases or liquids and surface cleanliness and conditioning of the electrodes in addition to the geometry and composition of the electrodes. Such information is of vital importance in setting the specifications of realistic tests of cable models as well as future operating systems. Methods of avoiding any deleterious effects of "field" dirt will be explored as they become evident. An essential feature of the program is that the investigations will include dc high voltage from a high power source. The high power test set will be employed later to investigate the effects of electrode damage resulting from repeated breakdown.

To date operation of cryogenic apparatus with dc occurs more often than with ac (e.g. superconducting magnets and electrical machinery are dc while projects on superconducting and cryoresistive electric power transmission lines consider either dc or ac).

2. Experimental Equipment

Three high voltage power supplies, two 600 kV dc units and one 700 kV ac unit, will be used in the program. In addition several lower voltage units, 60 and 130 kV dc and 80 kV ac, will be used for preliminary measurements.

The two 600 kV dc power supplies have been used for some years in the Thermonuclear Division. One unit, a highly regulated 600 kV 60 mA power supply, has been used for molecular cross section measurements and is presently available for other experiments. It was manufactured by E. Haefely and Cie (Baden, Switzerland) and employs silicon diodes in quadruple voltage connection, energized by an audio-oscillator (10 kc). The voltage can be continuously controlled from practically zero up to 600 kV. For work with any constant voltage, the voltage regulation is excellent (order of $1:10^5$). At the 600 kV level, dc currents of at least 10 mA can be used. The rectifier is protected by an automatic power switch. A 600 kV cable termination stand can be used for connecting high power voltage test facilities. Furthermore, a large insulated power supply stack is available with intermediate steps of 150, 300, and 450 kV which are obtained from a resistive voltage divider. This rectifier which works routinely is described in Appendix B.

The other unit is a 600 kV power supply employing a silicon diode rectifier for continuous currents up to 1.0 A. Four cascaded rectifier-transformers with 30° phase shift between transformers in connection with filter circuits provide dc with ripple of only 1%. Intermediate voltages of 150, 300, and 450 kV are available. This apparatus was manufactured by Allis-Chalmers Company for the DCX-2 plasma physics experiment and

has been employed afterwards with a test stand for a high voltage ion source. The work with this ion source test stand has been terminated in the meantime. The working experience with this high voltage rectifier is good, and it can be expected that its operation could be resumed without great difficulty. It is described in Appendix C.

The 700 kV ac 1050 mVA power supply is a cascaded set of 350 kV series resonant transformers rated at 525 kVA each. They may be employed independently for lower voltage testing. The units were manufactured by Hipotronics, Inc., and have been acquired from Simplex Wire and Cable Company. They will be installed in April 1973. The series resonant transformers are a very desirable power supply for cryogenic testing since breakdown causes defusing and there is little power follow-through. The resonant mode also provides a very pure sine wave at the fundamental exciter frequency which will facilitate partial discharge measurements. The specifications of the power supply are given in Appendix D.

Ceramic accelerator columns for 600 kV, large high voltage epoxy cylinders, and other useful items are available in the inventory of the Thermonuclear Division so that a cryogenic test cell can be built without capital expense.

To study the breakdown due to high voltage transients, we have available at ORNL a Fexitron flash x-ray unit with a power supply capable of delivering 500 A at 600 kV for a period of 1.20×10^{-9} sec. The device can also be used to study arc disintegration in a solid structure by use of the flash x-ray capability. High voltage capacitors are also available for building a Marx generator for impulse studies.

We plan to use some of the advanced electronic gear available to observe the onset of spark breakdown. This includes image converter and

image intensifier techniques to observe beginning of photon production. By cascading the presently available image converter devices (time resolution of $\approx 10^6$), we should be able easily to observe the very fast, faint phenomena occurring during breakdown. These studies will be conducted in cooperation with the Electrical Engineering Department of The University of Tennessee.

We also have on hand picosecond correlators, so that statistical details of high voltage breakdown can be observed. Finally, we have on hand nanosecond oscilloscopes (Tektronix No. 519) for observing very fast phenomena. We have people trained in Q-switched lasers on hand and could use a laser spark to initiate breakdown where desired.

3. Experimental Program

The experimental program is shown by program element in Fig. A-1. The initial tasks in each element, except for the partial discharge and impulse testing, have been started. These activities will require additional equipment which we can expect to acquire to develop as the program progresses. The literature survey included in the initial proposal has been reviewed and expanded to include papers on pre-breakdown phenomena in helium. A copy of this survey is included as Appendix A. Flashover experiments are well underway and are included as Sect. IV.A3b. The principal aim for the coming quarter is to continue the flashover experiments and to design the cryogenic vessel so that preliminary tests may be accomplished by July 1. During early January, we had a one-week visit by Dr. T. Praehauser of Haefely and Cie who discussed the full range of high voltage testing with the group. Each of the program elements is discussed below.

Figure A-1. Cryoelectric Program Work Schedule
First and Second Quarters, 1973

	January	February	March	April	May	June
Cryogenic Design & Construction	Air Flashover Design & Construction		1000 kV Design	1000 kV Construction		
			Rogowski Electrode Design	Rogowski Electrode Construction	Small Impulse Generator Design	Small Impulse Generator Construction
			Low Voltage Cryostat Design & Construction			
Flashover	Air Flashover Site Preparation	Air Flashover Experiments - to 100 kV		Air Flash-over Exp. - to 80 kV ac		Low Voltage Flash-over in Liquid He
dc Breakdown	Site Preparation - 600 kV dc & 700 kV ac Test Stand					Low Voltage Breakdown in Liquid He
ac Breakdown			700 kV ac Site Preparation & Set Up		Test 700 kV	80 kV Breakdown in Liquid He
Partial Discharge Tests				Consider Technique	Procure Equipment	Experiments
Impulse Tests		Test Capacitors		Generator Considerations		Small Generator Tests

a) Cryogenic Apparatus Design

The primary problem in the design of a cryostat for high voltage breakdown measurements in liquid helium is the very low dielectric strength of low temperature gaseous helium which requires a much larger distance than for other gases. At room temperature and atmospheric pressure, the electrical breakdown strength of helium is about two orders of magnitude smaller than that for air, and it is a very serious problem to design the high voltage test cell in such a way that undesirable external flashovers can be avoided. Unfortunately, the available data on breakdown of low temperature gaseous helium are very sparse and also somewhat inconsistent so that the task of building such a high voltage test chamber involves almost a contradiction in itself. In order to make a good design of this apparatus, the test results should be known in advance. We realize fully that much intuition is necessary and that such a piece of equipment must be built with a much higher safety factor than that which can be afforded for the design of cryogenic apparatus for practical use. We may find that a modular design with compartmented regions containing perhaps vacuum, gases other than helium, and/or helium under pressure as may be needed can be used to arrive at a reasonably compact apparatus which can be used to span the temperature range from room temperature to liquid helium with potential differences up to 600 kV. The experimental space at low temperature is expected to be a grounded enclosure containing the refrigerant cryogen with a high potential lead to which various geometrically shaped electrodes can be affixed. The experimental space will be constructed so that the breakdown can be optically monitored.

Our present thoughts on the design of a bushing to introduce high voltage into the cryostat are shown in Fig. A-2. The scheme is to employ vacuum as the principal dielectric between room temperature and helium temperature and to avoid the low breakdown strength of warm gaseous helium by extending ground potential in the liquid helium. Thus, the design problem becomes one of designing a disc or cup insulator to serve with helium liquid on one side and vacuum on the other. Radiation shields will be incorporated within the vacuum space to reduce the heat load on the helium charge and ease the thermal stabilization problem. We have initiated a study of the dielectric problems of this design concept and have set up an analog field plotter to investigate the voltage grading with various configurations of the elements. We expect to have a model in April to check the design and a working high voltage bushing by July.

b) Flashover Experiments

In order to design the cryogenic high voltage bushing previously described, information is required about the flashover characteristics of various dielectrics in air, vacuum, and liquid helium. Consequently, the initial part of our experimental program has as its objective the collection of such data for plastics and epoxies of cryogenic interest. A flashover test stand has been constructed for the tests in air as shown in Fig. A-3. The electrodes are 8 in. in diameter and 1 in. thick. One inch from the center, the surface of each electrode begins to taper off at an angle of 2° to the electrode plane and terminates in a circular section at the edge. Hence, the gap is smallest at the center, and field enhancements at the electrode edges are decreased. The high voltage electrode hangs from a 3-ft square corona shield supported at the corners

Figure A-2. High voltage cryogenic bushing schematic.

Figure A-3. Air flashover test stand.

by insulators rated at 150 kV. The grounded electrode is mounted on a small hydraulic jack which simplifies positioning the electrodes and keeps all samples under a uniform contact pressure.

The test stand is surrounded by a grounded (15 ft x 20 ft) metal fence enclosure (Fig. A-4). The gate is provided with an interlock to the high voltage supplies which makes it impossible to enter the enclosure while the supplies are energized. In addition, the standard portable ground wands are provided at the entrance.

The samples used were solid cylinders or tubes approximately 3 cm in diameter and of lengths varying from 1 to 6 cm. Several materials have been tested to date, among them Synthane G-10 fiberglass, Lexan, polyethylene, micarta, and Shell Epon 815 epoxy (100 parts resin plus 40 parts Versamaid hardener). The air flashover results are summarized in Fig. A-5. For comparison, breakdown values for dry air at STP taken from the literature are also shown. The scatter was typically about 2 kV (but up to 5 kV). Polyethylene, Epon, G-10, and Lexan all performed nearly as well as air in their flashover characteristics. In fact, for the best samples, the discharge often tended to take place in the surrounding air rather than over the sample surface before the electrodes were tapered to reduce the edge field. Micarta flashover values were less than half those of the other samples. This may be partially due to the somewhat rougher surface condition of this material, since a second 3-cm G-10 sample with a rough surface following the weave of the fiberglass cloth also showed greatly reduced performance. The data for all samples indicates that the flashover voltage rises roughly linearly with sample length.

Figure A-4. Flashover test area.

ORNL-DWG 73-3309

Figure A-5. Flashover voltage vs sample length..

Of the four materials with flashover voltages close to the air breakdown voltage, Epon appears to be the best choice for a bushing because of its greater resistance to formation of carbon tracks after several flashovers. The flashover strengths of the other materials appeared to start decreasing after ten shots. It remains to be seen how a large casting of Epon will perform at helium temperatures under the large mechanical strain which will develop due to the thermal contraction mismatch between the epoxy and any metal parts embedded in it. Some of the Epon samples also showed a large decrease in flashover strengths after merely setting in air for a few days. However, washing the samples in trichlorethylene restored their original performance.

Further experiments are underway to investigate the flashover properties of glass-filled low-contraction materials, such as G-10, coated with other finishes. In this respect, G-10 with ordinary Krylon laquer appears to be promising. Preparations are also underway for lower-voltage (< 100 kV) flashover experiments in liquid helium on these materials.

c) dc Breakdown

An experimental site adjacent to the 600 kV Macfely power supply has been cleared. An experimental stand previously used for DCX-2 will be modified to provide a platform 3.5 m high for the high voltage bushing. The high voltage electrode will be about 2 m above floor level to facilitate optical measurements. The cryostat will be supported under the platform around the electrode assembly.

Initial measurements await installation of the bushing.

d) ac Breakdown

The 700 kV ac transformers will be shipped from North Berwick, Maine in late March and installed in early April. They will be located in a position to share the experimental site and platform set up for the dc breakdown tests. The platform is large enough to accommodate two bushings and dewars if the experimental program requires two locations.

Initial measurements also await installation of the bushing.

e) Partial Discharge

A review of partial discharge measurement will be initiated in the coming quarter. S. W. Schwenterly will attend a course on partial discharge measurements conducted by the Biddle Company in late March.

f) Impulse Testing

Seventeen 50 kV 0.2 μ F capacitors have been acquired from stores and tested in preparation for future design of impulse tests.

B. SUPERCONDUCTING MATERIALS

1. Introduction

The application of superconductivity to underground transmission of electricity is limited by the characteristics of the superconducting materials. The "ideal" superconducting material for ac transmission would have the following characteristics:

1. A high superconducting to normal transition temperature (T_c) to allow for operation at sufficiently high temperatures (6-8 K) to minimize refrigeration costs.
2. Very low ac losses under normal operating conditions.
3. The ability to withstand fault conditions where the current (field) may rise a factor of ten. A combination of high T_c , reasonably high upper critical field H_{c2} , and high critical current density J_c are required.
4. Sufficient mechanical strength and ductility to meet fabrication and service requirements.
5. Be economically competitive. Here the cost of the raw material as well as fabrication costs must be considered.

No single material known today meets all of these requirements. Niobium has been the choice of most design studies due to its low ac losses, good mechanical properties, and cost. It, however, has a low T_c and by itself cannot withstand fault conditions, therefore necessitating the use of a composite conductor with a higher field superconductor and/or a pure resistive conductor (Cu or Al) bonded to the Nb. The BNL study group

has suggested the use of a high T_c , high field material such as Nb_3Sn .¹ However, ac losses are several orders of magnitude larger in Nb_3Sn than in Nb, Nb_3Sn has undesirable mechanical properties, and material and fabrication costs are relatively high. More materials work is therefore necessary on the superconductor.

