**NASA-NBS STUDY**

# THE ROLE OF SUPERCONDUCTIVITY IN THE SPACE PROGRAM:

# AN ASSESSMENT OF PRESENT CAPABILITIES AND FUTURE POTENTIAL

**PREPARED FOR NASA**
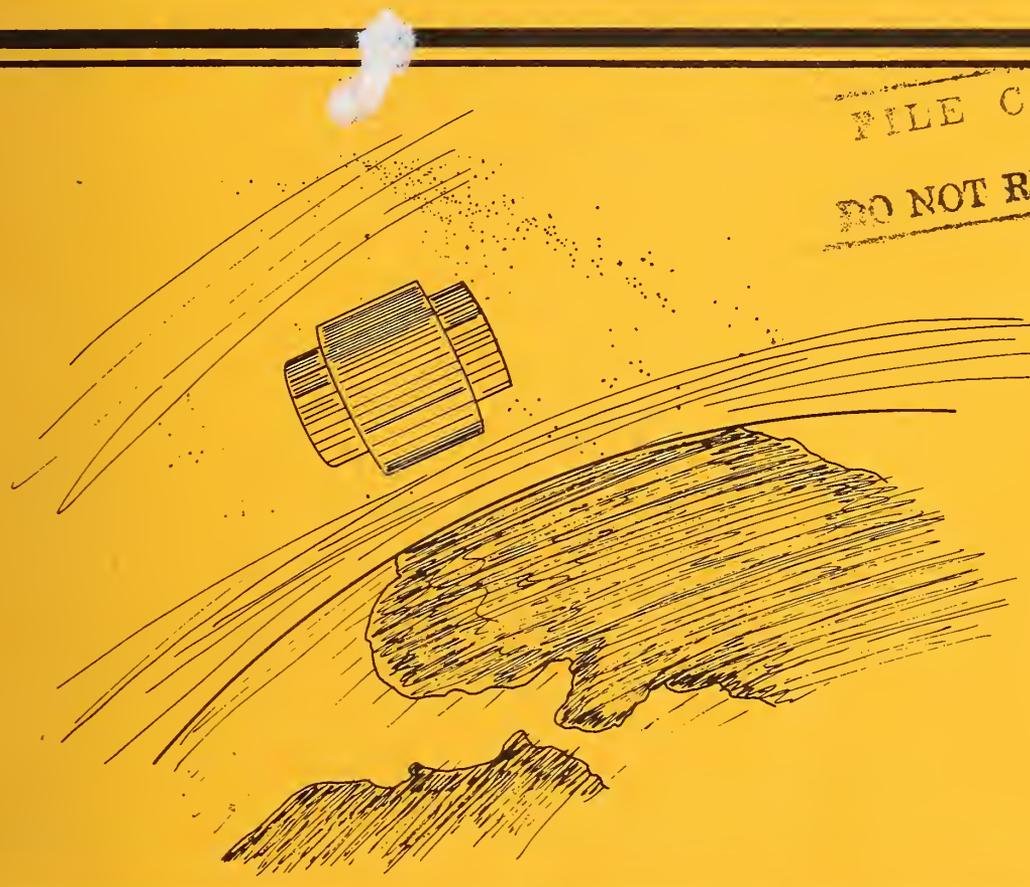
**BY**

**NATIONAL BUREAU OF STANDARDS
BOULDER, COLORADO**

NASA-NBS STUDY

# THE ROLE OF SUPERCONDUCTIVITY IN THE SPACE PROGRAM:

# AN ASSESSMENT OF PRESENT CAPABILITIES AND FUTURE POTENTIAL

Edited by

D.B. Sullivan

Contributions by

F.R. Fickett, C.A. Hamilton, R.E. Harris, R.L. Peterson, S.R. Stein and J.E. Zimmerman

ABSTRACT

This report describes the results of a study designed to assess the role
which superconductivity might play in the U.S. Space Program.  The study
was performed by members of the staff of the Boulder Laboratories of the
National Bureau of Standards.  Six technical subject areas were considered;
high field magnets, magnetometers, digital electronics, high-frequency
detectors, instruments related to gravitational studies and ultra high-Q
cavities.  The study identifies a number of applications of superconduc-
tivity which are of potential interest to NASA.  Wherever possible, the
devices are related to specific types of space missions.

Key words:  Computers; digital electronics; gravitational studies; high-Q
cavities; infrared detectors; magnetometers; magnets; microwave detectors;
space; superconductivity.

IMPORTANT NOTICE

THE ROLE OF SUPERCONDUCTIVITY IN THE SPACE PROGRAM:
AN ASSESSMENT OF PRESENT CAPABILITIES
AND FUTURE POTENTIAL

EXECUTIVE SUMMARY

This report describes the results of a study designed to assess the role which super-
conductivity might play in the U.S. Space Program. The study was performed by members of the
staff of the Boulder Laboratories of the National Bureau of Standards. Six technical subject
areas were considered; high field magnets, magnetometers, digital electronics, high-frequency
detectors, instruments related to gravitational studies and ultra high-Q cavities. The study
identifies a number of applications of superconductivity which are of potential interest to
NASA. This summary presents some of the more prominent opportunities. The identification of
an opportunity should be divorced from a suggestion for priority; the setting of priorities
for the space program is not the function of the study group.

Superconductivity has long been singled out as a unique technology, perhaps because of
the dramatic instrument improvements which are made possible by it or maybe because of the
low temperature environment which is essential to the applications. Superconducting devices
can be lumped into two general categories; those which benefit from reduced electrical losses
and those exhibiting improved signal-to-noise performance. The first category includes items
such as magnets and electrical generators. Magnetometers and high-frequency detectors are
examples in the latter group. Digital electronics is a good example of an area which bene-
fits from both categories.

There are several superconducting devices which might be considered adequate for space
applications in their present state of development. Both SQUID magnetometers and high-field
research magnets have been developed commercially with excellent success. Some work would be
needed to qualify them for space flight, but that would seem to be a straightforward task.
Other superconducting devices would require varying degrees of development before being put
on space craft. Many items in this class offer performance improvements which simply cannot
be overlooked. One example is the superconducting oscillator which is important for certain
classes of space experiments and for space navigation and ranging. The stabilization of
oscillators with high-Q superconducting cavities is established as the state-of-the-art, and
further advances are expected.

We must interject a few words of caution, lest we get trapped in the credibility prob-
lems which were common to the early years of applied superconductivity. Refrigeration of
superconducting instruments for extended space missions is a non-trivial problem. This
subject is addressed at the end of this summary. Also, not all superconducting instruments
will win their competitions with conventional devices. Superconducting high-frequency detec-
tors look promising, but their conventional counterparts are also undergoing further improve-
ments. It is not yet clear which devices will win out. Most likely, superconductivity will
contribute, but to what degree is yet uncertain.

In each of the following classes, specific applications will be suggested along with the identification of a superconducting device (or devices) which might be useful for that application. The bold type indicates a specific suggestion which the study group has identified as possibly important for the space program.

## High Field Magnets

Superconductivity offers the only economical means, from an energy standpoint, to the production of high magnetic fields. Many space applications of such magnets can be suggested (see Chapter II), but only two are mentioned here. The first application is to cosmic ray analysis. Elementary particle physicists may be near their dollar limit for high energy accelerators. Beyond colliding beams, it will probably be difficult to justify significantly larger machines. Thus we might expect increasing interest from the physics community in the long-term flight of particle analysis systems, since cosmic radiation consists of a variety of highly energetic particles. The analyzers will require intense magnetic fields because of the high energies, and superconducting magnets would appear to be the only reasonable choice. The need for long-term exposures (to collect sufficient information) provides further impetus to the selection of superconducting systems since power requirements for conventional magnets would then be prohibitive.

Magnetic energy storage has been considered for specialized applications on earth but has not received serious consideration for space flights. Present information indicates that extremely good weight-to-energy ratios are achievable, but further study of the subject is suggested. A key consideration for superconducting magnets in space is the weight of the structural materials, which account for a large fraction of total system weight. Weight is not presently an important concern of magnet designers. But modern composite technology, properly applied to magnet structural components, could make impressive reductions in the specific weight of large magnets.

*It is suggested that materials programs, directed toward magnet weight reduction, be stimulated by NASA in order to provide a base for optimization of the specific weight of superconducting magnet systems.*

The reduction of specific weights could provide longer term benefits to the space program. Many of the more ambitious programs for space colonization and travel involve superconducting magnets (e.g., fusion reactors or MHD generators for energy production, the mass-driver system, plasma or MHD propulsion engines, etc.).

## Low-Frequency Superconducting Sensors

The primary device in this class is the SQUID (Superconducting QUantum Interference Device) magnetometer. This device has no real competition from conventional devices, either in sensitivity or bandwidth. The SQUID has been highly developed by commercial interests, in both magnetometer and gradiometer configurations. Despite this state of development, there have been no serious proposals for its use in the study of magnetic fields in space. The

preponderance of opinion seems to be that conventional magnetometers are adequate for measurements in space, so that the use of superconducting instruments is not justified. However, it might be pointed out that ten years ago, exactly the same view prevailed with respect to terrestrial geomagnetic measurements, yet today SQUID magnetometers are widely used for precisely this purpose. The parallel is interesting, but substantive considerations should prevail.

> *The measurements of planetary and interplanetary magnetic fields should be evaluated to determine whether the increased sensitivity and bandwidth of the SQUID magnetometer provides information unobtainable by any other technique.*

The bandwidth and sensitivity could offer a means for measuring short range (and short term) gradients of the interplanetary fields driven by the solar wind. Chapter III describes such applications in more detail.

## Digital Applications of Superconductivity

Digital superconducting electronics is a newly emerging technology of significant promise which must, however, pass the test of real-world applications. The motivation for the development of this technology is rooted in some very general and fundamental considerations. The Josephson switch is extremely fast and can potentially achieve switching speeds of 1 ps, but its most attractive attribute is its small dissipation. The level of dissipation is sufficiently small to allow extremely close packaging of active elements and thus allow dramatic reduction of intracircuit communication delays. Furthermore, the use of superconducting striplines for this communication provides the opportunity for unparalleled freedom from dispersion and attenuation of signals.

Interest in the technology is expanding, but the prime driving force behind this technology is a major commercial program to develop a superconducting computer. With some knowledge of the characteristics of the simple logic elements, it is relatively easy to show that order-of-magnitude (and greater) advances can be made in both speed and capacity. The increased speed follows from a reduction in size. Overall power dissipation drops many orders of magnitude below that for conventional computers. All of these changes (increased speed and capacity, decreased size and dissipation) are in a direction favorable to space applications. The development of such a computer may be 10 to 20 years in the future, but it is not too early to consider the opportunities, perhaps revolutionary ones, which may appear.

Given the possibility of taking really powerful computers (perhaps 10 to 100 times the speed and capacity of today's best machines) into space, what might one accomplish? Numerous suggestions arise. The processing and compression of complex raw data might provide a means of conserving the limited power available for information transmission. Weather modeling and forecasting from data-gathering satellites might be feasible. Intelligent (computer) spacecraft might reduce the need for some difficult manned space missions. The Mars landing (Viking) was completely computer-controlled because control from earth would have involved prohibitive delays (signal transit times) between sensing of required corrections and actuation of the desired maneuvers. For more distant planets, computer control of landings, as

well as of rover vehicles, will be an absolute necessity.  Besides the computer applications there are a whole realm of improved instrumentation possibilities; analog-to-digital converters, digital filters, fast Fourier analyzers, etc.

The opportunity to dramatically improve computer and instrument speed and capacity should provide new possibilities for space missions.

*It is suggested that NASA generate a comprehensive in-house appraisal of the new possibilities for digital electronics provided by superconductivity.  The appraisal should be made available to anyone involved in mission plans and development.*

Section IV.4.0. describes a source of information which might well provide a basis for the appraisal suggested above.  A careful appraisal of the technology would probably identify specific areas of NASA interest.  Stimulation of development, especially in the instrumentation field, would certainly speed progress toward new devices.

### Microwave and Infrared Detectors

*It is probably fair to state that, in general, superconducting detectors demonstrate no overwhelming advantages over conventional devices.*  In some instances, the performance of the superconducting detector represents the state-of-the-art, but never by a wide margin. For superconducting detectors, development effort has been only modest, at best.  This situation is likely to prevail for the near future.

The space applications of these detectors would probably center on radio and infrared astronomy and on communications, areas where the best possible noise performance is desired. Low noise performance almost certainly requires liquid helium temperatures for any type of detector and indeed, the planned IRAS program supports this contention.  Thus, the environment for superconductivity will usually exist for any low noise missions, and superconducting detectors will be able to compete on an almost equal footing with their non-superconducting counterparts.

The development of several superconducting detectors should be followed.  The Josephson mixer for millimeter and sub-millimeter wavelengths already performs well.  The SUPARAMP (SUperconducting PARametric AMPlifier) could perhaps be operated with success in the millimeter range.  The super-Schottky diode (metal layer of the diode is superconducting) with its attractive noise performance might be extended to frequencies well above X-band.  These devices are receiving modest attention at a few laboratories in the U.S. and Europe.  At present funding levels, the questions on ultimate performance levels might well be answered during the next five- to ten-year period.

In summary then, superconducting detectors, while offering significant advantages, do not appear to be a panacea for the problems of all high-frequency instruments.  However, the full story is not yet told.  A lot depends on how closely the superconducting and non-superconducting devices approach theoretical performance levels.  Presently, there appears to be no really strong incentive for large increases in developmental funding levels.  The major question of ultimate performance levels should be settled during the next decade at present

spending levels. However, should some of the superconducting devices (particularly the junction devices) gain clear advantage, then it would seem essential to stimulate work directed toward thin-film realizations of the devices, in order to satisfy the stability requirements demanded by space flight.

## Instruments for Gravitational Studies

*Superconducting instruments will probably play an important role in many tests of gravitational theories.* In general, these experiments require performance which is not yet available, and superconductivity is introduced as a technology which might provide the needed advances. It is also interesting that some of the devices needed for the tests are also useful for navigation (gyroscopes, accelerometers, stable oscillators). Thus an investment in fundamental research could ultimately pay dividends in the form of advanced navigational instruments.

The gyroscope-precession experiment is an extremely sophisticated and demanding use of superconductivity. Development is in an advanced stage, and the system may fly within the next decade. The gyroscope stability will eclipse that of all others by several orders of magnitude. A successful flight may lead to interest in navigational applications.

Two other instruments of special note are the superconducting accelerometer and superconducting gravimeter. The accelerometer is being developed as a sensor for gravitational-wave antennas. Projected sensitivity is impressive, and the device might also be considered for inertial navigation. The gravimeter is an operational device which is already contributing to terrestrial research. The attractive feature of this instrument is its very low drift level, which makes it the only gravimeter capable of low frequency measurements. It would be especially interesting to emplace such a gravimeter on the moon or another planet.

The suggestions for experiments on gravitational theories are many, and it is difficult to select any one for special encouragement. It might be best to let the individual researchers develop their proposals to a higher level before any major commitments are made. Obviously these researchers will need minor funding for this work.

## High-Q Cavities

*There are many applications for superconducting high-Q cavities, but for space applications the most prominent is the use of such cavities as stabilizing elements in clocks and oscillators.* The best Q for a superconducting cavity achieved to date is $5 \times 10^{11}$, and the best stability is $3 \times 10^{-16}$. Since it is generally possible to find the center of a resonance line to one part per million, it is reasonable to expect that a stability of $2 \times 10^{-18}$ will be achieved using present technology. This might be accomplished within ten years. On the other hand, large increases in Q values will require major advances in superconducting technology. The likelihood of it happening within the next ten years cannot be reasonably assessed.

One intriguing potential space application of these oscillators is their use for ranging. The possibility that gravitational radiation might be detected by more sensitive ranging to a drag-free satellite should warrant careful consideration. Ranging is important

in many other contexts.  For example, superconducting oscillators must surely be considered
if large improvements are needed by NASA's Deep Space Net or the Global Positioning System.
Present performance of the superconducting oscillator is impressive, but the potential for
improvement puts this system into a class of its own.

Current research efforts are being directed toward application of these oscillators in
terrestrial experiments.  Little effort is directed toward the improvement of Q values and of
clock performance in general.  Stimulation of work toward improved performance will have to
be driven by applications which require such improvement.  It would seem that such improve-
ment would be of significant benefit to NASA.

*It is suggested that NASA consider stimulation of further improvements in supercon-
ducting cavities and oscillators for the purpose of improving the measurement of
distance and distance changes in space.*

## Refrigeration

Refrigeration requirements are without doubt the greatest impediments to broader use of
superconducting devices.  For large-scale terrestrial applications, the cost of refrigeration
is a secondary consideration, although it raises the level of sophistication and causes
concern about reliability.  For small-scale commercial devices, refrigeration requirements
are a primary consideration.  To date, most such devices have been cooled with liquid helium
in evaporative cryostats.

Space applications are even more restrictive than terrestrial ones since the reliability
problems which accompany conventional refrigerators cannot be solved by a simple call to the
repair man.  For this reason the first cryogenic satellites will use evaporative helium
cooling with cryostats designed for hold times of up to one year.

The development of reliable refrigerators would greatly alter the logistics of super-
conductivity in space and could tip the balance in favor of some programs.

*Further work on refrigerators for space flight is highly recommended.  Such coolers
could be applied not only to superconducting instruments, but also to other sensitive
sensors (e.g., infrared sensors).*

PREFACE

The U.S. Space Program, under the guidance of NASA, has, from its very inception, been involved with sophisticated systems which are at the very forefront of science and technology. Indeed, NASA has often been forced to go beyond the available technology in order to meet the challenge of its mission assignments.

Thus, it is perhaps essential that NASA keep abreast with advances in superconductivity, a field which offers real promise for surpassing present state-of-the-art performance for many areas, including high-field magnets, magnetometers, digital circuits, high-frequency sensors, stable time and frequency references, gravimeters and accelerometers.

Suggestions for applications of superconductivity in space have been with us for years, and indeed NASA is actively working on several programs. However, major cryogenic satellites are only now nearing reality, and the benefits of this new state of matter to space exploration are all in front of us. It thus seems timely to look at this technology in a comprehensive way to determine what potential applications might warrant serious consideration for space missions.

One might argue that such a study is backwards. Shouldn't one really start with the desired goal in space and then decide what means will be used to reach it? There is merit to the question, but the answer is simply this: One needs to know what tools are available, and that knowledge may not be easy to obtain with emerging technologies. Are new mission possibilities developing along with a technology? Can the performance of a space task be improved with a new approach? Can significant cost savings result from a new technology? When does a concept change from remote possibility to real opportunity? For example, does a ten-year-old assessment of high-field magnets in space have meaning in light of today's state of the technology? These types of questions suggest that it is prudent to look through one's bag of tools periodically to find out whether new tools are available. Although one might do this in a number of ways, this study, done outside NASA, is one reasonable approach. Only time will permit a measurement of its success.

The NBS study group consisted of the editor and the six NBS co-authors of this report. The study was divided into six technical sections, each relating to a specific type of instrument or instruments and developed by a single member of the group. The study group sought to present the state-of-the-art in each of the six areas and where possible to identify specific space objectives for the technology. Risky as it is, the group has also tried to project performance into the future. Such projections are "educated guesses" and should be treated as such. However, it would be absurd to assume that this study covers the subject area in a fully comprehensive manner. The emphasis of the report reflects to some degree our individual biases and speculations about future developments. It is hoped, however, that the effort provides a reasonable perspective and a starting point for in-depth studies of subject areas which might prove of interest to the space program.

The study was sponsored by NASA's Office of Aeronautics and Space Technology and guided from NASA Headquarters by Mr. Stanley Sadin and from Ames Research Center by Mr. John Vorreiter. The NBS study group would like to thank Mr. Vorreiter and Mr. Sadin for their guidance in this effort. We also thank Mrs. Norma Lear for turning our scratchings into a

presentable form and Mr. Nick Sanchez for his work on the graphs and illustrations. Needless to say, we have received input from many specialists in the scientific community both within and outside NASA and NBS. The list of such people is too long to include here, but we wish to express our deepest gratitude for their time and thought, which have added greatly to this report.

## TABLE OF CONTENTS

TABLE OF CONTENTS, cont.

# CHAPTER I

# INTRODUCTION

The first fifty years following the discovery of superconductivity in 1911 were marked by intense academic endeavors to understand this new state of matter. Little of practical interest evolved until the late fifties and early sixties when, in very rapid succession, high field superconductors were discovered, a microscopic theory was developed and the Josephson effect was predicted and observed. This flurry of activity marked the birth of applied superconductivity, a new technology which is just now beginning to provide major new scientific tools.

Applications of superconductivity have spanned a wide range of technical areas; geophysics, high-energy physics, materials science and medicine, to name a few. *In each application it is the capability for vastly improved performance or the ability to perform tasks which were not previously feasible, which is the incentive for the use of superconductivity.* Many of the technical problems which have found solutions in superconductivity are problems that also exist in the space environment outside this planet. In addition, space exploration poses new sets of problems, some of which might be solved through utilization of superconducting devices. This report reviews the applications of superconductivity which might be useful in the varied and challenging tasks considered for space missions.

In the first portion of this introductory chapter we provide an outline of the study to help the reader locate material which may be of particular interest. We follow with some general comments on superconductivity which might be useful to the uninitiated reader. Finally, we offer a note on refrigeration, an essential consideration for any superconductive device.

## I.1.0. FIELDS OF APPLICATION

The study has been organized so as to best use the talents of the members of the study group. Thus, division is made between classes of devices rather than fields of application. This is not the most effective way to present information to a reader who is interested in, for instance, properties of interplanetary space. To help remedy this problem we present here a "roadmap" for those oriented toward a particular field, rather than a device. The four major categories are subdivided, and references are provided to the six technical chapters which follow.

### CROSS-REFERENCE GUIDE -- APPLICATION VS DEVICE

Physical Properties of Space and the Planets

    Radio and Infrared Astronomy - Chapter V (All) - Chapter VII (Sec. VII.3.0.)
    Elastic and Vibrational Properties of Planets - Chapter VI (Sec. VI.4.0)
    Planetary and Interplanetary Magnetic Fields - Chapter III (Sec. III.2.2)
    Background Temperature of the Universe - Chapter V (All)

Fundamental Questions in Physics

Information

Logistics of Space Travel and Living

## I.2.0.   BACKGROUND

### I.2.1.   Superconductivity

For some purposes, it is sufficient to say that a superconductor is a material which exhibits no electrical resistance below given limits of temperature, magnetic field and current density. While this might suffice for a discussion of magnet applications, for example, it is completely inadequate for the other applications considered in this study. Although this is not the place for a treatise on superconductivity, a brief discussion of some fundamental considerations will draw together the diverse phenomena considered in this report. An understanding of these fundamentals is not essential for a reading of the study, but some may prefer to see the thread of commonality in the applications.

Superconductivity is a unique state of matter characterized by an attractive inter-action between pairs of electrons. This attractive force is weak and of negligible importance at room temperature, but it becomes very important at low temperatures where the energy associated with the attraction is comparable to or greater than the energy of thermal vibra-tions. In this case, the electrons are able to re-order themselves into a state (the superconducting state) in which they are bound together, a state lower in energy than the normal state. To excite the system from this state requires the input of a minimum energy $\Delta$, which is called the energy gap. The superconductor can be described by a mathematical func-tion which is wave-like in character. This wave-like model is important for an understanding of the Josephson effect and quantum interference.

Perfect conductivity results from this description in the following way. If a current is passed through a superconductor, then the electrons all attain some added velocity along the direction of current flow. In a normal conductor, the lattice vibrations and imperfec-tions would result in scattering of some of the electrons and a consequent loss of energy.

2

The normal state thus requires an electric field to sustain a current, and energy (voltage times current) is continuously dissipated. In the superconducting state, the scattering of a single electron is disruptive of the entire bound state and is therefore not favorable (from the standpoint of energy conservation). The wave function is said to be coherent (rigid), since any external stimulus must affect the entire body of electrons. Only when the current exceeds some maximum value, the critical current, will scattering be possible. This occurs when the energy in the driving current overcomes the scattering restriction mentioned above. At this point, the superconductor reverts to the normal conducting state. It is important to note that *no electric field is needed to support the flow of a supercurrent*.

The quantization of magnetic flux in a superconductor also follows from the introduction of this rigid wave function. For a superconducting ring (a donut) the wave function which describes the state of the system must be continuous and close on itself in going around the ring. This means that if there are spatial oscillations in the function, only integral numbers of oscillations are permitted. These different but distinct wave functions are associated with discrete currents and thus with discrete flux states of the ring. This is analogous to the requirement which gives rise to discrete energy levels in the Bohr atom. Each atomic orbit is associated with a wave function which has an integral number of spatial oscillations about the orbit. As with the Bohr atom, the description of flux quantization requires the consideration of wave-like behavior.

The device which depends on flux quantization is the SQUID (Superconducting QUantum Interference Device). The SQUID is a superconducting ring interrupted by a weak connection, a Josephson junction. This weak connection provides a means for changing the flux state of the ring and for observing such changes in state. The SQUID is, in essence, a very sensitive magnetometer.

A Josephson junction results from any very weak connection between two pieces of super-conductor. It may take the form of a tunneling junction, a point contact, or a very narrow constriction in a superconducting film. The properties of this junction are derived from an interaction between the wave functions in the two pieces of superconductor which are linked. Current flow through the junction results whenever there is a difference in phase between the wave functions on either side of the junction. A voltage impressed across the junction causes this phase difference to shift in time, resulting in an oscillatory current flow as the wave functions shift into and out of phase. The high frequency of these oscillations make the Josephson junction useful for certain microwave and infrared applications.

The Josephson junction is also valuable as a fast logic element (a controllable switch). The switch is controlled by a weak magnetic field. This field is generated by a current in a simple control line which crosses the junction. Once induced to switch, the junction response is controlled by the intrinsic frequency limitations of the Josephson effect. This limit is set by the value of the energy gap in the superconductors which make up the junction. This frequency limit is approximately $10^{12}$ Hz, which corresponds to switching times of the order of one picosecond ($10^{-12}$ s).

The diverse phenomena of the superconductive state are seen to result from a rather small set of underlying principles. This type of approach is perhaps more satisfying than

3

the introduction of a separate explanation for each successive phenomenon which is discussed. The phenomena associated with the superconductivity are unique and extremely useful, as will be seen in the text.

### I.2.2. Benefits of a Low-Temperature Environment

Unless major materials breakthroughs are achieved, superconductivity will remain a low temperature phenomenon. However, one should recognize that the low-temperature environment needed for superconductivity is useful for other reasons as well. For example, the low thermal noise associated with low temperatures is crucial for infrared astronomy. In fact the IRAS (Infrared Astronomy Satellite) program has been forced to provide low temperatures (2 kelvin) in order to achieve low thermal noise.

Besides low thermal noise and superconductivity, other benefits of low temperatures can be cited. At liquid-helium temperature the expansion coefficient of solids becomes negligible, and this results in extremely good dimensional stability. Thermoelectric phenomena are reduced in significance, yielding benefits such as elimination of unwanted thermal emf's. Ionic conduction ceases to cause leakage problems. Failure mechanisms for electronic devices such as diffusion and electromigration become relatively unimportant. Where heat must be dissipated, superfluid helium provides almost complete freedom from convective limitations because of its enormous "effective" thermal conductivity.

Some of these advantages are important to the applications discussed in the study. The stability of the superconducting cavity stabilized oscillator (Chapter VI) is at least partly due to the dimensional stability of the cavity. Once in operation, a superconducting computer or other digital instrument should be free from failure mechanisms which plague conventional systems.

### I.2.3. Refrigeration

Refrigeration requirements are without doubt the greatest impediments to broader use of superconducting devices. For large-scale terrestrial applications, the cost of refrigeration is a secondary consideration, although it raises the level of sophistication and causes concern about reliability. For small-scale terrestrial devices, refrigeration requirements are a primary consideration. To date, most such devices have been cooled with liquid helium in evaporative cryostats.

Space applications are even more restrictive than terrestrial ones since the reliability problems which accompany conventional refrigerators cannot be solved by a simple call to the repair man. For this reason the first cryogenic satellites will use evaporative helium cooling with cryostats designed for hold times of up to one year.

The development of reliable refrigerators would greatly alter the logistics of superconductivity in space and could tip the balance in favor of some programs. A discourse on refrigeration is beyond the scope of this study, but some comments are in order. For space applications it is particularly interesting to consider use of the low background temperature of space for radiative cooling. Appendix I.A offers some of our speculations on the refrigeration problem and specifically dwells on the potential of radiative cooling.

CHAPTER II

HIGH FIELD SUPERCONDUCTING MAGNETS

F. R. Fickett

## II.1.0.   INTRODUCTION

In the mid-1960's NASA and DOD sponsored a great deal of work to evaluate the possibilities for applying the relatively new science of high-field superconductivity to problems related to space flight.  Many interesting and, often, impractical suggestions resulted. Much of the impracticality occurred because the technological experience with large superconducting magnets was limited and, furthermore, the superconducting materials available were very crude by present standards.  By the time the modern generation of superconducting wires and magnets came to be, the large NASA programs were no longer in existence, and many of the ideas had effectively been forgotten.  Here, we want to take a fresh look at some of those ideas, as well as evaluate the overall role that superconducting magnets might play in the space adventures of the future as they now appear to be developing.

In this chapter we will look at present applications of superconducting magnets, discuss the advantages and disadvantages of these devices, and attempt to assess possible future developments and their impact on applications in aerospace technology.  Along the way we will take a look at the state-of-the-art and discuss research which, we feel, will help us to realize the full potential of these devices.  A good bit of what we have to say will deal with terrestrial applications for two quite simple reasons:  first, very few superconducting magnets have ever flown anywhere, and; second, the applications, construction techniques and general magnet configurations will not be greatly different regardless of where the magnet is located.

## II.2.0.   GENERAL MAGNET APPLICATIONS

When one looks at magnet applications in a general way, the actual functions in technological applications are quite few in number.  In one way or another they all make use of the ability of magnetic fields to interact with charged particles which are in motion relative to the field.  One classification scheme is given in the following list along with one representative application for each class:

1.   Deflection, focusing or confinement of charged particles (high energy physics);
2.   Introduction of energy into systems of charged particles (plasma heating for fusion devices);
3.   Deflection of non-magnetic metals (levitated transport);
4.   Deflection, suspension or steering of magnetic objects (steering of magnet-tipped catheters through the brain);
5.   Inductive energy storage (power plant peak shaving);
6.   Conversion of energy (motors and generators); and
7.   Control of chemical reactions (magnetocatalytic effects).

While normal magnets* are useful in each of these classes, the higher fields and smaller mass and physical size of superconducting magnets make them quite attractive in all cases. This is particularly so in aerospace applications where the relatively small mass becomes of prime importance.

Large numbers of both large and small superconducting magnets have been constructed in recent years and used in an amazing variety of applications ranging from high-energy physics to medicine. In Appendix II.A we describe many of these applications. The magnet systems are in an advanced state of development. We also give a few brief comments on the current status and future prospects of each application where appropriate. Obviously this latter assessment is the authors' alone. A detailed description of many large-scale applications is given in the book edited by Foner and Schwartz (1974) and in the Proceedings of the Applied Superconductivity conferences and the Cryogenic Engineering conferences. The book also has a number of chapters describing the worldwide research efforts in large-scale applications as of 1972. In general the trend in research in this field has been to less funding and smaller projects since then. The exception is the large program to develop the use of controlled fusion of light nuclei as a power plant concept.

## II.3.0.  MAGNETS FOR SPACE APPLICATIONS:  A GENERAL DISCUSSION

In Section II.4.0. we discuss a large number of specific applications which have been proposed for superconducting magnets in space. Here we outline very briefly some of the general advantages and disadvantages of these magnet systems. The technology is advancing quite rapidly, but little attention has been paid to optimizing the systems for space flight for the simple reason that very little development money has come from NASA in recent years. The high energy physics laboratories have been the major users, and their requirements are for higher fields, larger field volumes, reduced energy consumption and short- and long-term reliability. The resulting magnets (see Appendix II.A), thus tend to be heavy and large. This is not necessary. If one is willing to make some modest sacrifices in these requirements, light and small magnets become quite feasible. Research is needed to determine the best ways to handle the tradeoffs, but no insurmountable problems appear to exist and specific weights of $\sim$ 25 kilograms per megajoule of stored energy seem to be attainable for large magnets.

As a quick indication of where superconducting magnet technology is now, consider the following list of parameters for existing magnets and materials:

Largest superconducting magnet - 4.7 m-bore bubble-chamber magnet at CERN, 3.5 T field, coil weight $166 \times 10^3$ kg, 830 MJ stored energy

Highest continuous field superconducting magnet - 17.5 T, 3.1 cm bore lab magnet of $Nb_3Sn$ and $V_3Ga$ by Intermagnetics General Co.

---

*   The term "normal magnets" refers to conventional systems which usually have liquid-cooled copper coils and most often contain large amounts of iron and/or steel.

Highest continuous field hybrid (superconducting outer coil, copper inner coil) magnet - 30.1 T, 3.2 cm bore lab magnet by the National Magnet Laboratory at MIT

Highest high field superconductor current density - $10^5$ A/cm$^2$ at 20 T in V$_3$Ga, $\sim 10^6$ A/cm$^2$ in Nb$_3$Sn at lower fields

Typical current density in a superconducting composite wire - 5 x $10^4$ A/cm$^2$ at 5 T for both NbTi and Nb$_3$Sn (vs 100 A/cm$^2$ for copper).

Clearly, very good, dependable superconducting magnets exist.