Our original proposal for materials work for superconducting transmission included work on both ac and dc conductors. We have concentrated on the ac conductor this fiscal year. We will outline below the research we have carried out in the first three months of the project and discuss our plans for the remainder of the year.

Our goal is to understand the mechanisms, and the relative importance of material parameters, which control ac losses so that these losses might be minimized in high T_c materials. Work on mechanical properties and fabrication techniques will follow the ac loss studies but the practicality of the conductor will be continually kept in mind.

2. Work Completed Through February 1973

a) Niobium-Rare Earth Dispersion Studies

Several years ago we observed² that rare-earth metals such as Gd, Y, and La dispersed in Nb markedly increased the magnetic hysteresis and relative critical current density. These increases in J_c exceeded those obtainable by severe cold deformation and were similar to the increases obtained by massive doses of fast neutrons.³ Since above H_{c1} ac losses are believed to be inversely proportional to critical current density, the Nb rare-earth dispersions should be well suited for a study of the effects of material parameters on ac losses. Furthermore, Nb is

still a candidate for the ac conductor and optimizing its properties is desirable.

We have begun our systematic investigation of ac losses in Nb dispersions with the Nb-Y system. The dispersions have been obtained on solidification from the melt, since due to the large differences in atomic sizes of Nb and Y the metals are mutually insoluble in one another in the solid state. Difficulties in controlling the dispersion size and distribution from the melt can be understood by referring to the Nb-Y phase diagram⁴ presented in Fig. B-1. It is noted that even in the liquid state at the Nb-rich end of the system (our region of interest) there is a miscibility gap and Nb-rich and Y-rich liquids, mutually insoluble, are in equilibrium. In order to obtain a fine random dispersion, these immiscible liquids must be thoroughly mixed prior to casting. The most efficient method for doing this is by the use of high frequency induction levitation melting where the metal is suspended and melted by the rf field. On the advice of Prof. B. Oliver (Chairman of the Metallurgy Program at The University of Tennessee and consultant in melting and solidification to the Metals and Ceramics Division), we have designed and built a levitation melting rig using our existing Lepel rf power supply and high vacuum system. An overall view of the levitation melting equipment is presented in Fig. B-2. The system consists of the Lepel rf 10 kVa power supply, a transformer to reduce the voltage at the coil, rf vacuum lead-throughs, the coil, and a copper mold. The vacuum system consists of an ion-pump and a Ti sublimation pump and vacua of better than 10^{-9} torr are routinely obtained. The design of the coil was not trivial. In fact several investigators claimed in the literature that Nb could not

ORNL-DWG 73-2114

Figure B-1. The Nb-Y phase diagram.

Figure B-2. A view of the levitation melting equipment.

be melted by the levitation technique. However, after numerous refinements of our coil geometry we now have melted Nb and a number of Nb-Y dispersions and cast them into 1/8-in. diameter cylinders. Figure B-3 shows a coil, the copper mold, and a casting.

Simultaneous with our development of the levitation melting facility, we prepared a series of Nb-Y dispersions by arc-melting and drop-casting into 7/16-in. diameter molds. The castings were then cold-swaged to 1/8-in. rod, a 92% reduction in area. The compositions of the alloys were nominally Nb, Nb-0.1 at. % Y, Nb-0.5 at. % Y, Nb-1.0 at. % Y, Nb-2.0 at. % Y, and Nb-5.0 at. % Y. The Nb stock was from a large ingot of pure Nb we had obtained from Wah Chang Corporation with 300 ppm Ta the major metallic impurity content. It was not possible to drop-cast the Nb-5.0 at. % Y alloy, but we hope the levitation melting technique will allow us to prepare these higher Y concentration alloys.

Metallographic samples were taken from the as-cast ingots and transverse sections are illustrated in the micrographs in Figs. B-4a, B-4b, B-4c, and B-4d for the 0.1 Y, 0.5 Y, 1.0 Y, and 2.0 Y specimens, respectively. The micrographs are in the as-polished condition and at a magnification of 500X. As the Y concentration increases, it is evident that the concentration of spherical particles increases until at 1 at. % Y some grain boundary precipitate is seen along with a high density of spherical particles. The 2 at. % Y alloy shows massive grain-boundary precipitation and a general coarsening of the Y dispersion.

Superconducting property measurements have been made on the cold-worked samples. T_c measurements gave values of 9.27 ± 0.08 K for the pure Nb and 9.37 ± 0.08 K for the Nb-Y dispersions. The increase of

Figure B-3. The rf coil, a typical casting, and the copper drill mold for sample preparation by levitation melting.

Figure B-4a. Photomicrograph of Nb-0.1 at. % Y, as cast. Transverse section. 500X.

Figure B-4b. Photomicrograph of Nb-0.5 at. % Y, as-cast. Transverse section. 500X.

Figure B-4c. Photomicrograph of Nb-1.0 at. % Y, as-cast.
Transverse section. 500X.

Figure B-4d. Photomicrograph of Nb-2.0 at. % Y, as-cast.
Transverse section. 500X.

~ 0.1 K on the addition of Y is not fully understood but must relate to the influence of the dispersions on the dislocation structure and/or the sample resistivity. A more marked increase in the upper critical field H_{C_2} , as determined from dc magnetization measurements, with Y content is noted after a small decrease for the 0.1 at. % Y alloy. The T_c and H_{C_2} results are plotted against at. % Y in Fig. B-5. Direct current magnetization curves were obtained by the ballistic technique using a modified Ward magnetometer.⁵ Representative curves are presented in Fig. B-6 for the pure Nb and Nb-2 at. % Y samples. The already large hysteresis observed in the cold-worked Nb is considerably increased by the Y dispersions. We take the remanent magnetization, B_R , as a measure of the hysteresis (and therefore presumably critical current density) and plot B_R against at. % Y in Fig. B-7. B_R reaches a maximum at 1 at. % Y. The decrease in B_R for the 2 at. % Y sample presumably reflects the coarser dispersion (see Fig. B-4d).

While it is clear that the Y particles strongly increase magnetic hysteresis in Nb, direct measurements of ac losses must be carried out to see whether the prediction of concomitant reduction of ac losses is verified. We will discuss below our progress in providing capability for the measurement of ac losses.

b) Alternating Current Loss Measuring Techniques

General Background and Literature Survey. The following ideas regarding mechanisms for ac losses are based on our best reading of the literature at present. In considering ac losses, the two cases of the self-field H_s at the surface of the conductor either less than or greater than H_{C_1} must be dealt with separately. For $H_s < H_{C_1}$, the current and

Figure B-5. T_c , H_{c2} vs atomic percent Y for Nb-Y dispersions cold-worked 92% reduction in area.

ORNL-DWG 73-2116

Figure B-6. Magnetization curves ($-4\pi M$ vs H) for the pure Nb and Nb-2 at. % Y samples cold-worked 92% reduction in area.

Figure B-7. Remanent magnetization, B_R , vs atomic percent Y for Nb-Y samples cold-worked 92% reduction in area.

field are confined to the surface, and therefore all losses occur there. Surface condition then determines loss rate. For operation with $H_s < H_{C1}$, it is generally agreed that Nb with the highest known H_{C1} is the material of choice.

We are more interested in the second case, $H_s > H_{C1}$, since for all known high T_c materials, H_{C1} is too small to allow operation of a transmission line with $H_s < H_{C1}$. There are at least three sources of losses in this case: 1) surface losses, 2) hysteretic losses, which result from the flux lines overcoming pinning forces, and 3) viscous losses, which result from the motion of flux lines through the bulk of the superconductor. If the mechanisms for loss in the surface are the same as for $H_s < H_{C1}$, then surface losses are much less than hysteretic or viscous losses, and the surface is then important primarily because it is possible for the surface to impede the motion of flux through it, and thereby to reduce the amount of flux moving through the specimen and overcoming pinning forces. On the basis of dc magnetization measurements, Ullmaier and Gauster⁶ introduced a parameter ΔH which is an increment by which the field at the surface of a superconductor can be changed without affecting the distribution of flux within the bulk. To minimize viscous and hysteretic losses, one wishes to maximize ΔH . Thus, the properties of the surface, or near-surface region, upon which ΔH depends, are important in determining ac losses in the mixed state. According to the Bean-London⁷ critical state model, hysteretic losses vary inversely with the critical current density J_c . Also, in a high current density material the motion of flux within the superconductor is inhibited, resulting in lower viscous losses. Thus, to minimize ac losses in the mixed state in a given material, one should maximize the quantities ΔH and J_c .

There are two points about which one should be cautious. One is the use of the critical state model to predict hysteretic losses at low fields in high field materials. The Bean-London model is known to be a poor approximation for fields close to H_{C1} , or for very high current densities, so that one may not gain as much as expected by increasing J_c in, say Nb_3Sn , at surface fields of 2 kOe. Also, it is possible that there are loss mechanisms associated with the surface in the mixed state which as yet have not been recognized.

On the basis of our previous work,⁸ we are prepared to measure ΔH and J_c in cylindrical specimens. With the addition of ac loss measuring equipment, we will be in a position to make an effective study of these matters.

Plans for ac Loss Measurements. We have spent some time reviewing the methods described in the literature for measuring ac losses. The choice of a particular method depends upon several factors, such as sample geometry, the level of losses to be measured, and whether temperature is to be varied. In general, the methods can be divided into two categories--calorimetric, and electrical or electronic.⁹ Calorimetric methods usually involve measurement of the rate of evolution of helium from the bath containing the specimen or a comparison of the energy dissipated in the specimen with that in a known resistance. They have the advantage of being conceptually simple, and one is assured of measuring all of the losses, but they appear to be difficult and tedious experimentally. Also, at least in most cases, measurements cannot be made at temperatures above 4.2 K. Therefore, we have decided that electronic methods are more appropriate for our purposes. Attainable sensitivities appear to be as

good as with calorimetric methods, and there are no unusual complications associated with elevated temperatures.

There are two specimen geometries on which we may wish to make measurements. We are primarily interested in cylindrical specimens, about 1/8 in. in diameter and 1 in. long, since there is a convenient geometry for metallurgical studies and magnetization measurements, and is therefore the geometry of our Nb-Y dispersions. We may also wish at some later date to measure losses in strips or wires wound in bifilar coils. These two geometries require quite different measuring techniques, but in both cases the measurement can be reduced to the multiplication of two voltages and the averaging of the product over a cycle of an alternating current. This has been achieved by other workers in a variety of ways, involving lock-in amplifiers, Hall multipliers, etc. However, as we learned on our recent trip there, the Instrumentation Division at Brookhaven National Laboratory, at the request of Dr. M. Garber, has designed a low power wattmeter utilizing time division multiplication which appears to fulfill our needs. We have decided that we can obtain the capability for measuring ac losses most quickly, and with the least duplication of effort, by arranging to have the Instrumentation Division of BNL build a similar instrument for us.

c) Expansion of Program to High T_c Materials Such as Nb_3Sn

If the ac losses of Nb_3Sn (or other high T_c materials) could be lowered, it would be the clear choice for the ac superconductor. We are therefore planning to expand our program on ac losses to the A-15 compounds (or other high T_c materials).

The materials group at BNL is actively investigating ac losses in commercial Nb_3Sn as well as experimental material. We visited Brookhaven on January 17-19 to discuss materials work with Dr. D. Gurinsky and the members of his group. A trip report has been separately prepared and is appended (Appendix E). The trip was very informative, and we have tentatively decided to complement the Brookhaven materials work in the following areas:

1. Techniques to reduce ac losses. We plan to accomplish this by increasing T_c at low fields in Nb_3Sn and by optimizing ΔI by varying the surface condition. It is planned to use the Nb-rare earth dispersions as the substrates for preparation of Nb_3Sn by diffusion from molten Sn.
2. Study of ac losses in other high T_c materials which may have potential as the ac superconductor such as V_3Si , Nb_3Al .
3. Study possible techniques for improving the ductility of Nb_3Sn composites.
4. Explore the recent technique of Dr. Tsuei for preparing Nb_3Sn or other A-15 superconductors from dilute solution in copper from the melt.

In addition to the information we received on our visit to Brookhaven, we are carrying out a study of the literature in this area so that we may define our experiments more precisely in the next quarter.

3. Work Planned for the Remainder of FY 1973

a) Nb-Rare Earth Dispersions

The Nb-Y dispersions will be more completely characterized by using transmission electron microscopy. The alloys, initially studied

in the as-cold worked condition, will be given a series of annealing treatments and then characterized and the superconducting properties measured. The dispersion distribution will be altered by changing the melting conditions with the levitation technique.

Other rare earth elements, Gd and La, will be used to reinvestigate the influence of the magnetic properties of the dispersed phase on fluxoid pinning. Finally, the ac losses will be directly measured with the ac loss measurement equipment when it is operational.

b) Alternating Current Loss Measuring Techniques

The first priority for the remainder of the fiscal year will be the construction of the ac loss equipment as described in the previous section.

c) Work on the High T_c Superconductors

The literature study will continue and experiments will be defined. Specimen preparation and characterization will begin.

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(Examples of most methods which have been used to measure ac losses are contained in the references of this article.)

C. DISPERSION HARDENING OF ALUMINUM

1. Introduction - Statement of Problem

Most of the published design studies of superconducting cables for power transmission assume that the current-carrying conductors will be some form of composite, either tapes¹ or tubes² consisting of a superconducting material (Nb or Nb₃Sn) "joined" to a normal conducting metal (Cu, Al, etc.). The function of the normal material may then be one or more of the following: to mechanically support the superconductor, to act as a barrier between vacuum and helium-filled channels, to carry fault currents, and to produce a path for the rated current should the superconductor temporarily or locally go normal. High purity aluminum is being considered as a candidate material to serve these functions in cables of the future.

To be acceptable as a fault current carrier aluminum must have a very low resistivity at the operating temperature of the cable. Taylor³ estimated that in an Nb/Al tubular conductor composite, for example, a residual resistivity ratio, RRR ($= \rho_{300K}/\rho_{5K}$) of approximately 2500:1 would be required for the aluminum. The current Brookhaven design¹ specifies a 5000:1 RRR aluminum backing on a Nb₃Sn superconducting tape. Commercially available high purity (99.999%) aluminum might meet these requirements but its purity would have to be maintained during processing, construction, and service.

A major disadvantage in using high purity aluminum is its low yield strength. According to the data of Arp, Kasen, and Reed⁴ aluminum with RRR = 1900:1 had a yield stress (σ_{YS}) of only about 4000 psi. Baylis⁵

suggested that for design purposes a σ_{YS} of 6500 psi should be considered in aluminum-stabilized tubular superconducting cable. Hence, the specification of a slightly prestrained aluminum was proposed to meet the strength requirement. While prestrain raises the yield strength to the desired levels, it also introduces defects such as dislocations into the material. These defects significantly increase the resistivity of the material thereby reducing its fault-current carrying capabilities to at best only a marginally acceptable level.⁵ Thus it would appear to be highly desirable to discover new methods for producing a suitably strengthened aluminum (6500 psi) with an adequate resistivity ratio (2500:1).

2. Scope of Work

a) Hypothesis and Rationale

A one-manyear research effort in the Metals and Ceramics Division at ORNL was begun on November 1, 1972 to explore the possibility of dispersion (second phase) hardening a very dilute aluminum-base "alloy" seeking to find the optimum dispersion characteristics that might meet the above mentioned criteria. The rationale upon which our belief that dispersion hardening of a controlled-purity aluminum matrix with a high conductivity might be achieved is as follows: Residual electrical resistivity in aluminum is strongly increased by dissolved impurity atoms and lattice defects⁶ (dislocations, vacancies, grain boundaries, etc.). Transition element impurities seem to increase the residual resistivity five to ten times more (per atom) than non-transition impurities, and therefore they are very undesirable. Some impurities are extremely insoluble in aluminum, e.g., they prefer to be gathered together and exist as second phase

particles embedded in a pure aluminum matrix. These insoluble particles would also be expected to increase the resistivity of the material in a way that probably depends upon the mean free path between particles. This contribution, however, is expected to be much smaller than that due to an equivalent amount of impurity completely dissolved in the aluminum. Second phase particles can be very effective strengthening agents. We think that by a controlled addition of a specific impurity to an already very high purity aluminum, we can combine extremely low solid solubility and the precipitation hardening possibility to achieve an acceptable RRR as well as σ_{YS} .

Our previous studies⁷ of the aluminum-gold system suggested that gold may have an extremely low solid solubility in zone-refined aluminum, perhaps as low as 1 at. ppm at 100°C.* The unpublished data from our earlier work which is shown in Fig. C-2 indicates that the impurity resistivity of dissolved gold in aluminum is $1.68 \times 10^{-12} \Omega\text{-m/ppm}$ or an anticipated RRR = 14,000:1 per ppm if no other hindering factors are present. Heimendahl⁸ has reported a remarkable age hardening in aluminum-gold alloys. In an alloy containing 270 at. ppm (0.2 wt %) gold, the dispersion of gold in the form of Al_2Au precipitates can be manipulated by heat treatment to increase the room temperature yield stress by a factor of three.

* During recrystallization, grain boundaries were observed to move at very fast rates through a 40 ppm alloy in which the gold was completely precipitated in an aluminum matrix (see Fig. C-1). In a 3 ppm alloy with the gold all in solid solution, on the other hand, the boundary migration rates were very much slower. Interpretation of these results on the basis of the solute-drag theory of grain boundary migration leads to the supposition that the aluminum matrix in the precipitated 40 ppm alloy contained about 1 ppm gold.

Figure C-1. Microstructure of an aluminum + 40 ppm gold alloy in the fully precipitated state. Note large Al_2Au particles in the grain boundary regions and finer particles in the grains. Electro-polished and anodized. 100X.

Figure C-2. Electrical resistivity vs alloy concentration for aluminum-gold alloys.

b) Program Plan

We will be preparing ~ 300 g each of three alloys containing 0.2, 0.1, and 0.05 wt % gold (270, 135, and 70 at. ppm, respectively) in zone-refined aluminum. These alloys are to be made by induction melting in ultrahigh purity graphite boats under a quartz glass enclosed vacuum of 10^{-5} torr (see Fig. C-3). To ensure macroscopic chemical homogeneity, a molten zone will be passed along the length of the finger-shaped ingots, alternately in both horizontal directions. This process, known as zone leveling, will be repeated 24 times. The directionally solidified alloy will be diffusion-annealed for two weeks in the solid state at 600°C to eliminate microscopic chemical inhomogeneities. The ingots will be fabricated to rods by cold rolling. Specimens will be cut from the rods, annealed, solution-treated at 600°C , and water-quenched to room temperature. Aging treatments will be carried out for various times at temperatures between 100 and 400°C .

At this stage in our study we hope to characterize the precipitation of the gold-rich phase(s) by means of electron microscopic and microhardness measurements. We will be seeking then to establish relationships between microstructure (i.e., precipitate type, size, shape, number, and distribution) and properties (microhardness and electrical resistivity). Next, we will select certain of the heat treatments and prepare mechanical property specimens from the alloys. Specifically, yield strength (and other tensile properties) will be determined as a function of test temperature, alloy content, and precipitate dispersion state. Electrical resistivity measurements in conjunction with the mechanical property data will allow us to "map out" the $\sigma_{\text{YS}}/\text{RRR}$

Figure C-3. Photograph of the melting and zone-leveling facilities used for preparing laboratory melts of controlled purity aluminum alloys.

relationships for the aluminum-gold system. At every stage in our study we will carefully characterize our alloys as to purity and microstructure and will compare our results with those from unalloyed, zone-refined aluminum.

3. Progress

Time has been spent training a technician in the procedures and techniques necessary to carry out this program. In addition, considerable effort was expended in searching the published literature for background information on superconducting cables.

Five thousand grams of specially zone-refined aluminum in ingot form were ordered from Cominco Products, Inc., and have been received. This aluminum was stated by the supplier to have a $RRR = 13,000 \pm 1000$. We have measured the resistivity ratio in our laboratory to check their claim. Material for four test specimens was removed from the as-received ingot and machined by centerless grinding to rods 0.100 in. in diameter by 2 in. long. A four-point dc probe technique was used for the resistance measurements at 298 K and 4.2 K. High-purity aluminum current leads were fusion welded to the rods under inert atmosphere. Voltage leads were very carefully taped to the specimens in an effort to prevent accidental deformation of the material. The average RRR of the four as-machined rods was 6165 (corrected for size effect). Annealing the machined rods for 1 hr in air at 610°C followed by a slow furnace cooling to room temperature raised the average RRR to 9772. The annealing treatment apparently removed dislocations that were invariably introduced into the material during the grinding operation. If the specimen rods are rapidly quenched into a brine solution following the annealing treatment at 610°C , the RRR becomes

2800. The faster quenching rate likely produces excess vacancies and point defect clusters which are thought to be chiefly responsible for the low RRR. The results point up the need to be very careful in handling and dealing with ultrahigh purity aluminum.

The Cominco aluminum ingot was sawed into shapes appropriate for melting and alloying with gold. Care must be taken at all stages in the preparation of these aluminum alloys to prevent accidental contamination. Therefore, after sawing the aluminum was carefully cleaned by chemical polishing in a solution by volume of 70% phosphoric acid, 25% sulfuric acid, and 5% nitric acid heated to between 60 and 80°C. Previous experience has shown that a 10-min cleaning operation will remove any surface contamination due to the sawing. After chemical polishing, the aluminum was rinsed in distilled water, dried in air, and stored in argon-filled plastic bags until it is used.

To date we have prepared 280 g of a master alloy containing 1.1 wt % gold in zone-refined aluminum. The high purity gold (99.999%) supplied in wire form 1/16 in. in diameter was purchased from Leytess Metal and Chemical Corporation. Figure C-4 shows one of the master alloy ingots following the melting and zone-leveling operation. After removal of the ends (where a certain macroscopic segregation is thought to still exist), the ingot was replaced into the graphite boat, sealed off in quartz under 1/2 atm of argon (see Fig. C-5), and homogenized for 2 weeks at 600°C.

4. Expected Results (Second Quarter CY 1973)

We hope that by July 1, 1973 all the alloys will have been made, homogenized, and fabricated to rods. Also we anticipate that some preliminary results of our age hardening tests may be available.

Figure C-4. Photograph of as-cast master alloy containing 1.1 2t % gold in zone-refined aluminum.

Figure C-5. Photograph of raster alloy in readiness for solid state homogenization anneal at 600°C .

5. Visits

On December 12, 1972 we attended a meeting at the AEC in Washington, D.C. to discuss and review the status of superconducting cable projects at BNL, LASL, and ORNL.

We also attended the IEEE-PES Conference on Research for the Electric Power Industry held in Washington, D.C., December 11-14, 1972.

Brookhaven National Laboratory was visited on January 18-19, 1973 to discuss in detail the accomplishments, current status, and plans for the proposed BNL test facility. Several important points pertinent to the aluminum work arose out of these discussions.

1. The thermal conductivity of the stabilizing conductor may be an important factor as well as RRR.
2. RRR for aluminum should not be less than 2000:1 else copper could be used.
3. Strength is not a very important consideration if an additional component (such as stainless steel) is added to the cable design to mechanically support the conductors. But a high strength-low resistivity aluminum would be gladly accepted if it is economical.
4. If aluminum is used as the stabilizer, several problem areas present themselves. a) The joining or bonding of the aluminum to the Nb_3Sn ribbon without "contaminating" the aluminum by impurities or defects. Possible research proposals should be considered here. b) The cost of ultrahigh purity aluminum at the present time is prohibitively high. Discussions with the

aluminum producers about the possibility of cost reduction should be considered.

A trip to National Bureau of Standards in Boulder, Colorado, to visit F. R. Fickett and exchange and gather information about approaches for producing high resistance ratio aluminum and copper will be planned for later this year.

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APPENDIX A

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DIELECTRIC STRENGTH OF LIQUIDS AND GASES AT
CRYOGENIC TEMPERATURES--A LITERATURE SURVEY

W. F. Gauster and S. W. Schwenterly

All specialists working in various fields of cryogenic electric power engineering agree that presently available data on the dielectric strength of liquid and low temperature gaseous helium, hydrogen, and nitrogen are not sufficient for engineering design purposes and that more research in this respect is absolutely necessary. To demonstrate the correctness of this statement, a search of the literature has been conducted regarding liquid structure theory, liquid and gas breakdown theory, pre-breakdown effects, and experimental breakdown behavior in cryogenic liquids and gases. The following is a survey of the results. In addition to the papers discussed below, several general reference books¹⁻⁵ have been found to be useful.

I. LIQUID STRUCTURE THEORY

A. First-Principles Approach

Several authors⁶⁻⁸ have given comprehensive summaries of existing methods of calculating liquid properties from first principles. There are two major ingredients in such a calculation. The first is a knowledge of the interatomic potential. For dielectric liquids (those having no unlocalized electrons), the total potential energy is generally taken as the sum of the interaction energies of all possible pairs of

particles in the liquid. In the simplest case, the particles and pair potentials are spherically symmetric, consisting of a $1/r^6$ dipole attraction and a repulsive core which increases as $\exp(-r/\rho)$ or r^{-n} as $r \rightarrow 0$. Fortunately, liquid helium and other noble gases fall in this category. The other requirement is a knowledge of the radial distribution function $g(r)$, which gives the probability of finding another molecule at a certain distance from a given molecule in the liquid. In contrast to the pair potential, $g(r)$ varies with external conditions such as temperature and density. Although the computations are greatly simplified for liquids like helium, they are still extremely intricate and considerable approximation is necessary. For polar and non-spherical molecules, the angular dependence of the pair potential and possible internal degrees of freedom must also be considered.