## II.3.1.   Superconducting Magnet Systems

A superconducting magnet system consists of:  a magnet; a container for the magnet (a "dewar" or "cryostat") in which it is thermally isolated from its surroundings and cooled to $\sim 4$ K; a method of cooling, always a fluid in contact with the magnet, usually liquid helium; and a power source for starting ("charging") the magnet.  The last three of these are described in more detail in the following two subsections as they each represent either an advantage or a disadvantage in the use of superconductors over conventional magnets.  Here we wish to briefly describe the parts of the magnet itself.  The discussion applies to magnets of any size or shape, and there are many.

In its simplest form a superconducting magnet is a spool of superconducting wire wound, with appropriate insulation, on a bobbin of structural material and, frequently, banded on the outside with more structural material to contain the stresses (hoop stresses) which tend to expand the coil when it is energized.  Smaller magnets and pulsed magnets often are potted in an epoxy of some sort to prevent wire motion.  Larger magnets tend to have a more open structure to allow flow of coolant throughout the winding for improved heat transfer.

The superconducting material, which is only part of the wire, has the unique property of exhibiting zero resistance to the flow of direct current, but only below a certain critical temperature, ($T_c$), critical magnetic field ($H_c$) and critical current density ($J_c$).  This is illustrated graphically in Figure 1.  Below the surface the material is superconducting, above it is "normal", a state in which its electrical resistance is much higher than that of copper.  While it is certainly possible that a room temperature superconductor may some day appear, it is best not to wait for it.  All superconductors discovered to date have $T_c$ < 25 K and, thus, require large amounts of refrigeration, usually at $\sim 4$ K, for practical applications.

Only two groups of superconducting materials seem to offer any hope for large scale magnet applications in the near future:  the ductile NbTi alloys, which are now used extensively, and the brittle A15 compounds, most likely Nb$_3$Sn or, possibly V$_3$Ga.  (In Section II.3.4. we discuss the possibilities of other materials in the more distant future.) Table II-1 lists some of the properties of these superconductors.  The physics of the various critical field designations ($H_c$, $H_{c1}$, $H_{c2}$, $H_{c3}$) is covered in detail in many texts.  We have included elemental niobium in the table because it is extensively used in cryoelectronic devices and in superconducting powerline designs -- it obviously cannot be used in high magnetic fields.
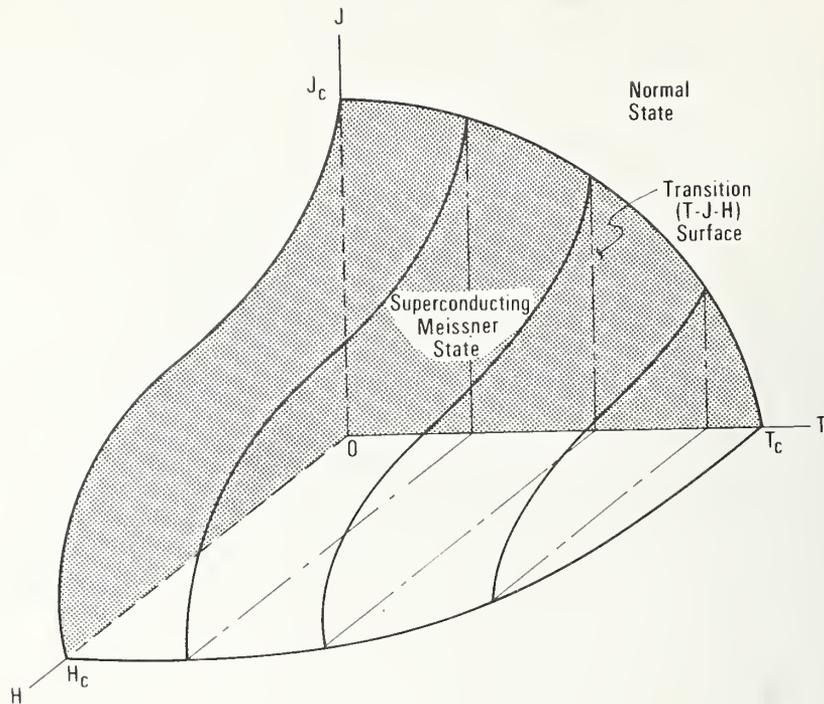
Figure II-1.   The critical parameter surface for a superconductor.   Under the surface, the material is superconducting, above it is a normal (usually poor) conductor.

TABLE II-1

NOMINAL PROPERTIES OF PRACTICAL SUPERCONDUCTORS

| Material | Crystal Structure | $T_c$ (K) | $\mu_o H_{c2}$[a] (T) | Max B (in use) (T) | $J_c$ @ 4.2 K @ B=4T (A/cm$^2$) | @ B=10T (A/cm$^2$) | @ B=17T (A/cm$^2$) |
|---|---|---|---|---|---|---|---|
| NbTi 45-48 wt. % Ti | bcc | 10.2 | 12 | 8 | $15 \times 10^5$ | $2 \times 10^4$ | 0 |
| $Nb_3Sn$ | A15 | 18.3 | 22 | 16 | $20 \times 10^5$ | $2 \times 10^5$ | $2 \times 10^4$ |
| $V_3Ga$ | A15 | 16.5 | 22 | 20 | $6 \times 10^4$ | $6 \times 10^4$ | $5 \times 10^4$ |
| Nb | Rhomb. | 9.5 | 0.25 | -- | $0$[b] | 0 | 0 |

a     $\mu_o = 4\pi \times 10^{-7}$ T/Am$^{-1}$, data at 4.2 K.
b     $7 \times 10^5$ at B = 0.

10

When used in essentially ac applications, such as pulsed magnets, superconductors do show a complex resistance, but it is still many times lower than that of the conventional normal metal conductors.

An actual commercial superconducting wire is a complex composite usually consisting of many fine (2 - 50 μm) continuous strands of superconductor embedded in a pure copper matrix and traversing the length of the wire, frequently with a twist pitch to the entire filament bundle. All of these aspects (pure metal matrix, fine filaments and twist) are necessary to provide stability in operation, i.e., to keep all of the superconductor in the superconducting state. In addition, if the wire is to be used in rapidly-changing fields, a high resistivity sheath, usually of copper-nickel is added to break up transverse eddy current paths in the wire. Furthermore, for reasons of manufacture, tin bronze is often an essential component of $Nb_3Sn$ wires. In this case a tantalum barrier is used between the bronze-superconductor region and the pure copper to keep the tin from migrating into the stabilizer and increasing its resistivity. *Truly, the practical superconductor is a very complex composite.* As you might suspect, it is also a *very expensive one*! Several dollars per meter is not unheard of for relatively small diameter (3 mm) $Nb_3Sn$ wire.

In commercial production, NbTi superconductor is made by drawing down a copper billet into which rods of the alloy have been inserted. Aluminum is sometimes used in place of copper. This technique works well, primarily because the NbTi alloys are quite ductile, and results in a relatively inexpensive wire (∿ $0.60/m). Furthermore, in magnet applications the wire can take quite large strains (> 5%) without destruction of the superconductivity. Unfortunately NbTi is not acceptable in all applications because of the restriction of its use to maximum magnetic fields of about 8 T, and the more complex $Nb_3Sn$ wire becomes necessary. Very little $Nb_3Sn$ is actually in use at present.

In very large magnets, stainless steel ribbon or wire is often either co-wound with the conductor or is bonded to it during manufacture in order to provide additional strengthening and, thus, decrease the total strain seen by the conductor. This is especially necessary for the strain-sensitive $Nb_3Sn$ conductors.

The amount of structural material necessary to hold the magnet together against the very large stresses created by the field increases dramatically with the size of the magnet and, in very large systems, the structure may well represent more than 80% of the total mass. In general this mass must also be cooled to the same temperature as the magnet. The materials most often chosen for this task are the austenitic (nonmagnetic) stainless steels. There is a great deal of potential here for significant weight reduction by the use of various composite materials. We at NBS are currently evaluating the low temperature properties of a number of specially formulated composites for such applications. An estimate of the absolute minimum total mass, M, of structure required to confine an amount of stored energy, E, in a simple magnet is given by

$$M = \frac{d}{\sigma} E, \qquad\qquad (II-1)$$

where d is the density of the structural material and $\sigma$ is its allowable stress level. As an example, titanium stressed to $1.6 \times 10^9$ $N/m^2$ gives $d/\sigma$ = 2.9 kg/MJ (MJ = megajoule).

## II.3.2. Advantages of Superconducting Magnet Systems

In aerospace applications conventional magnets with water-cooled copper coils and large volumes of solid iron consuming megawatts of power are not really feasible at all. Thus, if large field volumes are needed, superconducting magnets appear to offer the only option. For small fields and field volumes, of course, conventional magnets or permanent magnets are still the choice.

Superconductors can carry very large current densities, on the order of $10^4$ A/cm$^2$ overall in a magnet. Compare this to $\sim 10^2$ A/cm$^2$ for a copper coil magnet. This number determines the amount of winding required to obtain a given field in a fixed volume. Furthermore, the density of the superconducting wire is somewhat lower.

Except for very exotic systems, conventional magnets are limited in the field they can produce to about 2.5 T, the saturation field for iron. Superconductors are capable of producing fields to 15 T or higher. At these fields iron is superfluous. Even at lower fields, the lack of a requirement for iron has many advantages in machinery applications, allowing more insulation and, thus, higher operating voltages. When large field volumes are necessary, the ability of the superconductor to sustain high fields at the windings means that modest field values ($\sim 3$ T) can be maintained over volumes of tens of cubic meters, a feat which is impossible by any other means.

The electrical system necessary to operate large superconducting magnets is very simple, usually a low voltage (10-100 V), high current supply (an automotive battery bank is often used for small magnets). Once the magnet is energized, a superconducting short, called a persistence switch, can be made across the leads and the power supply removed. The magnet current will continue to circulate and maintain the field as long as the coil is kept cold. Conventional magnets often require megawatts of continuous power.

## II.3.3 Disadvantages of Superconducting Magnet Systems

Nearly all of the potential disadvantages of superconducting magnets for space applications are of a type which can be taken care of by serious investigation and good engineering. Most of these disadvantages exist today because of the direction which the field has taken historically, i.e., toward large laboratory systems.

The magnets require cooling to near 4 K. At present this is usually accomplished by filling the magnet container with liquid helium. If continuous cooling is necessary, it is provided by refrigerators and liquifiers which only now are becoming highly reliable. Removal of 1 W at 4 K requires a refrigerator input power of $\sim 500$ W at room temperature. In space, radiation of the heat removed could be a serious problem. Refrigerators are large and heavy, although the entire system weight (refrigerator + power supply + magnet) is still far below that of a normal magnet system.

A topic which needs investigation is the possibility of operating superconducting magnets in space without providing continuous cooling in the form of liquid helium. It seems possible that, at least beyond earth orbit and with adequate shielding, such operation might be feasible, particularly if the superconducting materials have critical temperatures in excess of 20 K.

The container, or dewar, must completely enclose the magnet and must keep the coolant for as long a period as possible. Liquid helium costs $\sim$ \$5/$\ell$. Thus, it behooves one to allow a minimum heat leak into the system. In terrestrial applications the helium is usually contained in a vacuum-insulated vessel which is, in turn, surrounded by liquid nitrogen ($\sim$ \$0.2/$\ell$), itself contained in a vacuum vessel. The liquids, the four metal walls and the standoffs represent a significant weight, but helium boiloff is low, 1-2%/day. Dewars insulated with many layers of aluminized mylar remove the necessity for liquid nitrogen and remove two of the walls, but at the cost of somewhat increased boiloff, although recent designs have holding times much the same as the nitrogen shielded ones. In any event, the dewar structure makes access to the magnet occasionally less convenient than in a conventional system, but this is usually more than compensated for by the larger free bore and field of the superconducting magnet.

Superconducting magnets contain large amounts of copper (or aluminum) to protect the superconductor against momentary transitions out of the resistanceless state. This stabilizes the magnet against transitions induced by fluctuations, and also prevents catastrophic destruction of the energized magnet (or magnet system) when it reverts to the normal state. This stabilization greatly increases the conductor weight and decreases the overall current density. As the amount of copper is decreased, the magnet becomes more susceptible to a total loss of superconductivity (a "quench") upon excessive shock loading, vibration, field changes or thermal excursions. This topic is one on which much research is presently underway.

The very high-field superconductors ($Nb_3Sn$ and $V_3Ga$) are brittle intermetallic compounds and wires containing them are quite susceptible to degradation of their properties at strains $\sim$ 0.6%. This increases the requirement for structural material and increases the weight. Again, strain-insensitive superconductors can most probably be made, but very little cash is available for the necessary research and development. For this reason few of the existing magnets described in Appendix II-A use these materials, concentrating instead on the ductile alloy NbTi which has a significantly lower critical field.

## II.3.4.  New Developments

The improvement of commercially available superconducting wire is occurring quite rapidly. The production of multifilamentary $Nb_3Sn$ conductor on a commercial scale is almost a reality today. This conductor will offer higher fields and faster charging times as well as decreased overall weight.

There are many other superconductors about which much has been published. $V_3Ga$ has actually been deposited on a tape conductor and used in a magnet. Reports of multifilamentary wire have been made. This material offers higher critical currents than $Nb_3Sn$ at very high fields, $\sim$ 18 T. It appears to be the only serious competitor to $Nb_3Sn$ in a commercial sense. Other materials such as $Nb_3Ge$ ($T_c$ = 23.2 K); $V_2Hf$ ($H_{c2}$ = 20 T at 4 K); $Nb_3(Al,Ge)$, ($H_{c2}$ = 41 T at 4 K); ternary molybdenum sulfides ($H_{c2} \sim$ 60 T) and a host of others are being actively investigated but, to date, have proven to be very difficult or impossible to fabricate in a usable form. If significant improvements in critical current density at high fields can be achieved with these materials, then their development might well gain a very high priority. Not enough is known at present to evaluate this possibility.

13

The use of high-strength nonmetallic composites for constraining large, cold magnet structures and dewars offers the possibility of great improvements in both total mass and refrigeration requirements, since the strength-to-weight ratio is large, as is the strength-to-thermal conductivity ratio. Also, the fact that rapidly-changing magnetic fields do not cause eddy current heating in the cold structure will further reduce the refrigeration needs in pulsed systems.

The problem of the cause of training of superconducting magnets should be solved soon. This effect manifests itself as a repeated quenching of the magnet at higher and higher fields when it is first energized. It is not usually a problem with simple solenoids but always is with more complex magnets. It probably results from wire motion within the winding or, less likely, from motion of the superconducting filaments within the wire.

A comment is needed regarding the possibility of a high-temperature superconductor. Several, predominantly organic, systems have been suggested as possibly superconducting at near room temperature and a lot of basic physics money has gone into investigating them. *It seems highly unlikely that any such system will be found which could be put into commercial production within the forseeable future.* There is, however, the strong possibility of developing superconductors, such as $Nb_3Ge$, to the point where they will be able to maintain high fields at liquid hydrogen temperatures ($\sim$ 20 K). Use of such, as yet undeveloped, materials would greatly improve the economics of the magnet systems, but would not greatly alter their complexity.

## II.3.5.  Other Considerations

There are several problems related to space applications of large magnets that are unique. Again, none appear to be really serious, but they are deserving of special mention.

The effects on humans of magnetic fields of an intensity other than that found on the earth's surface are not known. This is true both for high-field intensities and for fields near to zero. A certain amount of work has already been done by NASA, DoD and by scientists in the USSR. Arbitrary field limits have been set for human exposure. The overall conclusion at present seems to be that no serious long term effects occur at any field. However, there is enough disturbing information from experiments on mice and lower life forms, that more definitive research is probably needed. One concern often expressed is that a significant fraction of the population may be sensitive to magnetic fields, but no one from that population has ever been tested or even accidentally exposed. The situation was reviewed recently in some detail by Brechna (1975).

The effect of stray magnetic fields on the spacecraft instrumentation and guidance systems is also a major concern. Some examples from NASA (Golden, 1975): unshielded photo tubes are affected at $\sim$ 30 $\mu$T, ferrite cores at 0.01 T; relays and solenoids stick at 0.3-0.5 T. At present, the maximum allowable stray field is proposed to be $\sim$ 0.01 T for spacecraft. Passive shielding of relatively high-field magnets to this level is possible but may involve large amounts of material. Active shielding by appropriately-placed small superconducting coils is probably a better alternative at higher fields.

Another field interaction of concern is that between an on-board magnet and the plane-
tary and solar magnetic fields. This interaction could turn the ship into the world's largest
compass -- an undesirable situation in general. An unshielded coil of $\sim$ 0.7 m ID x 0.1 m
long operating at 7 T max field has been calculated to be subject to a torque of $\sim$ 70 Nm in
earth orbit (Pope, Smoot, Smith and Taylor, 1975). They claim that this must be reduced to
$\sim$ 0.07 Nm in order to be acceptable. In their design a second shielding coil is used to null
out the stray fields.

The near zero-g environment of space allows the liquid helium most often used as a
coolant to behave in ways which might not be anticipated. Any small g-force created by
rotation of the ship will, of course, move the liquid around and that has created some prob-
lems in situations where the liquid enters the fill tube. The IRAS (InfraRed Astronomical
Satellite) system will use a sintered nickel porous plug to resolve this problem. A more
exotic effect involves the magnetic forces on the liquid helium. Helium is diamagnetic and
is thus subject to forces in a field gradient which tend to move it away from the high-field
region. For the magnet just described, these forces can be as high as that produced by 1/3
of the acceleration of gravity. Proper cryostat design, the use of supercritical or super-
fluid helium and a (heavy) sponge or wick system are all possible solutions depending on how
serious the problem really is.

## II.4.0 PROPOSALS FOR SPACE APPLICATIONS OF SUPERCONDUCTING MAGNETS

Over the last fifteen years, a great many proposals have been brought forth outlining
the potential for use of high magnetic fields over a broad spectrum of aerospace applica-
tions. Most of the proposals were good, and the technology of magnet systems was steadily
advancing. But the dollars for advanced space applications were declining, and many of the
ideas faded into obscurity. Here we collect most of these and give a brief description of
the magnet system thought to be required. We cannot assess the feasibility or the desirability
of the proposed use, but we can, and will, make some evaluation of the magnet technology
required. It seems clear that superconductors are the only way to produce fields of reason-
able magnitude over even modest-sized volumes in a space environment. Conventional magnets
and their associated power supplies are just too heavy and too large. Unfortunately, even
superconducting magnets can be quite heavy and, perhaps, that explains their relative lack of
use to date. Clearly, in our present space program, the high magnetic fields may be de-
sirable, but we have done without them. Whether or not the stage will be reached where this
is no longer true is a topic far outside our field of competence. It is a question for the
NASA long-range planners.

Unless stated otherwise, the applications described relate to spacecraft exclusively.
In a few instances the major interest is for military aircraft applications, and these will
be so noted. Of course, a system suitable for aircraft use might well find application in
space with only minor modifications. Some systems, such as fusion reactors, large active
shields and magnets for ore separation are quite plausible for applications in space coloni-
zation schemes proposed for the far future. These are also mentioned briefly.

In order to put the proper perspective on this topic, we have included in Appendix II.B
a discussion of all of the actual instances that we know where a superconducting magnet has

left the ground (we exclude several rather dramatic laboratory accidents where the departure was unintentional). There are only a few such cases and, if we insist on actual space flight (as opposed to rockets and balloons) they are nearly nonexistent.

## II.4.1.  Cosmic Ray Analysis

Several magnets of this type are described in the appendices. Magnetic spectrometers are accurate, easy to calibrate and provide the means of measuring the sign of the charge of the particles. Furthermore, they allow a relatively high maximum detectable rigidity ($\sim$ 100 GeV), but their resolution decreases with increasing energy, and they tend to have limited geometry factors. Good statistics require long flights, and flight times from seven days to one year have been proposed for magnet systems.

The magnets needed can be constructed now. The problems associated with long-term storage of liquid helium and its use in a weightless environment are presently being solved in conjunction with other space applications of the cryogen. Problems of making the coil configuration so as to cancel the dipole interaction with the earth's field and to protect other field-sensitive instrumentation on the satellite are not insurmountable and have already been considered in some detail in the designs already described.

There are competing detection techniques which are being continually improved and, at present, it looks like the major application for the magnets will be on orbital experiments of relatively short duration, say to $\sim$ 30 days, in later Spacelab flights. Several groups are presently considering designs for Shuttle/Spacelab flights.

## II.4.2.  Shielding of Spacecraft

The possibility of shielding spacecraft crews from charged particle radiation by large superconducting magnets was investigated in detail a decade or more ago. The concept seemed to offer promise for shielding large volumes to quite high particle energies with relatively low weight. The designs varied from a simple circular coil creating a dipole field to a convoluted torus which had no field external or internal to the magnet. The former system, while simple in concept could guard against basically monodirectional radiation and would subject the crew and instruments to magnetic fields on the order of 0.1 T. Calculation of expected accumulated dose and other considerations showed the magnet systems to be attractive for very long manned flights or for very large vehicles, but not so much for the shorter flights in small ships. This was especially true at the time because superconductors were very expensive and the stabilization and structural material required by the technology made the systems quite heavy. An early NASA study showed that a 30 $m^3$ volume could be adequately (but see below) protected by a 4 T magnet of $\sim$ 50-100 MJ stored energy and concluded that the production of such magnets was within existing capabilities although lighter structure and more reliable refrigeration were much to be desired. A larger volume, 144 $m^3$, could be protected from protons with energy < 1 BeV by a system weighing 150 tons. Most of this is structure. The recent study on space settlements also considered (and rejected) active shielding for the habitat, arriving at a magnet weight of 10,000 tons for a 0.5 GeV/nucleon cutoff. That study (Johnson and Holbrow, 1977) brought out the fact that secondary production of charged particles in the magnet structure by the (unshielded) primary flux above

2 GeV/nucleon would require additional mass shielding anyway. They concluded, quite rightly, that an active shield with a cutoff of 15 GeV would involve unacceptable amounts of structure to hold the magnet together.

The only shielding magnet ever built was constructed at Lockheed. It was a circular magnet of 1.8 m i.d. with a 0.1 T central field (1.5 T at the winding). This magnet would protect a volume of several cubic meters from particles with energies of ~ 100 MeV. The entire system had a mass of 85 kg, including the cooling system, and could operate for 5-10 days.

In the future it seems to us that this concept might be reconsidered for certain types of flights or for space stations. Advances in materials, both superconducting and structural, and in magnet reliability might change the economies of the situation in particular cases. The very large magnets being produced in the fusion energy program will go a long way toward demonstrating modern construction techniques and reliability of large cooling systems.

An entirely different concept of shielding was once proposed which would trap an electron cloud around a space station by means of relatively low field (0.2 T) magnets and use the resulting electrostatic repulsion to shield the station. Apparently the concept did not prove to be viable.

## II.4.3. Energy Storage

Storing energy in the field of large superconducting magnets offers a number of advantages over more conventional techniques, such as capacitors and batteries. The first is a significant weight reduction; the low voltage, high current storage mode is also often an advantage, as is the ability to handle rapid discharges and high repetition rates.

The possible applications for inductive energy storage range from high field, small (10-100 kJ) pulsed coils for plasma guns, masers and laser systems, through larger (1-10 MJ), more slowly pulsed coils for plasma heating to the enormous coils storing $10^6$-$10^8$ MJ, which have been proposed for electric utility peak shaving systems. Any or all of these applications are quite reasonable for space systems. Furthermore, the economics of competing storage methods are not the same in space (it is hard to store energy by pumping water uphill for instance), and many of the magnetic systems look very attractive. A case in point is the use of a warm reinforcement system in which a very large storage magnet is buried in the ground so that the magnetic stresses can be taken up by the bedrock. This system on earth is calculated to be marginally competitive with other energy storage schemes (Powell, 1974), but only at very large sizes. In applications on other planets or the moon, the reduced insulation and, thus, refrigeration requirements might make such a system very practical.

Smaller energy storage magnets, charged before launch from, say, a Shuttle vehicle seem to be extremely practical systems for long-term energy storage for unmanned interplanetary flights (fuel cells seem the more likely alternative for manned flights). They obviously become more efficient as it gets colder, and their specific weight is quite low and decreases rapidly with stored energy in the 0-100 MJ range. The vacuum environment simplifies the insulation problems greatly. Also, because of limited interest in the past, very little has really been done to minimize the specific weight of superconducting energy storage devices. New superconductors and structural materials make a significant reduction seem quite feasible.

The type of magnet deserves some comment. The most efficient design, and the easiest to build is a simple solenoid, but this device has a large associated dipole field, which may be undesirable in itself and/or may lead to high losses due to inductive heating of nearby metallic parts when operating in a pulsed mode. A toroidal configuration is the more desirable magnetically but significantly more of a structural problem.

Existing magnets are described in Appendix II.A, but a few comments are in order here. Pulsed 100 kJ magnets have been made. Pulsed coil tests show that high rates of field change ($10^4$ T/s) are possible, high coil voltages (10's of kV) can be handled as can pulse rates around 5 pps. DC magnets now store as much as 800 MJ, and these are bubble-chamber magnets not optimized for storage. Existing magnets, again not optimized for storage, have specific weights as low as 200 kg/MJ (for the winding plus structure at the 10 MJ level). Studies of optimum geometries indicate that specific weight values of windings alone could be as low as 3 kg/MJ at the 1000 MJ level for solenoids and 7 kg/MJ for toroidal coils. Increasing the stored energy to $10^6$ MJ drops these numbers by about another factor of five (note that dynamite has 0.24 kg/MJ, but its use in a controlled energy-release mode suffers from some technical problems). Of course, the magnet structure begins to represent nearly the whole mass at these higher values of stored energy, and when this is taken into account the specific weight tends to be $\sim$ 10 kg/MJ for the high energy systems. Optimizing the coil for energy storage with minimum mass involves a number of complex trade-offs, but in general a large winding, thin compared to its radius, and with a relatively low central field is best. Simple solenoids have a lower specific mass than other configurations. It may well be that an actively or passively shielded simple solenoid still has a mass advantage over a toroid. For comparison to the above figures, long-life capacitor storage systems have a specific weight in excess of 1000 kg/MJ. Also capacitors store energy with a density of about 0.4 MJ/m$^3$ while in high field magnet systems, this is closer to 30 MJ/m$^3$. Battery systems have a specific weight of about 12 kg/MJ and an energy density of $\sim$ 100 MJ/m$^3$. On a pure weight basis, magnets and batteries are comparable. However, the rate of energy removal is restricted, as is the number of charge-discharge cycles, and the systems are both expensive and temperature sensitive.

One very serious problem with large energy storage coils is that of switching, particularly where fast pulse times are required. Various superconducting switches have been investigated. The state-of-the-art is a discharge of about 1 MJ in 100 ms or 300 kJ in 2 ms. There is quite a bit of research on this subject because of the possible applications in laser energy storage and in fusion devices. It is not a trivial problem.

Specific proposed space applications for energy-storage magnets have been very few in the literature. One is the proposal by Olson (1974) to use a relatively large magnet to create an artificial miniature magnetosphere in space using either an injected plasma (Shuttle experiment) or the solar wind itself for higher orbits. This "minimag" experiment would allow studies of magnetospheres on a scale closer to reality than the existing laboratory experiments. It would also give information on the forces exerted on the earth by the solar wind. No description is given of the magnet required, but the implication is that a 2 m simple coil with a relatively high field of about 9 T at the winding would be adequate. Experiments would have to be performed far enough from the earth to avoid interaction with the earth's field which would tend to orient the experimental magnet -- and anything attached to it, like the experimenter.

Another application might come in recovering energy produced by decelleration of the mass driver system described below, which is proposed as a means of sending material mined on the moon to a processing center in orbit.

## II.4.4. Energy Conversion – Motors and Generators

Superconductors offer significant size and weight advantages in various types of rotating machinery. In terrestrial applications these advantages are overshadowed by economic considerations and concerns for very long term (30 yr) reliability, which ties the whole problem up with the uncertainties associated with long-term operation of 4 K refrigeration systems. It seems quite reasonable that many of these concerns would not be as crucial in space applications while the reduced mass and size would be quite desirable. In spite of the concerns expressed above, superconducting motors have been built and operated. They are described in Appendix II-A.

The state-of-the-art of superconducting machinery for aerospace applications is not as dismal as it is in many other applications of superconductors. This is nearly entirely due to the Air Force program on airborne machinery. The program is relatively small, but the fact that it has remained in operation over the last several years has allowed the consideration and introduction of modern materials technology. The situation has been reviewed recently (Oberly, 1977) and was one of the topics of an earlier comprehensive evaluation by an AGARD panel meeting (Fuhs, 1972).

Both dc and ac machinery have been investigated. The dc machines operate at high current levels and require ferromagnetic return paths for the flux. They are relatively easy to build because the superconducting windings are stationary. The potential for space applications would probably be limited to rather specific "industrial" operations such as providing power for aluminum ore processing, etc. Superconducting ac machinery, on the other hand, appears to be promising for a variety of inflight uses. The type most investigated uses a rotating superconducting field winding inside a stationary armature with a normal copper winding. The high fields available with superconductors allow removal of the ferromagnetic core of the field windings and the armature teeth. The machines are lighter and smaller than conventional ones with the same power rating. A comparison (on paper) by Westinghouse of two 1200 MVA (central power station, big!) generators showed reduction in weight of more than 75% and a length reduction of nearly 50% for the superconducting machine. The specific weight was 0.53 kg/kVA for the conventional machine and 0.12 kg/kVA for the superconducting one. We have neglected all associated cooling and refrigeration equipment.

Present aircraft alternators run from about 10-500 kVA with a specific weight of ∿ 0.2 kg/kVA at the high end and with significant reductions in this value expected as new materials, such as high-strength composites, become available. In this power range, superconductors do not seem to be competitive, even if stored liquid helium is used instead of a refrigerator. The specific weights required (for a 6 hr flight for a 50 kVA generator) are calculated to be 0.28 kg/kVA with stored liquid and 0.33 kg/kVA with a refrigerator. Refrigerator weight is assumed to be ∿ 100 kg/watt of refrigeration.

19

For the power range above 1 MVA, superconducting devices appear to offer significant advantages over conventional designs, although the ever-present uncertainties regarding the additional weight required for reliable refrigeration still exist. The Air Force feels that specific weights for the machinery alone of $\sim 0.05$ kg/kVA are possible for alternators in the 50 MVA class.

A superconducting generator has been under development for the Air Force for about six years. It represents the state-of-the-art for airborne systems. The machine is a 5 MVA, 400 Hz, 1200 rpm, 4-pole generator. Its specific weight is $\sim 0.09$ kg/kVA.

A 1 MVA dc superconducting generator with a 5000 V output has been proposed for use with a small nuclear power plant to provide electropropulsion for deep space missions (Cooper and Kuhns, 1966).

The potential for electrical conversion machines in space seems good. A large amount of materials research and engineering design work is needed if this potential is to be realized.

Other energy conversion systems using superconducting magnets have been proposed involving the use of thermal energy to cycle superconductors or helium in and out of the superconducting/superfluid state which would result in motion of flux provided by a superconducting magnet which would then be transformed to electrical energy. At present none of these concepts appears practical on a large scale.

The transmission of electrical energy by superconducting power lines has received a great deal of attention in recent years. The concepts appear workable for both ac and dc transmission but the economics on the earth do not look good except at power levels beyond any current demand. Refrigeration is a major problem for these extended systems. Space applications appear unlikely, since long distance power transmission by solid conductors is not one of the primary problems.

## II.4.5.   Energy Generation

Power generation in space is already a reality with nuclear power plants perhaps as large as 100 kW (estimated for the ill-fated Cosmos 954 reactor, which fell in Canada early in 1978) actually in orbit. The objection to fission plants in space are similar to those here on earth. Any alternatives should be investigated. Two such options are thermonuclear fusion and magnetohydrodynamic (MHD) power generation. The first of these is still in the physics experiment stage, but the experiments are beginning to reach the sizes predicted for power plants. MHD power generation is a technology now in use. Both systems require superconducting magnets for economical operation even on earth. Both systems seem very promising for space applications.

The physics of fusion devices seems to require very large magnet confinement systems for a net energy output and, thus, these power plants would seem to be feasible only for very large space habitats or planetary installations. Most of the energy from reactors using the most reasonable fuel (deuterium-tritium) is in the kinetic energy of neutrons which must be slowed down in a "blanket" in order to recover the energy. Conventional thermal-electric conversion plants are then necessary. If more advanced fuel cycles become practical, the energy will reside in charged particles and direct conversion might be possible. The size and shape and maximum field of the magnets is not yet known. Some terrestrial systems for large experiments are described in Appendix II.A.

In MHD power systems, a very hot (2000° C) ionized gas flows at high velocity between the poles of a magnet which deflects the charged particles to collection plates on opposite sides of the channel, resulting in a current output from these electrodes. The source of the gas is termed a combustor and in most cases it is much like a rocket. The power output is proportional to the volume of the channel and the square of the applied field. By using superconducting magnets optimized for light weight, MHD has the potential of having the smallest specific weight of any power generation system, predicted to be $\sim$ 0.1 kg/kVA at the 10-100 MW level.

Large superconducting magnets for terrestrial MHD systems have been built and are described in Appendix II.A, but these have used cryostatically stabilized superconductors with copper-to-superconductor ratios of as much as 20:1, resulting in very heavy magnet systems (2000 kg/MJ stored energy at the 10 MJ level for the NASA-Lewis system). This high specific weight can be reduced only by operating with less stabilization of the superconductor (Cu:Sc ratios $\sim$ 2-3) which, in turn, makes the magnet subject to training and sensitive to quenching by mechanical shock. Oberly (1977) states the situation very well: "The vision of a superconducting magnet in the confined space of an aircraft undergoing training quenches with more than 1000 $\ell$ of liquid helium vented in a couple of hours would not inspire pilot confidence." The problem of designing large, dynamically-stabilized superconducting magnets is by no means trivial, and it is a matter of the greatest importance for all the magnet applications described in this report. Stability problems have plagued the few lightweight magnets which have been built. A contributing factor to this lack of success is that the magnet cannot be a simple solenoid but must be a rather complex saddle-shaped coil (race track coils can be used but they require double the mass and volume of conductor, structure and dewar) and complex coils are much more subject to training than are solenoids. Nevertheless the Air Force has recently proposed a flyable design with 3.88 MJ of stored energy which will have a specific weight of 335 kg/MJ. The magnet is 68% conductor, 22% structure and 10% dewar. Note that, even in the best cases, these magnets have much higher specific weights than those used for energy storage, indicative of the severe penalty paid for using noncircular coils.