B. Phenomenological Approach

Of particular interest in the discussion of pre-breakdown phenomena are the calculations of viscosity and diffusion coefficients. Eyring⁹ has developed a phenomenological theory of liquid transport properties which considers the thermally activated motion of particles across potential barriers into the potential wells of adjacent holes in the liquid. The viscosity turns out to be proportional to $\exp(E_0/k_B T)$. The activation energy E_0 is compounded of the energy to provide a hole in the liquid and the height of the potential barrier around a molecule. The viscosity of a classical gas is on the other hand proportional to $T^{1/2}$. Liquid helium follows neither of these laws, having essentially a constant viscosity above 2.5 K, as measured by Taylor and Dash.¹⁰ These authors explain this result using a kinetic model which takes account of

the quantum-mechanical zero-point energy as well as the thermal kinetic energy of the particles.

II. PRE-BREAKDOWN PHENOMENA

The observation of pre-breakdown phenomena in dielectric liquids as a function of external parameters, such as electric field, temperature, and pressure, provides information about the physical nature of the charge carriers. In cryogenic liquids, the ion density is usually increased through the use of radioactive sources, field emitters, photocathodes, or tunnel diodes. The parameters measured most often are the electron injection energy and positive and negative ion mobilities. Other phenomena, such as light emission, current pulses, and liquid motion, have been observed in conventional dielectric liquids, but such observations in cryogenic liquids have been limited.

A. Electron Injection Energy

The behavior of charged particles in a liquid is strongly dependent upon their interaction with the liquid molecules. The electron injection energy is one measure of this interaction.

1. Halpern et al.¹¹ have measured the injection energy of electrons into liquid argon by comparing the curve of emission current vs incident photon energy for a photocathode immersed in the liquid to that observed in vacuum. The curve in argon was shifted downward by about 0.33 eV, indicating that the electron-argon interaction is weakly attractive. Using the same method, Woolf and Rayfield,¹² on the other hand, measured a work function increase of about 1.0 eV in liquid helium, implying a repulsive electron-helium interaction.

2. Sommer¹³ obtained a value of $1.3 \text{ eV} \pm 0.3 \text{ eV}$ in helium with a cell having three electrodes--one at the electron source in helium gas, one at the liquid surface, and one immersed in the liquid. Electrons having insufficient energy to penetrate the surface are swept out by the surface electrode. The surface barrier energy is found by taking the ratio of the surface current to the total current flowing on the surface and through the liquid. This is compared with the value calculated by integrating the theoretical energy distribution for electrons drifting through the gas in an electric field up to some energy ϵ_0 . The value of ϵ_0 giving best agreement is taken as the barrier energy.

3. Silver et al.¹⁴ have injected high-energy electrons into various liquids from a tunnel diode junction consisting of a thin layer of aluminum insulated from a gold substrate by an aluminum oxide film. Electrons tunneling across the oxide layer are accelerated by a bias potential of about 10 V and pass through the aluminum film into the liquid with effective temperatures which can reach 15,000 K. The barrier energy was found by measuring the increase in slope of the logarithm of the emission current vs inverse diode voltage curve when the diode was operated in vacuum and in the liquid, resulting in values of 2-3 eV. These authors also were able to measure the distance the hot electrons penetrated before being thermalized to their lowest energy state. This range was only about $70 \text{ \AA}$, and the authors call attention to the possible contributions of electron back-diffusion to the electrode or liquid surface neglected in previous results.

B. Ion Mobilities - Experimental

An ion injected into a liquid in an electric field accelerates until it reaches a limiting drift velocity where the electrostatic force

on it is balanced by the viscous drag of the liquid. If v_{dr} is the drift velocity and E the field strength, the mobility μ is defined by the relation

$$v_{dr} = \mu E.$$

If the ion is larger than the liquid particles, μ is determined by the ionic radius and liquid viscosity. In the following, we summarize several experimental ion mobility measurements in cryogenic liquids.

1. Meyer, Rice, and their co-workers have published several papers¹⁵⁻¹⁷ on ion mobilities in liquid argon and krypton. In all of this work, a time-of-flight method was used whereby "gates" consisting of pairs of electrodes were placed at either end of a 1-cm drift space containing a field E_0 . E_0 was limited to 200 V/cm to avoid breakdown in the gas above the cell. The gates were simultaneously closed by applying a square wave pulse so as to change the field to $-E_0$ in each gate periodically. When the ion drift time equaled an integral multiple of the gate pulse repetition time, a maximum in the ion current was observed. In the early experiments,¹⁵ the negative ion mobilities were found to be very low, a surprising result if the negative carriers were assumed to be free electrons. However, the work of Swan¹⁸ indicated that if oxygen impurities were present, nearly all the electrons would be taken up as O_2^- ions, thus greatly reducing their mobility. In the later work of Meyer, Rice et al.,^{16,17} much purer gas was used, and the measured negative ion mobilities increased by about five orders of magnitude. These authors attempt to explain their results using a modified Boltzmann equation approach where the free argon atom cross section is multiplied by the liquid structure factor. However, the calculated mobility is a factor of two higher than that observed. Some of their

results are found in the Table, which summarizes positive (μ^+) and negative (μ^-) ion mobility measurements in several cryogenic liquids by various authors.

2. Swan¹⁹ and Williams²⁰ have measured ionic mobilities in liquid argon up to fields of 100 kV/cm and 160 kV/cm, respectively. Williams also included liquid helium I and II in his studies. Both of these authors used a cell containing an α -particle source at high voltage on one end and a collector grounded through a capacitor at the other end of a drift space about 1 mm in length. Each particle produces a swarm of ions which induce a constant current in the collector circuit as they approach the collector. The current falls to zero when the ions reach the collector. Hence the time for the ions to traverse the drift space is obtained from the time for the collector capacitor voltage to reach its maximum value. Bandwidth limitations on the amplifiers used smoothed out the ideal ramp-shaped voltage pulse, so this method is not as precise as that of Meyer et al. Some results of Swan and Williams are shown in the Table. The μ^- argon results lie in the intermediate range between the early and late measurements of Meyer, Rice et al., probably reflecting a somewhat greater impurity concentration offset by the lower probability for electron capture by impurities in the shorter drift space. Swan¹⁹ noticed one other unusual impurity effect in liquid argon--addition of 0.4% nitrogen doubled the electron mobility. To explain this he conjectured that inelastic scattering of the electrons by nitrogen atoms decreases the mean electron energy, leading to a Ramsauer-type decrease in the effective electron-argon cross section. However, later calculations²¹ have indicated that the Ramsauer effect may not exist in liquid argon. The measurements

of Williams in helium I (Table) surprisingly showed a negative ion mobility which was only one-fifth to one-fourth of the positive mobility. Impurities cannot be blamed in this case because all would be frozen out at 4.2 K.

3. Meyer et al.²² have also measured positive and negative ion mobilities in helium I using the same time-of-flight method as for their argon work. Again the fields were limited to 200 V/cm. At these low fields, μ^+ and μ^- were found to be independent of field strength and only weakly dependent on temperature. μ^+ showed a rapid linear decrease with density, while μ^- displayed a weak maximum in the neighborhood of 0.15 gm/cm³ for temperatures between 2.2 K and 4.2 K. μ^+ and μ^- began to increase rapidly at T_λ , as the increasing superfluid fraction decreased the effective liquid viscosity. The measured μ^- values (Table) agree well with those of Williams, but the μ^+ values are only half as great.

Meyer et al. compared their data with the predictions of classical hydrodynamic theory for spheres of radius a and charge e moving under an electric field through a fluid with viscosity of η . Hence

$$\mu = \frac{e}{6\pi\eta a}$$

Using published viscosity data, the Stokes radius a is then 4.3 Å for positive and 8.5 Å for negative ions.

4. Using a similar method to that of Meyer et al., Bruschi and co-workers²³ have measured μ^+ and μ^- for helium at 4.2 K, nitrogen at 77 K, argon at 90 K, and carbon tetrachloride at room temperature. Their results (Table) are in general agreement with the others for

helium. In all the liquids investigated, these authors noticed small but definite steps in the mobility which were periodic in a certain critical drift velocity $v_{dr,c}$. Doake and Gribbon²⁴ investigated positive ion mobilities in liquid nitrogen using a cell in which a square wave potential on the drift space reversed the direction of ion current in every cycle. They observed a lower mobility (Table) and no discontinuities, and proposed that the discontinuities and excess mobilities observed by other authors were due to macroscopic fluid flow which develops as the fluid is dragged along by a dc ion current in the drift space.

C. Ion Mobilities - Theory

The positive ion mobilities have been explained satisfactorily by Atkins,²⁵ who suggested that the neighboring atoms were attracted to an ion by dipole forces and are dragged along by it. In fact, calculations show that in helium, for radii less than $6.7 \text{ \AA}$, the effective electrostrictive pressure is greater than 25 atm, resulting in a sphere of solid helium surrounding the ion.²⁶ This radius agrees reasonably well with the $4.3 \text{ \AA}$ Stokes radius of Meyer et al. Similar considerations hold for both positive and negative ions in other cryogenic liquids. On the other hand, this explanation breaks down for electrons in helium because of the repulsive interaction with the liquid previously mentioned. Instead, the most likely explanation appears to be that the electron occupies a bubble in the liquid so that its energy increase due to localization of the wave function and the work required to form the bubble is offset by the decrease in its repulsive potential energy with respect to the liquid. The equilibrium bubble radius at 4.2 K has been calculated to be about $12.4 \text{ \AA}$.²⁷

Hence, the negative ion mobility should be less than the positive ion mobility, in agreement with experiment.

Further evidence for the validity of the bubble model for negative ions in liquid helium has been provided by the work of Levine and Sanders,²⁸ who measured μ^- in cold helium vapor at 4.2 K. They found that when the pressure reached about 75% of the saturated vapor pressure, the mobility dropped sharply to values approaching those in the liquid. Presumably at this pressure the density reached the point where the barrier energy was large enough to make the formation of bubbles energetically favorable.

D. Other Pre-Breakdown Effects

1. Coelho and Sibillot²⁹ have investigated field emission phenomena in liquid nitrogen, using a 300 Å radius field emission point opposite a solid plane or flat grid electrode. The emission current started abruptly in liquid nitrogen at two and one-half to four times the threshold voltage for emission in vacuum and varied roughly quadratically with applied voltage. Observation of small bubbles near the point indicated liquid motion in this region, accompanied by a faint greenish glow. Similar results were observed with both positive and negative point polarity. The V^2 dependence of the emission current indicates that it is space-charge limited. The authors deduce ion mobilities on the order of $10^{-3} \text{ cm}^2/\text{v-sec}$ from their emission curves, in good agreement with other results in the Table. From the fact that the surface field at the point could reach 100 MV/cm without detectable pre-breakdown phenomena, the authors suggest that the usual "breakdown fields" of about 1 MV/cm observed for liquid

nitrogen result from artifacts such as cosmic ray ionization, bubbles, or particle contamination, field emission having a relatively minor role.

2. Megahed and Tropper³⁰ have made a thorough study of pre-breakdown conduction current pulses in transformer oil for gaps up to 0.125 mm and voltages up to 9 kV. By recording the pulses on a high-speed tape recorder having two playback heads with variable relative displacement, they obtained the frequency vs pulse height distribution. The pulse frequency increased exponentially as the pulse height decreased for a given gap length. The frequency for a given pulse height increased with the gap length. This suggested to the authors that a charge multiplication process of some sort was occurring. A reduction in pulse activity was noted with increasing pressure, indicating that the pulses may arise from ionization in microscopic gas bubbles. Hopefully, similar observations might be made in liquid helium using a partial discharge detector.

3. Smith and Calderwood³¹ have used an image intensifier to study pre-breakdown light pulses in dielectric liquids. The photographs indicate that breakdown is accompanied by the formation of luminous regions around the cathode and anode which grow together until they meet at the instant of breakdown. For pre-breakdown events, the light is confined to the cathode region. High-speed oscilloscope studies of the pre-breakdown voltage and current waveforms for a 1-mm sphere-plane gap in hexane indicated several small pulses of 0.5 nsec width occurring about 10 nsec before the main breakdown pulse, which was 6 nsec wide and had a rise-time of about 0.4 nsec. For a 1-mm sphere-sphere gap in liquid nitrogen, the results were similar except that the breakdown rise-time increased to 4 nsec. The current pulses correlated closely

with the light pulses observed. Other investigations of these authors show the existence of pre-breakdown liquid motion and the production of 100 kHz acoustic waves at breakdown.

III. DIELECTRIC BREAKDOWN OF CRYOGENIC LIQUIDS AND GASES

A. Dielectric Strength of Low Temperature Gaseous Helium and Nitrogen

As is well known, research on the electric breakdown of gases has been performed for many years, and the basic physics of these phenomena is in general well understood.^{1,2} However, certain special problems are still under investigation, and one practical important group of these not yet entirely elucidated problems is the electrical breakdown performance of gases, such as helium, hydrogen, and nitrogen, at very low temperatures. In the following we will briefly review some of the recent investigations in this special field.

1. A paper by Fallou et al.³² deals with the electric breakdown of cold gaseous helium in gaps between the electrodes of 0.1 and 1.0 mm length in uniform fields and with gaps with lengths up to 10 mm in non-uniform fields. The gas temperature could be regulated between 4.2 and 50 K. Most of the experiments were made with ac 50 cycles. The experiments demonstrated that gaseous helium shows normal behavior in the entire temperature range from 4.2 K to room temperature. The ratio of the breakdown strengths at these temperature limits is over 60. Cold gaseous helium seems to obey Paschen's law in uniform and non-uniform fields. Anomalous behavior has been observed only near the boiling point. Strong polarity effects of the dielectric strength occur

with non-uniform electric fields. Furthermore, with a negative point electrode, the scatter of observed breakdown voltages is high in contrast to the voltage scatter observed with other electrode arrangements.

2. The previously mentioned work on the electric breakdown strength of low temperature gaseous helium has been continued by J. Thoris et al.³³ Since the test equipment permitted the application of 50 cycles ac voltages of about 110 kV (rms), it was possible to measure at atmospheric pressure breakdown voltages with gap widths from 1.0 cm at a temperature of 6 K to 8 cm at temperatures between 60 and 240 K. At each electrode spacing, twenty values of breakdown voltages were recorded. The observed scattering indicated a normal Gaussian distribution. The breakdown voltage followed, as to be expected, approximately a linear relationship to the reciprocal value of the absolute temperature. Finally, breakdown measurements were made with hypercritical helium with a gap of 1.77 mm and pressures between 2.26 and 10 bars.

3. Other investigations with low temperature gaseous helium were reported by Meats.³⁴ Rogowski electrodes of 60 mm diameter made of brass or niobium were used with horizontal gaps of 0.5, 1.0, 1.5, 2.5, and 3.0 mm spacing. The best voltage of up to 100 kV dc was applied with a rate of rise of about 500 V/sec. After initial conditioning, average values of at least ten breakdown voltages were taken at each temperature level. This author also finds that the electrical breakdown of cold helium gas obeys Paschen's law for comparatively high values of Nd , when the field is below a certain field emission threshold. Beyond this limit the dielectric strength shows less increase with density and approaches a limiting value of about 300 kV/cm. This phenomenon is similar to the

observed voltage limit of vacuum insulation.³⁵ At densities equivalent to that of liquid helium but above the critical temperature, the breakdown voltage curve changes drastically. An electric breakdown strength of about 450 kV/cm occurs at a density of about 0.14 g/cm³.

4. The reviewed paper by Fallou et al.³² concludes with the remark: "Even if these results may be considered as sufficient, at present, for the design of cryogenic materials, there is still much work to be done to understand many of the features particular to gaseous helium at low temperatures." We cannot entirely agree with this statement. We think that the following additional points deserve special attention: First, practical applications will need data on the dielectric strength of cold gases at much higher test voltages than have been used up to the present. Cryogenic cables will be operated with several hundred kilovolts and, therefore, test data should be available for voltage up to at least half a million volts. As has been mentioned in more detail in another place in this report, in the Thermonuclear Division the necessary high voltage power supplies and also expensive parts for building high voltage test cells are available, however, it should be borne in mind that the design of such a test cell is itself a difficult problem.

However, it is not only the question of sufficient high voltage. We must also consider certain test types of the conventional high voltage technique³⁶⁻³⁸ which proved to be necessary as the basis of efficient and reliable design of conventional high voltage equipment. We mention here especially experimental arrangements with concentric cylindrical electrodes (this configuration is of great importance for cryogenic cables) which will be discussed later for tests with liquefied

gases. The results of similar experiments with low temperature gases are not available yet.

B. Dielectric Strength of Liquid Helium and Nitrogen

In the following we review several publications on the dielectric strength of liquid helium, hydrogen, and nitrogen. We start with more basic investigations and proceed later to tests of liquid gases for technical applications.

1. Blank and Edwards³⁹ investigated the dielectric strength of liquid He⁴ in a temperature range from 1.2 to 4.2 K. They built a test chamber similar to that described by Seki.⁴⁰ They used spherical steel electrodes of 9.52 mm diameter and gap widths of 0.15, 0.5, and 1.0 mm. Other experiments were performed with "plane to plane" and "point to plane" arrangements with the mentioned three distances between the electrodes. Despite very careful purification of the liquid helium, the measured breakdown voltages showed very large scattering. All electric breakdown experiments were made with dc and no pre-breakdown currents could be observed. The electric resistivity of liquid helium proved to be extremely high (order of 10^{18} ohm cm). The "point to plane" tests indicated strong polarity effects (with negative point and positive plane about half the values as measured with opposite polarity).

2. Very careful experiments on the electrical breakdown of liquid helium were made by Goldschvartz and Blaisse. A special test cell was built⁴¹ for measuring the dielectric strength with gap widths between 0.01 and 0.1 mm at temperatures between 1.3 and 4.2 K. Later improvements resulted in a maximum error of the gap width of only 0.0025 mm.⁴²

The influences of the following parameters have been investigated: Purity of the liquid helium, gap distance between the electrodes, temperature, speed of rise of the voltage applied, time lag between breakdown, duration of a breakdown and destruction of the electrodes, and finally, pre-stressing effects.

The mean value standard deviation of series of 50 measurements for each voltage value was very low (2.2 to 2.9%), however, the ratio of the observed highest value to the observed mean value of each series of measurements increased with the gap width to ratios of 1.3 to 1.5. Furthermore, the authors compared measurements performed as carefully as possible under equal conditions on various days in a time interval of several months. Breakdown voltage ratios of up to 1.6 could be observed. In this connection, the authors draw attention to the observation of Swan and Lewis^{43,44} that the presence of possibly metastably dissolved oxygen in the liquid helium increases the dielectric strength. Goldschvartz and Blaisse think that with their test equipment with very narrow gaps between the electrodes and with their elaborate test procedures the electrical breakdown of liquid helium can be sufficiently controlled. They feel that their finally observed values for the "intrinsic" dielectric strength of liquid helium at boiling point are reasonable, however, they mention that the situation is still uncertain, and a considerable number of experiments should be carried out in order to obtain more consistent and conclusive results.

3. B. Fallou et al.⁴⁵ investigated the high voltage dielectric behavior of liquid and hypercritical helium. Three different test cells have been used. One had an inside diameter of 55 cm and

optical observations in two perpendicular directions could be made employing three windows with 30 cm diameter. AC voltages up to 100 kV (rms) could be applied. A similar cryostat with an inside diameter of only 6 cm was built for test voltages of up to more than 50 kV. Both test cells could be pressurized up to 20 bars. A third test chamber was built for measurements with still higher gas pressure, and it proved to be necessary to use for this test chamber a bushing in the form of a tightly fitting cable.

For measurements with almost uniform electric fields, sphere-plane electrode arrangements were employed. AC breakdown measurements with gap widths up to 10 mm, corresponding to voltage values of up to somewhat less than 100 kV (rms), were made. Experiments with point-plane electrode arrangements and gap widths up to 10 mm showed very appreciable polarity effects. Certain light phenomena, movement of the liquid helium, and pre-breakdown currents up to a few microamperes could be observed. With a constant gap distance of 1.0 mm irradiation by means of a source of iridium 192 of 15 mCi was applied and resulted in a very appreciable reduction of the ac breakdown voltage.

Finally, with a constant gap width of 1.7 mm, dielectric strength measurements were performed with hypercritical helium (at 5.2 K the pressure was varied from 2.26 to 10 bars). For gap widths from 0.1 to 2.0 mm a large number (20, 50, 100, and 115, respectively, shots for each gap width) of measurements of the breakdown voltage of liquid helium have been performed. The standard deviation for each gap width was between 23.8 and 13.2%. The authors emphasize that as yet it appears to be difficult to describe the essential physics of the electrical breakdown in liquid helium. Gas bubbles and impurities seem to be of

appreciable influence. Finally, the authors draw attention to the fact that much more work has to be done in order to supply reliable data for the practical design of cryogenic electric power apparatus.

4. Many interesting results concerning the dielectric strength of liquefied gases are due to K. N. Mathes and co-workers. His paper, published in 1963,⁴⁶ is partly superseded by another paper published in 1967.⁴⁷ Both deal not only with the electrical breakdown properties but also with the dielectric constants and dielectric losses. The following short review concentrates on the dielectric strength measurements as reported in the second paper.

For his experiments, Mathes used an ac 60 Hz power source for voltages up to 50 kV (rms) and a test cell with 1/2 in. steel spheres as the electrodes. He was interested in the statistical distribution of his test results, and he found by plotting on Gaussian probability paper the logarithm of the breakdown voltage versus cumulative probability that the repeated individual voltage values (nine to 16 shots for each spacing) followed with good approximation a Gaussian distribution. Gap widths from 0.075 to 1.25 mm have been used for determining the dielectric strength of H₂ at 14 and 20 K, H₂ at 63 and 77 K, and He at 4.2 K. The dielectric strength decreases in the following order: H₂ at 14 K, N₂ at 63 K, N₂ at 77 K, H₂ at 20 K, for comparison good insulating oil (at 23°C), and finally, He at 4.2 K. Mathes derived from his diagrams showing breakdown voltage V versus gap spacing d an empirical law in the form

$$V = Ad^n$$

with different values of the constant A for the different liquid gases,

however, with the same $n = 0.9$ supposed that all measurements were made with the same spherical electrodes of $1/2$ in. diameter.

The temperature dependence of the dielectric strength of liquid helium was tested in the range 2.2 to 4.2 K. Unfortunately, the λ -point (2.19 K) could not be reached, and the temperature control was not perfect which conditions resulted in a large scattering of the electrical breakdown values. A diagram showing the 60 Hz breakdown strength of liquid helium for a gap spacing of 0.19 mm demonstrates the increase of the dielectric strength with decreasing temperature. The authors refer to unpublished work of B. S. Blaisse who found a discontinuity of the dielectric strength of liquid helium at the λ -point. Finally, Mathes discusses the influence of small particles dispersed in liquid. He mentions that B. S. Blaisse (not published) filtered superfluid helium through a fine pore fritted glass filter which resulted in an increase of the dielectric strength. Probably small drops of frozen air have been removed in this way. However, Mathes thinks that Kok's approach⁵⁰ is not entirely sufficient for explaining the phenomenology of the dielectric strength of liquefied gases.

5. Gerhold⁴⁸ has measured the breakdown strength of liquid and cold gaseous helium for voltages to 40 kV dc and gaps up to 1 mm. The cryostat was capable of pressurization to 5 atm, and the temperature could be varied between 4 and 30 K. The electrodes used were spherical caps of 25 mm radius and were made of niobium, stainless steel, or copper. For densities less than 0.02 gm/cm^3 , the breakdown field strength in the gas was proportional to $\rho^{0.9}$ at a gap of 1 mm. The author states that "obviously the breakdown field strength E has to be inversely proportional

to $d^{0.1}$ according to Paschen's law when the gap width $[d]$ is varied at constant density." However, he shows no data to verify this. In non-boiling liquid at 4.2 K, the mean breakdown field dropped slowly with increasing gap to about 500 kV/cm at $d = 0.5$ mm. As with other authors, Gerhold observed roughly 10% scatter in the liquid breakdown strengths and negligible scatter in the gas. With clean surfaces, the breakdown voltages in both liquid and gas were insensitive to electrode material; however, in the liquid a lead coating on the copper reduced the voltages by about 35%. Surface oxidation produced a drastic reduction in breakdown voltage only for copper electrodes, and the author concludes that copper should be avoided in high-voltage cryogenic apparatus. Frozen air particles in the liquid had no effect on the breakdown voltages, but frozen oil vapor appeared to completely destroy the insulation qualities of the liquid.

6. M. J. Jefferies and K. N. Mathes⁴⁹ discuss the dielectric loss and voltage breakdown in liquid nitrogen and hydrogen. The tests were made with 60 Hz ac and a test voltage of up to 150 kV (rms) could be applied. In contrast to the previous experiments,⁴⁷ a new test cell was developed in which conical spacers in the enlarged ends provide a spacing of 0.250 in. (0.635 cm) between concentric cylinders in the central portion. Voltage breakdown always occurred in the central portion of the test specimen. The outer copper electrode and the inner stainless steel electrode were polished, however; they could not be considered chemically clean. The test cell could be pressurized, and the temperature was kept at 20 K for hydrogen and 77 K for nitrogen, i.e. the measurements were made with subcooled liquids.

The elevated pressure eliminates the effect of boiling (bubbles!), and the electric strength is appreciably increased. With further pressure increase, the electric strength shows little or no additional increase. For liquid nitrogen, the observed voltage stress at breakdown (in V/mil; 1 V/mil = 0.4 kv/cm) was between 180 and 202 (boiling), between 224 and 296 at 1 psi pressure = 0.068 atm, between 260 and 410 at 10 psi, between 400 and 450 at 20 psi, and between 320 and 466 at 75 psi. Somewhat higher values but with the same trend were observed with liquid hydrogen. For the statistical evaluation of the test data, the authors assume a Gaussian distribution.

In the discussion of the test results the authors refer to Kok's work⁵⁰ on the influence of dispersed particles, on the investigations by Crow et al.,⁵¹ who suggest that voltage breakdown is proportional to the density of the liquid, and to Krasucki's⁵² formula, which considers density, surface tension and pressure, and which is based on the mechanism of vapor formation.