Most of the preceding discussion has application to what are called "open-cycle" MHD systems. Some closed cycle systems using very high temperature fluids heated by fission reactors have been proposed. They apparently pose too great a danger for use on earth, but it has been suggested that they be placed in a synchronous orbit and the generated power beamed to earth by microwaves.

## II.4.6. Levitated Transport

Magnetically levitated vehicles capable of carrying passengers have already been operated on earth. They offer the potential of speeds well beyond 300 km/hr which is apparently the limit for wheel-and-axle vehicles. This concept of guided electromagnetic flight would seem to have great potential for use in transportation systems associated with planetary settlements. It has, in fact, been quite extensively studied as a means of launching ore from the moon -- the mass driver system. More about that shortly.

Levitation is possible using conventional electromagnets or, even, permanent magnets and ferromagnetic materials. This "attractive" system requires a small gap ($\sim$ 1 cm) between the

21

levitated vehicle and the track and is inherently unstable. Both of these considerations tend to limit the usefulness of this system to low speeds. The repulsive system, and several other similar suspensions, rely on the repulsion between a large superconducting magnet on board the vehicle and a conducting track to provide levitation. Large gaps ($\sim$ 10 cm) are possible and the system is compatible with various desirable propulsion systems. These propulsion systems are essentially linear motors. The linear synchronous motor, which involves a complex electrically-active track is the one most heard about today, but linear induction motor schemes have been proposed and, if all else fails, one can always mount a jet engine on the vehicle. In all cases, mathematical models are highly developed, and test vehicles of various shapes and sizes have been run. The problems seem to primarily have to do with feedback control of various unwanted modes of motion of the vehicle. They are not trivial, particularly if the vehicle is to transport humans.

The only detailed study of levitated systems for space applications has been made by the National Magnet Lab at MIT on the mass driver system. It is described in the Space Settlements Study (Johnson and Holbrow, 1977) and in several other papers. Its purpose is to semicontinuously launch small quantities of ore, mined on the moon, from the surface to a catcher in space, where it is loaded onto larger vehicles for transport to the space colony. The proposed system will launch 10 kg of compacted lunar material at a time from a vehicle aptly called a bucket. This involves acceleration to 30 g. One to five launches will be made each second. Each bucket will have relatively small superconducting magnets operating at $\sim$ 3 T, and be driven by a linear synchronous motor system. Problems of stability and aiming are quite challenging, but not insurmountable.

The mass driver concept has also been proposed for use as a reaction engine for sending material from one orbit to a higher one, making it an effective upper stage for, say, transport from a Shuttle vehicle to geosynchronous orbit (O'Neill, 1977). The drive is accomplished by accelerating and launching very small masses ($\sim$ 14 g) at the rate of 5 per second. The economics of the system as presented by the author make it seem most attractive. Furthermore, the magnet coil technology appears well within present day capabilities.

## II.4.7. Propulsion

There is no real competition for the existing rocket systems for attaining earth orbit. However, these high-thrust systems are not the most desirable for interplanetary travel. Very long travel times are necessary. The low-thrust rocket systems, on the other hand, offer the possibility of reasonable transit times to all but the most distant planets. These systems have very low thrust, but provide it continuously, and thus they cause the ship to travel in complex, but relatively straight trajectories. High thrust system propulsion results in trajectories which are portions of conic sections. A number of different systems have been proposed for low thrust engines: MHD, or plasma, engines have been used by both the USA and the USSR. Basically they make use of the forces produced by a plasma current interacting with a magnetic field to accelerate a plasma created by an electrical discharge in a diverging magnetic field; electric engines use a plasma also, but accelerate the ions by strong electric fields applied to grids. Thermonuclear rocket concepts use unidirectional leakage of a reacting plasma out of its magnetic confinement, usually with a parallel hydrogen

22

gas stream into which the enormous energies of the fusion particles are diffused. Laser drive systems have been proposed in which the plasma is created and driven by a high-power laser and, in a different approach, a system has been proposed in which lasers mounted on asteroids are aimed at spacecraft with "sails" to capture the energy. All systems except the very last require relatively high magnetic fields over large volumes, and all serious proposals have assumed the use of superconducting magnets, since specific weight is the controlling factor in transit time. The round trip time to Mars for a 10 kg/kW (ratio of total vehicle mass to engine power) one stage system is 450 days, while a 1 kg/kW system makes the trip in 150 days. The magnet problems for all of these types of systems have been discussed above. Again, the desire for very lightweight magnets leads to a need for superconductors with high current density capabilities and strong lightweight structures. Many of these systems are described by Moeckel (1969) with a special emphasis on the thermonuclear fusion rockets. These, of course, suffer from the same problems as the power plants discussed earlier -- no one yet knows if controlled fusion is possible.

The various engines which use nonreacting plasmas all require magnetic confinement, since the hot plasma should not be allowed to interact with material walls. In addition, the pulsed plasma acceleration devices require large energy pulses, usually proposed to come from condenser banks of high specific weight (500 kg/MJ). It has been proposed that a similar short term (on the order of milliseconds only) energy storage system might be possible with a "plasma condenser" since a plasma rotating in a constant magnetic field behaves like a dielectric of high dielectric constant. Peschka and Carpetis (1966) have designed several such systems on paper which store $\sim$ 2 kJ using a 1 T field generated by high current density $Nb_3Sn$ superconductor and having a specific weight of $\sim$ 10 kg/MJ. The magnets do not appear to be complicated, but the entire system concept may have not proven itself, since nothing more has been heard about it.

One severe shortcoming of all these pulsed plasma systems should be noted. They are extremely noisy electrically and, thus, are not well loved by the instrumentation people.

A different plasma system is the proposed ion scoop which would use a spaceship-borne magnet to create a field to channel charged particles from the solar wind or interstellar space into an electric engine system. The magnet would have to produce a dipole field in excess of the galactic field ($\sim 10^{-10}$ T) at $10^4$ km from the ship in order to gather usable quantities of ions. It has been calculated (Matloff and Fennelly, 1974) that this could be accomplished by a scoop 0.8 km in diameter and 0.4 km long carrying a sheet of supercurrent of $\sim 10^{11}$ A, flowing in a thin layer ($< 10^{-4}$ cm) of $Nb_3Sn$. No serious consideration has been given to the structural problems involved, but this may well take the prize for the largest magnet system yet proposed.

Let's move back a little closer to reality for our last topic here. It was proposed in the early 1960's that a superconducting magnet might be wound around a rocket exhaust port in order to use the axial field to pull the exhaust gases away from the wall and, thus, effectively reduce the thermal transfer to the wall. An experiment was performed by the Navy using a relatively small model with a 1.5 T superconducting magnet. The thermal transfer was unaffected and the field seemed to interfere with the ignition characteristics and the dynamics of the exhaust gases. A larger field (5.3 T), produced by a cryogenically cooled normal magnet, was tried. It worked the same way (end of project).

## II.4.8. Re-Entry

The hot, high-conductivity plasma created upon entry of a hypersonic spacecraft into a planetary atmosphere can potentially be used as the working substance of an MHD braking system. In such a system the flux could be conceivably caused to at least partially break away from the body, causing a decrease in the heating. The energy would be transferred to the superconducting magnet on the spacecraft, resulting in increased current in the magnet. Since superconducting magnets can create fields over a large region, the effective braking area may be quite large. Furthermore, the braking action would tend to start significantly further out from the planet than is presently the case. Theoretical investigations and a very few laboratory studies have been carried out, but no conclusions as to the actual desirability of employing such a system were reached.

## II.5.0. SUMMARY AND CONCLUSIONS

Large superconducting magnets are definitely feasible for use in a variety of space applications. Very high fields and current densities are achievable with relatively low weight magnets, although few development efforts to date have stressed the weight consideration. The magnets can store and deliver large amounts of energy with a high density and low specific weight when compared with other systems. Advanced techniques of power production, such as MHD and fusion, will rely heavily on superconducting magnets. These energy sources are particularly well suited to space use.

The technology of superconducting magnets for terrestrial applications is still advancing rapidly, and one can assume that significant improvements will continue to be made in superconducting materials and coil design. These developments are being driven by the high-energy physics community, the Department of Energy, the Military and others. The concern for weight, which is clearly important for space applications, does not presently represent a major concern for magnet designers. *Modern composite technology, properly applied to magnet structural components, could make impressive reductions in the specific weight of large magnets.* This is one clear objective which might be considered by NASA for development programs.

The less likely developments, such as the discovery of a high-field superconductor with a transition temperature above, say, 80 K, should also be kept in mind, since such a material could greatly alter many of the designs for space stations and colonies. This possibility appears remote at the present, and thus extensive development work in this direction would likely not be cost-effective. A second type of materials effort might be considered. In Section II.3.4. we mentioned a number of ultra-high-field superconductors which have been discovered in recent years. The development of any of these into practical composite conductors could have a significant impact on magnet characteristics (field, weight, size, etc.). Commercial interests will probably not pursue this development with their own resources since the price tag may be $10^6$ dollars or more. The precise value of improvement in magnet performance should probably be assessed carefully before such an investment is considered. Such an assessment is beyond the scope of this study.

It is difficult from our perspective to place priorities on projects in the space program, but some casual observations may be in order. Elementary particle physicists may be near the limit of dollar expenditures for higher energy accelerators. To obtain information at substantially higher energies may well require long-term exposure to primary cosmic rays outside the earth's atmosphere. For particles of this energy, superconducting magnets would appear to be essential components of analysis systems. Thus, we might expect increasing interest in the physics community for the long-term flight of large superconducting magnets.

A second application which might deserve further study is energy storage (see Section II.4.3.). Earth-bound systems have been built and tested with good results, but little work has been directed toward the question of specific weight. Present information indicates that extremely good weight-to-energy ratios are achievable, but further study of the subject is suggested. The reduction of weight through use of composite structural materials, as indicated above, would be valuable.

Finally, we suggest that the scientific community at large be made aware that high-field magnet systems of modest size are perfectly reasonable pieces of equipment to use for experiments in Spacelab. We suspect that many interesting experiments in organic chemistry, biology and physiology could be done with such magnets in space. We don't mean to slight physics and materials science, but most researchers in those fields are probably well aware of the potential for high-field experiments.

## II.6.0.  REFERENCES

Brechna, H. (1975).  Medical Applications and Biological Effects of Magnetic Fields.  In *Proc. Fifth Int. Conf. on Magnet Technology*, Laboratori Nazionali del CNEN, Frascati, Italy, 351-366.

Cooper, D.W. and Kuhns, P.W. (1966).  Electrical Generator with a Superconducting Magnetic Field for Use in a 1-Megawatt Rotating Space Power System.  *Intersociety Energy Conversion Eng. Conf. Tech. Papers AIAA*, 298-307.

Foner, S. and Schwartz, B.B. (1974).  *Superconducting Machines and Devices:  Large System Applications*, Plenum Press, New York.

Fuhs, A.E. (1972).  Energetics for Aircraft Auxiliary Power Systems.  *NATO Advisory Group for Aerospace Research and Development*, AGARD-CP-104, Available from NTIS.

Golden, R.L. (1975).  Superconducting Magnets for Space Flight.  In *Research Goals for Cosmic-Ray Astrophysics in the 1980's*,  European Space Agency ESRO SP-109, p 91 (Available as N76-12934).

Johnson, R.D. and Holbrow, C. (1977).  *Space Settlements:  A Design Study*, NASA SP-413.

Matloff, G.L. and Fennelly, A.J. (1974).  A Superconducting Ion Scoop and Its Application to Interstellar Flight.  *J. Brit. Interplanetary Soc.* *27*, 663-673.

Moeckel, W.E. (1969).  Propulsion Systems for Manned Exploration of the Solar System.  *Astronautics and Aeronautics* *7*, 66-77.

Oberly, C.E. (1977).  Air Force Applications of Lightweight Superconducting Machinery.  *IEEE Trans. Mag.* *MAG-13*, 260-268.

Olson, W.P. (1974).  Potential Experiments with Superconducting Magnets in Earth Orbit.  *Space Science Reviews* *13*, 899-904.

O'Neill, G.K. (1977).  Mass-Driver Reaction Engine as Shuttle Upper Stage.  Paper presented at *AIAA Princeton Conf. on Space Manufacturing*, May 1977.

Peschka, W. and Carpetis, C. (1968).  On the Use of Cryogenic Techniques for Space Propulsion and Energy Conversion.  In *Propulsion and Re-Entry*, (ed. M. Lunc) Gordon and Breach, New York, 287-304.

Pope, W.L., Smoot, G.F., Smith, L.H. and Taylor, C.E. (1975).  Superconducting Magnet and Cryostat for a Space Application.  *Adv. in Cryo. Eng.* *20*, 47-60.

Powell, J. (1974).  Large Scale Applications of Superconductivity, [see Foner and Schwartz, 1974], Chap. 1.

CHAPTER III

LOW FREQUENCY SUPERCONDUCTING SENSORS

J. E. Zimmerman

## III.1.0.  INTRODUCTION

Although this chapter deals with several low-frequency instruments and devices, most of the discussion relates to SQUID magnetometers and gradiometers, since these are perceived as the instruments with the greatest potential for applications in space. Presently, the preponderance of opinion seems to be that conventional magnetometers are adequate for measurements in space, so that use of superconducting instruments is not justified. However, it might be pointed out that ten years ago, exactly the same view prevailed with respect to terrestrial geomagnetic measurements, yet today SQUID magnetometers are used to advantage by several groups for precisely this purpose (see, for example, papers by W.D. Stanley and others in Flynn and Zimmerman, 1978). It is fairly safe to predict that similar developments will occur in space measurements, that as the analysis and understanding of the available data improve, needs will arise for more advanced instruments. Also, it is not just that SQUID magnetometers can perform unique functions because of superior linearity, sensitivity, and frequency response, but they can do less-demanding jobs better than conventional instruments as well. (For an operational comparison of superconducting and conventional magnetometers, see Zimmerman and Campbell, 1975).

SQUID's are made in two forms (Fig. III-1). One form comprises a single Josephson junction in a superconducting loop, inductively coupled to a radio-frequency resonant circuit and bias oscillator-amplifier system which, in effect, measures the SQUID impedance (see Zimmerman, Thiene, and Harding, 1970, or Zimmerman and Campbell, 1975). The latter reference contains a qualitative description more suitable for non-specialists. This form is usually referred to as the rf-biased SQUID, or simply "rf SQUID".

The other form comprises two junctions in a superconducting loop. The loop is directly connected to a bias source and amplifier circuit, so the dc properties of the SQUID can be measured. Although the measurement can be made with either dc or low to medium-frequency ac bias, this device is referred to as the "dc SQUID" (Clarke, Goubau, and Ketchen, 1976).
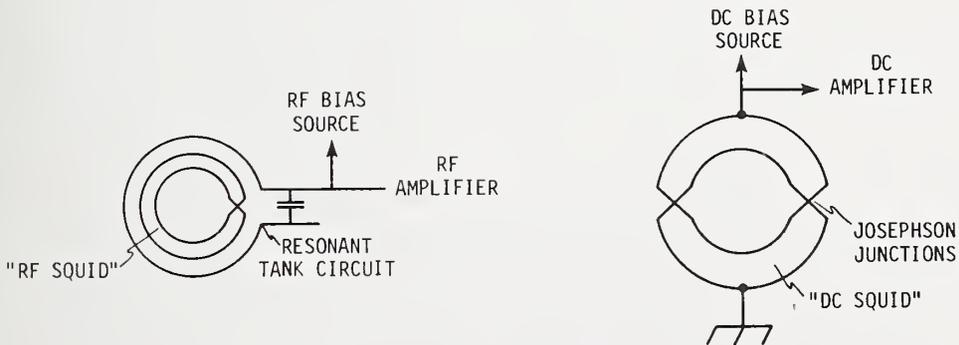


Figure III-1.  Schematic representation of rf and dc SQUID's with bias and signal amplifier connections.

The dc and the rf SQUID's have essentially identical applications, at least in low-frequency sensing, and their ultimate sensitivities are comparable (Clarke, 1976).  Except for those made by Clarke and his colleagues (Clarke, et al., 1976), nearly all SQUID's in use at this time are rf SQUID's.  The reason for this is that the single Josephson junction has been more reliable and easier to make.  However, great progress in junction manufacturing techniques has occurred in recent years, so dc SQUID's may be more widely accepted in the future.  Instruments incorporating rf SQUID's have been commercially available from several companies for several years.  In this report we refer primarily to the rf SQUID, but the dc SQUID could equally well be used in every case.

A SQUID is basically sensitive to magnetic flux, as described below and in the references given above, and can be used directly as a magnetometer.  By the addition of appropriate coupling coils, it can be adapted to various related functions such as galvanometer, volt-meter, ammeter, current comparator, dc amplifier, VLF antenna, first- and second-derivative magnetic gradiometers, susceptometer, magnetic resonance spectrometer, and others.

In all but one or two characteristics, SQUID's equal or greatly surpass the performance of all other types of low-frequency magnetic sensors.  They are superior in sensitivity, frequency response, range, and linearity; and they are competitive in cost, portability, reliability, and mechanical simplicity.  Their main disadvantage, in addition to the require-ment for a stable low-temperature cryostat, is that their operation is disturbed by fast transients and strong high-frequency signals, so they must be more carefully shielded against these disturbances than other types of sensors.

SQUID's are in a state of advanced and continuing development.  Their potential impor-tance to technology is indicated by an international conference on the subject held two years ago, the proceedings of which are available as a book (Hahlbohm and Lübbig, 1977).

There are a number of other low-frequency superconducting devices of potential use in some experiments.  Superconductivity can provide essentially perfect ac and dc magnetic shielding, as well as almost zero-field ($\sim 10^{-12}$ T) enclosures.  The zero resistivity of superconductors is useful for current and flux transformers, and these are commonly used in conjunction with SQUID's, both for coupling to magnetic fields and their spatial derivatives as noted above, and for impedance-matching to voltage and current sources.

A unique device which utilizes flux flow to provide transformer action (meaning transfer of power between primary and secondary) at zero frequency and above is called a "dc trans-former."  It will be discussed only briefly, since it has not reached the point of practical application.

There are several relatively recent and rich sources of information on low-frequency superconducting and cryogenic technology, some of which are referred to in this chapter and which deserve special emphasis, namely:  the report on the Stanford relativity experiment (Everitt, 1977), the book on SQUID's (Hahlbohm and Lübbig, 1977), the Proceedings of the Cryocooler Applications Conference (Zimmerman and Flynn, 1978), the Proceedings of the Navy Summer Study on Superconductive Electronics (Silver, 1976), and the Proceedings of the Con-ference on Future Trends in Superconductive Electronics (Deaver, 1978).

### III.2.1.  SQUID Magnetometers and Gradiometers

A SQUID is a superconducting quantum interference device whose essential topology is that of a ring or a loop.  Its output varies periodically with the magnetic field B applied perpendicular to the plane of the SQUID loop (Fig. III-2).
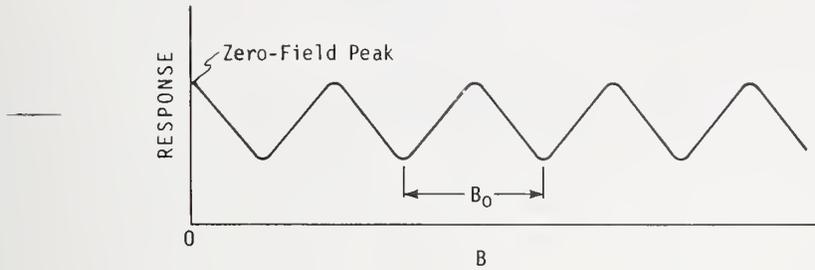


Figure III-2    Response of a SQUID to magnetic field B.  The periodicity $B_0$ is equal to the flux quantum $\phi_0$ multiplied by the effective area of the SQUID loop.

The response is a vector function; there is no response to field components parallel to plane of the loop.  Note that the zero-field peak is exactly like all the others; it has no special distinguishing feature.  The effective loop size of a typical SQUID is several $mm^2$ in area. The flux periodicity is a fundamental constant $\phi_0$ = h/2e = 2.07 x $10^{-15}$ W.  Thus, the field periodicity $B_0$ indicated in Fig. III-2 is typically a few tenths of a nanotesla (a "gamma" is equal to a nanotesla).

A SQUID may be used as the sensing element of a magnetometer, but for flexibility in different applications, it is more common to shield the SQUID and to couple it to the field by an auxiliary passive superconducting loop known as a flux transformer (Fig. III-3).
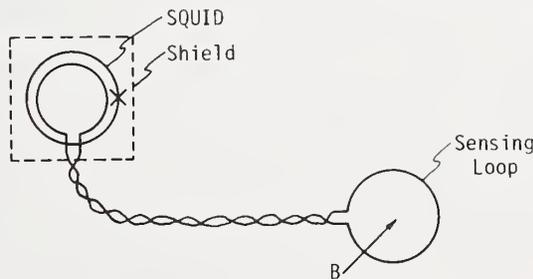


Figure III-3.    Schematic representation of a shielded SQUID coupled to the field B through a flux transformer.  Bias and amplifier circuit is not shown. The SQUID is shown here symbolically as a circle with a small cross representing the junction.  The entire transformer, including the sensing loop is superconducting.

The flux transformer consists of a coupling loop in the SQUID connected by a two-wire line to an external sensing loop to which the field B is applied. The sensing loop can be tailored for any desired orientation and field periodicity. The flux-transformer concept is also very useful for measuring field gradients. A pair of identical sensing loops connected in series opposition (Fig. III-4) will feed a signal to the SQUID proportional to a component of the gradient ($\Delta B_x/\Delta x$, $\Delta B_x/\Delta y$, etc.).
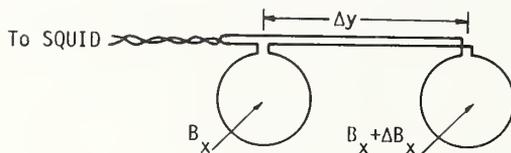


Figure III-4.   Flux-transformer sensing loops in series opposition to measure magnetic-field gradient, $\Delta B_x/\Delta_y$.

The oscillatory nature of the SQUID response vs magnetic field, B, lends itself naturally to digital recording. An algebraic or "up-down" counter on the SQUID output will give digital readings of B in units of $B_o$. Through the use of a flux transformer, the unit $B_o$ can be set at any specific value in an enormous range, at least from $10^{-11}$ T to 0.1 T or higher. A $B_o$ smaller than $10^{-11}$ T may require an impractically large sensing loop. Such extremes may be impractical for another reason also, namely that the maximum reliable counting rate $f_{max}$ of the system imposes a limit on the size of $B_o$ relative to the time rate of change of signal dB/dt which the instrument is required to handle, that is: $\frac{1}{B_o}\frac{dB}{dt}$ must be less than $f_{max}$, or $B_o > \frac{dB}{dt}/f_{max}$.

Digital operation of a SQUID only allows readout to within one unit of $B_o$, which might be, for example, 1 nT. Analog output is achieved by operating the SQUID in a phase-locked loop (Fig. III-5), in which a low-frequency reference signal with a peak-to-peak flux amplitude of $\sim \phi_o$ is applied to the SQUID. The synchronously-detected response is then applied to the SQUID through a feedback resistor, to lock the dc flux in the SQUID onto one particular peak (or valley, depending on the reference phase) of the response pattern of Fig. III-2). The voltage across the feedback resistor constitutes the analog output, since the feedback current in this system is precisely proportional to the applied field B. The limiting sensitivity that is ordinarily achieved with analog operation is $10^{-3}$ to $10^{-4}$ $B_o/\sqrt{Hz}$, so that if $B_o$ is 0.1 nT, one might be able to detect field changes as low as $10^{-14}$ T with a 1 Hz bandwidth.

There is no reason, of course, why the analog output cannot be digitized through the use of a conventional A/D converter, but as noted above, the SQUID is itself a digital device in units of $B_o$. Most practical systems, therefore, use this natural digital feature for large field changes and the analog phase-locked loop for small field changes.
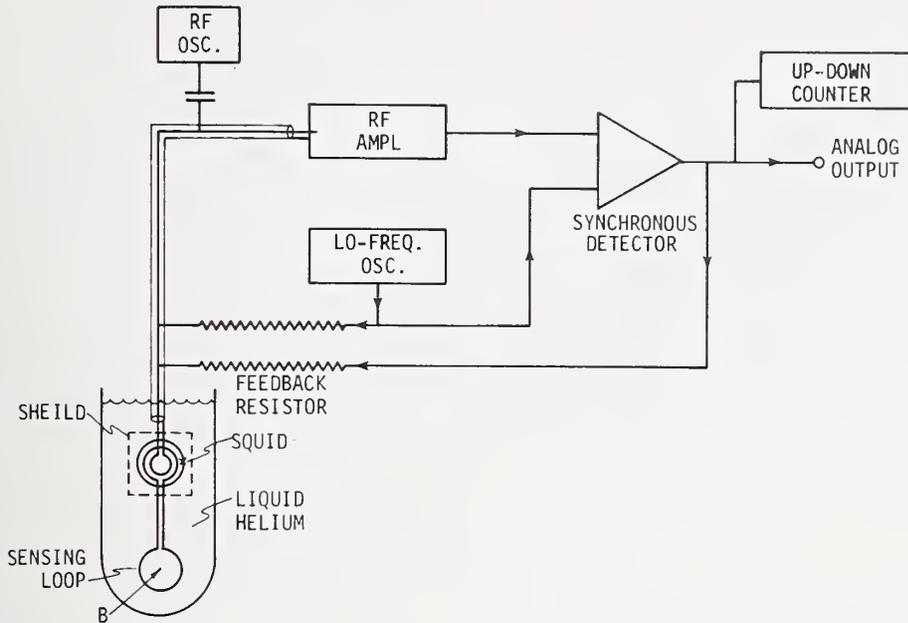
Figure III-5.  Block diagram of complete single-component magnetometer, with
digital readout and analog output.

A way of digitizing the signal is to arrange for the phase-locked loop to break lock for a field change greater than $B_o$ and to reset itself onto the adjacent peak of the response pattern (Fig. III-2).  This discontinuity in the analog output (Fig. III-5) can be used to trigger the up-down counter.  Figure III-6 shows a hypothetical case where the field B has
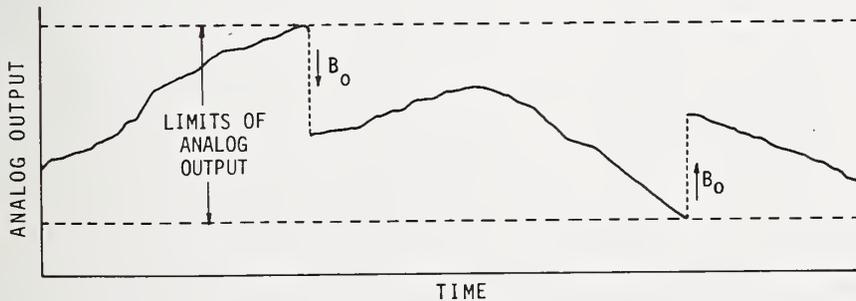


Figure III-6   Hypothetical output vs time of an analog magnetometer, with
downward and upward resets at the analog-output limits.

33

increased for a certain length of time, resulting in a downward reset, and then decreased for a time, resulting in an upward reset. The magnitude of each reset is of course precisely $B_o$, which serves as a standard unit to calibrate the record. An example of an actual record with many such resets is given by Zimmerman and Campbell (1975).

An operational comparison of a SQUID magnetometer with several types of conventional magnetometers for geomagnetic measurements was conducted by Zimmerman and Campbell (1975). They concluded that the only instrument with comparable sensitivity is a large-sized induction loop (with an integrator), but the frequency response of the latter is quite inferior, since it must be tuned for particular ranges of frequency.

Since $B_o$ for a particular SQUID is a highly reproducible unit, it has been suggested that a SQUID is a convenient secondary standard for calibration of other instruments. In fact, $B_o$ for thin-film cylindrical SQUID's can be calculated from the geometry to about a part in $10^4$, but for a primary standard this is not as good as the magnetic resonance instruments can achieve.

Gradiometers are useful for detection and mapping of magnetic anomalies at short to moderate ranges. Present terrestrial applications are detection and tracking of military targets such as submarines, and biomagnetic measurements such as mapping magnetic fields of the human heart and brain. The military application is still in the stage of preliminary development. Measurements on the heart (magneto-cardiography) have reached the stage of being considered for routine clinical use at several universities, notably MIT (David Cohen), Stanford (William Fairbank), Vanderbilt (John Wikswo), and Helsinki Technical University T. Katila).

The most advanced development of gradiometers for magnetic detection and tracking has been done at the Naval Coastal Systems Laboratory (Wynn, et al., 1975). Instrument noise level achieved is about $10^{-13}$ T/m at frequencies in the neighborhood of 1 Hz, with pickup loops a few cm diameter, 30 cm apart.

The general characteristic of gradiometers which makes them useful for these applications is that they are insensitive to the temporal fluctuations of large uniform ambient fields such as the earth's field. This permits sensitive mapping of short-range anomalies, as described above, without interference from fluctuating long-range sources. A superconducting gradiometer was used at NASA Ames Laboratory to map the field due to remanent magnetization of spacecraft on the ground (E. Iufer, private communication).

III.2.1.1.  *Present State-of-the-Art*

Here we summarize the approximate quantitative capabilities of present SQUID instruments.

1.   Range: SQUID's can measure, or be used in, ambient fields approaching the critical field of the superconducting material, which for niobium is greater than 0.1 T, or 1000 times the maximum earth field. There may be some drift and hysteresis problems at such high fields, but since this seems outside the scope of this report, we will not pursue the matter. In a word, for space applications SQUID's are not limited by their dynamic range.

2. Sensitivity: The inherent instrumental noise level of present laboratory systems has been reported (J. Clarke, 1977) to be $10^{-28}$ J/Hz, corresponding to field sensitivities of the order of $10^{-14}$ T/$\sqrt{Hz}$, frequency-independent above 0.1 Hz or so, with "1/f" noise below that frequency. SQUID systems used for biomagnetic measurements have demonstrated operating sensitivities in the range of 1 to 5 x $10^{-14}$ T/$\sqrt{Hz}$ (Cohen, 1975; Williamson, Kaufman and Brenner, 1977; Zimmerman, 1977). For gradiometers the figure is about $10^{-13}$ T/m (Clark, 1977).

To put these figures in the context of the real world, the steady field at the earth's surface is $\sim$ 5 x $10^{-5}$ T, with fluctuations, depending primiarily on solar activity, of $\sim 10^{-7}$ T at frequencies below 0.001 Hz, and $\sim 10^{-10}$ T or less at frequencies approaching 1 Hz. The ac field of the human heart, measured close to the chest wall, is of the order of $10^{-11}$ T, and the so-called alpha rhythm of the brain produces an ac field near the back of the head of $\sim 10^{-12}$ T or less. If the earth could be represented as a simple dipole, the magnetic gradient at the surface would be $\sim 10^{-11}$ T/m.

3. Linearity: SQUID instruments are inherently linear. Non-linear effects, of the order of a part per million, have been seen (R. Clark, private communication) which were ascribed to ferromagnetic impurities in the associated mounting structures, electronics, and so on. Presumably, such non-linearities should be no worse than for other types of instruments. Similar effects were seen when superconducting thin films were used in the construction of the SQUID's. With pure or nearly-pure bulk niobium, as is widely used for SQUID's and flux transformers, the inherent linearity may be of the order of a part in $10^7$ for B up to 0.1 T.

4. Digital Counting Rate and Slew Rate: As described above, there is a maximum rate of change of B that a SQUID instrument can cope with. In the "natural" digital mode, inherent noise limitations permit counting up to the order of $10^5$ $\phi_o$ per second, so if $B_o$ for a particular system is $10^{-9}$ T, the system could marginally handle $10^{-4}$ T per second. This rate of change of field corresponds roughly to what would be seen by a magnetometer loop mounted transverse to the spin axis of a satellite rotating in the earth's field at 0.1 revolutions per second. In the analog mode of operation, the ability of the phase-locked loop to hold on a particular peak of the response pattern (Fig. III-2) is limited in exactly the same way. That is, a simple feedback loop with a 6 dB-per-octave gain curve (a broad-band amplifier with an integrator) can handle a rate-of-change of input field (slew rate) of the order of $10^5$ $\phi_o$ per second. However, in present laboratory and commercial systems the gain curve has been tailored to have more than 6 dB per octave rolloff at low frequencies, which permits handling considerably greater slew rates, approaching $10^6$ $\phi_o$ per second, for low-frequency input signals. The restriction to low-frequencies is not too significant since most applications of SQUID magnetometers are to measurements at low frequencies, dc to a few kHz.

5. Frequency Response: Present phase-locked loops generally incorporate reference oscillators at 100 kHz or less, and the upper frequency limit of the SQUID, operated in this mode, is about half that value. Any rf signal with a field amplitude the order of $B_o$ or

larger will make the system inoperative, since it will average a complete cycle (or more) of the response pattern of Fig. III-2. SQUID's are inherently sensitive to the entire radio spectrum up to $10^{12}$ Hz. Therefore, SQUID's for use in or near the earth must be enclosed in an rf shield. For best reliability, such shields are often of such thickness that the cutoff frequency is just above the highest frequency at which the system is to be used. A cylindrical room-temperature aluminum shield 10 cm diameter and 1 mm thick has a cutoff frequency of about 140 Hz. The rf shield can also be put inside the cryostat around the SQUID or around the SQUID and flux transformer. Johnson flux noise produced by the shield will be seen by the SQUID and may limit the sensitivity, particularly if the cutoff frequency is low (a thick-walled shield), but this would not be a significant operational limitation in most applications.

6. Power Requirements: Bias power requirement of a SQUID is less than $10^{-10}$ W. The associated electronics (rf oscillator and amplifier, reference oscillator, phase-locked detector, video amplifier, etc.) requires from one to several watts in typical systems. An up-down counter might require a comparable amount of power. However, there is no inherent reason why these systems should not be designed to operate on much lower power.

7. Drift: Few applications of SQUID's have required measurements at dc or very low frequencies, so that drift has not been a problem, and there is not much "typical" data to quote. Large drifts (and hysteresis as noted above) have been seen when thin-film SQUID's were operated in field changes of $10^{-4}$ T, but this was eliminated by the use of bulk niobium. Drift can result from several effects associated with temperature instability, such as thermal emf's and other uncompensated effects in the phase-locked loop circuit, and variation of SQUID parameters with temperature. The most important SQUID parameter, $B_o$ (Fig. III-2), might change with temperature, but only by an exceedingly small amount, of the order of a part per million, owing to temperature dependence of the (London) penetration depth.

8. Absolute-Value Measurements: The periodic response of Fig. III-2 contains no clue as to the absolute value of $B_o$, and SQUID's are not ordinarily used for absolute-value measurements. Nevertheless, there are in principle several ways the absolute value can be determined. The most direct is to rotate the instrument about an axis perpendicular to the SQUID pickup-loop axis, so that the peak-to-peak change of field is 2B. Another way would be to slide a movable superconducting shield over the pickup loop to provide a near zero-field reference. A third way would be to incorporate into the instrument a relatively insensitive auxiliary SQUID (or set of SQUID's) with a value of $B_o$ sufficiently large that the zero-field peak of the response is unambiguously determined from the approximately known characteristics of the field being measured. Such cascading may be limited to 2 orders of magnitude per SQUID. The zero-field peak of the auxiliary SQUID can be used to locate the zero-field peak of the primary highly-sensitive SQUID. The zero-field peak could also be located by the use of a simple flux-gate or rotating induction loop magnetometer. The use of an auxiliary SQUID may have other merits, however, in terms of following fast field changes and transients which the primary SQUID lock-on system cannot handle.

9.  Refrigeration Requirements:  SQUID's are generally operated in liquid helium cryostats at temperatures in the neighborhood of 4 K.  The inherent refrigeration power required for a SQUID and its electrical leads can be made negligible, so the total refrigeration power is essentially that used by the cryostat itself.  Helium evaporation rates vary from less than one liter per day for cryostats holding a few liters, to 1.8 liters per day for a 180-liter SQUID cryostat (> 100 days between refills) built for the Naval Research Laboratory (Davis and Nisenoff, 1977).  The latter would be of interest in connection with possible experiments in space.  More to the point are the extensive analyses and experiments at Stanford (Final Report on NASA Grant 05-020-019) for the well-known relativity experiment, which envisions an 800-liter cryostat in space with a one-year operating time, and a similar cryostat for the Infrared Astronomy Satellite (IRAS).

An alternative to liquid helium is the use of a closed-cycle cryocooler to cool the SQUID and flux transformer.  A cryocooler might be relatively compact compared to a six-month or one-year liquid-helium cryostat, but it would add significantly to the power required by the whole system.  In any case, a space-qualified cryocooler suitable for operating a SQUID probably will not be available for several years.

### III.2.1.2.    *Ultimate Potential Performance*

Increasing the bias frequency of an rf SQUID can give significant improvements in inherent sensitivity, maximum counting and slew rates, and in frequency response.  Very high frequency bias systems have been demonstrated in the laboratory, but are not available commercially.  It is probable that a factor of ten or more increase in these parameters can be achieved, a sensitivity to field of $10^{-15}$ $T/\sqrt{Hz}$ for example.  Using a large-area flux transformer sensing loop might provide another factor of ten improvement in field sensitivity, but possible problems from noise generated by the cryostat and other parts of the system have not been investigated at levels below $10^{-14}$ T.

In the case of gradiometers the sensitivity is proportional to the distance of separation of the pickup loops as well as to the loop dimensions.  Within the limits of practical cryostat sizes, present gradiometers are limited by the inherent SQUID sensitivity.  The usefulness of gradiometers for magnetic anomaly detection, biomagnetic measurements, and other applications would be greatly enhanced by improved SQUID sensitivity.

The sensitivity of SQUID magnetometers is more than adequate for most applications, and current efforts are directed primarily toward improving other characteristics such as operating convenience, portability, immunity from transients and rf interference, and slew rate.

### III.2.1.3.    *Projected Development Rate*

Most of the performance characteristics of SQUID's are more than adequate for terrestrial and space applications.  The stimulus for increased sensitivity comes primarily from the Naval Coastal Systems Laboratory gradiometer development and from a few laboratories (Cohen, 1975; Williamson, et al., 1977; and Zimmerman, 1977) using SQUID's to measure brain fields.  In view of this, it may be five to ten years before near-ultimate SQUID sensitivity is routinely realized.

III.2.2. Applications to Magnetic Measurements in Space

Magnetic field measurements are of practical and academic interest in many ways. The prime classical example is the use of a compass needle for navigation on the earth's surface, and it is not entirely inconceivable to suppose that the magnetic field in space or in the vicinity of other planets might also be used as a navigational aid. Magnetic measurements are currently vitally important in geophysical research (e.g., sea-floor spreading and plate tectonics), in mineral prospecting, and in geothermal prospecting.

Magnetic surveys for geophysics and for mineral prospecting are carried out on the surface, from the air, and recently by satellite. Measurements of the temporal variations of the magnetic field at the earth's surface, together with electric field measurements, permit a calculation of the conductivity of the upper layers of the planetary crust, which in turn is related to the sub-surface temperature. The estimate of crustal temperature obtained in this way is of interest in connection with locating geothermal energy sources (see W.D. Stanley, 1978).

A magnetic sensor satellite (MAGSAT) is scheduled for operation in the near future (Langel, 1978). The advantage of satellite surveying is that an enormous amount of data on spatial variations can be obtained over the entire planet in a relatively short time. This first MAGSAT mission will not include a SQUID magnetometer. Assuming success in this mission one might want to consider the inclusion of a SQUID in similar future programs. The superior sensitivity of the SQUID could well reduce the averaging time which is necessary to accumulate a magnetic map of adequate resolution. However, magnetic micropulsations rather than SQUID sensitivity would in most cases determine the amount of averaging required to map the finer details of the geomagnetic field. More importantly, the frequency response of the SQUID could offer an interesting means of studying the interactions between magnetic micropulsations and the ionosphere. A correlation (in time) of micropulsations measured in space and at the earth's surface provides all the information needed to determine the temporal variations of the current sheath within the ionosphere. The SQUID would provide the best possible resolution of such time-varying fields.

It is interesting to consider the magnetic field gradients generated by objects on earth and sensed at a satellite orbit. The magnetic gradient of the earth, considered as a simple dipole, is $\sim 10^{-11}$ T/m at the earths surface. Natural and man-made inhomogeneties (ore bodies, steel structures, etc.) produce a broad spectrum of magnetic anomalies with much larger local gradients. SQUID gradiometers are useful for mapping of such anomalies. A gradiometer, in effect, discriminates against interference from distant fluctuating sources, since the field and the field gradient of a dipole source vary as $1/\rho^3$ and $1/\rho^4$, respectively, where $\rho$ is the distance from the source. We might digress for a moment to note that second-derivative gradiometers, whose response varies as $1/\rho^5$, are currently seen as the best instrument for cardiography and other biomagnetic studies, which are more or less the ultimate in "local" magnetic mapping. On the other hand, gradiometers will be of somewhat limited utility for mapping terrestrial surface anomalies from orbit. For example, a highly-permeable body (like soft iron) 100 m in diameter in the earth's field would produce an anomaly of $\sim 10^{-14}$ T (field) and $\sim 10^{-19}$ T/m (gradient) at an altitude of 200 km. The latter number is far below the sensitivity of any present or projected gradiometer. If the body were much larger (like

1000 m diameter) or strongly magnetized (like 0.1 T), then it still would not be detected by a gradiometer at 200 km, but it would be well within the detection sensitivity of a SQUID magnetometer. The latter would probably be limited by interference from more distant sources such as solar wind fluctuations and their interactions with the magnetosphere. In order to discriminate against such interference, it would be worth considering two (or more) magnetometers in a pair (or more) of satellites separated by 100 km or so -- in effect, a very long baseline, highly sensitive gradiometer (see Fig. III-7). With present SQUID magnetometers, a gradient sensitivity of the order of $10^{-19}$ T/m $\sqrt{Hz}$ would be realized with 100 km separation. Presumably, best signal-to-noise ratio for detection of anomalies on the earth's surface would be achieved when the magnetometer separation is of the same order as their altitude, e.g., 200 km.
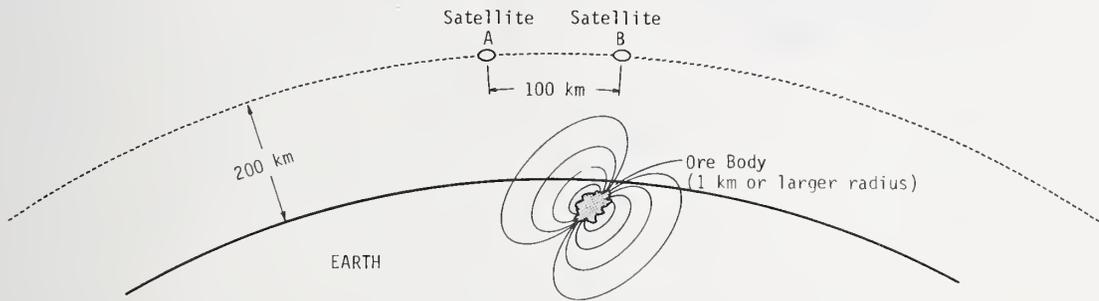


Figure III-7. Suggested system for magnetic survey of the earth. Magnetometers are located in each of the two satellites. The system acts as a very long baseline gradiometer, thus discriminating against interference from distant sources.

The magnetic field in space is a fundamentally significant factor in determining the trajectories of charged particles from the sun and from outer space. For example, the relatively modest magnetic field of the earth acts as a shield against the potentially damaging bombardment by cosmic rays, and it has been suggested that the extinction of species like the dinosaurs might have been associated with a reduction of the earth's field, allowing a lethal dose of cosmic rays.

Except in the vicinity of the planets, the magnetic field is that of the sun. This field is locked into a plasma of charged particles, primarily protons and electrons, emanating from the sun, generally known as the solar wind. Since there are almost no collisions in the rarified plasma constituting the solar wind, the magnetic field pattern imposed on the plasma at the source (i.e., the sun) is locked into it, and plasma and field pattern together flow out from the sun at an average speed of about 400 km/s. One might, for example, find current vortices imbedded in the solar wind which would be observable as magnetic field pulses measured by a stationary instrument. Although the particles do not collide, elements of the plasma can interact through the electromagnetic field, and so can dissipate energy and relax toward thermal equilibrium.

The rotation of the sun causes an instantaneous picture of a field line to be an Archimedes spiral, like the pattern of water droplets from a rotating lawn sprinkler. The field lines are further modified by fluctuations and turbulence at the source. A qualitative picture of these effects, from a review paper by Smith and Sonett (1976), is shown in Fig. III-8. It demonstrates the complex nature of the solar field, its intimate interaction with the solar wind, and the effect on charged particles from outer space (cosmic rays).
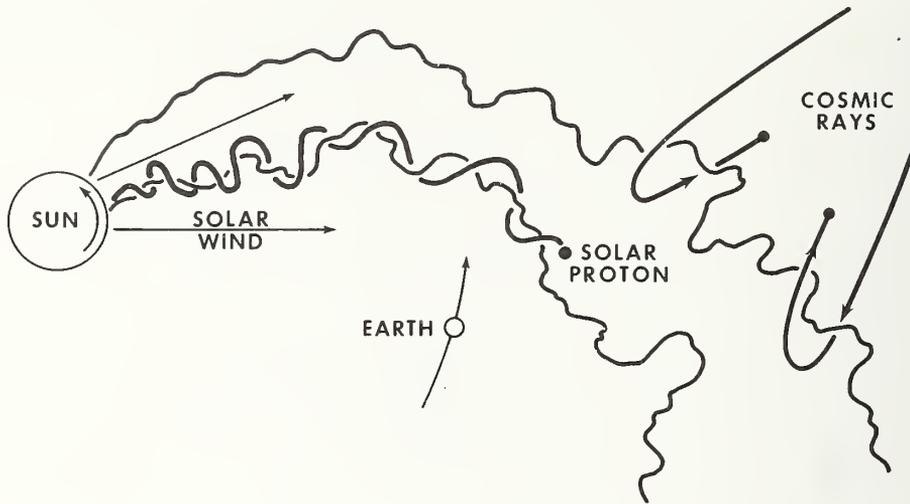
Figure III-8. Hypothetical instantaneous picture of two representative field lines. The path of a high-energy proton spiraling around a field line is indicated, and also the paths of charged particles (cosmic rays) from outer space (from Smith and Sonett).

In the neighborhood of planets and their satellites a variety of complex magnetic effects are seen, depending upon whether or not the body has an ionosphere and whether or not it has an intrinsic magnetic field. The case of an intrinsic field with no ionosphere is exemplified by Mercury, where the solar wind compresses the field pattern on the windward side and draws it out into a tail on the leeward side. Conversely, the intrinsic field deflects the solar wind around the planet and prevents the plasma from impinging directly on it. Venus has an ionosphere but no (or very small) magnetic field. The solar wind and solar magnetic field therefore impinge directly on, and are deflected by, the ionosphere, and so the planet is enveloped much more closely by the solar wind than it would be if it had a large intrinsic magnetic field. The intrinsic field of the planet Earth deflects the solar wind at distances of the order of 10 earth radii. This interaction and interactions with the ionosphere of solar particles leaking through the magnetosphere result in a variety of bizarre phenomena, aurorae, radio interference, magnetic storms, and electrojet currents. These effects have been and will continue to be, intensively studied for both practical and academic reasons. The moon has neither an atmosphere nor an overall magnetic moment, although it does have a complex pattern of local magnetization, so its effect on the solar wind

and cosmic particles is simply to intercept them and create a shadow on the downstream side. Fluctuations of the solar magnetic field carried along with the plasma induce eddy currents in the moon. Measurements of the eddy-current contribution to the field near the moon have been used to infer the electrical conductivity, and from this the temperature profile, inside the moon, in the same way that natural magnetic field fluctuations at the surface of the earth are used in geothermal prospecting (see above).

These examples show that magnetic field measurements are crucial to the experimental study of the physics of the solar system. One can predict that this will continue to be the case in the forseeable future, and that by this means various phenomena will ultimately be better understood. Some examples are the origins and variations of sunspots, with their associated intense magnetic fields, the origin or lack of planetary magnetic fields, and in the case of the earth, the frequent reversals of magnetic field during recent ($\sim$ 10 million years) geologic history, and the interaction of the solar plasma and field with the more rarified interstellar medium.

According to numbers quoted by Allen (1973), there are less than $10^5$ electrons/cm$^3$ (p 265) in interstellar space (near the galactic plane), and the magnetic field is of the order of 1 nT (p 269). These values are somewhat smaller than the corresponding numbers for the solar plasma and magnetic field at the earth's orbit. However, if the latter vary inversely as the square of the solar distance, then they should become comparable to the former somewhere within the orbits of the outer planets. The dynamic pressure of the solar wind pushes the interstellar medium out to greater distances, however, so a study of interaction may be somewhat beyond the capability of present space probes (Mason, 1978; Smith, et al., 1975).

Since the plasma constituting the solar wind is a nearly perfect conductor, spatial variations of magnetic field take place over a characteristic minimal distance, the analog of the London penetration depth in a superconductor, namely

$$d = \left(\frac{m}{n\mu_o}\right)^{1/2} \frac{1}{e}$$

where m, n and e are respectively the mass, number density, and charge of the particles. For $5 \times 10^6$ electrons per cubic meter, d is about 2 1/2 km. The solar-wind speed being the order of 400 km means that the characteristic time for field changes is of the order of 0.01 s. However, spatial field variations of the order of 10 nT cannot take place over such short distances as this would require electron velocities in the current sheet greater than the velocity of light.

According to Sonett (1978) the characteristic distances for magnetic field change are $\sim 10^5$ km in interplanetary space and $\sim 10^3$ km at the "bow shock" wave where the solar wind begins to interact with the earth's magnetic field. In either case, the field changes are of the order of 10 nT, corresponding to current sheets of the order of $10^{-2}$ A/m or current densities j of $10^{-10}$ A/m$^2$ and $10^{-8}$ A/m$^2$ respectively. Assuming a plasma density n of $5 \times 10^6$ electrons/m$^3$ leads to drift velocities of

$$V = j/ne \simeq 10^2 \text{ m/sec for interplanetary space,}$$
$$\text{and } \sim 10^4 \text{ m/sec in the bow shock.}$$

The gradients represented by the above numbers are $10^{-16}$ T/m and $10^{-14}$ T/m respectively. For a wind velocity of 400 km.sec the time derivatives are $4 \times 10^{-11}$ T/sec and $4 \times 10^{-4}$ T/sec. Belcher and Davis (1971) refer to Alfvén waves in the solar wind with wavelengths as short as $10^3$ km and amplitudes of several nT, indicating gradients of the order of $10^{-14}$ T/m. These gradients are well below the measurement capability of any existing or projected gradiometer. However, the solar plasma could in principle sustain much greater magnetic gradients. With $5 \times 10^6$ electrons/m$^3$ moving at one-tenth the speed of light, the gradient would be about $3 \times 10^{-10}$ T/m. This is within the range of present gradiometers, which might therefore be useful for studying local anomalies of high current density in the solar wind or planetary ionospheres.

III.3.0.  GALVANOMETERS, VOLTAGE AND CURRENT SENSORS, AND WIDE-BAND AMPLIFIERS

SQUID's are used in many laboratories as low-impedance galvanometers or galvanometer amplifiers. An example which might be pertinent to space application is the use of a SQUID to amplify the output of a thermoelectric element or a bolometer for measuring absolute radiation levels or small temperature changes. A common application is the use of a SQUID as a null detector in a cryogenic potentiometer for measuring resistivity of highly-pure metal specimens.

The voltage or current sensitivity of a SQUID galvanometer is a function of the inductance $L_{in}$ of the input coil. If the SQUID can detect a magnetic field energy $E_{min}$ of the order of $10^{-28}$ J/Hz (see Section on SQUID magnetometers), then the current sensitivity is derived from $1/2\ L_{in} i_{min}^2 \sim 10^{-28}$ J/Hz. The practical range of values for $L_{in}$ is perhaps $10^{-8}$ H to $10^{-2}$ H, although this can be extended either way through the use of an auxiliary superconducting current transformer. This gives a range of current sensitivities $i_{min}$ from $\sim 10^{-10}$ A/$\sqrt{\text{Hz}}$ to $10^{-13}$ A/$\sqrt{\text{Hz}}$. The input coil is assumed to be superconducting, so it has no resistance, and the voltage sensitivity cannot be defined in the usual way. If the input coil is connected to a signal source whose internal resistance is $R_s$, then the minimum detectable source voltage $E_{min}$ is $i_{min} R_s$, and the response is exponential with a time constant $L_{in}/R_s$. If it is required that the circuit respond with a time constant of 1 second, for example, then the range of values for $R_s$ and for $E_{min}$, given a range of $10^{-8}$ H to $10^{-2}$ H for $L_{in}$, is $10^{-8}\ \Omega$ to $10^{-2}\ \Omega$ and $10^{-18}$ V/$\sqrt{\text{Hz}}$ to $10^{-15}$ V/$\sqrt{\text{Hz}}$, respectively.

Thermal noise in a single loop circuit, such as a source resistance $R_s$ connected to an input coil $L_{in}$ at temperature T, is given by $1/2\ k_B T$, where $k_B$ is Boltzmann's contant ($1.4 \times 10^{-23}$ J/K). At 4 K, thermal energy is $5 \times 10^{-23}$ J, which is $10^6$ times greater than the minimum energy the SQUID can detect. Therefore the above numbers for $L_{min}$ and $E_{min}$ are academic in the sense that in many practical cases the predominant circuit noise is thermal noise in the source itself. The effective noise temperature (by the usual definition) of a SQUID galvanometer is of the order of 1 µK. By measuring the thermal noise power from a resistance $R_s$, a SQUID can be used as an accurate absolute thermometer from less than a

millikelvin up to a temperature at which the resistor melts or otherwise changes its proper-
ties. This application was originally suggested and reduced to practice by Kamper, in a
version where the source resistance $R_s$ was built into the SQUID itself (Kamper, Siegwarth,
Radebaugh and Zimmerman, 1971).

If flat response from dc to high frequency is required, then the time constant $L_{in}/R_s$
must be reduced accordingly. The SQUID noise energy $E_{min}\Delta f$ is proportional to the input
circuit bandwidth $\Delta f = R_s/2\pi L_{in}$ and the noise temperature is $T_n = E_{min}\Delta f/k_B$. For example, a
bandwidth of dc to 100 MHz would give $T_n \sim 10$ K, which is still a rather low noise tempera-
ture. Such wideband amplification is somewhat outside the context of low-frequency sensors,
but it illustrates the versatility of SQUID's, and also the point mentioned elsewhere that
strong high-frequency signals may interfere with SQUID operation unless rf shielding is
provided. The possibility of using SQUID's for uhf and vhf amplification was discussed by
Zimmerman and Sullivan, (1977).

### III.4.0. MAGNETIC SHIELDING

An enclosure with superconducting walls a millimeter or so thick provides essentially
perfect shielding against changes of external ac and dc magnetic (and electric) fields.
Also, since magnetic flux can only penetrate a superconductor in integral multiples of the
flux quantum $\phi_o$, it is theoretically possible, by cooling such an enclosure in sufficiently
low field, that one may end up with absolute zero field inside the enclosure. The technical
obstacles are formidable, however, and zero field has not been experimentally realized in
large ($\gtrsim 0.1$ m inside dimensions) enclosures. Trapped residual fields lower than $10^{-11}$ T
have been achieved at Stanford, with rather sophisticated techniques (Everitt, 1977).

Very low residual field is essential for highly precise superconducting gyroscopes, as
used in the Stanford experiments, and possibly for other applications such as inertial
guidance, force-free satellites, and gravitational wave experiments.

The perfect shielding property of superconducting enclosures (as distinct from the
possibility of zero or very low residual field) is routinely used in SQUID susceptometers and
other laboratory instruments to eliminate externally generated magnetic interference. The
degree of shielding that is realized depends entirely upon the size and shape of the access
ports. Geometry of the access ports is perhaps the only subtle aspect of the design of
superconducting shields. Arbitrary geometries are probably best analyzed numerically or
empirically. For a cylindrical shield with open ends, an externally applied field drops by
about a factor of 30 per shield diameter, inside the shield.

### III.5.0. DC TRANSFORMER

The superconducting dc transformer was invented by I. Giaever (1968). This is a thin-
film device in which flux-vortex flow in a primary film induces a nearly identical pattern of
vortex flow in a secondary film which overlays the primary. By this mechanism dc or ac
power is transmitted from the primary to the secondary, and impedance transformations can be
effected by making the films multi-layered. Being a thin-film device, the dc transformer is

adaptable to microcircuit fabrication. Suggested uses include impedance matching to low impedance devices such as superconducting bolometers and other infrared sensors, and the like. Such applications have not yet been demonstrated, however.

Significant advances in fabrication have been made by J. Ekin (1977), who has developed thin films with low flux-pinning forces, to improve the efficiency of the transformer.

Shot noise, analogous to shot noise in vacuum tubes and transistors, is produced by the vortex flow in the dc transformer. Although some measurements of vortex shot noise have been made on single films, its effect on the ultimate performance of the dc transformer in low-noise circuits has not been analyzed or measured. Such measurements must be made in order to establish the potential usefulness of the dc transformer.

Work on the dc transformer is continuing at NBS/Boulder Laboratories, and there is considerable literature on the pertinent properties (i.e., flux flow) of thin films.

### III.6.0. SUMMARY AND CONCLUSIONS

*The SQUID performance surpasses that of all other magnetic sensors in sensitivity, frequency response, range and linearity. The SQUID is moderate in cost, reliable and portable.* Its use (or non-use) in the space program will certainly be determined by the performance requirements for particular missions. If the low-temperature environment must be added to an otherwise non-cryogenic mission, then the superior performance needs will have to be justified. However, we believe that it is reasonable to assume that, as one collects more information on magnetic fields in space, the need (and desire) for better temporal and spatial resolution will provide this justification.

The results from the impending flight of MAGSAT should be enlightening. Will conventional magnetometers provide sufficient detail for the location of magnetic anomalies (perhaps ore bodies)? Detailed study of MAGSAT records should indicate whether increased sensitivity might reveal significant new information.

We suggest that SQUID instruments, both magnetometers and gradiometers would be of value in studies of the dynamics of interplanetary and planetary fields. Such instruments could reveal details concerning local anomalies of high current density in the solar wind or variations in the ionospheric currents of the planets, particularly the earth (see Section III.2.2.)

The SQUID as a low-frequency amplifier may offer certain advantages for amplification of transducer signals. For example, one may need to provide gain immediately following a sensitive cryogenic bolometer (see Chapter V). The SQUID is an excellent low-noise amplifier, especially for low impedance sources (such as some bolometers) and provides ample gain in the cryogen with sub-microwatt dissipation. This last fact could affect the lifetime of cryogenic missions, where the heat load on the cryogenic environment must be kept to a minimum.

The SQUID is in a quite advanced stage of development and only needs space qualification of components to be considered for space missions. This would seem to be a straightforward process, since commercial SQUID systems are already rugged and reliable. The device sits waiting for a space application which demands its performance.

## III.7.0. REFERENCES

Allen, C.W. (1973). *Astrophysical Quantities*, Athalone Press, London.

Belcher, J.W. and Davis, L., Jr. (1971). Large-Amplitude Alfvén Waves in the Interplanetary Medium, 2. *J. Geophys. Res. 76*, 3534-3563.

Clark, R.H. (1977). Naval Coast Systems Laboratory, Panama City, Florida. *(Private Communication)*.

Clarke, J., Goubau, W.M. and Ketchen, M.B. (1976). Tunnel Junction dc SQUID: Fabrication, Operation and Performance. *J. Low Temp. Phys., 25*, 99-144.

Clarke, J. (1977). Summary and Conclusions. [see Hahlbohm and Lübbig, 1977], 587-594.

Cohen, D. (1975). Measurements of the Magnetic Fields Produced by the Human Heart, Brain and Lungs. *IEEE Trans. Mag., MAG-11*, 694-700.

Davis, J.R. and Nisenoff, M. (1977). [see Hahlbohm and Lübbig, 1977], 439-484.

Deaver, B., Jr. (1978). *Proceedings, Conference on Future Trends in Superconductive Electronics*, AIP Spec. Pub., to be published.

Ekin, J. (1977). *U.S. Patent 4,044,298*.

Everitt, C.W.F. (1977). editor, *Perform a Gyro Test of General Relativity in a Satellite and Develop Associated Control Technology*. Final Report on NASA Grant 05-020-019.

Giaver, I. (1968). *U.S. Patent 3,394,317*.

Hahlbohm, H.D. and Lübbig, H. (1977), editors, *Superconducting Quantum Interference Devices and Their Applications*. Walter de Gruyter, Berlin.

Kamper, R.A., Siegwarth, J.D. Radebaugh, R. and Zimmerman, J.E. (1971). Observation of Noise Temperature in the Millikelvin Range. *Proc. IEEE, 39*, 1368-1369.

Langel, R.A. (1978). NASA Goddard Space Flight Center, Greenbelt, Maryland. *(Private Communication)*.

Mason, P. (1978). Jet Propulsion Laboratory, Pasadena, California. *(Private Communication)*.

Silver, A.H. (1976). editor, *1976 Navy Study on Superconductive Electronics*. ONR Report No. NR 319-110.

Smith, E.J. and Sonnett, C.P. (1976). Extraterrestrial Magnetic Fields: Achievements and Opportunities. *IEEE Trans. on Geosci. Electronics, GE-14*, 154-171.

Sonnett, C.P. (1978). University of Arizona, Tucson, Arizona. *(Private Communication)*.

Stanley, W.D. (1978). Cryogenic Techniques and Geophysical Measurements. [see Zimmerman and Flynn, 1978], 205-206.

Williamson, S., Kaufman, L. and Brenner, D. (1977). Biomagnetism. In *Superconductor Applications: SQUID's and Machines*. (eds. B.B. Schwartz and S. Foner), 355-402, Plenum Press, New York.

Wynn, W.M., Frahm, C.P., Carroll, P.J., Clark, R.H., Wellhoner, J. and Wynn, J.M. (1975). Advanced Superconducting Gradiometer/Magnetometer Arrays and a Novel Signal Processing Technique. *IEEE Trans. Mag., MAG-11*, 701-707.

Zimmerman, J.E., Thiene, P. and Harding, J.T. (1970). Design and Operation of Stable rf-Biased Superconducting Point-Contact Devices and a Note on the Properties of Perfectly Clean Contacts. *J. Appl. Phys., 41*, 1572-1580.

Zimmerman, J.E. and Campbell, W.H. (1975). Tests of Cryogenic SQUID for Geomagnetic Field Measurements. *Geophysics, 40,* 269-284.

Zimmerman, J.E. (1977). SQUID Instruments and Shielding for Low-Level Magnetic Measurements. *J. Appl. Phys., 48,* 702-710.

Zimmerman, J.E. and Sullivan, D.B. (1977). High-Frequency Limitations of the Double-Junction SQUID Amplifier. *Appl. Phys. Lett., 31,* 360-362.

Zimmerman, J.E. and Flynn, T.M. (1978). editors, *Proceedings of the Conference on Applications of Closed-Cycle Cryocoolers to Small Superconducting Devices,* NBS Special Publication SP-508.

CHAPTER IV

DIGITAL APPLICATIONS OF SUPERCONDUCTIVITY

R. E. Harris

Superconducting electronics offers remarkable new capabilities for both ground-based and space applications.   In fact *it appears that it will be possible in 10 to 20 years to construct a satellite computer having the computing power of today's most powerful ground based computers.*   This technology also will make possible new instruments capable of examining phenomena occurring on a picosecond ($10^{-12}$ s) time scale.

Superconducting electronics uniquely offers a variety of properties which make these revolutionary advances exciting.   In computer language the technology consists of a fast active element (the Josephson junction), an active element with remarkably low dissipation, and essentially lossless transmission lines which can be terminated by matched loads to minimize reflections and achieve the fastest response.   In the language of instrumentation, superconducting electronics offers ultra-low-noise, high speed of response and immense bandwidth.

These advantages, when compared with conventional electronics, are the result of some fundamental physical laws and not due to lack of development of conventional electronics.   In fact superconducting electronics has achieved these advantages in the infancy of its development, while semiconductor electronics is a most mature technology.   For applications requiring the ultimate in performance, there appears to be no presently known competitor to superconducting electronics, although, of course, some new technology may appear in the future.

Because the technology is so new we begin by discussing fundamental considerations which appear to suggest that cryogenic technology be used for future digital devices.   Secondly we show how the active element in superconducting electronics (the Josephson junction) works and discuss the technology for fabricating the devices.   Finally we review the characteristics of published circuits, and project the capabilities of future superconducting computers and instruments.

## IV.1.1.    Difficulties with Present Digital Technology

Serious difficulties are being encountered in achieving substantial further increase in computer speed.   Because of the finite speed of light, the maximum dimension of a processor may be not bigger than say half the distance an electromagnetic signal can travel in one machine cycle time.   The Cray-1 is apparently now the fastest available computer, having a cycle time of 50 ns.*   Its processor and one million 64-bit words of memory are crammed into only 1.7 m$^3$.   Its maximum dimension, measured in terms of the time required for light to traverse it, is 5 x $10^{-9}$ s.   Within that space are dissipated 115 kW.   It is a remarkable engineering feat to remove that heat.

In order to construct a future 1 ns computer, the diameter should be no more than about 5 cm (2 in.),** having a volume of 6.5 x $10^{-5}$ m$^3$ (65 cm$^3$).   As will be shown later, it is likely that such a computer, constructed with the same technology as the Cray-1, would in

_____

*  Within some repetitive calculations the Cray-1 can seem to have a cycle time of 12.5 ns.
** The velocity of propagation is assumed to be reduced by a factor of 3 from that of free
   space because of the reduced velocity within microstriplines in the machine.

fact dissipate more heat than the Cray. Thus the task of cooling such a computer would be still more difficult than with the Cray, perhaps impossible.

## IV.1.2. Fundamental Principles Governing Digital Logic Devices

The fundamental principles which demonstrate the advantages of superconducting electronics have been well discussed by Keyes (1969, 1970, 1975, 1977). Indeed, his papers are required reading for those wishing to thoroughly investigate the subject.

Keyes begins by pointing out that the power dissipated by any device is described by $V^2/Z$, where V is some average voltage across the device and Z is its impedance. He then develops the values of V and Z using the following arguments.