The authors conclude that "voltage breakdown in liquids is still not well understood. Further studies of these cryogenic liquids, which have very interesting and different physical properties, could add much to the understanding of the subject." We agree with this statement which concerns liquid nitrogen and hydrogen, however, we think that the most pressing problem (when considering superconductor applications) is, of course, to investigate the dielectric strength of liquid helium. We must keep in mind that the electric breakdown performance of helium differs very appreciably from that of hydrogen and nitrogen.

7. A companion paper to Ref. 49, written by the same authors,⁵³ deals with the measured dissipation factor and electric breakdown strength

of certain dielectric materials (wood cable paper and, the synthetic materials, DuPont's "Nomex" and "Tyvck") impregnated with the liquefied gases N_2 and H_2 suitable for cryoresistive cable application. Only a small number of tests were made with liquefied helium impregnation since this group of investigators (General Electric Company) is mainly interested in the application to cryoresistive cables. Most of the tests were made in subcooled cryogenic liquids under pressure. The test voltages were 60 Hz ac, 50 kV (rms) for small samples and 150 kV for large samples. Only a limited number of small sample tests were made in liquefied helium.

These tests considered the size of cable specimen, the outer electrode configuration, the nature of the material, the moisture content of the material, the liquid impregnant, and the pressure. The measured breakdown strengths for the smaller specimen in liquid nitrogen and hydrogen were not appreciably different; however, the small samples immersed in liquid helium are indicative of sizably smaller dielectric strength of this cryogenic liquid.

The experiments showed that the mechanism of voltage breakdown is not related to "thermal runaway" (as in solids⁵⁴). The dielectric strength of the composite was appreciably influenced by electric breakdown strength of the liquids and increased with the paper density. The experiments did not show time influence when voltages were applied for many hours; however, much longer electrical stress times very probably will demonstrate certain long-time voltage effects (see Sect. V).

8. Minnich and Fox⁵⁵ published a summary of a study undertaken by the Research and Development Center of the General Electric Company on cryogenic (mainly cryoresistive) underground power systems. This study

was sponsored by the Edison Electric Institute and the Tennessee Valley Authority as part of the Electric Research Council's Underground Transmission Research and Development Program. Concerning the dielectric strength of liquefied gases, Table 2 (p. 46 loc.cit.) of this study is of special interest.

	V_{ac}/mil		
	N_2	H_2	He
1/2 in. spheres 0.025 in. gap, 1 atm	1120	1000	560
Cylindrical 0.046 in. gap, 1 atm	370	260	300
Cylindrical 0.046 in. gap, 6 atm	650	650	500

The dielectric strength values are indicated in 60 Hz rms V/mil, and all data were taken at the normal boiling temperatures. The influence of the pressure is obvious. Furthermore, the authors make the following comment:

"It is well known, from statistical data, that increased surface area of the electrodes leads to lower dielectric strength. The data in Table 2 seem to confirm this trend." The electrode areas of the test arrangement with concentric cylindrical electrodes are much larger than the effective area of the sphere gap (unfortunately, numerical values of the radii and the length of the cylindrical electrodes are not indicated in the reviewed paper). In Sect. V of this appendix, we will discuss in detail the "area effect" of the electrical breakdown in insulating liquids.

In Table 3 of their paper, Minnich and Fox show breakdown stresses obtained with cylindrical electrodes taped with conventional wood insulating paper and with some of the newer synthetic papers (DuPont's "Tyvck" and "Nomex"). The radial thickness of the insulating layer was

0.040 in.

	V_{ac}/mil	
	Nitrogen	Hydrogen
"Tyvck"	1400	1400
"Nomex"	1350	1250
Paper	1150	1250

The stress values are again in V/mil. The pressure is not indicated, however, at any rate the values of Table 3 are much larger than those of Table 2. Data for impregnation with liquid helium are not given.

Finally, the following quotation from this paper is of interest: "While the data obtained to date have been favorable, the values cannot be extrapolated directly to higher voltages. Until the time when test values are obtained at higher voltages, conclusions based on the use of these data are tentative." Complaints about the lack of reliable dielectric strength data of liquid and low temperature gaseous helium, hydrogen, and nitrogen have been made by many other authors working in the field of cryogenic electric power engineering.⁵⁶

9. Burnier et al.⁵⁷ describes two test facilities of Société Alsthom, Massy, France. One is for operation up to approximately 60 kV rms (constructed and tested in 1966) and another for 200 kV rms (which went into operation in April 1969). The great portion of the results have been obtained with the 60 kV test facility. In this paper the authors summarize the results discussed in more detail in a previous paper⁵⁸ as follows:

(a) The observed scatter in the breakdown strength of the cryogenic liquids was up to 25%.

(b) The dielectric strength of liquids and cold gases was found to be quite sensitive to pressure. Between spherical electrodes of 62.5 mm diameter and gaps between 1 and 2 mm, the highest dielectric strength was observed with N_2 at 5 bars (absolute), then follow H_2 at 5, N_2 at 3, and H_2 at 3 bars, then (for comparison) transformer oil at room temperature, N_2 at 1, H_2 at 1, and finally, He at 1 bar. A corresponding diagram, representing breakdown voltage versus gap spacing for the eight cases, is shown on page 83 of that paper. As to be expected, the dielectric strength decreased with the gap width.

(c) Measurements were made of the dielectric strength of low temperature gases contained inside an inverted copper cup (supported by the upper electrode), the lower edge of which was in contact with the cryogenic liquid, i.e. gas and liquid temperatures were approximately equal. The ratio of the dielectric strength of the cold gas to that of the liquid was found to be much more favorable than the ratio of the dielectric strength of warm gases to that of normal liquids. The authors find this fact encouraging when one considers the danger of ionization in gas bubbles in the liquefied gas.

(d) Solid dielectrics (Mylar films) immersed in liquid helium showed a much lower breakdown strength of the composite than observed with liquid hydrogen and nitrogen. The flashover voltages of solids in liquid helium were very low. The authors conclude their paper as follows; "High-voltage dielectric tests in cryogenic fluids require extreme care; large investments and specially trained teams are needed. The effort, nevertheless, is worthwhile, both because of the lack of data presently available for cryo-electrotechnical use and because of the different behavior of insulators under cryogenic conditions."

10. The Linde Superconducting Cable System Program has lately published dielectric breakdown data for liquid helium extending to voltages of almost 200 kV and gaps of 12 mm.⁵⁹ The electrodes used were a 22.5-cm sphere and 30-cm plane electroplated with niobium. The dc and ac dielectric strengths were found to be roughly 170 kV/cm, while the 1 x 40 lightning impulse strength was about 270 kV/cm and the 200 x 2000 switching impulse strength was 180 kV/cm. In this regime, the breakdown voltage increased nearly linearly with gap, aside from a slight falloff from a strictly linear dependence at the largest gaps. Pressurizing to 2 psig to prevent bubble formation raised the dc and ac strengths to about 220 kV/cm, increased the 200 x 2000 strength to 240 kV/cm, and left the 1 x 40 strength unaffected. The effects of particulate contamination were also studied by introducing powdered SiO_2 or frozen air between the electrodes. This had no effect on the breakdown strengths. However, finely divided copper powder decreased all breakdown strengths by 40 to 50 kV/cm.

IV. THEORIES OF LIQUID BREAKDOWN

At present there is no clear consensus on the mechanisms of breakdown in liquids. However, nearly all the theories attempt to explain breakdown in terms of a disruption of the liquid by a separate phase, either solid or gaseous. Sharbaugh³ has summarized and compared the existing theories of breakdown, and we shall follow his discussion closely in this section.

A. Electronic Theory

Some of the earliest efforts to understand breakdown in liquids attempted to apply the Townsend theory of electronic breakdown in gases to liquids. It is supposed that in the course of several elastic collisions

with liquid atoms, an electron gains enough energy to ionize an atom.* This so-called α -process results in an exponentially-growing electron avalanche propagating through the liquid. Secondary processes (γ -processes) at the cathode, such as positive ion collisions with the surface, produce additional electrons. Breakdown is assumed to take place when for every avalanche, γ -processes produce at least one extra electron at the cathode to start a new avalanche, resulting in a self-sustained discharge. However, the experimental evidence shows that electrons in liquid helium are confined to large, massive, slow-moving bubble structures, while the positive ions are electrostrictively bound to large clumps of neutral atoms. Hence it is unlikely that either electrons or ions could gain enough energy from the field to produce an α - or γ -process in liquid helium. Furthermore, the Townsend mechanism depends strongly on the electron mean free path which is nearly independent of pressure in liquids, but the breakdown strength in helium increases considerably with pressure.

B. Particle Theory

Kok and Corbey⁶⁰ have attempted to explain the breakdown strengths of liquids by assuming that small dielectric particles suspended in the liquid collect at local field distortions near electrode irregularities and form a bridge across the electrode gap which initiates breakdown. The long-time breakdown strength is given by

$$(g^2 - 1) r^3 E_0^2 = 2 kT$$

where g is the surface field enhancement coefficient and r is the particle

* In molecular gases, where the electron can lose energy to internal molecular degrees of freedom, elastic collisions are much less frequent, and the electron must gain the ionization energy in only one mean free path.

radius. If $g = 3$ for a hemispherical irregularity, with observed short-gap breakdown strengths for liquid helium, this relation gives a particle radius of about $3 \text{ \AA}$, whereas the Linde experiments indicated that with macroscopic particles the breakdown strength was unaffected. The theory also predicts that E_0 increases as $T^{1/2}$, but experimental studies show that even at constant pressure E_0 drops as the temperature rises.

C. Clump Theory

It is possible that the clump hypothesis, which was first theoretically investigated by Cranberg⁶¹ with respect to vacuum breakdown, may be relevant to helium breakdown. The basic idea is that small metal particles may either be suspended in the liquid as contamination or pulled out of the electrodes by electrostatic forces. A particle touching an electrode gains a surface charge density proportional to the local field and can be accelerated. Straightforward calculations indicate that a copper particle 10^{-3} cm in radius can attain energies of several hundred ergs and speeds on the order of the speed of sound in liquid helium in a 5-cm gap. The shock waves of such particles might easily produce vapor bubbles in the liquid. The experiments of the Linde group with copper particles in helium support these ideas.

D. Bubble Theory

The dependence of the liquid breakdown voltage on pressure suggests that vapor bubbles in the gap might contribute to breakdown behavior. The theory of Kao⁶² suggests that once a bubble is formed in the gap, it will lower its energy by elongating in the field direction into a prolate spheroid. Breakdown occurs in the bubble when the voltage drop along it equals the minimum voltage on the Paschen curve for gaseous helium, or alternatively when the bubble bridges the gap. The latter

process has been observed by Krasucki⁶³ in very viscous oils. The theory does not consider the question of how the bubble is initially produced, but in liquid helium the negative ions provide a ready-made source of bubbles. The breakdown voltage is found to depend on the initial radius of the bubble, making comparison with experiment difficult.

V. STATISTICAL EVALUATION OF THE TEST RESULTS

As has been mentioned previously, in several cases series of test values obtained with liquefied gases have been evaluated by assuming a normal (Gaussian) distribution. Careful evaluation of test series with gases and liquids at room temperature indicated sometimes the occurrence of normal probability distributions, however, very often the scattering of the test results followed other distribution laws and in certain cases it is not even possible to find any appropriate distribution function.⁶⁴ A similar situation can be expected for cryogenic electric breakdown experiments. The statistical evaluation of cryogenic dielectric strength tests is very important, since scaling from the size of the test electrodes to the many order of magnitude larger effective areas of cryogenic cables is necessary (c.f., the following summary of Weber and Endicott, Ref. 72). It is fortunate that much work on the statistical evaluation of electrical breakdown experiments performed at room temperature has been done so that the developed mathematical methods can be applied to cryogenics experiments.

A detailed presentation of the various approaches concerning the statistical evaluation of electrical breakdown tests with liquids (with an extensive list of references) has been given by W. F. Gauster,⁶⁵ and we follow here partly his presentation. For only technically pure liquids, a model can be used which Griffith⁶⁶ already many years ago has successfully applied to a statistical theory of the mechanical strength of solids.

He assumes that a solid body consists of a material of very high mechanical strength and that "flaws" with low strength are distributed at random in the volume. Independently of Griffith, Milnor⁶⁷ applied a similar concept to the problem of the dielectric strength of thin layers of insulators. Epstein⁶⁸ showed that the "Theory of Extreme Values" as developed by Tippett⁶⁹ can be applied to problems of mechanical and dielectric strength. This theory of extreme values was further developed in great detail and applied to many practical cases by Gumbel.⁷⁰ In these and other cases, instead of the normal (Gaussian) distribution, other types of distribution functions, e.g. the well-known Weibull distribution,⁷¹ may be more appropriate.

Weber and Endicott⁷² made very careful tests on the dielectric strength of thin layers of transformer oil. The uniform-field Rogowski gap was selected for a basic test of the scale (e.g. volume or area) effect on dielectric strength. An intricate automatic device has been used to make a very great number (1600) of tests. Four sets of gaps were tested simultaneously under identical, controlled conditions with 60 Hz ac. A detailed analysis of the experimental data yielded the following results:

(a) There is no position effect (horizontal or vertical position of the electrodes).

(b) The breakdown of transformer oil follows an extreme-value distribution rather than a normal distribution.

(c) The standard deviation of the observed dielectric strength value was independent of the electrode area.

(d) The extreme-value theory yields a precise equation for predicting the breakdown voltage for electrodes of any area for a uniform field, if breakdown voltage and the standard deviation are known for any one area for the oil used.⁷⁰ The difference between the breakdown voltage

measured with the areas A_1 and A_2 , respectively, is

$$V_{A_1} - V_{A_2} = 1.797 S_v \log_{10} \frac{A_2}{A_1}$$

where S_v (which is independent of area) stands for the standard deviation of the observed voltage values measured for any one area for the oil used. The experimental data are in excellent agreement with this theoretically derived equation.

(e) For the particular oil used, a tenfold increase of the electrode area resulted in a 16% decrease of the dielectric strength.

Two different types of time effects concerning the electrical breakdown of gases, liquids, and solids have been carefully investigated. One is the time lag in the case of surge breakdown. The time between applying a voltage pulse on the test specimen of an insulating material and the occurrence of the electrical breakdown is of the order of microseconds. Tests repeated under identical conditions yield series of values of the time lag which should be statistically evaluated in an appropriate way. Basic work for the electrical pulse breakdown in air has been done by Strigel⁷³ and has been treated in great detail by many other authors. Similar investigations have been made with liquids (see, for instance, Ref. 51) and with solids.⁷⁴

Another type of time effect is observed if a test specimen is exposed to a constant dc or ac voltage for an extended time (from minutes to days and even years). This long time effect, especially important for electric cables, depends on the magnitude of the applied voltage and the geometry of the electrode areas and the dielectric. Basic investigations on the long time electric breakdown statistics have been done by

Meyer.⁷⁵ Recently, specialists working in the field of electrical cable technology applied modern methods of statistics to these problems. A summary of that kind of work has been presented by Occhini.⁷⁶ Theoretical predictions of the "life functions" of cables are in satisfactory agreement with experiments if the appropriate distribution functions are assumed. One special case of these distribution functions is the Weibull distribution.⁷¹ The theory shows that for a satisfactory cable performance with regard to life function, low scattering, and high average dielectric strength are equally necessary (similar to Weber and Endicott's results on the area effect in transformer oil⁷²). Using scattering and dielectric strength values of commercial cables with extruded insulation, theory in satisfactory agreement with practical experience shows that an increase in the length of the cable installation by a factor of the order of 100 causes an approximately 50% decrease in the dielectric strength of the cable. It is, of course, very important that the results of experiments with short pieces of a cable can be used to predict in a satisfactory way the performance of the cable of a given length. As far as we know, no similar work on the statistical evaluation of long time test results has been done concerning the dielectric strength of cryogenic design elements. However, the determination of the reliability of electronic components through statistical evaluation has been treated in recent publications.⁷⁷ Furthermore, statistical evaluations of insulation systems are being used in the insulation coordination of EHV power transmission systems.⁷⁸ There will be need for sufficient data to perform similar coordination for cryoelectric systems.

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TABLE. Ion Mobilities in Cryogenic Liquids

d(mm)	Liquid	T(K)	P(atm)	E(kV/cm)	Polarity	$\mu(\text{cm}^2/\text{V-sec})$	Worker(s)
1	Ar	90	1	20	-	50	Williams, 1957
1	Ar	90	1	150	-	7.4	Williams, 1957
1	Ar	90	1	140	+	2.8	Williams, 1957
10	Ar	90	4.7	0.2	-	7.8×10^{-4}	Davis, Rice, & Meyer, 1962
10	Ar	90	68.8	0.2	-	5.99×10^{-4}	Davis, Rice, & Meyer, 1962
1	Ar	90	1	20	-	35	Swan, 1964
1	Ar	90	1	100	-	7.5	Swan, 1964
10	Ar	90	7	0.2	-	390	Schnyders, Rice, & Meyer, 1966
0.15	He	4.2	1	130	-	0.022	Williams, 1957
0.44	He	4.2	1	46	-	0.021	Williams, 1957
0.44	He	4.2	1	46	+	0.080	Williams, 1957
10	He	4.2	1	0.2	-	0.022	Meyer, Davis, Rice, & Donnelly, 1962
10	He	4.2	1	0.2	+	0.053	Meyer, Davis, Rice, & Donnelly, 1962
10	He	4.2	7.5	0.2	-	0.028	Meyer, Davis, Rice, & Donnelly, 1962
10	He	4.2	7.5	0.2	+	0.042	Meyer, Davis, Rice, & Donnelly, 1962
2-7	He	4.2	1	5	+	0.035	Bruschi, Mazzi, & Santini, 1970
2-7	N ₂	77	1.8	1	-	0.00113	Bruschi, Mazzi, & Santini, 1970
	N ₂	77	1.3	1	+	0.00096	Bruschi, Mazzi, & Santini, 1970
3	N ₂	77	1	2	+	0.00071	Doake & Gribbon, 1971

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APPENDIX B

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STABILIZED HIGH VOLTAGE DC POWER SUPPLIES OF THE SHIELDED DESIGN

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This paper describes recent progress in the design of the fully enclosed, stabilized High Voltage power supply.

The performance characteristics and operating life of a 600 kV power supply of this type are discussed.

High voltage dc power supplies are required for a wide variety of applications in the field of nuclear physics. Typical examples are: positive ion accelerators for nuclear research, electron accelerators for extra high voltage electron microscopy and for irradiation purposes, particle beam separators in large orbital accelerators, and test installations for the development of ion sources and accelerating tubes. Nearly all these applications require low ripple voltages, and most of them a high stability of dc output voltage. As these power supplies are considered to be auxiliary equipment only, they have to be compact in design and simple in operation. A first step towards the compactness was made when a type of dc power supply was built into one single cylinder of insulating material or porcelain. However, these power supplies were still of the so-called air-insulated design. Today completely shielded power supplies housed inside steel tanks are available from leading manufacturers in this field. As these units are enclosed in steel tanks, repairs cannot be performed as easily as in the case of the open ones. Therefore, the entirely shielded units have to be designed for the highest degree of reliability and long life.

This paper deals with a dc high voltage power supply which is based upon the principle of the Cockcroft-Walton cascade rectifier^{1,2}. The size of the main components, such as capacitors and transformers depends on the insulating properties of the material which is used for the filling and impregnation of the tank, and on the frequency at which the rectifier is operated. A high operating frequency will not only reduce the size of the components, but also considerably decrease the

capacitance of the coupling and smoothing capacitors and thus the total stored energy.

High quality mineral oil was chosen for the filling of the rectifier tank. The same oil is used for the impregnation of the capacitors, transformers and rectifiers. For this reason, these components do not have to be individually enclosed. Mineral oil has excellent insulating properties, low losses and a much better thermal conductivity than compressed gases.

As already mentioned, the operating frequency plays a major part in the design of a cascade rectifier. Experiments have proven that the maximum operating frequency of selenium rectifiers is in the order of 20 kcps. Therefore, an operating frequency of 10 kcps was chosen which allows for a considerable reduction in the size of the components. As far as frequency response is concerned, silicon diodes are better than selenium rectifiers. It is well known, however, that silicon diodes are very sensitive to over-voltages and over-currents which may frequently occur during the operation of high voltage equipment. Moreover, silicon diodes cannot be simply connected in series in order to obtain higher peak inverse voltages. Additional shunt capacitors and series resistors have to be provided in order to protect the silicon diodes. Out of economic considerations, it can be proven that silicon diodes are preferable to selenium rectifiers in high voltage techniques if the rated dc current exceeds 50 mA³.

The maximum output voltage of the dc power supply was rated at 600 kV, since this was the limit for the cables that were available. Today, 1000 kV cables are available, and future high voltage dc power supplies will be manufactured for this voltage. For most applications a relatively weak dc current of a few milliamps is sufficient and, therefore, the rated current was limited to 5 mA.

For the rated output power of 3 kW, the input frequency of 10 kcps can easily

be electronically generated, thereby avoiding noisy and expensive rotating machines as frequency converters.

Figure 1 shows the block diagram of the complete high voltage power supply. The cascade rectifier is composed of 4 stages of 150 kV each. The ac input voltage is supplied from the secondary winding of a high voltage transformer. In case of external short-circuits the full dc voltage may appear across the secondary of the transformer. Normally, a spark gap in parallel with the secondary winding is used in order to protect the high voltage transformer. However, a spark gap under oil or insulating gas would create other problems. Therefore, the secondary winding is designed in such a way as to provide a large parallel capacitance which automatically short-circuits the surge voltages.

The top terminal of the smoothing column is connected to the built-in measuring potentiometer through a protective resistor. This damping resistor limits the dc current in case of external short-circuits and simultaneously acts as a filter resistor in combination with the capacitive part of the measuring potentiometer. Depending on the capacitances used for the capacitors of the rectifier stack and the measuring resistor, the residual ripple voltage is between 0.01 percent and 0.05 percent of the dc output voltage.

The assembly of the rectifier stack and metering potentiometer is surrounded by several cylindrical layers of insulating material acting as electrostatic shielding against the wall of the steel tank. The high voltage terminal of the measuring potentiometer is connected to a contact inside a socket made of insulating material which fits into the plug at one end of the high voltage cable. A bleeder chain is provided on the surface of the socket in order to obtain a uniform voltage distribution from one end to the other which is at ground potential. The small slit between the outer surface of the plug and the inner surface of the socket has to be filled with a special type of oil. This can be done in less than half an hour, while the disassembling of the plug from the socket takes only a few minutes. Figure 2 is a photograph of the high voltage dc power supply, showing the rectifier steel tank and the racks for the input voltage supply and stabilization.

It can be seen from this photograph that the surface of the steel tank is provided with cooling pipes for forced dissipation of the internal power losses. No water or fan cooling is necessary even under permanent operation at full load and maximum ambient summer temperatures.

Figure 1 also explains the block diagram of the electronic voltage supply and stabilization. The operating frequency of 10 kcps is generated by an rc oscillator. The oscillator voltage is amplified in a driver chain and applied to the primary winding of the high voltage transformer directly connected to the anodes of the power amplifier tubes and with its center tap to the anode voltage supply. The power amplifier of the driver chain and the rectifier for the plate voltage supply are rack mounted. The so-called stabilization rack contains the reference voltage source, the dc and ac amplifiers, the modulator of the stabilizing circuit as well as the control unit.

The reference voltage source is connected to a pair of helipot for coarse and fine control of the dc output voltage. The preset reference voltage is compared with the secondary voltage of the measuring potentiometer. Any deviations, i.e. error signals, are amplified by ac and dc amplifiers and finally applied to the grids of the power amplifier tubes.

The control unit is included in the stabilization-rack. The number of control switches and pilot lights has been minimized in the control and supervision of the complete installation. The power supply is provided with protective devices against over-voltages and over-currents. An "out of stability" indicator is also included which is very useful for the automatic operation of beam separators.

Under full load the stability of the dc voltage is 0.05 percent of the preset output voltage in the range between 100 kV and 600 kV. The long-term stability (drift) is better than 0.5 percent per hour.

A particular feature of this type of dc power supply is that it can be frequently and directly short-circuited without any harm to the cascade rectifier or the electronic tubes of the driver chain. Repetitive short-circuit tests at 600 kV have proven that the power supply will exceed the life-time of the high voltage cable which can be replaced in case of emergency within less than half an hour.

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Fig. 1. Block diagram of a 600 kV dc power supply.

Fig. 2. 600 kV power supply with racks for the input voltage supply and stabilization.

APPENDIX C

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600 kV RECTIFIER

(Manufactured by Allis-Chalmers Manufacturing Company
Milwaukee, Wisconsin)

This power supply is a silicon diode rectifier rated 600 kV; 1 ampere output continuous, with alternate outputs as listed below available by simple reconnections:

1. 150 kV - 2 amperes - 1% maximum ripple
2. 300 kV - 2 amperes - 1% maximum ripple
3. 450 kV - 1 ampere - 1% maximum ripple
4. 600 kV - 1 ampere - 1% maximum ripple.

By the addition of approximately 50% more equipment, an output of 900 kV at 0.5 ampere could be obtained.

By means of a step regulator in the 13.8 kV line, the voltage can be reduced approximately 25 to 40%, depending upon load below any of the above outputs.

The power supply can withstand complete or partial short circuits in the load without damage.

As a line disconnect and protection device, a circuit breaker rated for the capacity of this unit at 13,800 volts has been provided.

Feeding the No. 1 Transformer on this cascaded unit, a near zero to full voltage regulator is being used for no-load starting; with a built-in plus 0 minus 40% manual control for running, and plus or minus 5% control for automatic regulation. This regulator is rated at 1000 through kVA, 13,800 volts, 3 phase, 60 cycles.

Both the starting regulator and the running regulator are incorporated in the same tank.