In a computer, a signal must progress through a large number of active devices and transmission lines. If only a small amount of noise is added to the signal at each stage, the signal will rapidly become lost in the noise. Thus each stage of a computer standardizes the signal as illustrated in Fig. IV-1. As can be seen, variations of the input signal are
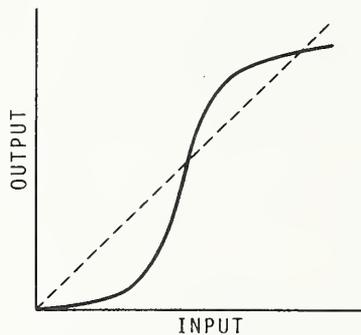


Figure IV-1. Illustration of the non-linearity required of each active element in a digital system. Because a wide range of inputs give either a low- or high-level output, noise at the output is reduced. The output is said to be standardized.

moderated by the non-linear responses; that is, small amounts of noise at the input are suppressed at the output. To achieve such standardization, a non-linear device must be used. To achieve a non-linear response the input voltage must be greater than kT/e. If V << kT/e, then the motions of the charge carriers in the device would be affected little in comparison with their thermally-induced motions, and a linear response would result. For the sake of simplicity we will assume that $V \geq 10$ kT/e.

The impedance of the device is obtained by noting that all computers or instruments must eventually communicate with the outside world at impedance levels of the order of that of free space. The latter has an impedance of $Z_o = 377$ Ω. For the most efficient power transfer, the device impedance must not be too far from $Z_o$. Thus, for our order of magnitude argument, we use $Z_o$ for the impedance of the device. Therefore, remembering that we have assumed that $V \geq 10$ kT/e, the minimum power dissipation is

$$P \geq (10 \ kT)^2/Z_o \ . \qquad\qquad (IV-1)$$

The minimum dissipation varies as $T^2$ having a value of $1.66 \times 10^{-4}$ W for T = 300 K and $2.95 \times 10^{-8}$ W at T = 4 K.

A further consideration shows that dissipation will increase with increasing speed of response. When a device changes state, the voltage across it changes. To develop this voltage, energy $1/2 \ CV^2$ must be added. The capacitance C is that of the device. Now when the device is returned to its original state, the energy is dissipated. Thus the minimum dissipation for a device which is charged and discharged every $\tau$ seconds is

$$P = CV^2/2\tau \ . \qquad\qquad (IV-2)$$

Hence if a cycle time $\tau$ is required, then the clear goals of technology are to reduce the temperature and the capacitance. Capacitance is largely determined by device dimensions. In turn, these are determined by the method of lithography used to produce the device. Thus, technologies do not differ too much in capacitance. Therefore whenever it becomes difficult to remove excess heat, the clear advantage will go to the technology which provides the lowest heat dissipation. As demonstrated above, this might be best accomplished with a low temperature technology.

A useful way of characterizing the dissipation in a logic gate is through the product of its power dissipation and logic delay time. The result is roughly the energy dissipated in a switching process. Fig. IV-2 shows a plot of delay time as a function of dissipation for a variety of semiconductor and superconductor devices. The diagonal lines represent a constant P$\tau$ product. It can be seen that superconductor devices have a large advantage (1000 - 10,000 better P$\tau$ product).

IV.1.3.  Josephson Logic Gate

Many of the difficulties with conventional digital logic are overcome by superconducting logic. The active device in superconducting logic, the Josephson logic gate, is formed from one or more Josephson junctions. A Josephson junction is formed by two superconducting electrodes, separated by a thin insulating layer only a few tens of angstroms thick. To achieve its remarkable properties, the junction must be cooled to a low temperature ($\sim$ 4 K) so that the junction electrodes are superconducting. Junctions have been used in two configurations to form Josephson logic gates.

The first is simply a single Josephson junction having insulated control wires over it, as shown in Fig. IV-3. As is discussed in Appendix IV-A, it is the magnetic field produced by a current flowing through the control wire which causes the junction to change state.

The second type of Josephson logic gate is called a Superconducting QUantum Interference Device, or SQUID. It is composed of two, three, or more small Josephson junctions. A three-junction device is shown in Fig. IV-4. Connected in parallel, these junctions are small
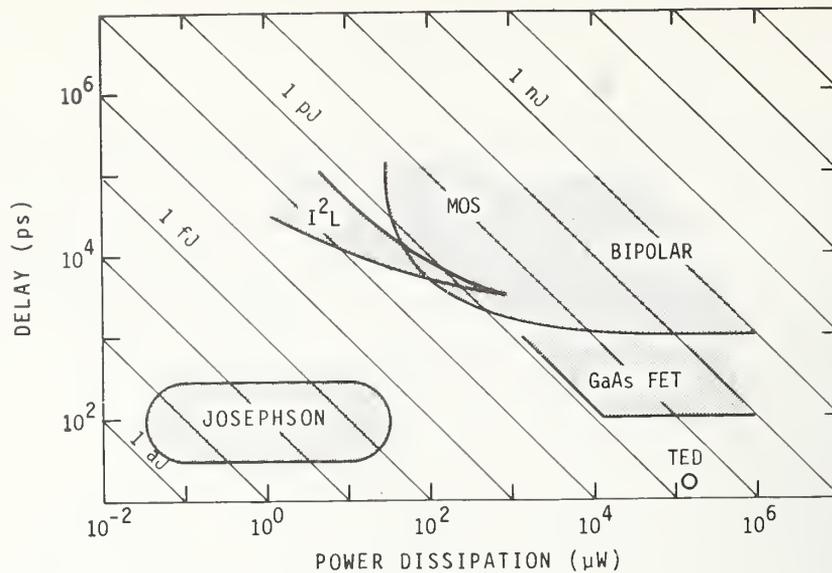
Figure IV-2. Delay time as a function of power dissipation for a variety of electronic technologies. The product of delay and dissipation gives roughly the energy required for one switching operation. The diagonal lines are for equal energies. Josephson devices are seen to be as fast as any other technology, but to produce 1000 to 10,000 times less energy. The energy units (nJ, pJ, fJ, aJ) are $10^{-9}$, $10^{-12}$, $10^{-15}$ and $10^{-18}$ joules, respectively.
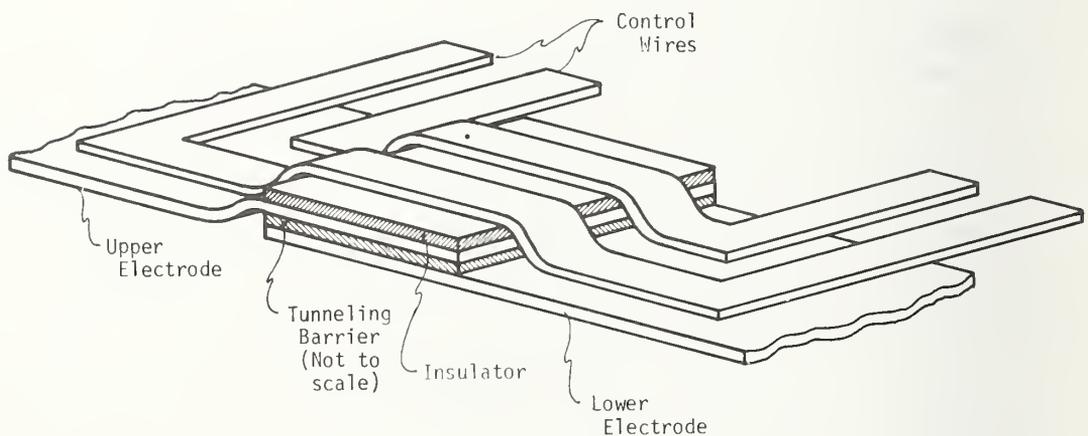


Figure IV-3. Illustration of a thin film, Josephson junction. Two control lines are shown above, and insulated from, the junction.

52
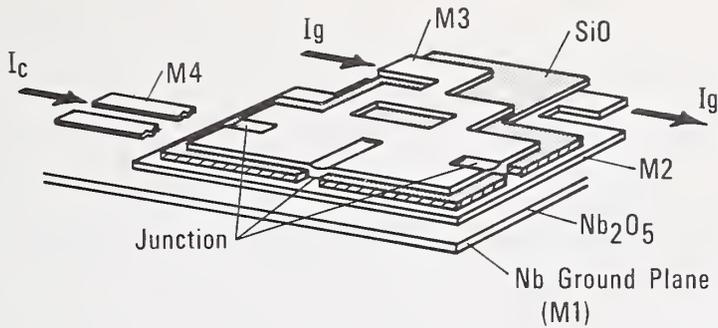
Figure IV-4.    Quantum interference Josephson gate composed of three junctions in
parallel.  The labels Mn refer to different layers of metallization.
Two control lines are shown at the left.  They are not drawn across
the top of the device so as to reveal junction structure.  $I_c$ is a
control current, and $I_g$ is the bias current for the gate.

enough that the magnetic field produced by the control wire does not affect them directly.
Instead, the switching is induced by the field passing through the loops of superconductors
connecting the junctions.  This type of device is more sensitive to magnetic fields than is
the single junction, and is therefore a better candidate for miniaturization.  It is ex-
pected to be the dominant type of device in the future, although most published work to date
concerns the single junction.

IV.1.4.    Advantages of Superconducting Technology

IV.1.4.1. *Device Speed*

The intrinsic response time, $\tau_g$, of a Josephson junction is determined by the super-
conducting energy gap, $2\Delta_o$, by the relation,

$$\tau_g = \hbar/2\Delta_o .$$                    (IV-3)

For lead, which has an energy gap of $2.5 \times 10^{-3}$ eV, $\tau_g = 0.27$ ps.

A more serious limitation is due to the intrinsic capacitance C in a device consisting
of two planar electrodes separated by an exceptionally thin insulating layer.  An RC time
constant, where R is the junction normal state resistance, determines the response time of
the device.  Although data on this time constant is scarce for realistic alloys from which
junctions are made, R can be estimated from information in a patent for an alloy of Pb with
6.5% In.  The capacitance C can be approximated from a variety of papers.  The resulting
dependence of RC on the current density $j_c$ and the barrier thickness is shown in Fig. IV-5.
The figure is probably correct to half an order of magnitude.  Reliable junctions have been
fabricated with critical current densities up to at least $2 \times 10^3$ A/cm$^2$.  This corresponds to
$RC/\tau_g = 13$.  Thus, for superconducting lead, RC = 3.5 ps, an extremely low value when com-
pared to conventional electronic devices.

53
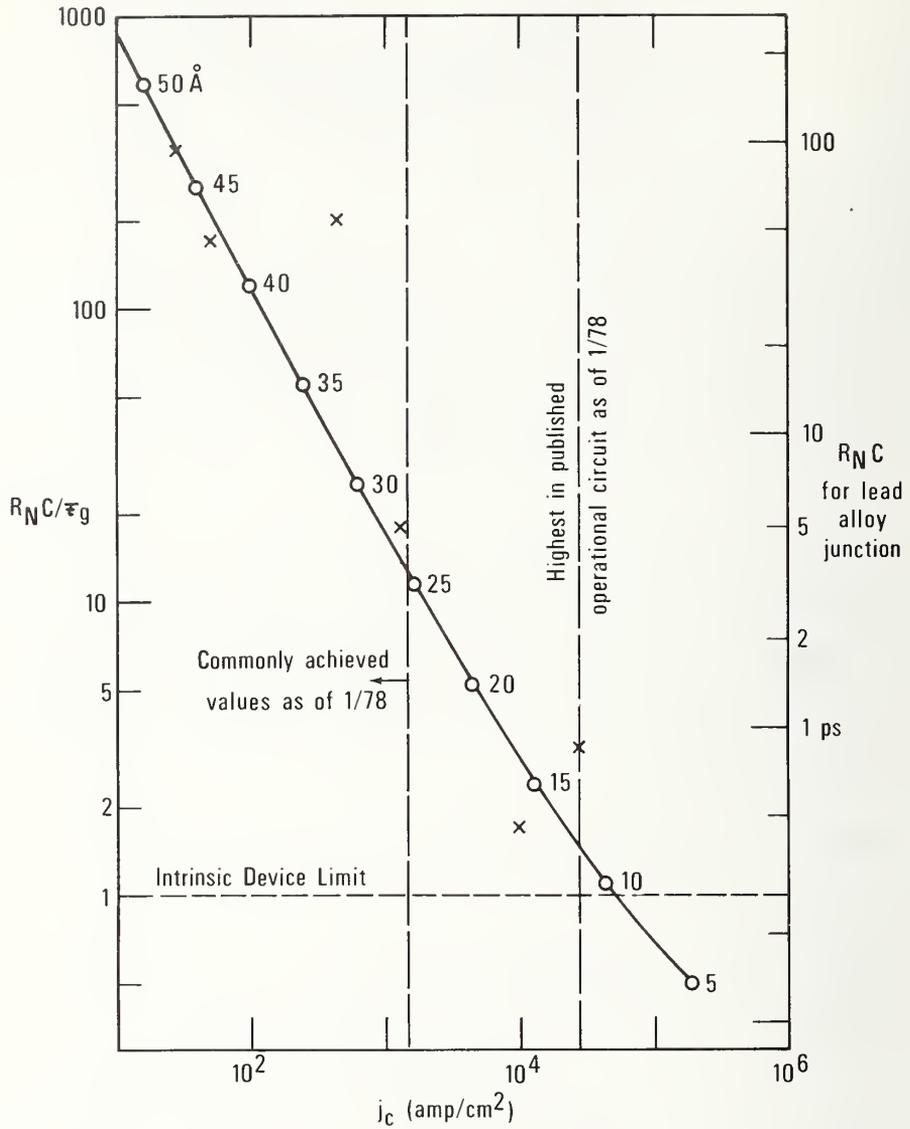
Figure IV-5. Response time of Josephson tunnel junction, when limited by RC, as a function of critical current density. $R_N$ is the normal state resistance of the junction and C is its capacitance. The left ordinate gives $R_N C$ normalized to the intrinsic response time $\tau_g = 2\Delta_0/e$. The right ordinate gives the time in ps for a lead alloy junction. The solid line (with circles) is from an analytic expression derived from a variety of papers and a patent. The x's are measured values from several papers.

It may be possible to fabricate reliable devices having much higher critical current densities, making it possible to achieve the intrinsic device response time. However, as is usual, other parameters will also serve to make it very difficult to achieve this performance in a circuit.

### IV.1.4.2. *Dissipation*

That Josephson junctions offer dramatically lower dissipation than semiconductor devices has been discussed in Section IV.1.2. It should be noted here, however, that low dissipation is probably a more significant advantage than high speed. We note that in Fig. IV-2, the Transferred Electron Device (TED) exhibits similar response time compared to a Josephson junction.

### IV.1.4.3. *Superconducting Transmission Lines*

Although the superconducting technology offers a remarkably fast, low-dissipation active element, there remains another very significant advantage over semiconductor technology -- lossless, low dispersion microstrip transmission lines.

In a very fast integrated circuit it is important that high speed signals be propagated throughout each chip, and from chip to chip, faithfully. Thus, waveguide-like structures are required. In thin-film technology a convenient structure is the microstrip line. This line is composed of a conducting ground plane, covered by an insulator, with a narrow line of conductor on the top. When used properly, this structure will propagate signals with little loss or dispersion. We will demonstrate, however, that such a line is not satisfactory when miniaturized for use in a small integrated circuit.

Microstrip lines are often fabricated in larger sizes using printed circuit technology. We illustrate the characteristics of such a line in Fig. IV-6. The line is assumed to be 0.69 cm wide on a 0.16 cm thick printed circuit board which has a dielectric constant of 3. The line has an impedance of 50 $\Omega$. The conductors are assumed to be 0.0075 cm thick. We show in the figure the attenuation $\alpha$ per unit length and the phase velocity $v_\phi$. The attenuation is shown to rise with frequency to a maximum of about $10^{-3}$ dB/mm at $10^{11}$ Hz. This should be quite acceptable for common-sized PC boards. The phase velocity is seen to be the same for all high-frequency components, but to drop off for low frequencies. It is important for all frequency components to travel at the same velocity so that waveforms such as pulses are not distorted as they propagate down the line. The low frequency drop-off can be understood in terms of the ratio of the electromagnetic skin depth $\delta$ to the dielectric thickness S. The skin depth is given by $\delta = \sqrt{2/\omega\mu_0\sigma}$ so that it becomes smaller with increasing frequency. At high frequencies when $\delta \ll S$ the field is confined within the lossless dielectric and there is negligible dispersion. That is, all frequency components in this range travel with the same velocity $v_\phi$. However, as $\delta$ becomes larger than S, the field pattern changes with frequency and the dispersion becomes substantial, as reflected by the change in $v_\phi$ with frequency. Examining the graph, it can be seen that signals having a fundamental frequency component of about $10^5$ Hz or greater can be faithfully propagated by this example line.

When we consider a miniaturized line, however, normal state lines work very poorly if indeed they can be said to work at all. Consider the example in Fig. IV-7a for a 2 $\mu$m-wide

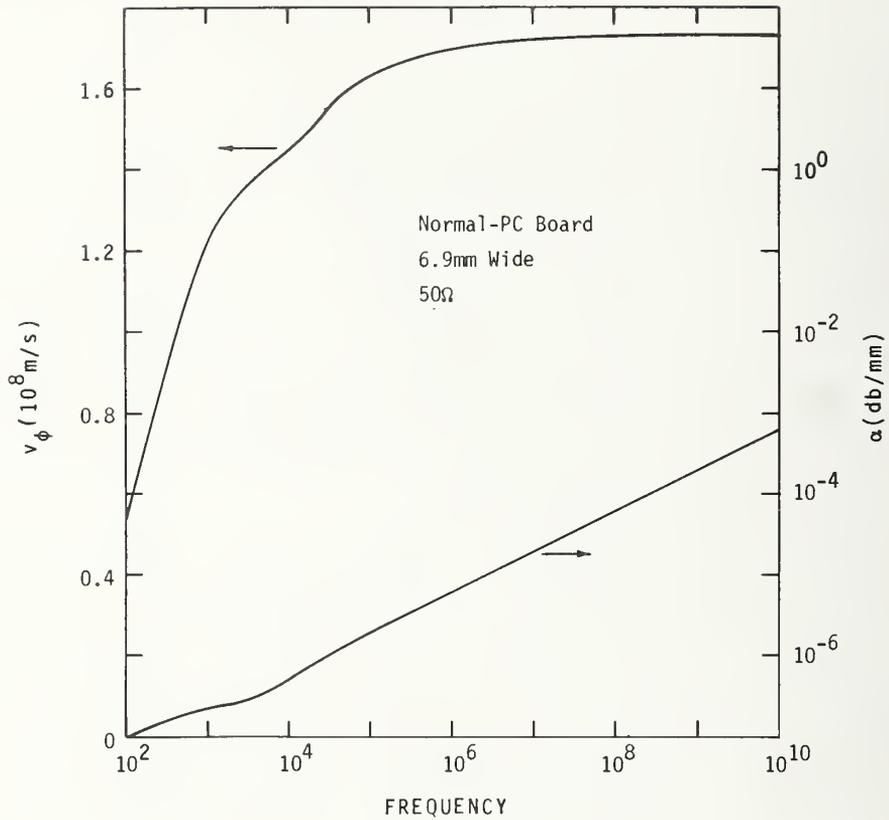Figure IV-6.   Phase velocity $v_\phi$ and attenuation $\alpha$ of a room-temperature copper strip-line on a printed circuit board.   Dimensions are given in the text.
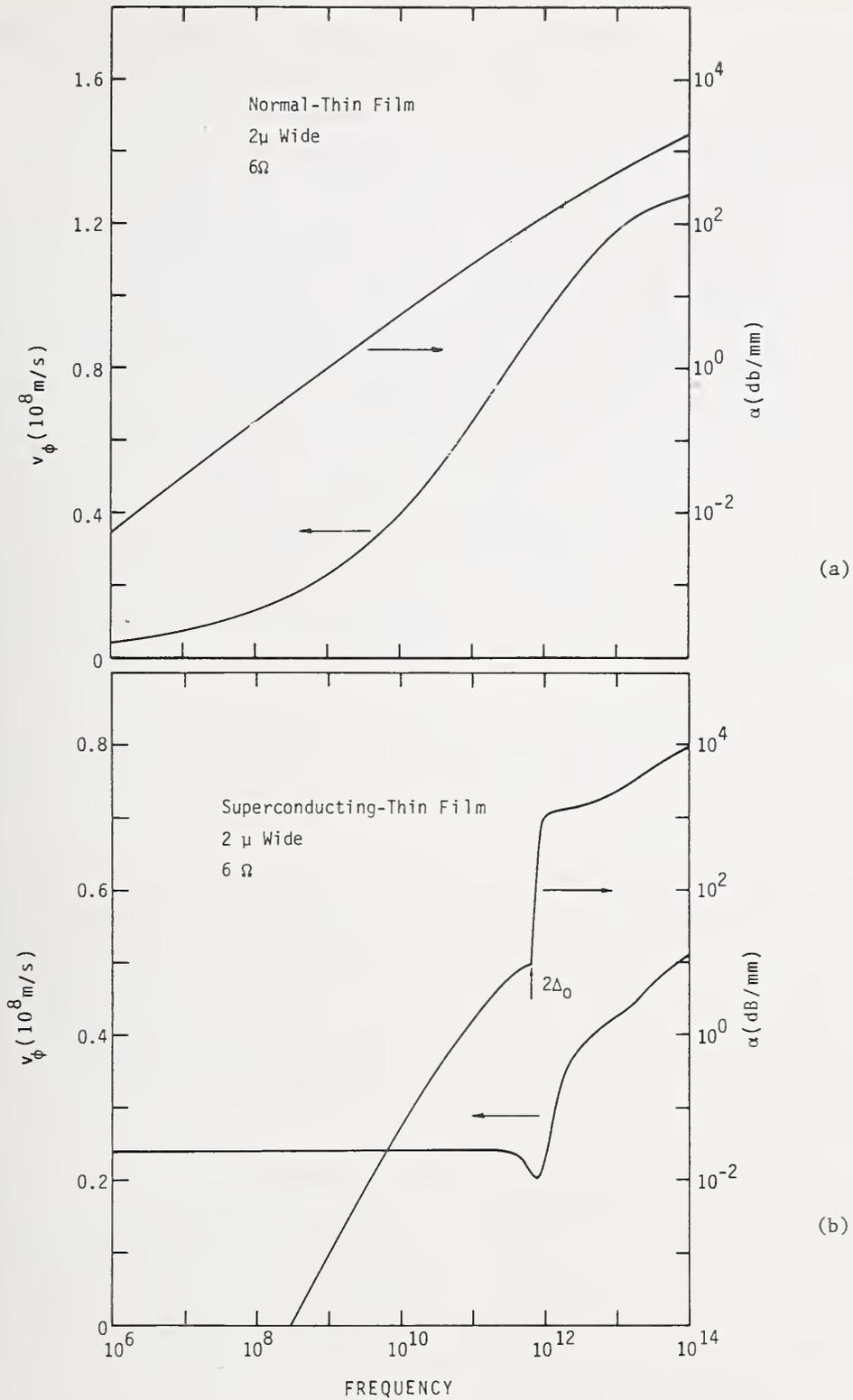
Figure IV-7.   Phase velocity $v_\phi$ and attenuation $\alpha$ for normal and superconducting thin-film striplines. (a) is for a room-temperature copper line and (b) is for a superconducting line. Each has impedance 6 $\Omega$. Details are given in the text.

line, above an insulator such as SiO having a dielectric constant of 5 and a thickness of 712 Å. The line has a limiting impedance of about 6 Ω at frequencies above the range of the graph, a convenient value for superconducting circuits (although this is a normal state line). The conductors are copper, having a resistivity of $1.6 \times 10^{-6}$ Ω/cm and thickness of 1000 Å. As can be seen from the figure, the attenuation exceeds 1 dB/mm for frequencies above $10^9$ Hz. Even more detrimental to its performance, perhaps, is the significant dispersion revealed by $v_\phi$ over the entire range of frequencies shown. Thus, we conclude that decreases in width and height of normal state lines, which are required for them to be used in dense circuitry, render them essentially useless as waveguide structures.

However, superconducting lines of the same size make lossless and dispersionless waveguides up to rather high frequencies. In Fig. IV-7b, we show $\alpha$ and $v_\phi$ for a superconducting lead alloy line above an oxidized niobium ground plane. The dielectric $Nb_2O_5$ has a dielectric constant of 29 and a thickness of 740 Å. The line shows negligible dispersion up to a frequency of about $3 \times 10^{11}$ Hz. The attenuation is satisfactory for propagation within a chip up to about $3 \times 10^{10}$ Hz and for propagation between chips up to about $5 \times 10^9$ Hz.

Further reduction in attenuation is possible by using wider lines which have thicker dielectrics. Wider lines, used for major transmission lines only, would not seriously degrade the circuit density. Wider lines would be particularly useful for connections between chips.

*Thus the superconducting transmission line provides significant advantages for computers and instruments at very high speeds.* It also permits the use of one more technique as we see below.

### IV.1.4.4. *Matched Terminating Resistors*

When superconducting transmission lines are used, the low loss permits them to be terminated by a matched load. Thus, reflections from the ends of the lines are substantially reduced. Such reflections might interfere with the devices sending the signal, or at least reduce the effective rise time of the signal to that time which is required for the reflections to die off. Normal state lines cannot be properly terminated because of the large distributed losses in the lines themselves.

### IV.1.5. Fabrication of Superconducting Integrated Circuits

For several years published descriptions of methods for fabricating reliable Josephson junctions have been available. Only recently, however, has this technology moved beyond the IBM Research Laboratories. The technology not only includes processes for fabricating lead alloy junctions (Pb-Au-In), but also resistors ($AuIn_2$), and microstrip lines. Furthermore, special designs for packages which permit fast signals to move on and off a chip have appeared in the patent literature.

Little is available in the published literature about the yield or reproducibility of the processes. However, it has been revealed that junctions can survive the order of 500 thermal cycles to liquid helium temperature and back to room temperature. Another report shows that they change resistance irreversibly when stored at room temperature. The changes amount to tens of percent per month. However, storage in the freezing compartment of

an ordinary refrigerator inhibits changes for periods of many months. Substantial improvements over these capabilities are expected to have been developed already but not published. Further progress should continue in the future.

What appear to be large-scale efforts to construct a superconducting computer at IBM suggest that whatever the detailed success of fabrication technology, it is sufficient for simultaneous operation of multitudes of these devices.

Further details on fabrication technology are given in Appendix IV-B.

## IV.1.6.  Superconducting Circuits Already Achieved

A variety of logic and memory functions have already been achieved in superconducting integrated circuitry. Published results are shown in Table IV-1.

### TABLE IV-1

### SUPERCONDUCTING CIRCUITS ALREADY ACHIEVED

| Type | Response Time (ps) | Dissipation | Number Junctions | Linewidth (μm) | References |
|---|---|---|---|---|---|
| Single Junction | 38 | 0.1 μW | 1 | 1 | Jutzi, et al. (1973) |
| NDRO* | 80 | | 3 | 2 | Broom, et al. (1975) |
| NDRO* | 600 | | 3 | 50 | Zappe (1975) |
| NDRO* | 95 | | | 2 | Jutzi (1976) |
| SFQ* | 50 | | 1 | 25 | Zappe (1974) |
| SFQ* | 100 | | 1 | 3 | Gueret, et al. (1977) |
| Logic | 165 | | 1 | 50 | Henkels (1974) |
| Logic | 170 | 28 μW | 1 | 25 | Herrell (1974b) |
| Logic | 235 | 40 nW | 3 | 3 | Zappe (1975) |
| Logic | 60 | 17 μW | 3 | 5 | Baechtold, et al. (1975) |
| Logic | 42-120 | 1 μW | 3 | 2.5 | Klein, Herrell (1978) |
| Adder (1 bit) | 500 | | 7 | 25 | Herrell (1974a) |
| Multiplier (4 bit) | 27000 | 35 μW x 45 | 45 | 25 | Herrell (1975) |
| Memory (64 bit) | 5000 | | 322 | 13 | Henkels (1978) |
| Shift | 6200 | 20 μW x 8 | 8 | 25 | Yao, Herrell (1975) |
| A/D | 16000 | | 20 | 25 | Klein (1976) |

NDRO - nondestructive readout memory

SFQ  - single flux quantum memory, destructive readout

*    - these units could form the basis for a random access memory

It should be noted for all of the devices having linewidths of 25 µm or more that no attempt has been made to achieve maximum speed. Several results do show, however, that delay times under 100 ps are possible, when linewidths not much bigger than 5 µm are used.

It is difficult to project the rapidity with which delay times will be further reduced. Several points should be noted, however:

1. Reductions in delay time will accompany further reduction in linewidth.
2. Reductions in linewidth, as in semiconductor technology, below about 2 µm can be achieved using electron beam lithography.
3. Because superconducting circuits made using optical lithography already offer so much improvement over semiconductor circuits there may be little driving force for further reductions in delay time and size for some time.

### IV.2.0. THE SUPERCONDUCTING COMPUTER

#### IV.2.1. Description of a Hypothetical Superconducting Computer

The most compelling reason for constructing a computer out of Josephson tunneling logic is that by taking advantage of its low dissipation, more compact, higher-speed computers can be constructed. We assume that it will eventually be possible to construct a computer having a cycle time of 1 ns or less. We consider the implications of this speed on the size, dissipation and memory density required in such a machine. The arguments given are very general. To be made more specific, a particular machine would have to be designed for a particular function. In space for example, one might choose to minimize dissipation at the expense of speed, versatility, or memory capacity. On the ground, dissipation will be a minor problem.

#### IV.2.1.1. *Cycle Time*

To attempt to justify the assumption that a 1 ns machine can be built, we simply note that 100 ps simple logic devices have been constructed. In a typical computer a signal must propagate through 8 to 10 logic levels during one machine cycle. Thus 8 to 10 times 100 ps gives about 1 ns. A second, and seemingly frivolous, argument is based on the folklore that a cryogenic device can supplant a room temperature one only if it does something otherwise impossible or improves the performance of the room temperature device by a factor of ten. We note that a cycle time of 1 ns is roughly a factor of fifty better performance than the Cray-1 (the fastest computer constructed to date).

Given the intrinsic response time of less than 1 ps for a Josephson junction, it is conceivable that computers having cycle times in the range of 10 to 100 ps may one day be built. However, an improvement in speed of one to two orders of magnitude will provide so much more computing power than today's machines that pressures for faster machines may not develop until after 1 ns machines have substantially penetrated the market.

IV.2.1.2. *Density*

It is simple to show that the required density in such a machine is well within the present state-of-the-art. We assume the computer is contained within a sphere of diameter 5 cm. This hypothetical computer is illustrated schematically in Fig. IV-8. If we consider the total machine volume of 65 cm$^3$ to be one-tenth processor and the remainder memory we can ask for the density required in each.

Let us assume the processor has the same number of circuits as an IBM 370/168 which is 2 x 10$^5$. Thus a density of 3100 circuits/cm$^3$ is required. If we further assume that the integrated circuits are on 0.25 mm-thick substrates (a common value for present silicon wafers) and that these substrates are spaced by 0.25 mm, we find 20 layers/cm. In addition we assume that packaging limitations decrease the available space by a factor of 10. Thus we require only 1600 circuits/cm$^2$ or an area per circuit of 6.3 x 10$^{-4}$ cm$^2$. One would expect each circuit to occupy no more than 10$^{-4}$ cm$^2$ so this requirement is not restrictive. The spacing between the wafers is sufficient for the coolant (liquid helium) flow.

In the case of the memory, the requirements are slightly more stringent. Let us assume the memory contains one million words, each having 100 bits, or a memory of 10$^8$ bits. Using the same wafer and spacing as before, and assuming that 90 percent of the area is for control circuitry, one requires a density of 86,000 bits/cm$^2$, or an area per bit of 1100 $\mu$m$^2$. Since a memory device with non-destructive readout has already been reported having an area of 900 $\mu$m$^2$, the requirements for memory density can be assumed not to be a restriction.

In fact a recent U.S. Patent suggests the possibility of constructing a memory cell having an area of only about 10 $\mu$m$^2$. Such a device would be fabricated undoubtedly using electron-beam lithography. Allowing a factor of ten for decoding circuitry and packaging, our 10$^8$ bits could be contained within 5 cm$^3$, a package 1.8 cm on a side. Heat removal could be more difficult with this exceedingly high density.


IV.2.1.3. *Power Consumption*

It is the low dissipation of superconducting electronics which makes possible the high density computer described above. Of particular significance is that superconducting memory requires no stand-by power, the information being stored in the form of circulating super-currents. In these order-of-magnitude arguments, we shall assume that heat removal from the memory can be neglected.

Heat removal from the processor is also encouraging. We consider our hypothetical computer to be constructed of the most-recently published logic. A single tunnel junction, when in the voltage state, carries a current of order 1 mA and a voltage about equal to the gap voltage of 2.5 mV. Thus it dissipates a few $\mu$W. SQUID logic devices having a dissipation of about 1 $\mu$W have been reported. We assume for simplicity that each "circuit" in our computer contains ten gates, giving 10 $\mu$W for each circuit. Multiplying by the 2 x 10$^5$ circuits in this machine and 0.5 because we assume no more than half the processor gates are operating at a given time, we arrive at a net dissipation of 1 W, exceedingly small when compared with conventional machines. However, this heat must be removed at 4 K using an approximately 300 K work input. Carnot efficiency multiplies these powers by a factor of approximately 75. Furthermore, it is thought that refrigerator inefficiency and heat leaks
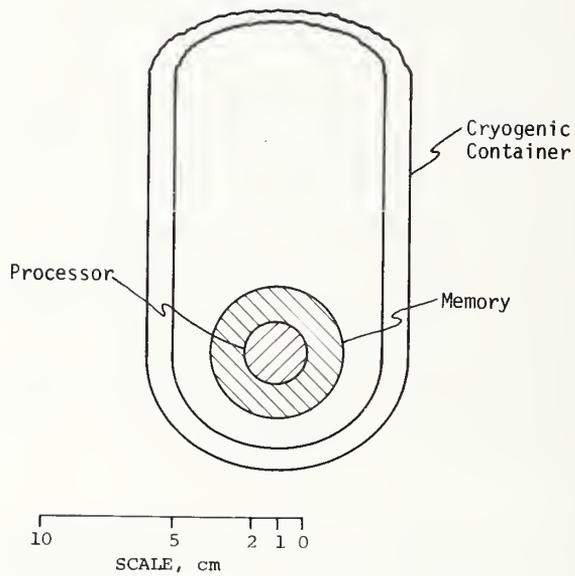
Figure IV-8.    Illustration of a hypothetical superconducting computer, giving
a suggestion of the size of processor, memory and cryogenic con-
tainer.  A space-borne container would probably be designed
differently.

can be accounted for by another factor of ten. *Thus the dissipation at room temperature would be about 750 W, still much smaller than conventional machines, such as the 115,000 W dissipation of the Cray-1.*

It therefore appears quite likely that a superconducting computer having the processing capability and memory of today's most powerful machines would dissipate sufficiently low power to be flown in space. Its extreme speed also makes it a strong candidate for replacing many ground-based computers.

## IV.2.2.   Applications of a Superconducting Computer

As with most computers, the range of applications of a superconducting computer is quite broad. However, because the superconducting computer offers such a major advance in computing speed, it may make possible applications which are more than just evolutionary.

One can think of this range of applications as divided into three areas, each being more removed from present applications than the preceding.

Applications of the first kind consist of usual applications of computers for logging data, data reduction and analysis, etc., but with substantial increases in speed. Furthermore, decreases in dissipation may make computing in space more widespread.

Applications of the second kind rely on the increased computing speed and larger memories which are possible in a superconducting computer. For example, weather modeling and forecasting may become much more timely and accurate given the capabilities of a superconducting computer.

Applications of the third kind are those in which a computer performs revolutionary new tasks made possible by increased speed and memory. One must ask when considering what these applications might be: What are the implications on artificial intelligence-like tasks of such a powerful computer? Can one, without waiting for theoretical developments, perform tasks by brute force? What tasks, which were previously impossible, could be performed in real time? Could one send such a computer on an interplanetary voyage, trusting it to analyze data and only selectively return it to earth? Would such a computer reduce the need for man in space? Never before has it been possible to conceive of sending such a powerful machine, which requires so little power, into space. The implications of these machines could be profound indeed!

## IV.2.3.   The Present State-of-the-Art

The list of achieved superconducting circuits in Table IV-1 gives some suggestion of the present state of superconducting computer development. All of the papers listed are a result of a massive program at the IBM Thomas Watson Research Center in Yorktown Heights, New York, and to a lesser extent at the IBM Zurich Research Laboratories. A great deal of extremely high-quality research has resulted from this program. Furthermore, it appears that this program is directed toward producing a prototype superconducting computer as soon as possible, say, within five years. Personnel at IBM will not, however, discuss the aims of their program. We do know from personal contact that the program is large enough to involve separate groups with various responsibilities such as materials development, circuit design, packaging, and lithography. We guess that it may involve 100 professional scientists and engineers.

IV.2.4.  Ultimate Achievable Performance

The 1-ns computer described previously probably does not represent the ultimate achievable from this technology.  Given the 0.27 ps response time of a single junction, it is conceivable that a computer having a cycle time below 100 ps is possible.  Supporting this possibility is the fact that even a 1-ns machine does not tax the density acheivable from the technology.  However, it should be noted that while very fast integrated circuits have been developed, there exists no published work on packaging these circuits in such a way as to maintain speed in a whole assembly of the circuits.

IV.2.5.  Projected Development Rate

It is possible that a prototype superconducting computer will be demonstrated within five years.  Such a projection is difficult to make since almost all of the work is closely guarded by IBM.  However, within ten years, a commercial superconducting computer may be available.  IBM staff have mentioned in public that this technology may be cost competitive in medium scale computers, as well as providing revolutionary new capability in large computers.  Perhaps mid-range computers will be where IBM's principal thrust will in fact be, since they have historically left the supercomputer field to other companies.

It should also be emphasized that this technology is much more difficult than previous computer technologies.  The higher speed of response now requires attention, which was not required in the past, to all interconnections which must be properly matched microstrip lines with proper terminating resistors.  Furthermore, packaging must be done much more carefully with similar attention to interconnections. These factors may seriously interfere with the present distribution system of electronics components.  That is, it may be much more difficult for one company to make a superconducting integrated circuit for sale to another company which assembles these circuits into a computer.  The circuit manufacturer might necessarily produce a much larger, more integrated piece of hardware.  Because of the more detailed engineering required, these factors may work to the disadvantage of small companies.

Because a superconducting computer produces such small dissipation, it is a natural candidate for deployment in space.  Of course, the circuitry would have to be made space-worthy.  However, a much bigger task is the construction of a suitable lightweight, reliable refrigerator.  (Refrigerators will not be a problem on the ground, as it is possible to achieve reliability using serveral, and weight is no problem.)  The reader is directed to the Introduction (Chapter I) and Appendix I-A for a discussion of small refrigerators and of passive cooling.

IV.3.0.  SUPERCONDUCTING INSTRUMENTS

The needs for very fast measurements in military devices and the potential arrival of very fast computers both require new fast measurement capabilities.  That Josephson tunneling logic is a compelling candidate for this new class of instruments is suggested by its known high speed and low dissipation, by its past successes in this field (some Josephson instruments are now available commercially), and by the development of technology for making reliable thin-film Josephson junctions. The following is a brief review of past and present

applications of Josephson devices, many of these applications having originated or having
been perfected at the National Bureau of Standards.

In the past, Josephson junction-based instruments have been characterized as containing
a single Josephson junction. Typically, this junction was a point contact (like a cat's
whisker diode), or possibly a tiny constriction in a thin film. The use of one junction,
rather than more, was largely because photolithographic techniques had not been applied to
Josephson devices.

The single Josephson junction was typically incorported into a loop of superconducting
material to form a Superconducting QUantum Interference Device (SQUID, see Chapter III). A
SQUID is capable of detecting very small magnetic fields, of order $10^{-14}$ T($10^{-10}$ oersted).
Most of the Josephson junction-based instruments now in use incorporate this device. SQUID
devices are available commercially from at least five companies.

When used directly to detect magnetic fields, or their gradients, SQUID devices are used
for magnetic anomaly detection (such as submarines), for magnetocardiography (a non-body-
contact method of measuring human heart performance), magnetoencephalography (magnetic brain
waves), geophysical measurements and prospecting. Additional uses of SQUID's are for rf
power and attentuation standards, ultra-low temperature thermometry, and precise current
comparison. In each case the Josphson device made possible previously impossible measure-
ments, or made a substantial improvement over previous measurements. In addition, single
Josephson junctions, not used in the SQUID configuration, are used to maintain the U.S. legal
volt, and for ultrasensitive broadband or heterodyne detection in the millimeter and far
infrared region of the electromagnetic spectrum. Single Josephson junctions have been used
for microwave and infrared harmonic generation and mixing at frequencies up to 30 THz (10 μm
wavelength).

The development of lithographic fabrication methods for complex (multi-junction) super-
conducting circuits provides new opportunities for high-speed devices. Fast instruments
demand a number of characteristics from the technology from which they are formed. In many
ways they are quite similar to very fast computers.

One must consider what is "fast". An instrument should be capable of characterizing
events on a time scale which is shorter than that in which the event occurs. Of course that
means as fast as possible, because there are always events of scientific interest which offer
remarkable speed. A more practical measure of "fast" might be a speed somewhat faster than
events occur in commonly available circuitry, such as in future computers. Thus, instrument
response times of the order of 1 ps would be most useful, since the fastest present instru-
ments are sampling oscilloscopes with response times of 25 ps. Superconducting technology
should be capable ultimately of speeds in the 1 ps range.

A more comprehensive definition of "fast" might recognize the difference in types of
measurements. For example, it might take more than a second to make an exceptionally high
accuracy measurement of voltage. However, even for a measurement of this sort, the total
time required can be reduced through the use of faster active devices.

Along with high speed is the concurrent requirement of small size. Recall that signals
propagating at the speed of light travel only 300 μm (0.030 cm) in 1 ps. If a variety of

sensors in an instrument are to analyze a signal at close to the same time, they must be in
close proximity to one another. The size scale is, of course, determined by the time scale.

If a variety of elements in the circuits are located close together, their dissipation
must be sufficiently small that their operating temperature can be maintained. The heat
produced by conventional very fast devices already prevents more than a small number from
being located on the same integrated circuit chip. The need for an improved technology is
thus evident.

If an instrument is to analyze analog signals, those signals must be accurately trans-
mitted throughout the instrument. Thus, the use of lossless, properly terminated, lines is
of great advantage in a fast instrument.

All of these considerations are, of course, the same as those discussed earlier with
respect to computers. Thus, in the fastest instruments the use of superconducting technology
is compelling.

### IV.3.1.    Important Elements of Instruments

There are a variety of possible instruments, but those to be discussed here make use of
two simple components, a current comparator and a sample-and-hold circuit.

#### IV.3.1.1. *Current Comparator*

A Josephson gate is essentially a current comparator. It is used in its simplest form
in digital circuits where it must determine only whether a signal represents a "0" or a "1".
However, it can also be used in an analog sense as well. If the gate is biased in the zero
voltage state, with some current flowing through it, then the gate will switch at some well-
defined current flowing through the control line over the gate. One can vary the switching
point by providing a bias current through a second control line over the gate. Thus, an
adjustable current comparator results. It should operate as fast as any Josephson gate --
that is, ultimately in less than 1 ps. Such current comparators would be important elements
in many of the devices below or they might be the fundamental element in a fast trigger
circuit.

#### IV.3.1.2. *Sample-and-Hold*

Sample-and-hold circuits are conventionally used to sample a voltage in a very short
time, and maintain it (as in the form of a charge on a capacitor) until it can be charac-
terized by a slower device. A sample-and-hold circuit may also be useful in a supercon-
ducting instrument for the same purpose. Alternately, some superconducting instruments may
operate in such a short time that a sample-and-hold circuit will not be necessary. One
possible kind of superconducting sample-and-hold device would simply store a current in a
superconducting persistent current loop. The current would be switched in and out of the
loop using a Josephson junction in the loop. The product of the critical current $I_o$ of the
junction and the inductance L of the loop would have to be sufficiently large, however, since
the maximum flux in the loop $LI_o$ is quantized in units of $\phi_o = 2.07 \times 10^{-15}$ $Wb/m^2$, the super-
conducting flux quantum. The flux quantum would have to be smaller than the resolution
desired from the sample-and-hold circuit. The speed of response of such a simple circuit

would be determined by the time required for the Josephson junction to go from the normal state to the superconducting state where the flux would be trapped. Times as short as 1 ps might be achieved.

### IV.3.1.3. *Logic Circuits*

One may also use logic in an instrument. A counter, for example, must perform logical operations. Such elements of an instrument might be quite similar to those in superconducting computers.

### IV.3.2. A Few Possible Josephson Instruments

### IV.3.2.1. *Sampling Device -- Analog*

Unpublished reports of sampling devices suggest that such instruments have already been constructed having a time resolution of a few ps. Such sampling devices are constructed from current comparators of the type described above. Such devices provide the best means for characterizing fast repetitive signals.

### IV.3.2.2. *Fast Counters*

It should be possible to construct fast counters using superconducting technology. The speed of response would be determined by the speed of the circuitry for the least significant bit. More significant bits would change state more slowly and would therefore not be as important. Careful engineering of this portion of the circuit for the least significant bit might bring the response time down to a few picoseconds, corresponding to a counting rate of order 500 GHz. Examples of the use of such fast counting rates might be in high accuracy clocks or in detecting particles at very high flux.

### IV.3.2.3. *A/D Converters*

In conventional electronics the fastest, and seldom used, analog-to-digital converters are of the parallel type. That is, the converter contains one current (or voltage) comparator for every possible level of the input analog signal. Thus, a 4-bit converter might have 16 comparators (15 comparators if one level is considered as a fixed reference). Subsequent circuitry then condenses the 16 bits of level information into a 4-bit binary word. A similar design in superconducting technology would undoubtedly also provide the highest possible speed. The sampling rate would probably be determined by the time required to store the digitized signal in preparation for the next one. Sampling rates as high as 10 to 100 GHz might be achieved.

A/D conversion is subject to the limitation that one cannot digitize a signal which is changing faster than the time resolution of the converter. Sample-and-hold circuits are used to maintain a signal until it can be digitized. The aperture time $t_{ap}$ of a sample-and-hold circuit may determine the fastest signal which can be digitized. It seems unlikely in superconducting technology that a sample-and-hold circuit could operate in less than the intrinsic response time for a Josephson junction: $h/2\Delta = 0.27$ ps for lead. During this period the signal is allowed to change only by less than one part in $2^n$ for an n-bit converter. Assuming a sine wave at frequency f, one finds

$$f_{max} = \left[ \pi 2^n t_{ap} \right]^{-1} .$$

The maximum sampling frequency $f_{max}$ is plotted in Fig. IV-9 as a function of the number of bits of accuracy. It is readily seen that a reduction in the aperture time of the sample-and-hold circuit dramatically increases $f_{max}$. Thus achieving the minimum aperture time represents a high priority task if extremely high-speed A/D converters are to be realized. A long range goal might be to reduce $t_{ap}$ below a few ps.

Applications of very fast A/D converters might include communications (where digital filtering or image processing is used), data acquisition (conversion of rapidly varying signals to digital form), and very broadband radars.

### IV.3.3.   Digital Instruments for Real-Time Signal Processing

Given a high-speed digital technology, it becomes possible to conceive of real-time applications of computational techniques which previously were done off-line, or which could be applied only to very slow signals. One such example involves Fourier analysis of signals. Such signals might pass through a superconducting A/D converter of the type discussed above, and then be digitally analyzed using a special-purpose fast Fourier transform processor designed to perform these calculations at the highest possible speed. Such an FFT processor could engender a variety of instruments, including fast digital filters.

#### IV.3.3.1. *Agile Digital Filtering*

Digital filtering is an extremely useful concept, applicable to areas such as communications and noise reduction. Filtering can be done with rapid change in frequency, line-shape, etc., possibly controlled by the incoming signal. One application of this type of filter might be in the interpretation of frequency coded signals.

#### IV.3.3.2. *Multi-Channel Spectrum Analyzer*

Superconducting digital technology would enable the construction of an analyzer which has higher speed than those using conventional technology. Such analyzers are already being worked on, using conventional technology in the Search for Extraterrestrial Intelligence (SETI). Such a device could also be coupled with processing, possibly using special purpose circuits to examine the data in real time, thus reducing the quantity of data which must be stored or transmitted.

### IV.3.4.   Present State-of-the-Art

There already exists a variety of superconducting instruments. The great majority of them involve point contact or cat's whisker type Josephson junctions. Some superconducting instrumentation has been built using integrated circuitry in conjunction with the development of a superconducting computer. For example, analog sampling has been done with a response time of perhaps a few picoseconds -- close to ten times better than with conventional instruments. Ultimate achievable performance for some instruments has been briefly discussed along with the instrument descriptions (Section IV.3.0.)
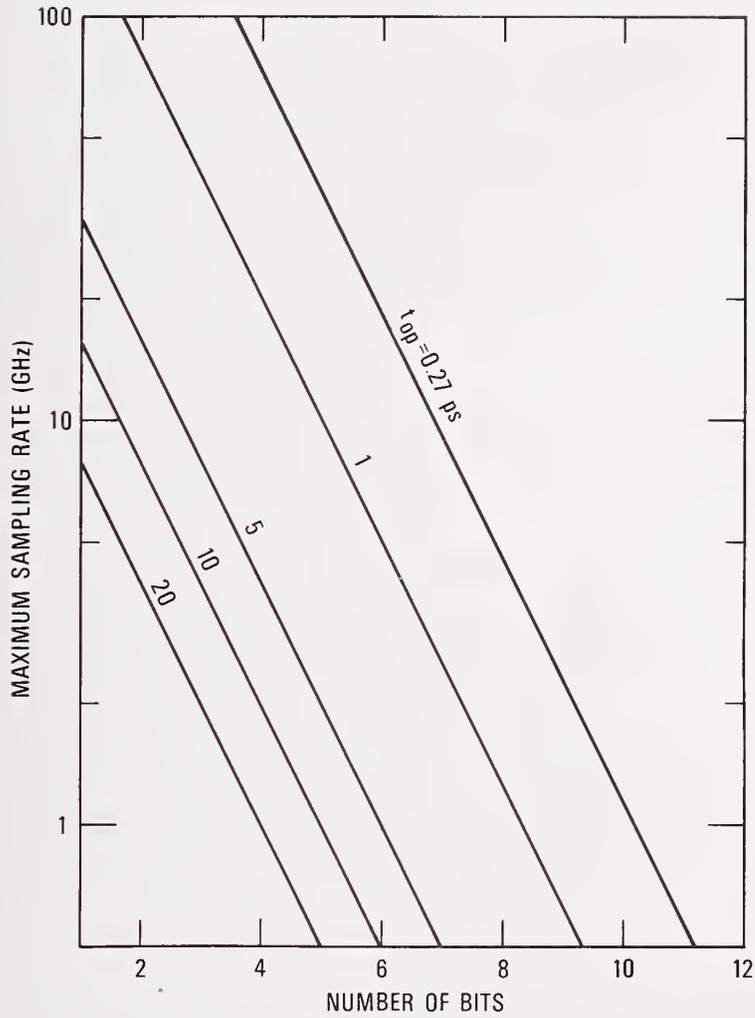
Figure IV-9.    Maximum sampling rate for A/D converter as a function of accuracy, or number of bits.   Curves shown are for various aperture times $t_{ap}$ of the sample-and-hold circuit.

IV.3.5.   Projected Deployment Rate

The superconducting computer is the dominant force in the development of the technology. Programs for instrumentation development are few, and their sizes are small. However, substantial funding, which would bring other institutions into the field, would speed their introduction. For example, a small Navy-funded program now exists at the National Bureau of Standards to develop an A/D converter. Much broader funding of this type is needed if the introduction of these instruments is to be speeded up.

Refrigeration problems are the principal barrier to deployment in space. However, small, low-dissipation instruments, combined with passive cooling and a helium reservoir, might remain operational in space for a considerable period of time.

## IV.4.0.   SOURCE OF ADDITIONAL INFORMATION

The Office of Naval Research has contracted with International Business Machines Corporation to perform a Josephson technology computer assessment. It is understood that this assessment may result in a report divided into several parts: An open report, an IBM proprietary report, and a report which will be distributed to only a very small number of people outside IBM. Under terms of the contract, the report will be completed within one year.

IBM has offered to provide at least some of this report to NASA when it is complete. For further information, contact Dr. W. Anacker at the address below and refer to contract number N00014-77-C-0179.

> Dr. W. Anacker
> Thomas J. Watson Research Center
> P.O. Box 218
> Yorktown Heights, New York  10598
>
> (914) 945-3000

It is highly recommended that NASA acquire this information. IBM has made a large number of exceedingly high-quality contributions to the field of superconducting electronics.

## IV.5.0.   SUMMARY AND CONCLUSIONS

Digital superconducting electronics is a newly emerging technology of significant promise which must, however, pass the test of real-world application. The motivation for the development of this technology is rooted in some very general and fundamental considerations (see Section IV.1.2.). The Josephson switch is extremely fast and can potentially achieve switching speeds of 1 ps. Its most attractive attribute is its small dissipation. The dissipation is sufficiently small to allow extremely close packaging of active elements and thus allow dramatic reduction of intracircuit communication delays. Furthermore, the use of superconducting striplines for this communication provides the opportunity for unparalleled freedom from dispersion and attenuation of signals.

Broad interest in the technology is expanding, but the prime driving force behind the technology is a major commercial program to develop a superconducting computer. With some

knowledge of the characteristics of the simple logic elements, it is relatively easy to show that order of magnitude (and greater) advances can be made in both speed and capacity. A necessary result of increased speed is reduced size, and overall dissipation drops many orders of magnitude below conventional computers (see Section IV.2.0.). All of these changes (increased speed and capacity, decreased size and dissipation) are in a direction favorable to space applications. The development of such a computer may be 10 to 20 years in the future, but it is not too early to consider the opportunities, perhaps revolutionary ones, which may appear.

Several applications can be suggested now. The processing and compression of complex raw data from space experiments would provide a means of conserving the limited power available for information transmission. For example, the mapping of the heavens in any frequency region involves tremendous amounts of data. A certain amount of data filtering can be accomplished without a large computer, but a really smart satellite could provide much more intelligent selection of data. A really powerful computer in space could offer a means to improved weather modeling and forecasting on a global scale. The combination of the acquisition and processing of weather data could simplify and speed up the modeling process, and thus produce more timely and accurate forecasts.

These applications are founded on established concepts, but it is also exciting to consider more exotic ideas (see Section IV.2.2.). Never before have we been faced with the potential for such a large computing capability in space. Could such computers assume intelligence-like roles? If so, would the need for some difficult manned space missions be reduced? These are difficult questions which have certainly been considered before, but reconsideration might be appropriate in light of the new opportunities which are now developing.

Other types of fast instrumentation (Section IV.3.0.) are made possible by this new technology. Ultra-fast A/D converters, digital filters, counters and spectrum analyzers are just a few of the devices which should be considered. The applications of such instruments are myriad. For example, improved A/D conversion could improve signal acquisition in the Search for Extraterrestrial Intelligence (SETI). Coupled with a superconducting computer, such A/D converters could perform real-time processing of microwave signals in a very broad frequency band. This type of system would essentially be an ultra-broadband digital receiver. Broader bandwidth offers larger information capacity and a valuable savings in power required for transmission.

All of these applications are highly speculative. We assume that commercial interests will develop the computer, but that is, by no means, certain. Should NASA place a priority on such developments, it might be wise to assess the probability of success and to provide some partial stimulus to assure this success. The peripheral development of other digital instruments will probably accompany the computer effort. No doubt, there are instrument developments which would be important to the space program and which would then deserve some NASA encouragement.

# IV.6.0.  REFERENCES

Baechtold, W., Forster, Th., Heuberger, W. and Mohr, Th.O. (1975).  Complementary Josephson
Junction Circuit:  A Fast Flip-Flop and Logic Gate. *Elec. Lett. 11*, 203-204.

Broom, R.F., Jutzi, W. and Mohr, Th.O. (1975).  A 1.4 mil$^2$ Memory Cell with Josephson Junc-
tions. *IEEE Trans. Mag. MAG-11*, 755-758.

Gueret, P., Mohr, Th.O and Wolf, P. (1977).  Single Flux Quantum Memory Cells. *IEEE Trans.
Mag. MAG-13*, 52-55.

Henkels, W.H. (1974).  An Elementary Logic Circuit Employing Superconducting Josephson
Tunneling Gates. *IEEE Trans. Mag. MAG-10*, 860-863.

Herrell, Dennis J. (1974a).  A Josephson Tunneling Logic Adder. *IEEE Trans. Mag. MAG-10*,
864-867.

Herrell, Dennis J. (1974b).  Femtojoule Josephson Tunneling Logic Gates. *IEEE J. Solid
State Circuits, SC-9*, 277-282.

Herrell, D.J. (1975).  An Experimental Multiplier Circuit Based on Superconducting Josephson
Devices. *IEEE J. Solid State Circuits, SC-10*, 360-368.

Jutzi, W., Mohr, Th.O., Gasser, M. and Gschwind, H.P. (1973).  Josephson Junctions with 1 μm
Dimensions and with Picosecond Switching Times. *Elec. Lett. 8*, 589-591.

Jutzi, W. (1976).  An Inductively Coupled Memory Cell for NDRO with Two Josephson Junctions.
*Cryogenics 16*, 81-88.

Keyes, Robert W. (1969)  Physical Problems and Limits in Computer Logic. *IEEE Spectrum, May.*
36-45.

Keyes, R.W., Harris, E.P. and Konnerth, K.L. (1970).  The Role of Low Temperatures in the
Operation of Logic Circuitry. *Proc. IEEE 58*, 1914-1932.

Keyes, Robert W. (1975).  Physical Limits in Digital Electronics. *Proc. IEEE 63*, 740-767.

Keyes, Robert W. (1977).  Physical Limits in Semiconductor Electronics. *Science 195*,
1230-1235.

Klein, M. (1977).  Analog-to-Digital Converter Using Josephson Junctions. *1977 IEEE Int.
Solid-State Circuits Conference Digest of Technical Papers, Vol. 20*, IEEE Cat. No. 77CH
1172-6 ISSCC.  202-203.

Klein, M., Herrell, D.J. and Davidson, Arthur (1978).  Sub-100 Picosecond Josephson Inter-
ferometer Logic. *1978 IEEE Int. Solid-State Circuits Conference Digest of Technical
Papers*, to be published.

Yao, Y.L. and Herrell, D.J. (1974).  An Experimental Josephson Junction Shift Register
Element. *Int. Electron Devices Meeting, Tech. Dig.*, 145-148.

Zappe, H.H. (1974).  A Single Flux Quantum Josephson Junction Memory Cell. *Appl. Phys. Lett.
25*, 424-426.

Zappe, H.H. (1975).  A Subnanosecond Josephson Tunneling Memory Cell with Nondestructive
Readout. *IEEE J. Solid State Circuits, SC-10*, 12-19.

Zappe, H.H. (1975).  Quantum Interference Josephson Logic Devices. *Appl Phys. Lett. 27*,
432-434.

Zappe, H.H. (1977).  Josephson Quantum Interference Computer Devices. *IEEE Trans. Mag. MAG-
13*, 41-47.

CHAPTER V

MICROWAVE AND INFRARED DETECTORS

C. A. Hamilton

## V.1.0.  INTRODUCTION

Microwave and infrared detectors and receivers are widely used in space applications. These applications include ground-based communication and radioastronomy receivers as well as satellite receivers.  Mapping of background radiation, for example, is an important application requiring the ultimate in receiver sensitivity.  The success of a proposed program to search for signals from extraterrestrial life may well depend on the sensitivity of the receivers used.  In all of these cases, improved sensitivity yields benefits by making possible greater data transmission rates, reduced observing time or smaller antennas.

There is a wide variety of superconducting devices currently being developed for microwave and infrared detection.  In many cases, these devices offer comparable or improved performance over their conventional counterparts.  However, because these devices are relatively new, often unstable, and not always fully understood, few if any are currently being used in operational receivers.  It is the purpose of this chapter to review all of the promising superconducting devices which are being developed or contemplated for use as microwave or infrared detectors.

The most intensive efforts toward developing superconducting microwave and infrared detectors have been based on the Josephson effect.  The characteristics which make Josephson effect detectors attractive are (1) a very high degree of nonlinearity, (2) low temperature, low noise operation, and (3) demonstrated frequency response to $4 \times 10^{12}$ Hz.  Used as video detectors or mixers, Josephson junctions have achieved sensitivities which equal or surpass conventional devices.  In the mixing mode of operation, the required local oscillator (LO) power is very low and may be generated externally or internally using the Josephson self-oscillation.  The latter case has the advantage of simplicity (no LO source required) but resolution is limited by the linewidth (several hundred megahertz) of the Josephson oscillation.

The Josephson self-oscillation may also be used as a microwave source.  The linewidth of such a source could be narrowed by coupling it to a cavity with a sufficiently high Q. Although the power available is rather small it may be useful at frequencies above 100 GHz where other sources are rare.  Efforts are also underway to increase the power output by the use of synchronized arrays of Josephson devices.

All the Josephson detectors have some common disadvantages.  They are, for the most part, very low impedance devices and are therefore difficult to couple to radiation fields. In order to control parasitic elements, the most successful devices have generally been of the point-contact variety.  In their present form, these devices are probably not sufficiently stable for space applications.  A third problem arises from the fact that the Josephson mechanism operates at very low power levels.  This results in low-level saturation and a correspondingly small dynamic range.  The rapidly developing technology of thin-film Josephson integrated circuits may provide solutions to all of these problems.  For example, a 1 μm-square thin-film junction fabricated by electron-beam lithography with a current density of 2000 A/cm$^2$ should have an upper cutoff frequency of about 1000 GHz and a resistance of 100 Ω.  Series arrays of such junctions could be used to optimize input coupling as well as to increase the saturation level.

Parametric amplifiers are another very promising application of the Josephson effect for microwave and infrared receivers. Although experimental and theoretical investigations of Josephson parametric amplifiers are relatively recent, the results are impressive. As with the Josephson detectors, fabricating stable devices, impedance matching, and low-level saturation remain problems.

Two other very promising superconducting detectors which are not based on the Josephson effect are the super-Schottky diode and the superconducting transition edge bolometer. Super-Schottky diodes have achieved record sensitivities both as video detectors and mixers. As with the Josephson mixer, the super-Schottky mixer requires very little LO power and has a somewhat limited dynamic range. Considerable effort has been devoted to the development of superconducting composite bolometers in which the functions of radiation absorption and temperature measurement are separated. An aluminum film near its superconducting transition temperature is used as the thermometer. When operated at about 1 K, such devices have achieved nearly ideal performance.

The following sections describe in more detail superconducting bolometers, super-Schottky mixers, and Josephson sources, mixers and parametric amplifiers. The description includes (1) the physical mechanism, (2) theoretical limits on the ideal performance for a practically realizable device, and (3) the current state-of-the-art for the superconducting device as well as its non-superconducting competitors.

### V.2.0. BOLOMETERS

A bolometer is a thermal detector consisting of a radiation-absorbing element and a resistance thermometer. It produces an electrical signal by changing its resistance when it is warmed by absorbed radiation. For applications requiring the ultimate in sensitivity, the use of bolometers is usually limited to the far-infrared region (20 μm to 1 mm) at frequencies which are too high for heterodyne detectors and too low for quantum effect detectors. They are typically broadband devices with a slow response time (1 ms to 1 s). Cryogenic bolometers, especially those made from doped germanium, are widely used as sensitive infrared detectors.

Superconducting bolometers, although not in wide use, have been extensively studied. Before describing specific superconducting bolometers, a brief review of the fundamental performance limits is useful (see for example, Adde and Vernet, 1977). The principal parameters describing a bolometer are C (joules/kelvin) the heat capacity, G (watts/kelvin) the thermal conductance to an external heat sink and $R_V$ (volts/watt) the voltage (or current) responsivity. The bolometer time constant $\tau$ is equal to C/G. Since the various noise contributions are independent in a bolometer, they can be added quadratically to yield a system NEP (Noise Equivalent Power):

$$NEP^2 = \frac{4kTR}{R_V^2} + 4kT^2G + 8\ \sigma\epsilon kT_B^5 A\Omega + \frac{V_N^2}{R_V^2} \tag{V-1}$$

The first term is the Johnson noise associated with the bolometer resistance R. The second term is thermal noise from statistical fluctuations in the bolometer temperature T. The

third term represents the detector response to fluctuations in the background temperature $T_B$. $\sigma\epsilon$ is the detector emissivity, A its area and $\Omega$ the viewing solid angle. The fourth term represents any additional excess noise sources in the bolometer by a noise voltage $V_N$(V/$\sqrt{Hz}$). A high-performance bolometer must have a high responsivity to minimize terms one and four and it should be shielded as much as possible from unwanted backgound radiation to minimize term three. This usually involves a He-cooled mount and optics and perhaps cooled filters to restrict the input bandwidth. G and especially C should be as small as possible to minimize term two and at the same time achieve a reasonable response time $\tau$ = C/G. Since G can usually be made arbitrarily small, the ultimate sensitivity of a bolometer with a given $\tau$ is determined by the heat capacity C. This ultimate sensitivity for an ideal bolometer is given by the second term of Eq. (V-1), i.e., NEP = $(4kT^2G)^{1/2}$.

Bolometers have been built which are based on several different superconducting properties. The transition edge bolometer makes use of the rapid variation in resistance of a thin film at its superconducting transition edge. The recent discovery of the importance of a good thermal contact between the film and its substrate has led to major improvements in the performance of this device (Clarke and Hsiang, 1975a). The SNS bolometer is based on the temperature dependence of the critical current in a superconductor-normal metal-superconductor (SNS) junction (Clarke, et al., 1974). The extremely low impedance of SNS junctions ($\sim 10^{-6}$ $\Omega$) necessitates the use of a SQUID (Superconducting QUantum Interference Device) amplifier. A third device, known as the SIN bolometer (Clarke, Hoffer and Richards, 1974), makes use of the temperature-dependent quasiparticle tunneling current through a superconductor-insulator-normal metal junction which is biased at a voltage below the superconducting energy gap. The construction of all three types of bolometers is similar to that shown for the transition edge bolometer in Fig. V-1.
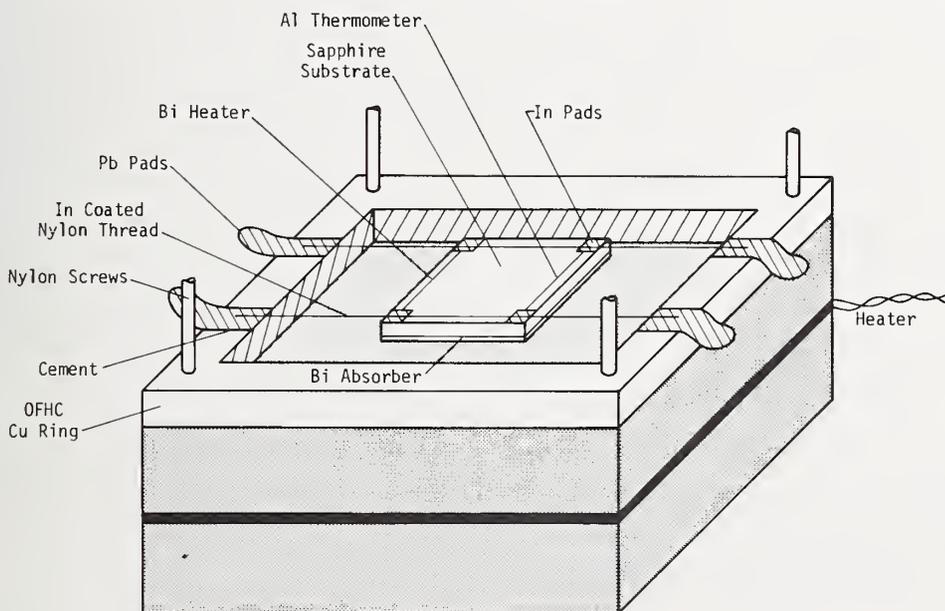


Figure V-1. Typical structure for a composite bolometer (after Clarke, et al., 1978). Radiation absorbed in the bismuth film heats the sapphire substrate causing a change in the resistance of the aluminum superconducting transition edge thermometer.