To obtain the necessary driving voltage for the 600 kV rating of the rectifiers, four transformers have been utilized. To modify the equipment for 900 kV, six transformers instead of four could be employed.

The existing four transformers are mounted on insulators for protection against grounding.

The total weight is 79,500 pounds per transformer, including approximately 34,000 pounds of oil.

In cascading the transformers for the high voltage necessary on this unit, the primaries of the four transformers are connected in delta, and the secondaries are connected in wye. The secondaries of Units 1, 2, and 3 are tapped at the 5,000 volt level to feed the primaries of Units 2, 3, and 4. With this connection, alternate transformers are shifted 30° to obtain effectively 12 phase operation when 2, 4, or 6 transformers are used in cascade.

Each 150 kV rectifier section consists of a three phase bridge made up physically of six phenolic tubes, one for each arm of the bridge, within which are mounted a series string of silicon diodes with shunting capacitors for voltage grading of recovery voltage. The diode assemblies are immersed in oil which is circulated and cooled as described herein after to carry away the losses. The phenolic tube diode assemblies are elevated above ground on stand-off insulators to a height convenient for connection to the transformers, each transformer and rectifier section being successively higher as the voltage to ground increases.

The filter consists of a T-connection of two 13,500 ohm resistor assemblies with the column of capacitors connected from the junction of the two resistors to ground. This arrangement serves to limit peak capacitor discharge current to the load, and peak rectifier current.

when the load becomes short circuited. Each resistor assembly is designed to withstand momentarily full rectifier output voltage (600 kV). In the event future additional equipment for 900 kV operation is used, the present resistor assembly will be adequate. The resistor assemblies consist of series strings of wire wound resistors, mounted on phenolic board and housed in tubes like those for the rectifier. Cooling and insulation is from the same recirculating oil system as the rectifier. These tubes are mounted horizontally.

The capacitor column consists of 72 capacitors connected in 12 series groups of six in parallel. The 12 groups are stacked vertically, and the series connections are externally accessible. Each capacitor section is shunted by a group of parallel discharge resistors to equalize dc voltage and to completely discharge the capacitors in a few seconds after the rectifier is shut down.

Similar capacitors, four in series, are connected between adjacent transformer tanks to stabilize tank potentials during voltage surges. These capacitors are also shunted by discharge resistors.

A bleeder resistor assembly is designed to draw 0.167 amperes at 600 kV with terminals at 0, 150, 300, 450, and 600 kV. In the event future additions increase the rectifier rating to 900 kV, the present bleeder resistor will be capable of carrying 0.25 amperes with terminals at 0, 225, 450, 675, and 900 kV. The bleeder is housed in a separate column of phenolic tubes like those used for the rectifier. Each tube contains a string of wire wound resistors mounted on phenolic and cooled and insulated by the common recirculating oil.

The bleeder resistance is not changed when reconnection for lower voltage is made.

A voltage divider is used for the indicating voltmeter and to provide sensing for the voltage regulator. It consists of a string of series-parallel connected carbon deposited resistors having a low temperature coefficient of resistance. These resistors are mounted on phenolic, immersed in phenolic tubes like the rectifiers, and cooled and insulated by the common circulating oil. The temperature of the oil entering the voltage divider column is held essentially constant by a temperature regulator in the cooling system.

Resistors forming the low end of the voltage divider are wire wound of very low temperature coefficient to minimize error due to ambient temperature variations. These resistors are mounted on the control panel. A surge arrester is connected across the low section. This voltage divider is designed to work equally well at either 600 kV or 900 kV.

A 1000 kV scale voltmeter in series with a precision multiturn potentiometer is connected across the low end of the voltage divider. Calibration of the voltmeter is as follows:

1. The resistance of each section of the voltage divider is accurately measured at room temperature and corrected to operating temperature by calculation.
2. From the total resistance of the divider as so determined, the setting for the precision potentiometer can be calculated, and this setting is obtained by bridge measurements of the potentiometer circuit resistance.

The dc load current is measured by means of a shunt connected in the ground circuit of the load and a dc millivoltmeter calibrated in amperes.

The millivoltmeter, voltmeter, precision potentiometer, and divider low end resistor are mounted on a control panel.

This panel is an enclosed panel for wall mounting, and contains the following, mounted and wired:

- dc ammeter
- dc voltmeter
- voltmeter calibrating potentiometer
- voltage divider low end resistor
- circuit breaker control switch
- regulator start-stop switch
- regulator manual raise-lower switch
- automatic voltage regulator
- automatic regulator transfer switch -- "auto-manual"
- automatic regulator level adjustment
- 2 - regulator position indicators.

A separate single phase cascade column of transformers has been provided. This column of transformers is designed to furnish isolated power of approximately 220 volt, 60 cycle, 10 kVA source at the 150 kV, 300 kV, and 450 kV levels, and a 50 kVA, approximately 220 volt, 60 cycle source at the 600 kV level. In case of future extension to 900 kV, these voltage levels would change to 225, 450, and 675 kV, respectively. These transformers are protected by sphere gaps against excessive voltage stress across one stage in the event of partial short circuits in the load.

The cooling system consists of an oil to water heat exchanger of sufficient capacity, an oil recirculating pump, and a temperature regulator.

The temperature regulator senses the temperature of the oil entering the heat exchanger, and controls the cooling water flow to hold this temperature constant.

A protection system for the step regulator, the transformers, and the rectifier diode strings has been provided which operates in the case of overload if any failure of the system should occur.

Induction overcurrent relays trip the OCB upon failure of the step regulator or a rectifier transformer. They also serve as back-up protection for a diode string failure or dc short circuit in case the other protective devices fail to operate.

In case of a diode string failure, the OCB is tripped by an instantaneous dc relay which compares the rectifier output current as measured by a shunt with the rectified secondary current of CT's in this 13.8 kV line.

Load short circuits trip the OCB through a contact making millivoltmeter, connected to the load measuring shunt. The D-3 relay has a small amount of time delay, which will prevent it from operating on a single load short circuit of short duration.

APPENDIX D

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SERIES RESONANT AC DIELECTRIC TEST EQUIPMENT

MODEL SR 7350/700-525/1050

Model SR 7350/700-525/1050 is a conservatively designed series resonant test system providing maximum flexibility when used separately as two 350 kV, 525 kVA independent systems, or when cascaded as a single 700 kV, 1050 kVA test system. The equipment consists of the following components:

- 2 - Delux shadow box slopefront consoles with writing desk, one instrumented for 350 kV, and one instrumented for 700 kV
- 2 - Voltage regulator sections
- 2 - Variable inductors (patented)
- 2 - High voltage transformers rated 350 kV, 525 kVA
- 2 - Exciter supplies, one 40 kVA, one 80 kVA
- 2 - 350 kV insulated platform for cascade operation
- 1 - Reactor control adapter

SPECIFICATIONS

Input	440/480 VAC, 60 Hz, single phase, 80 kVA and 40 kVA at unity power factor	
Output	Individually operated: 0-350 kV at 1.5 A each unit Cascade operation: 0-700 kV at 1.5 A	
Distortion	One half percent maximum	
Duty cycle	Continuous at 525 kVA individual operation and 1050 kVA in cascade; one hour at 150% of rated current	
System Q	20	
Capacitive Tuning Range	350 kV (Individual) 0.0006-0.0114 mF	700 kV (Cascade) 0.0003-0.0057 mF
Metering	Digital-all front panel output meters. For 0-350 kV individual operation using bushing capacitance $\pm 1\%$ of full scale accuracy. For 0-700 kV cascade operation using separate capacitors directly at output for 1% accuracy.	

SPECIFICATIONS (continued)

Size and Weight

350 kV High Voltage Transformers	84"D x 104"H + 7 ft bushing 34,316 lbs with oil, each unit
525 kVA Reactors	72"D x 96"H - 12,800 lbs with oil
40 and 80 kVA Exciter	36"D x 58" H - 2500 lbs with oil
Control Console	24"L x 36"W x 49"H - writing desk 18"; 150 lbs
40 and 80 kVA Regulator	37"L x 26"W x 68"H - 750 lbs
Insulating Platform	(350 kV) - 96"H

GENERAL FEATURES - (each system)

System input magnetic circuit breaker

Input control power breaker

Variable speed rate of voltage rise with automatic rundown when voltage is off

Overload trip circuit - arc detector

Automatic output voltage control

Zero start interlock

External interlock provision

External 115 VAC 250 VA test cage lighting circuitry

High voltage on-off switch

Raise/lower switch, tuning-high voltage

Automatic tuning

Front panel elapsed time meter

Front panel dwell timer and alarm, 0-60 minutes

High voltage transformer and reactor temperature indicators

High voltage transformer and reactor oil-level indicators

GENERAL FEATURES (continued)

Ball gap protection of exciter output bushing

Ball gap protection of transformer primary

Reactor position indicator

High voltage transformer and reactor oil sampling valves

Function indicator lights

 Main power

 Control power

 High voltage on

 Interlock open

 Off zero

 Overload

 Max. reactor limit.

 Min. reactor limit

THEORY OF OPERATION

The cable under test forms the capacitive part of a series LC tank. The output transformer/reactor forms the inductive portion. The reactor is variable over a band designed to test a wide range of cable.

An excitation voltage at 60 Hz is injected into the system by the series connected exciter supply. The inductance of the system is then varied by motor-positioning the reactor core until the system goes into resonance. A "Q" or multiplication factor of 20 is normal for this type of system, however, "Q" of 80-100 is possible in exceptionally well-designed sets; therefore the output voltmeter will peak rather abruptly and the tuning meter will zero. The excitation voltage may then be raised until the output is at test level.

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APPENDIX E

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INTRA-LABORATORY CORRESPONDENCE

OAK RIDGE NATIONAL LABORATORY

February 1, 1973

TO: H. M. Long

FROM: C. C. Koch

SUBJECT: Trip Report - DAT Superconducting Transmission Line Project,
Brookhaven National Laboratory, January 17-19, 1973

On the evening of January 17, C. C. Koch, D. M. Kroeger, and R. A. Vandermeer arrived at Brookhaven National Laboratory. The morning of January 18 we were escorted to the Materials Science Division and the office of Dr. D. Gurinsky. We spent most of the day discussing materials problems associated with the superconducting ac transmission project. Dr. Gurinsky gave us an overall view of the materials work at BNL and then suggested an area of research we might explore to complement their program. This was to study techniques for improving the ductility of Nb_3Sn tapes. At first examination, this would appear to be a horrendous problem, but further thought indicates a number of variables which may influence the overall ductility of the composite. This problem should be a challenging development project. Individual members of Gurinsky's group then discussed their special areas of materials research in more detail. Dr. M. Suenaga outlined his efforts to increase J_c and therefore hopefully lower ac losses in Nb_3Sn . Mr. C. Klamut discussed the design of a cryostat for mechanical property tests on commercial tape, as well as

Suenaga's experimental samples, the tests to be performed at 4.2 K with current through the sample. Dr. M. Garber then discussed his technique for measurements of ac losses. There was some discussion on the various aspects of theory and technique. His technique appears to be general in nature (i.e., measures "total" loss not merely the hysteretic losses, etc.). We had come to essentially the same conclusion with regard to choice of method from our study of the literature.

After lunch we had discussions with Dr. G. Morgan who has been doing many of the calculations of the design parameters for the total system. We talked particularly about the relative merits of Al or Cu as the matrix (substrate) material and tried to get numbers on strength and conductivity. However, he has not really worried about strength, leaving this to a structural substrate such as stainless steel. Garber then took us on a short tour of their test facilities where we had a brief look at the areas where the work on refrigeration and dielectrics is being carried on. We spent more time in Garber's own laboratory where we examined his ac loss measuring equipment in detail. He kindly provided us with a circuit diagram of the wattmeter designed by the electronics group at Brookhaven.

We ate dinner with M. Suenaga, and C. C. Tsuei of California Institute of Technology who was also visiting BNL, and continued to "talk shop" well into the evening.

Friday morning we talked briefly with M. Strongin about his interesting work on thin film superconductivity--lead on lead telluride--(exciton mechanism?). Eric Forsyth then talked with us about the general philosophy of the transmission line program. He supplied us with copies of their proposals, etc.

Friday afternoon we talked in more detail with M. Suenaga and examined his laboratories for materials preparation and characterization. He was explicit in his discussions of reaction temperatures, heat treating times, etc. We also discussed the available literature on Nb_3Sn and he pointed out a number of pertinent references.

In all, we believe the visit to BNL very stimulating and worthwhile. The BNL researchers were very gracious and supplied us with a good deal of information on both their materials work and the transmission line project in general. With the many challenging materials problems in this area we feel confident that the ORNL materials effort can complement such work at BNL to our mutual benefit. More explicitly, we plan to examine the mechanical properties of Nb_3Sn composites, study alternate techniques and the mechanisms for improving J_c (and lowering ac losses) in Nb_3Sn (for example use of rare earth additions to the Nb substrate) and to explore other likely materials such as V_3Si , Nb_3Al , or alloy superconductors. The construction of the ac loss measuring equipment will have the first priority.

cc: C. J. McHargue

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