This device consists of a thin sapphire substrate with an optically absorbing bismuth coating on one side. On the other side are an electrical heater for calibration purposes and an aluminum film which acts as the thermometer. Electrical leads and mechanical support are provided by four indium-coated nylon threads. Temperature stabilization of the mount ($\sim 10^{-6}$ K/$\sqrt{\text{Hz}}$) at the frequency of operation is provided by a combination of active control and a massive heat sink. Electrical NEP is determined by measuring the response to electrical heat dissipated in the bismuth heater. Since, in practice, the bismuth film will absorb only about half of the incident radiation, the reported electrical NEP's for these devices are about half of what could be expected for radiation detection.

Table V-1 shows the performance which has been achieved with the various types of bolometers. The listed performances are all based on a negligible noise contribution from background radiation. Except in applications with very low backgound radiation, any of these bolometers would be background-noise limited. Thus, the use of superconducting bolometers is justified only in applications with very low background radiation. The transition-edge bolometer has a superior performance to the SNS and SIN devices. Since it is easier to construct and can be used with a conventional FET amplifier, it is the preferred device at the present time.

TABLE V-1

BOLOMETER PERFORMANCE

| Bolometer Type | NEP (W/$\sqrt{\text{Hz}}$) | Theoretical[a] NEP (W/$\sqrt{\text{Hz}}$) | G (W/K) | $\tau$ (s) | Op. Temp. (K) | References |
|---|---|---|---|---|---|---|
| SIN[b] | | $2.5 \times 10^{-15}$ | | | | Clarke, et al. (1978) |
| SNS | $5 \times 10^{-15}$ | $1.1 \times 10^{-15}$ | $10^{-8}$ | 3 | 1.5 | Clarke, et al. (1974) |
| Trans. Edge | $10^{-14}$ | $2.5 \times 10^{-15}$ | $5 \times 10^{-8}$ | 0.13 | 1.5 | Clarke, et al. (1975) |
| Ge | $7 \times 10^{-13}$ | $4.2 \times 10^{-13}$ | $2 \times 10^{-4}$ | 0.0003 | 4.2 | Coron, et al. (1975) |
| Al Trans. Edge | $1.7 \times 10^{-15}$ | $1.3 \times 10^{-15}$ | $2 \times 10^{-8}$ | 0.08 | 1.27 | Clarke, et al. (1978) |
| Ga:Ge | $5 \times 10^{-15}$ | $2.2 \times 10^{-15}$ | $6 \times 10^{-8}$ | 0.025 | 1.2 | Nishioka, et al. (1978) |
| In:Sb:Ge | $6 \times 10^{-16}$ | $3.4 \times 10^{-16}$ | $1.7 \times 10^{-8}$ | 0.006 | 0.35 | Nishioka, et al. (1978) |

a   The theoretical limit is $\text{NEP}_{\text{th}} = (4kT^2G)^{1/2}$
b   No results are reported for operating SIN bolometers

The last three entries of Table V-1 show that there has been considerable progress recently. Bolometers with very nearly ideal NEP's have been built using both superconducting and non-superconducting thermometers. Further advances depend almost exclusively on the

ability to build devices with smaller and smaller heat capacities. *Thus, superconductivity does not offer the promise of any breakthrough in bolometer performance.* It does offer, however, a very simple, sensitive and low thermal mass thermometer which can be used with the new composite bolometers.

## V.3.0. SUPER-SCHOTTKY DIODES

Diodes in the four forms: semiconductor-normal metal (Schottky diode), semiconductor-superconductor (super-Schottky), superconductor-insulator-normal metal (SIN) and superconductor-insulator-superconductor (Josephson junction or JJ) have all been fabricated. Each of these devices has a nonlinear I-V characteristic and therefore can be used as a high-frequency mixer or detector. In addition to normal electron tunneling, the Josephson devices have a pair-tunneling current which greatly complicates their operation. One of the effects of the pair current is to up-convert low frequency fluctuations to the signal or i.f. frequencies, thus adding noise to the mixer output. The use of JJ's as mixers is treated in Section V.4.2. of this report.

The presence of the superconducting energy gap gives the SIN and super-Schottky diodes a much higher degree of nonlinearity than the conventional Schottky diode. The SIN device, however, relies on electron tunneling through a very thin oxide barrier. This thin barrier gives rise to a large capacitance which makes impedance matching at high frequencies very difficult. The super-Schottky diode has a much lower and wider barrier and therefore can achieve the same current density with a much smaller capacitance. This property, together with its high degree of nonlinearity, makes the super-Schottky diode a very promising mixer element. Experimental results so far support this conclusion.

Super-Schottky diodes (Vernon, et al., 1977) consist of an array of 5 μm diameter Pb dots electroplated onto heavily doped p-type GaAs. Electrical contact is made by a blunted whisker which touches at the edge of two or more dots. As a result of the high doping level, conduction is primarily by electron tunneling, and for voltages less than the superconducting energy gap, the I-V characteristic is highly nonlinear.

The I-V characteristic of either a conventional Schottky or a super-Schottky diode can be approximated by

$$I = I_o e^{(SV)} .$$
(V-2)

The parameter S is a measure of the nonlinearity and is therefore of central importance in determining the sensitivity of the diode as either a video detector or mixer. At 1 K, $S \simeq 300$ for a conventional Schottky, and $S \simeq 10,000$ for a super-Schottky diode. If the same conversion loss could be obtained, this implies a 40:1 improvement in sensitivity for the super-Schottky diode.

Figure V-2 is a curve of the intrinsic conversion loss of a super-Schottky diode resulting from the frequency conversion process. The absicca is $e\Delta/kT$ where $\Delta$ is the superconducting energy gap and e is the charge of an electron. For a Pb super-Schottky diode at 1 K, this intrinsic loss is 4 dB. In practice, additional losses are contributed by the

diode capacitance and series spreading resistance.  At X-band this parasitic loss is predicted to be about 3 dB.
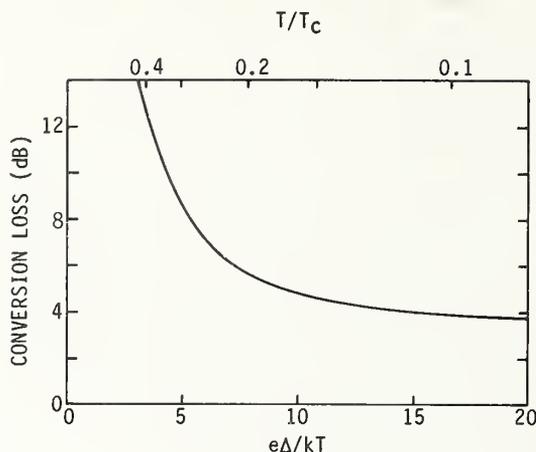


Figure V-2.    Intrinsic conversion loss of a super-Schottky diode as a function
               of the ratio of the energy gap $e\Delta$ to the thermal energy kT (after
               Vernon, et al., 1977).  In practice parasitic losses often considerably increase this loss.

Experiments at 9 GHz and 1.1 K have yielded a single sideband mixer noise temperature
$T_m$ = 6 K and a conversion loss $L_s$ = 7 dB.  This is the lowest microwave mixer noise temperature yet reported.  For receiver applications, the noise temperature of the super-Schottky mixer is comparable to parametric and maser amplifiers, while its bandwidth is considerably greater.  The saturation level of the super-Schottky diode can be estimated to be about $P_s \simeq P_{LO} \simeq 10^{-8}$ W.  This corresponds to a dynamic range of less than $10^5$ for $T_m$ = 6 K and B = 1 GHz.  This relatively small dynamic range may limit the usefulness of super-Schottky mixers in some applications.

The parasitic loss of these devices increases as $\omega^2$ and therefore presents a very serious problem for higher-frequency operation.  Efforts to reduce the spreading resistance by increased doping of the GaAs have not yet been successful because of the onset of an additional leakage current.  Progress may be made by using a parallel array of smaller diodes and by the use of other semiconductors in which higher conductivities can be achieved.

The use of a semiconducting barrier between two superconductors (Schyfter, et al., 1977) may be an attractive alternative to the present super-Schottky designs.  This device has the strong nonlinearity resulting from the superconducting energy gap, the low capacitance characteristic of a thick barrier device, and no loss from spreading resistance.  Although such devices have been fabricated, no serious effort has yet been made to develop them as mixers.

Current and projected performance of super-Schottky mixers (Silver and Hartwick, 1977) are plotted on Fig. V-3.  If the projected performance at higher frequencies is achieved, the super-Schottky diode may be the best mixer available.  The exceedingly low local oscillator requirements ($10^{-8}$ W) will also be an important advantage at the higher frequencies.
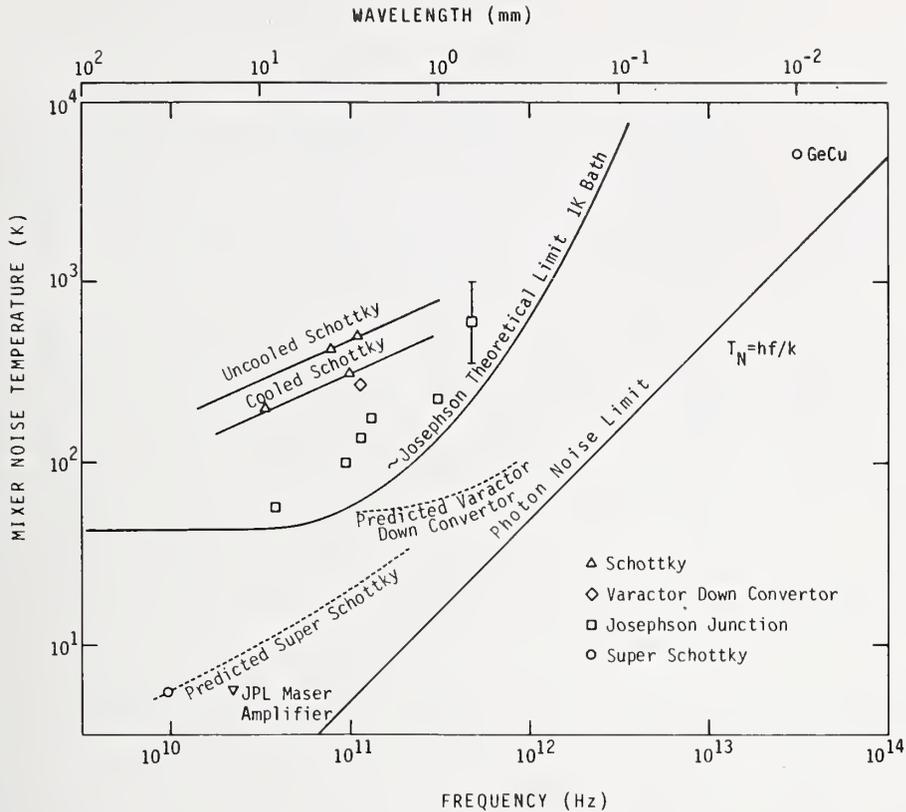
Figure V-3.     Theoretical and achieved mixer noise temperatures as a function
of frequency.


## V.4.0.   JOSEPHSON DEVICES

Josephson junctions are highly nonlinear low-noise devices.   The origin of the non-
linearity can be seen from the two familiar Josephson equations for an ideal junction:

$$I(t) = I_c \sin\phi \tag{V-3}$$

and

$$\frac{d\phi}{dt} = \frac{2e}{\hbar} V(t) \ , \tag{V-4}$$

where $\frac{2e}{\hbar}$ = 483 MHz/$\mu$V.   Equations (V-3) and V-4) show that a very small voltage across the
junction leads to a rapidly oscillating current through the device.   This property can be
exploited for high-frequency generation, mixing, detection, and parametric amplification.
Excluding parasitic effects, the inherent cutoff frequency of Josephson devices is a function
of the superconductors used and is given in Table V-2.

81

TABLE V-2

PROPERTIES OF A FEW SUPERCONDUCTORS

| Material | Transition Temperature (K) | Energy Gap (mV) | Cutoff Frequency $f_c$ (GHz) |
|---|---|---|---|
| Sn | 3.7 | 1.15 | 440 |
| Pb | 7.2 | 2.4 | 910 |
| Nb | 9.2 | 2.8 | 1060 |
| NbN | 16 | 4.8 | 1800 |
| $Nb_3Sn$ | 18 | 5.4 | 2100 |
| $Nb_3Ge$ | 21 | 6.4 | 2400 |

At frequencies above $f_c$, the Josephson effects die out rather slowly ($1/f$). It may therefore be possible to use Josephson devices at frequencies as high as 10 $f_c$. For example, harmonic mixing has been demonstrated at frequencies up to 4000 GHz ($\sim 4\ f_c$) using a Nb point contact junction (McDonald, et al., 1974).

### V.4.1.  Josephson Oscillator Sources

Equations (V-3) and (V-4) show that, if a constant voltage V is applied across a junction, the current will oscillate at a frequency 2eV/h. This suggests the use of a Josephson junction as a high-frequency generator. In practice, very low power and large linewidth make it quite difficult to utilize this high-frequency oscillator. Consider, for example, a typical 1 $\Omega$ Josephson junction dc-biased to produce a 50 GHz output ($\sim 100\ \mu V$). The maximum power which can be coupled out of such a device is on the order of $V^2/8R \simeq 10^{-9}$ W. Furthermore, Johnson and shot noise in the junction lead to voltage fluctuations which broaden the linewidth of the oscillation. At 4 K this broadening is on the order of 1 GHz for a 1 $\Omega$ junction. Both the available power and coherence can be improved by coupling the junction to a high-Q cavity. Output powers of $10^{-10}$ W with a linewidth of 4 MHz have been observed for this configuration (Dayem and Grimes, 1966). Future heterodyne receivers using Josephson or super-Schottky mixers with very low local oscillator requirements may be able to utilize a Josephson source as the local oscillator. This potential is greatest at very high frequencies where conventional sources are rare. Such a receiver design has been proposed (Silver, 1975) but not yet demonstrated.

Arrays of Josephson junctions in close proximity have been observed to oscillate coherently (Palmer and Mercereau, 1975). Carefully designed arrays in a very high-Q structure

offer the promise of producing significant narrow band power. Work in this direction is currently being pursued with electron beam lithography, and the results are encouraging (Sandell, et al., 1978).

## V.4.2. Josephson Mixers for Heterodyne Receivers

The most commonly used figure of merit for heterodyne receivers is their single sideband system noise temperature

$$T_{sys} = L_i \left[ T_M + T_{i.f.}/\eta \right] . \tag{V-5}$$

$L_i$ is the input loss, $T_M$ is the mixer noise temperature, $T_{i.f.}$ is the noise temperature of the i.f. amplifier and $\eta$ is the mixer conversion efficiency. For moderate conversion efficiency ($\eta > 0.2$), it is usually possible to reduce $T_{i.f.}$ so that the system noise is principally determined by $T_M$. If the background noise $T_B \lesssim T_M$, the rate at which information can be received is inversely proportional to the system noise temperature. Thus it is clearly desirable to achieve the lowest possible $T_M$.

The large cutoff frequency and low operating temperature of Josephson mixers make them attractive as a front-end component for low noise mm-wave receivers. Josephson mixers can operate with an external local oscillator or in a mode where a single junction acts as both local oscillator and mixer (internal LO). Both of these cases will be considered.

### V.4.2.1. *Josephson Mixer with Internal Local Oscillator*

If a Josephson junction is biased at a voltage $V_o$ and a signal frequency $f_s$ is applied, the junction will generate all of the frequencies $nf_o \pm mf_s$ where $f_o = 2eV_o/h$. Thus, if the bias is precisely set to $V_o = (h/2e)/(f_s \pm f_{i.f.})$, the junction will act as both mixer and local oscillator, i.e., the signal to be detected at $f_s$ mixes with the self-oscillation $f_o$ to produce an output at $f_{i.f.}$. Thus, the local oscillator is tuned by adjusting the dc bias and a separate local oscillator is not needed. At submillimeter and far-infrared wavelengths the availability of an internal local oscillator easily tuned over a wide frequency range is a considerable advantage.

The theoretically obtainable noise temperature for Josephson mixers with either an external or internal local oscillator is roughly equivalent (see Fig. V-3). However, in mixers utilizing the internal LO, the large linewidth of the self-oscillation requires that the i.f. be broadband and makes the mixer unsuitable for detecting narrow band (e.g., communication) signals. Its use will probably be limited to applications needing only moderate frequency selectivity such as radio astronomy and infrared spectroscopy.

Reducing the LO linewidth by resonant techniques is not practical because the junction must also couple effectively at the signal frequency. However, since the Josephson linewidth $\Delta f_o$ is proportional to the impedance at the junction squared ($\Delta f_o \sim R^2$), it may be possible to reduce the linewidth by connecting a low impedance shunt across the junction. Such a shunt will short out the low frequency fluctuations which broaden $f_o$ but it must have sufficient inductance so as not to short out the i.f. frequency. Satisfying both of these conditions may prove to be difficult.

The results which have been achieved with internal LO Josephson mixers are shown in Table V-3 and on Fig. (V-3). At the present time these results fall well short of the theoretical predictions. This is probably because the broadband nature of the internal local oscillator severely limits the usefulness of the device. As a consequence development efforts have been minimal.

### V.4.2.2. *Josephson Mixer with External Local Oscillator*

If both a local oscillator $(f_{LO})$ and a signal $(f_s)$ are applied to a Josephson junction, all of the frequencies $\ell f_{LO} + mf_s + nf_o$ are generated ($f_o$ is the Josephson frequency). The frequencies for which n = 0 are not subject to the line-broadening characteristic of $f_o$. Thus, the addition of an external local oscillator solves the line-broadening problem inherent to the Josephson internal LO mixer.

The operation of the Josephson mixer with an external LO is entirely different than that of conventional mixers and can be understood with reference to Fig. V-4 as follows: The application of local oscillator power $(P_{LO})$ to the junction produces a series of constant voltage steps in the I-V curve. These steps are separated in voltage by multiples of $hf_{LO}/2e$ and their amplitude is a function of the applied power. When a signal at $f_s$ is applied, the effect is roughly equivalent to an amplitude modulation of $P_{LO}$ at the difference frequency $f_{i.f.}$. For signal frequencies $f_s < f_c$ (see Table V-2) the conversion efficiency can be greater than one and because of the high order of the nonlinearity, efficient harmonic mixing is possible.
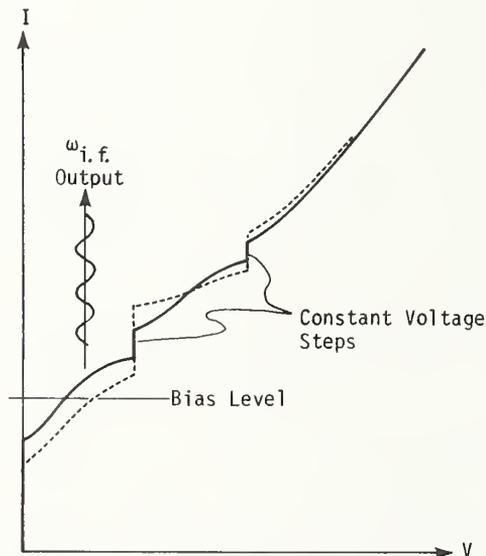


Figure V-4.    The I-V curve of a Josephson mixer with externally applied local oscillator power. Application of signal power causes the curve to vary between the solid and dashed lines at the difference frequency $(f_{i.f.})$.

TABLE V-3

MIXER PERFORMANCE

| Type | Frequency (GHz) | SSB Noise Temp. Tm (K) | Conversion Loss (dB) | Operating Temperature (K) | References |
|---|---|---|---|---|---|
| JJ Internal LO | 40 – 260 | 6000 | | | Avakjan, et al. (1975) |
| JJ External LO | 36 | 54 | Gain of 1.3 dB | 1.4 | Taur, et. al. (1974) |
| | 95 | 93 | 20 | | Kanter (1974) |
| | 115 | 140 | 2.4 | 1.8 | Taur and Kerr (1978) |
| | 130 | 180 | 5 | 4.2 | Claassen & Richards (1978) |
| | 300 | 220 | 9.5 | 4.0 | Edrich, et al. (1977) |
| | 450 | 500 | 11 | 4.2 | Blaney, et al. (1978) |
| Super Schottky | 9 | 6 | 7 | 1.1 | Vernon, et al. (1977) |
| Cooled Schottky | 15 | 186 | 6 | 18 | Weinreb and Kerr (1973) |
| | 33 | 196 | 5.8 | 15 | Weinreb and Kerr (1973) |
| | 100 | 300 | 5.8 | 77 | Kerr (1975) |
| Uncooled Schottky | 15 | 437 | 5.4 | 300 | Weinreb and Kerr (1973) |
| | 85 | 420 | 4.6 | 300 | Kerr (1975) |
| | 115 | 500 | 5.5 | 300 | Kerr (1975) |
| Varactor Down Converter | 115 | 275 | $\sim$ 9 | | Weinreb (1978) |
| GeCu Photoconductor | 30,000 | 5000 | | 300 | Teich (1969) |

Considerable experimental and theoretical effort has been devoted to the study of this type of Josephson mixer (Claassen and Richards, 1978). At low frequencies, $f_s \ll f_c$ (the cutoff frequency), the theoretical value of $T_m$ has been found to be approximately 40 T where T is the effective junction temperature. This effective temperature may differ from the bath temperature because of junction heating. The reasons for the excess noise are complex and are related to the fact that the junction self-oscillation can convert low-frequency fluctuations into the signal and i.f. bands. At frequencies $f \geq f_o$, the noise temperature increases as $f^2$. This behavior, assuming a typical Nb junction, is plotted in Fig. V-3.

Because of their low capacitance and nearly ideal non-hysteretic I-V curves, point contact junctions have been used almost exclusively in Josephson mixing experiments. Most of these devices are adjusted during the experiment to achieve the desired I-V curve. This mode of operation is clearly impractical for any field-usable or satellite-based receiver. Some very recent work with a permanently adjusted point contact has shown that it is possible to fabricate mixer junctions which are moderately immune to vibration and can be thermally cycled many times (Taur and Kerr, 1978). The mixer configuration used with this permanent-point contact is shown in Fig. V-5. The contact is made between a Nb wire and foil attached to metallized substrates which are glued to a third base substrate as shown in Fig. V-5(a). Choke patterns on the substrates reflect a proper reactive impedance for optimum coupling to the junction. The junction assembly is placed across a reduced height waveguide mount. This particular device has achieved a single sideband mixer noise temperature of 140 K at 115 GHz. This and other similar results with Josephson mixers are tabulated in Table V-3 and shown as the square points on Fig. V-3. Generally, the experimental results are within a factor of two of the predicted performance for Josephson mixers. In the frequency range 30 to 300 GHz their performance is the best reported to date. Although noise temperature is perhaps the most important figure of merit for a mm-wave mixer, other parameters which must be considered are conversion loss, instantaneous bandwidth, saturation and LO power requirements. Conversion loss for Josephson mixers is at least comparable to that for conventional mixers and in at least one case (Taur, et al., 1974), conversion gain has been reported. LO power requirements are exceedingly low ($\sim 10^{-9}$ W). However, since mixers begin to saturate when the signal power is comparable to LO power, Josephson mixers have a low saturation level. This also implies a relatively small dynamic range. The instantaneous bandwidth of Josephson mixers is in principal very large. However, if the mixer is exposed to a warm background, it is often necessary to restrict the input bandwidth to avoid saturation from the background. The use of resonant circuits to improve the signal coupling will also restrict the bandwidth.

As in the case of Josephson sources, the fabrication of arrays of thin-film junctions offers improved performance. Although the noise temperatures cannot, in principal, be lowered with arrays, improvements in impedance matching, bandwidth and saturation level should be possible.
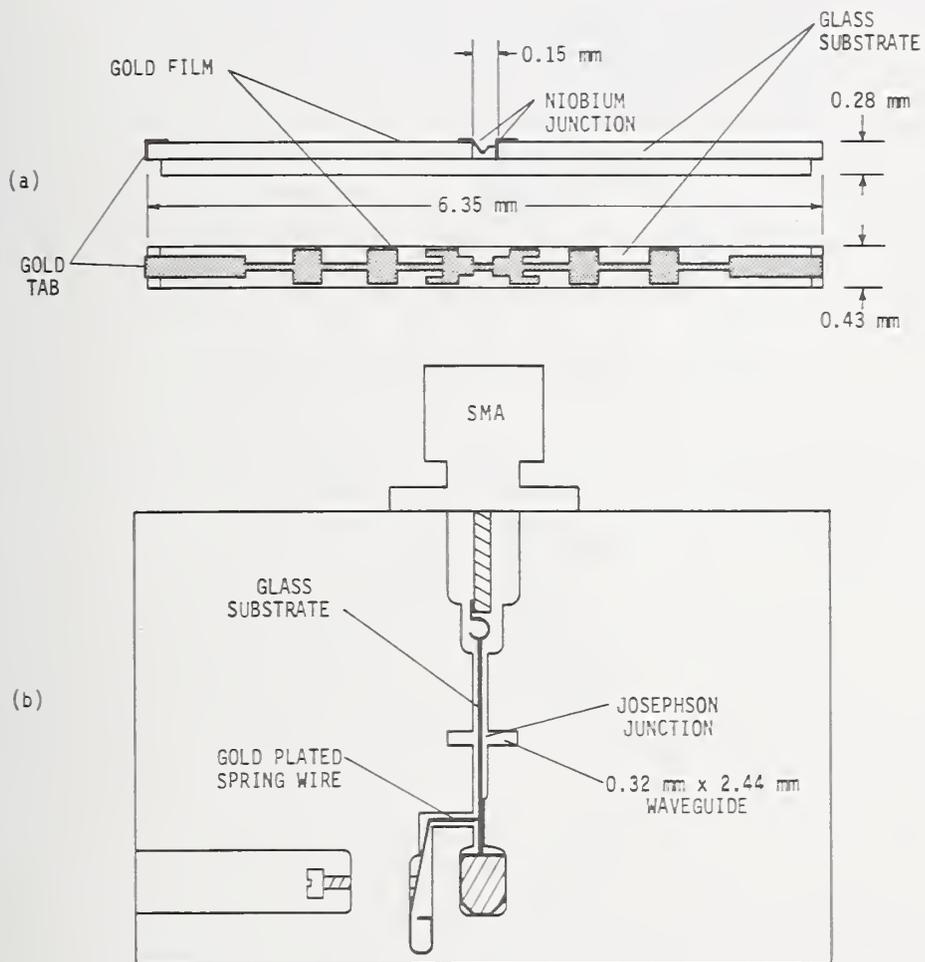
Figure V-5.   Configuration for a permanently adjusted, cyclable Josephson
mixer (after Taur and Kerr, 1978).

## V.5.0.  NON-SUPERCONDUCTING MIXERS

Because of their reliability and ease of operation, Schottky diodes are used almost exclusively in current microwave and millimeter wave receivers.  The performance of both cooled and uncooled Schottky mixers is shown in Fig. V-3 and is clearly not as good as the Josephson devices.  However, the results for Schottky mixers represent measurements for operational receivers while the Josephson data are mostly laboratory measurements.

The recent development of high-frequency (19 - 25 GHz) very low-noise (6 K) maser amplifiers at the Jet Propulsion Laboratory (JPL) has made practical the use of a Schottky varactor as a frequency down converter (mixer).  Although varactors can have a very low noise temperature, their conversion loss is about $f_s/f_{i.f.}$.  For typical i.f. frequencies, this conversion loss is unacceptable.  However, when used with the JPL maser as an i.f. amplifier, varactor down converters have achieved a system noise temperature comparable to the Josephson devices (Weinreb, 1978).  Furthermore, their theoretically obtainable performance exceeds that of the Josephson mixers (see Fig. V-3).

## V.6.0.  JOSEPHSON PARAMETRIC AMPLIFIERS

A Josephson junction can be operated at zero bias so that it behaves as a nonlinear inductor for currents less than the critical current.  The nature of the nonlinear inductance can be seen by rewriting the Josephson equations as follows:

$$V = \frac{d}{dt}\left[L_J(I)I\right]$$

$$L_J(I) = \frac{L_J \sin^{-1}(I/I_c)}{I/I_c} \tag{V-6}$$

$$L_J = \frac{h}{2eI_c} \quad .$$

An ideal Josephson junction is thus a nonlinear inductor with a characteristic inductance $L_J$ at zero bias.  Josephson parametric amplifiers based on this mode of operation have received the most thorough experimental and theoretical study and have become known as SUPARAMPS (Superconducting Unbiased PARametric AMPlifier).

These amplifiers have the advantages of simple construction, very low pump power requirements and wide instantaneous bandwidth.  Wide bandwidth relative to conventional paramps is possible because the self-coupling reactance in the SUPARAMP is small and there is no need to resonate it out (Feldman, Parrish and Chiao, 1975).  The principal disadvantage of the SUPARAMP is its low output saturation level.

Figure V-6 shows the configuration for a typical reflection type SUPARAMP.  Operating as a three-photon device, one pump photon decays into a signal photon and an idler photon giving $f_p = f_s + f_i$.  A more successful mode of operation uses two pump photons to produce one
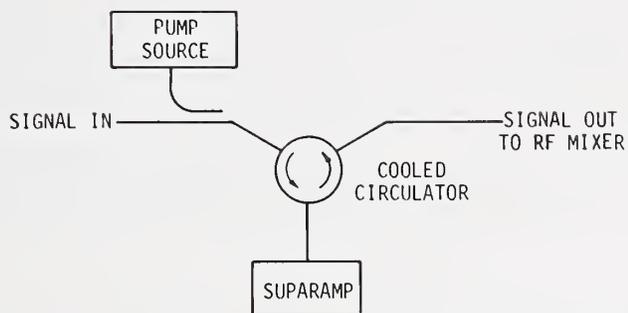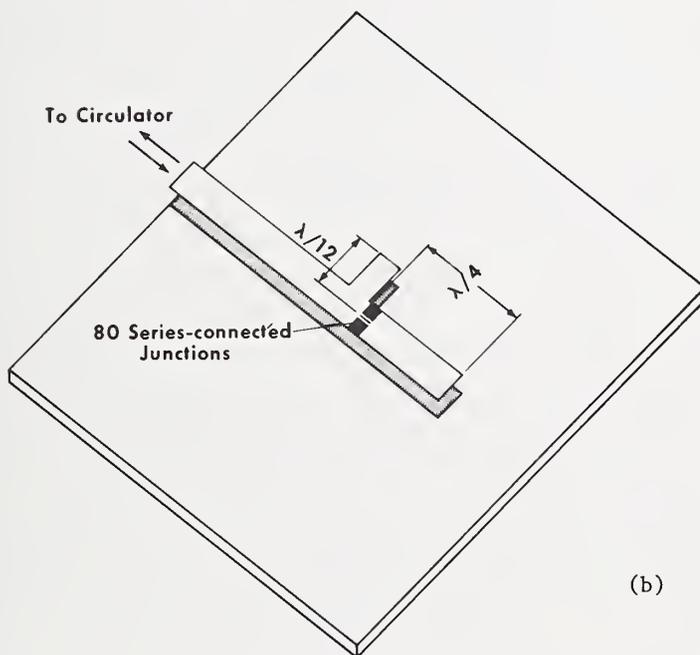
Figure V-6.    (a)  Microwave configuration for a reflection-type SUPARAMP and
               (b)  the detail of the microstrip circuitry (after Feldman,
               et al., 1975).

signal photon and one idler photon, $2f_p = f_s + f_i$. The success of this four photon doubly degenerate device depends on the fact that the unbiased Josephson junction is symmetric to a physical inversion. The high degree of nonlinearity of the Josephson junction normally creates a large number of active idler frequencies which dissipate the signal power. High gain requires that these parasitic frequencies be suppressed. The unique symmetry of the four-photon device causes parasitic currents at frequencies $\ell f_p + m f_p$ to vanish when $\ell + m$ is an even integer. The stripline stub at $\lambda/12$ is used to short out currents for $\ell + m = 3$ so that the lowest frequencies at which loss occurs are on the order of $5 f_p$. For reasons which will become clear shortly, Fig. V-6b indicates a series array of Josephson elements rather than a single device. The theory of the SUPARAMP is well developed and predicts that depletion of pump photons by the amplification process leads to saturation at an input temperature

$$ T_{sat} = 1.4 \ N^2 \nu_{GHz} \ \Gamma_p^{-5/4} \ (50/Z_o)F \ , $$

where N is the number of series-connected junctions, $\nu_{GHz}$ is the frequency in GHz, $\Gamma_p$ is the peak gain and F is a function of the coupling. For typical values $N = 1$, $\nu_{GHz} = 33$, $\Gamma_p = 100$ (20 dB gain) and $F = 1$, the saturation temperature is $T_{sat} = 0.14$ K. Achieving a practical saturation temperature therefore requires a large number of series-connected junctions. Since Josephson junctions typically have a resistance on the order of $1 \ \Omega$, the use of a series array also simplifies the impedance matching problem.

Saturation in the SUPARAMP is most appropriately characterized by a maximum output brightness temperature (Feldman, 1977). This output temperature cannot be exceeded regardless of the input temperature. Although this saturation is a severe limitation at present it may be less of a problem in space applications where background temperatures are usually low. The development of SUPARAMPS with larger $I_c R$ products and perhaps the use of rectangular arrays should substantially increase the achieved saturation levels. A summary of recently reported results with Josephson paramps is given in Table V-4. The last three entries show state-of-the-art results for conventional paramps and masers. It is fairly clear that at the present time the SUPARAMP does not offer any significant advantage over more conventional devices.

## V.7.0. SUMMARY AND CONCLUSIONS

*It is probably fair to state that, in general, superconducting microwave and infrared detectors demonstrate no overwhelming advantages over conventional devices.* In particular instances the performance of the superconducting detector represents the state-of-the-art, but never by a wide margin. For superconducting detectors, the magnitude of development efforts has been only modest, at best, and that situation will likely prevail for the near future.

The space applications of these detectors would probably center on radio and infrared astronomy and on communications, areas where the best possible noise performance is desired. Low noise performance almost certainly requires liquid helium temperatures for any type of

TABLE V-4

PARAMETRIC AMPLIFIER PERFORMANCE

---

SUPARAMP - 30 tunnel junctions in series (Wahlsten, et. al., 1977)
    10 GHz operating frequency
    12 MHz bandwidth
    24 dB gain
    $10^{-8}$ W pump
    $1.7 \times 10^6$ K maximum output brightness temperature

SUPARAMP - 80 or 160 series microbridges (Chiao and Parrish, 1976)
    33 GHz operating frequency
    3.4 GHz bandwidth
    15 dB gain
    $20 \pm 10$ K SUPARAMP DSB noise temperature
    220 K DSB system noise temperature

SUPARAMP - Single point contact (Taur and Richards, 1977)
    36 GHz operating frequency
    50 MHz bandwidth
    11 dB gain
    50 K noise temperature

Cooled (18 K) varactor paramp (Edrich, 1977)
    47 GHz operating frequency
    300 MHz bandwidth
    22 dB gain
    100 K system noise temperature
    50 K noise contribution from paramp

Uncooled varactor paramp (Okean, DeGruyl and Ng, 1976)
    15 GHz operating frequency
    500 MHz bandwidth
    25 mW pump power
    75 K system noise temperature

JPL maser amplifier
    19 - 25 GHz
    50 - 230 MHz bandwidth
    $6 \pm 2$ K system noise temperature

---

detector, and indeed, the planned IRAS program supports this contention. Thus, the environment for superconductivity will usually exist for any low noise missions, and superconducting detectors will be able to compete on an almost equal footing with their non-superconducting counterparts.

Besides the need for further improvements of performance, there is a need for development of more stable and long-lived devices. Point contacts may never be adequate for space flight, and even the present thin-film devices suffer failures. This situation may improve as the lithographic thin-film technology, generated by digital electronic development (see Chapter IV), becomes more widespread. Particular importance should be attached to the application of electron-beam lithography to the fabrication of high-frequency detectors. Photolithography, while useful in some cases, will probably not provide the very small dimensions required for high frequency work. While thin-film devices should, in principle, work as well as the point contacts, developmental effort will be required to demonstrate this.

There are several conclusions to be drawn from a study of Fig. V-3. First, the super-Schottky diode warrants further development. The big questions involve the suppression of parasitic losses and extension of work to higher frequencies. The Josephson mixer is clearly ahead of the conventional Schottky diodes and the varactor down converter, but the predictions for an improved varactor down converter are better than the theoretical Josephson limit. The questions here are clearly unsettled, and more work should be done on both devices.

The SUPARAMP, while not up to the performance levels of some non-superconducting devices, has certain attractive features. Prime among these are the wide bandwidth, low pump power requirement and very simple construction. Even with the very modest effort on development of the SUPARAMP, performance is quite respectable (see Table V-4) and further improvements are expected. The low pump power required of this device may be a key advantage for extended space missions where heat load in the cryogenic environment is of vital concern. This advantage also holds for the Josephson mixer.

Apparently, the key question in further bolometer development centers around the reduction of heat capacity. The selection of thermometer, superconducting or not, is primarily a question of convenience and simplicity. The superconducting transition-edge thermometer fairs well in this respect.

To summarize then, superconducting detectors, while offering significant advantages (both real and potential), do not appear to be a panacea for all high-frequency instruments. However, the full story is not yet told. A lot depends on how closely the superconducting and non-superconducting devices approach theoretical performance levels. Presently there appears to be no really strong incentive for large increases in developmental funding levels. The major questions should be settled during the next decade at present spending levels. However, should some of the superconducting devices (particularly the junction devices) gain clear advantage, then it would seem essential to stimulate work directed toward thin-film (lithographic) realizations of the devices, in order to satisfy the stability requirements demanded by space flight.

Adde, R. and Vernet, G. (1977). High Frequency Properties and Applications of Josephson Junctions from Microwaves to Far-Infrared. *Superconductor Applications: SQUIDs and Machines.* eds., B.B. Schwartz and S. Foner, Plenum Press, New York. 249-320.

Avakjan, R.S., Vystavkin, A.N., Gubankov, V.N., Migulin, V.V. and Shtykov, (1975). Milli-meter Waveband Signal Conversion in S-c-S Josephson Junctions with Self Pumping. *IEEE MAG-11*, 838-840.

Blaney, T.G., Cross, N.R. and Jones, R.G. (1978). Performance of a Josephson Heterodyne Re-ceiver at 450 GHz. *Proc. of Conf. on Future Trends in Superconductive Electronics,* Charlottesville, Virginia (to be published).

Chiao, R.Y. and Parrish, P.T. (1976). Operation of the SUPARAMP at 33 GHz. *J. Appl. Phys.* 47, 2639-2644.

Claassen, J.H. and Richards, P.L., (1978). Point Contact Josephson Mixers at 130 GHz. *Proceedings National Radio Science Meeting,* to be published.

Clarke, J., Hoffer, G.I. and Richards, P.L. (1974). Superconducting Tunnel Junction Bolom-eters. *Rev. Phys. Appl. 9,* 69-71.

Clarke, J. and Hsiang, T.Y. (1975a). Low Frequency Noise in Superconducting Sn Films at the Transition Temperature. *IEEE MAG 11,* 845-847.

Clarke, J., Hoffer, G.I., Richards, P.L. and Yeh, N.Y (1975b) A Superconducting Transition Edge Bolometer. *Low Temp. Phys. - LT14, Vol. 4,* eds. M. Krusius and M. Vuorio, American Elsevier, New York. 226-229.

Clarke, J., Hoffer, G.I., Richards, P.L. and Yeh, N.H. (1978). Superconductive Bolometers for Submillimeter Wavelengths. *J. Appl. Phys.,* to be published.

Coron, N., Dambier, G., Leblanc, J.L. and Moalic, J.P. (1975). High Performance Far-Infrared Bolometer Working Directly in a Helium Bath. *Rev. Sci. Inst., 46,* 492-494.

Dayem, A.H. and Grimes, C.C. (1966). Microwave Emission from Superconducting Point-Contacts. *Appl. Phys. Lett. 9,* 47-49.

Edrich, Jochen, Sullivan, D.B. and McDonald, D.G. (1977). Results Potentials and Limitations of Josephson Mixer Receivers at Millimeter and Long Submillimeter Wavelengths. *IEEE MTT-25,* 476-479.

Edrich, Jochen (1977). A Cryogenically Cooled Two-Channel Paramp Radiometer for 47 GHz. *IEEE MTT-25,* 280-285.

Feldman, M.J., Parrish, P.T. and Chiao, R.Y. (1975). Parametric Amplification by Unbiased Josephson Junctions. *J. Appl. Phys. 46,* 4031-4042.

Feldman, M.J. (1977). The Thermally Saturated SUPARAMP. *J. Appl. Phys. 48,* 1301-1310.

Kanter, H. (1974). Josephson Junction Mixer Using an External Local Oscillator. *Rev. Phys. Appl. 9,* 255-262.

Kerr, Anthony R. (1975). Low Noise Room Temperature and Cryogenic Mixers for 80-120 GHz. *IEEE MTT-23,* 781-787.

Lukens, J. and Sandell, R. (1978). *private communication.* SUNY at Stonybrook.

McDonald, D.G., Petersen, F.R., Cupp, J.D., Danielson, B.D. and Johnson, E.G. (1974). Josephson Junctions at 45 Times the Energy Gap Frequency. *Appl. Phys. Lett. 24,* 335-337.

Nishioka, N.S., Richards, P.L. and Woody, D.P. (1978). Composite Bolometers for Submilli-
meter Wavelengths. *Applied Optics*, to be published.

Okean, H.C., DeGruyl, J.A. and Ng, E. (1976). Ultra Low Noise, Ku-Band Parametric Amplifier
Assembly. *IEEE MTT-S*, International Microwave Symposium, 82-84.

Palmer, David William and Mercereau, J.E. (1975). Coherent Effects in Series Arrays of
Proximity Effect Superconducting Bridges. *IEEE MAG-11*, 667-670.

Sandell, R.D., Varmazis, C., Jain, A.K. and Lukens, J.E. (1978). Study of the Properties
of Coherent Microbridges Coupled by External Shunts. *Proc. of Conf. on Future Trends
in Superconductive Electronics*, Charlottesville, Virginia (to be published).

Schyfter, M., Maah-Sango, J., Raley, N., Ruby, R., Ulrich, B.T. and VanDuzer, T. (1977).
Silicon-Barrier Josephson Junctions in Coplaner and Sandwich Configurations. *IEEE MAG-
13*, 862-865.

Silver, A.H. (1975). Superconducting Low Noise Receivers. *IEEE MAG-11*, 794-797.

Silver, A.H. and Hartwick, T.S. (1977). New Horizons in Receiver Technology. *Report No.
SAMSO-TR-77-205*, Air Force Systems Command SAMSO.

Taur, Y., Claassen, J.H. and Richards, P.L. (1974). Josephson Junctions as Heterodyne
Detectors. *IEEE MTT-22*, 1005-1009.

Taur, Y. and Kerr, A.R. (1978). Low Noise Josephson Mixers at 115 GHz Using Recyclable Point
Contacts. *Proceedings National Radio Science Meeting*, to be published.

Taur, Y. and Richards, P.L. (1977). Parametric Amplification and Oscillation at 36 GHz Using
a Point-Contact Josephson Junction. *J. Appl. Phys. 48*, 1321-1326.

Teich, M.C. (1969). Homodyne Detection of Infrared Radiation from a Moving Diffuse Target.
*Proc. IEEE 57*, 786-792.

Vernon, F.L., Jr., Millea, M.F., Bottjer, M.F., Silver, A.H., Pedersen, R.J. and McColl, M.
(1977). The Super-Schottky Diode. *IEEE MTT-25*, 286-294.

Wahlsten, S., Rudner, S. and Claeson, T. (1977). Parametric Amplification in Arrays of
Josephson Tunnel Junctions. *Appl. Phys. Lett. 30*, 298-300.

Weinreb, Sander and Kerr, Anthony R. (1973). Cryogenic Cooling of Mixers for Millimeter and
Centimeter Wavelengths. *IEEE SC-8*, 58-63.

Weinreb, S. (1978). Low Noise Millimeter Wave Parametric Down-Converters. *Proceedings
National Radio Science Meeting*, to be published.

CHAPTER VI

INSTRUMENTS FOR GRAVITATIONAL STUDIES

R. L. Peterson

## VI.1.0.  INTRODUCTION

Of all the known forces of nature, gravity might be called the first-born, but the least well understood.  It has been said that if we knew as much about electricity as we now know about gravity we wouldn't yet have the electric light bulb.  The reason for our relative lack of knowledge is that gravitational forces are so very much smaller than the others.  Isaac Newton developed his theory of gravity based upon earlier observations of planetary motion.  This theory held up remarkably well until the early 1900's when Einstein developed his theory of general relativity, largely on philosophical grounds.  This theory was verified to a certain extent within just a few years in three ways, and thereafter because it was considered such a profoundly beautiful theory, it was not much questioned until about the early 1960's.  It was at about this time that it became clear that space technology would allow more tests of general relativity than people had ever imagined before.  This realization provided a great stimulus for critical thinking about Einstein's theory and for the invention of many new theories of gravity.

An example of an alternate theory is Dirac's "large-number hypothesis," which is itself philosophically grounded.  This theory has among its consequences that the gravitational constant G in fact should decrease with time.  Now in general relativity G is a constant; therefore if a test were to show that G is decreasing, this would have profound implications, bearing on the age of the universe and its evolution.  So, in the scientific community, it is now considered to be very important to make very good tests of the theory of general relativity to see whether in fact it is correct.  Some tests have already been carried out to rather great precision, and others are in progress or in the proposal stage.  Those for which superconductivity is making or can make a contribution are discussed in the following sections.  To repeat, it is the advent of space technology that has made possible these new tests of gravitation theories, and it is clear that the new results will come in the main from space exploration and instrumentation.

The superconducting cavity stabilized oscillator is a key instrument for the test of gravitational theories.  The importance of this device is such as to warrant separate coverage in the following chapter.  However, for cohesiveness, the discussion of tests of gravitational theories (Section VI.3.0. in this chapter) will cover such applications.  Cross referencing will be used to tie these two chapters together.

The measurement of the time-variation of the local gravitational field at the surface of a planet is also of considerable interest.  Such measurements provide useful information about the planet interior as well as the planet's interactions with other objects in space (moons, planets, etc.).  Superconductivity already plays a useful role for such measurements on earth (especially for long-term variations) and deployment of such instrumentation on the moon or other planets would provide interesting information.

Because of their relation to gravity, inertial guidance and gyroscope guidance are discussed in this chapter.  While serious proposals for the application of superconductivity to such guidance have not yet been made, the needs for improved autonomous navigation in the future may prompt thought in this direction.

## VI.2.1.   Accelerometers

Strictly speaking, an accelerometer measures accelerations. However at the present time the term accelerometer is also used for those instruments which are capable of detecting very small displacements, such as the displacements of the ends of the large cylindrical antennas used in the detection of gravitational radiation (see Section VI.3.1.).

Acceleration measurements per se are made by sensing the force necessary to keep a proof mass in place with respect to the accelerating frame, using Newton's second law to calculate the acceleration from the known mass and the measured force. The force is often a spring or a string under tension or some manifestation of electromagnetic or electrostatic forces. The conventional force rebalance accelerometers are electo-mechanical devices, and are typically designed for a given range of acceleration. We shall not further describe these conventional accelerometers except to point out the existence of a recently-developed low-g accelerometer which has the acronym MESA. This accelerometer was specifically developed for sensing small accelerations on space craft and will be tested and calibrated in Space Lab II. The measurement of acceleration in the MESA is accomplished by sensing the motion of the proof mass, which is a berylium cylinder, with respect to the instrument case. Electrostatic forces are generated to oppose the motion of the cylinder in a direction to restore it to its null or zero input position.

It seems clear that a superconductive analog of MESA could be designed and used profitably in special situations. Any vehicle with cryogenics on board might well use superconductive rather than electrostatic positioning and sensing. For example, the proof mass might be a hollow superconducting sphere. Superconducting coils might be used for generating the magnetic force for positioning the sphere, and a SQUID magnetometer might be used for sensing the position of this sphere. As noted below, the projected performance of a SQUID for such position sensing is expected to be excellent.

Many types of superconducting accelerometers, used as displacement sensors, have been proposed. Basically, they are all the same. That is, they use a pendulum which swings within some type of electrical system, thereby changing the properties of that electrical system, and that change is detected. There are both resonant and non-resonant types of accelerometers.

Perhaps the best-known superconducting accelerometer (at the moment) is the one developed at Stanford University (Paik, 1976) specifically for the purpose of detecting gravitational waves in conjunction with large cylindrical antennas. This instrument has been under development for several years. At 3 mK, which is the temperature at which the entire system is hoped eventually to operate, this accelerometer is projected to detect (ideally) a motion between the ends of the cylinder of $3 \times 10^{-20}$ m in a 1 Hz bandwidth. A superconducting niobium diaphram oscillates between two coils which are themselves made of superconducting material and carry a persistent current. The oscillating diaphram modulates the inductance of these coils, thereby changing the current. This current change in turn is detected by a SQUID magnetometer. This particular accelerometer is designed to resonate at the resonance frequency of the cylinder, about 1 kHz.

Another type of accelerometer which has been proposed has been called a flux gradient accelerometer (Hoffman, Douglass, Gram and Lam, 1976). It consists of a pair of cylindrical magnets in an opposing field configuration mounted rigidly to the end of the cylinder and hence vibrating with the cylinder. A pendulum with coils mounted on it hangs between the two magnets. The magnetic flux through the coils changes as the pendulum moves relative to the magnets, and this induces a voltage. A SQUID can be used to measure the flux change if the coils are superconducting. The projected sensitivity is $9 \times 10^{-20}$ m for a 1 Hz bandwidth. A preliminary version has been built but the device is not nearly as well developed as the tunable diaphram device mentioned previously.

Another accelerometer has been proposed in which a superconducting mass is supported by a superconducting magnetic field which is rigid with the case. An acceleration causes an inductance change which is detected, for example, by a SQUID. A variation of this, which will offer a more rapid response time, consists of tuning the support circuit for the superconducting mass at a high resonsance frequency, for example, 30 MHz. The voltage across the tuned circuit is measured and fed back to hold the mass at a constant position. The acceleration is proportional to the feedback current. This proposal might offer sensitivity to motions of $10^{-19}$ m at 1000 Hz.

Yet another idea for a superconducting accelerometer is based upon the use of superconducting re-entrant cavities. In this design (no publications yet), which has been constructed in a preliminary version, the cavity is mounted rigidly to the end of the bar whose motion is to be detected. The superconducting cavity is driven at its resonance by an oscillator (about 600 MHz). To the rear end of the cavity is mounted a small mass in the shape of a cylinder. The mechanical resonant frequency of the rear wall with its mass is about 10 Hz, much smaller than the approximate 1000 Hz resonant frequency of the large antenna cylinder. When the antenna vibrates, the relative motion between it and the small cylinder within the cavity changes the resonant frequency of the cavity, which change is detected by conventional techniques. However, this idea has been found to be inadequate because of the instabilities in the oscillator. These instabilities change the resonance curve so that the motional effect is obscured. An improvement on this concept is to use a second identical re-entrant cavity back-to-back with the first, fed by the same oscillator. If the signals from the two cavities are subtracted, the oscillator instabilites are eliminated to first order, but it is found that they are not eliminated entirely. Unambiguous gravitational wave detection with this system is still not possible. One needs a still better oscillator and the developers of this type of accelerometer say that this idea will not be successful until an oscillator with the capabilities of the superconducting cavity stabilized oscillator (Capter VII) has been developed.

A variant of this idea is to replace the two cylinders which are mounted back-to-back at the rears of the two re-entrant cavities, by a single cylinder which is levitated magnetically. This cylinder will be hollow with a hole in the side. Through the hole is fed a wire making a loop in the interior of the cylinder, levitating it. This cylinder passes through openings in the ends of the two superconducting cavities and is thus, for all practical purposes, freely suspended, and should offer greater sensitivity. But as in the preceding case, a more stable oscillator is needed for successful operation.

Finally, we shall mention a non-resonant accelerometer which has been called a single-axis superconducting accelerometer (Fairbank, et al., 1974). In this design a straight superconducting wire carrying a current passes through a horizontal niobium spool, levitating it. The accelerometer case is attached to the end of the antenna and moves with it. The spool remains fixed in space. A superconducting inductance is mounted on the case and its inductance is modulated because of the relative motion of the case and the spool. The inductance can be made part of a resonant circuit so that the resonant frequency changes with the motion of the bar. A prototype model has been built with a Q of greater than $10^4$ for the varied inductance, enabling measurements of deflections of the order of $10^{-17}$ m at 2 K. This is one of the older proposals. We have not heard of any recent extension of it and believe development on it has stopped.

For comparison with the above displacement sensitivities, the strain gauges used by Weber in the initial gravitational wave detection experiments could detect displacements of the order of $10^{-16}$ m.

## VI.2.2. Gravimeters

A gravimeter is an instrument in which the gravitational force acting on a mass is balanced by an elastic restoring force. Gravimeters may be called seismometers, but by convention the term is reserved for the measurement of periods greater than about 100 s. All the gravimeters using a mechanical spring for the elastic restoring force tend to creep under stress. This creep normally gives rise to irregular drifts. The best mechanical room temperature gravimeters are the La Coste gravimeters. These have drifts of about $10^{-8}$ g per day, which makes them unsatisfactory for measurements of phenomena whose variation is less than this. The fortnightly earth tides provide one example for which the La Coste gravimeters are inadequate. These motions are now being measured routinely by superconducting gravimeters.

In the late 1960's a superconducting gravimeter was developed by two groups using essentially the same design (Goodkind and Warburton, 1975 and Tuman, 1974). In this instrument a hollow niobium sphere which acts as a perfect diamagnetic body is supported by the extremely stable magnetic fields and gradients produced by the persistent currents in a set of superconducting coils. As long as the magnetic field is smaller than the critical field of the superconducting elements of the instrument, the magnetic restoring forces do not give rise to magnetic creep of measurable magnitude. The instruments are believed to be entirely free of magnetic creep because of the cylindrically symmetric construction which is all of aluminum and maintained at liquid helium temperature. In the superconducting gravimeters the signal drift is less than $10^{-9}$ g per day; better than $10^{-11}$ g per day is theoretically possible but not yet achieved.

A number of superconducting gravimeters are now being deployed throughout the U.S. in an earth-tide measurement program. These gravimeters use capacitive sensing of the position of the superconducting sphere. Other similar gravimeters, however use a more sensitive SQUID readout system.

The superconducting gravimeters developed to date are also more sensitive than the best La Coste mechanical gravimeters at frequencies lower than a few cycles per hour. At two cycles per month, for example, a superconducting gravimeter is 100 - 1000 times more sensitive.

In addition to the earth-tide measurement program, the superconducting gravimeters have been used to search for gravitational effects not contained in general relativity, specifically, evidence for a preferred reference frame and a possible variation of the gravitational constant. Upper limits were placed on the possible values of these effects. Also, as we will mention in Section VI.3.0., a superconducting gravimeter has been used in an effort to detect the influence of gravitational radiation on the earth's vibrational behavior. Another area of potential use lies in earthquake prediction. The so-called dilatancy theory predicts surface rises as high as 1 m per month in some cases (Goodkind and Warburton, 1975), which would correspond to a change in g of about $3 \times 10^{-7}$ g per month. Because of the great stability of the superconducting instrument it is apparent that it could be very useful here.

A La Coste gravimeter was placed on the moon in the Apollo 17 expedition. The primary purpose of that experiment was an attempt to detect gravitational radiation by looking at the moon's vibrations. However, the gravimeter did not function properly. The La Coste gravimeters are very sophisticated and complicated mechanical devices having springs, levers, and hinges. Since a superconducting gravimeter is an inherently simpler instrument, it might be appropriate to consider its use in future studies of the moon and planets.

Further development of superconducting gravimeter design is proceeding very slowly at present, if at all. At the moment, the groups are primarily interested in using their present instruments to make physical measurements. However, it is apparent that renewed development effort could be worthwhile since the sensitivities of the present instruments are some two orders of magnitude less than their theoretical sensitivities.

VI.2.3. Superconducting Bearings

There are very many applications in space where frictionless rotational or translatory motion of a shaft or cylinder would be useful. Examples include the chopping wheels used with infrared devices, servo-controlled tipping plates, rotating knife-edge detectors, the proposed equivalence principle concentric cylinder experiment (in space), and even an experiment on a rotating bucket of liquid helium. A particularly intriguing idea would be the use of bearings for a dilution refrigerator in space. Earth-based dilution refrigerators require gravity to effect the phase separation used for operation of the refrigeration cycle. A rotating cryogenic chamber would allow the phase separation in space to be effected centrifugally.

Efforts have recently begun on developing superconducting bearings of real technological utility, having small machining tolerances and high reliability. Of course several devices described in this report use superconducting levitation and accurate position sensing, for example the accelerometers and the gravimeters. But a systematic study of the engineering requirements for bearing performance specifically has not been made until recently. Many experiments (already proposed) could probably be improved and other experiments might become possible with the availability of a properly engineered superconducting bearing. Conventional bearings encounter severe trouble at cryogenic temperatures because of lubricant problems and heat dissipation.

Most of the work on superconducting bearings to date has been on the translatory mode of the bearing, and this by a single group (Worden and Everitt, 1974), so far as we know. The work has been done in connection with an equivalence principle experiment in space, which will be discussed in Section VI.3.2. In the apparatus now under development, the levitating magnetic field for the shaft or cylinder is provided by a series of wires wound back and forth in a cylindrical cradle. This reverses the current direction in adjacent wires so that the net magnetic field at large distances is zero, which is important for reducing the influence of the field in other parts of the space vehicle. The coils must be wound to very high tolerance to operate properly, since very large variations in the normal force can result from very small deformations in the support coil. Since the force is repulsive and decreases with the distance of the cylinder from each point in the surface of the cradle, the bearing is automatically self-centering and dynamically stable.

It is important not to confuse the type of levitation for these superconducting bearings with that used in superconducting generators (see Section II.4.4.) or the superconducting train. The train carries high-field superconducting magnets and runs over an aluminum track. At high speed the repulsive force between moving magnets and eddy currents in the track causes levitation; thus that bearing is inherently dissipative. The superconducting generators are being developed at MIT and several industrial companies. They substitute a rotating superconducting magnet for the armature winding of the conventional generator. Although such generators could use superconducting bearings, there has been little incentive for this, since a transition to room temperature has to be made at some point to couple the generator to the power source.

Superconducting bearings is an area of great potential "leverage" and has not received significant funding to date. A few years of development would probably result in bearing specifications of wide utility in space. The development to date has shown no insuperable problems, but clearly there is a long way to go before superconducting bearing design becomes standard. Included among the research still needed are: investigation of materials and construction techniques (magnetic contaminants have degraded performance); fabrication of bearings with lower eddy current dissipation and better manufacturing tolerances; and analysis of different possible configurations, such as thrust bearings, linear bearings, load bearings, and bearings with stiff and loose support.

## VI.2.4.  Superconducting Gyroscope

Work on the superconducting gyroscope has been supported almost entirely by NASA. The work began in about 1963, and has resulted in many conference reports and very many publications. Since the work has been so thoroughly described (Everitt, 1974; Lipa, Fairbank and Everitt, 1974) we shall not give many details here but simply make a few comments for the sake of completeness.

This device is without question the most sophisticated of the devices described in this report, and its design seems to be nearing completion. Among the advances needed in the state of the art of gyroscope technology were the following: A gyroscope with a drift lower by a factor of at least $10^6$ than the best conventional gyroscopes was essential. A telescope to provide a directional reference to a star to $10^{-3}$ arc seconds without drift for a

year was needed. A means to sense the pointing of the spin axis of the gyroscope to the same level of accuracy was needed (this has been accomplished by means of superconducting loops and detectors). Magnetic shielding to remove extraneous magnetic fields essentially to the zeroth magnetic quantum state was required. A servo system for drag compensation of the satellite to maintain the net acceleration field acting on the gyros below about $10^{-9}$ g was required (this has been accomplished through the development of the drag-free satellite, which has been shown to be good enough for this particular experiment). Also, a dewar for a full year's operation at liquid helium temperature was required (this should be demonstrated in the IRAS program).

Briefly, the superconducting gyroscope consists of the following elements: A 4-cm diameter quartz sphere is given a superconducting niobium coating. This sphere is electrostatically supported by an active 3-axis servo system. Changes in the spin axis direction are detected and read out by a SQUID and superconducting loops, which link the lines of magnetic flux that result from the so-called London moment of the spinning sphere. The Marshall Space Flight Center and Stanford University are designing alternative readout systems (Hendricks, 1975). Marshall is designing the SQUID readout system directly into the gyroscope housing, whereas Stanford uses a superconducting loop in the housing with a SQUID external to it. The largest remaining problem seems to be that of spin-up. At the earth's surface large electrostatic forces must be used to counteract the effects of gravity, and this makes the testing of the spin-up of the gyroscope a very difficult one. It is possible that some of this testing will be carried out on a space shuttle. Finally, theoretical work has been recently published on the torques on the sphere rotating in a magnetic field, and on the trapped-flux spin-down torques, and these have been found to be negligible.

## VI.2.5.    Inertial Guidance and Navigation Systems

Gyro-stabilized platforms are the heart of the usual inertial guidance and navigation systems. The accuracy of such systems depends ultimately on the accuracy with which the axes of the platforms can be maintained fixed in inertial space. Requirements at the extremes of operation are: (1) drift-free operation over long periods of time, for example, on the submarines in Navy usage, or on deep space satellites in the space program; and (2) accurate performance for brief periods of time in an environment of severe accelerations and vibrations, as in missile or rocket systems. The drift of the present navigational gyros is now of the order of 1 arc sec per hour (Section VI.5.0). Compare this drift with the drift of the superconducting gyroscope under development, which is designed for less than 0.05 arc sec per year. This comparison should be made with caution. The superconducting gryoscope will have the advantage of operation in zero gravity. A significant portion of its advantages would surely be lost if it were to be operated in the earth's gravitational field.

Twenty years ago, a proposal was indeed made to build a navigation system based upon a superconducting spinning sphere suspended in stable equilibrium by magnetic fields. Obviously this design is quite similar to those that have been discussed elsewhere in this report, for example, the gravimeters which are now very successful instruments. It is apparent that the superconducting gyroscope already basically developed for the general relativity program (Section VI.2.4.) could also be used as a navigational gyro.

Another type of inertial reference system based upon superconductivity was proposed about a dozen years ago in a patent (Clauser, 1965). In this design a microwave field is injected into a spherical superconducting cavity. Clauser argues that this field will maintain its orientation in space as the sphere rotates. A detector placed above an iris which is initially coincident with one of the node lines of the microwave field inside the cavity would then give a non-null reading when the sphere rotates. The angle necessary to bring back the null measures the deviation from the original course. A system of two or three such spheres gives complete directional information. A very high-Q cavity may be needed so that the field will not dissipate during the time of the necessary guidance. Aside from practical problems, we are not totally convinced that the principle is valid. The idea, which we mention for completeness, apparently has not been followed up, for we have not found anything further in the literature on it, but it might be worthy of further analysis.

## VI.3.0. TESTS OF GRAVITATIONAL THEORIES

### VI.3.1. Detection of Gravitational Radiation

Most theories of gravitation predict that gravitational waves should exist. These waves have not yet been unambiguously detected, but hold a great deal of popular interest. Work first seriously started in this area in about 1960, and in the late 1960's the first reports of the possible detection of gravitational radiation were published by Joseph Weber at the University of Maryland. He used a large aluminum cylinder (now called a Weber antenna) to absorb the gravitational radiation, and piezoelectric strain transducers to detect the resulting internal oscillations of the cylinder. Because signals were observed frequently, Weber instrumented two such antennas separated by about 1000 km, and searched for coincident signals. He reported an excess of coincident signals over chance, and ruled out other sources of excitation such as cosmic rays, seismic disturbances, or electromagnetic disturbances. Weber's techniques and results touched off a world-wide effort to repeat his experiments with various modifications.

However, none of the other groups have yet reported seeing enough coincidences to make them think they have seen gravitational radiation. The physics community today generally believes that what Weber saw was not gravitational radiation. There are two main reasons for this. One can calculate the intensity of a gravitational wave which would have excited the Weber antennas above the noise level. This intensity is several orders of magnitude higher than that which is reasonably expected from various sources of gravitational radiation, for example, the collapse of a star. The other reason, of course, is the fact that no one else has seen excess coincident signals, using supposedly more sensitive instruments. Nevertheless, the physics community almost unanimously believes that gravitational radiation has to be there, and many groups are proceeding with great vigor in constructing yet more sensitive Weber-type antennas.

The most important of the ideas today is that of lowering the temperature of the antenna to much less than 1 K; one group has announced a design goal of 3 mK. We will discuss this particular antenna in more detail because it is the one which uses superconductivity in several ways. Specifically, it uses a superconducting coating of niobium-titanium on the

surface of the aluminum cylinder in order that the cylinder can be levitated by superconducting magnets. This has been successfully accomplished. A superconducting accelerometer has also been built (see Section VI.2.1.), of such a sensitivity that the combination of this new accelerometer, with the excellent vibration isolation provided by the magnetic levitation and the reduction of thermal noise (proposed 3 mK temperature) suggests that this particular antenna will ideally be some six orders of magnitude more sensitive than the original Weber antenna. The sensitivity to relative motion of the two ends of the cylinder in an ideal case would be about $10^{-20}$ m. This system has not yet been put into operation although various parts of it have been tested. The cylinder has been brought to about 4 K and the superconducting accelerometer has measured the 4 K thermal noise. The apparatus is surrounded with superconducting shielding to eliminate extraneous magnetic fields.

Although not all groups are opting for magnetic levitation, there are two principle advantages to the magnetic support. For one thing, the support force is almost uniform across the length of the cylinder, so that there is no mode selection. In the mechanically supported versions there necessarily have to be nodes at the support points. Secondly, magnetic support provides probably the highest degree of isolation from vibrations which are inherent in the earth. A third advantage is that a magnetically suspended cylinder is relatively immune to heat leaks, an important consideration for a cooled cylinder.

Other designs and techniques for detecting gravitational radiation have also been proposed. For example, a hollow square gravitational wave antenna has been proposed. Aluminum disk antennas have been built. Detection of the induced beat frequency between two crossed rotating dumbells has been proposed. It has also been pointed out that so far as the cylindrical antennas are concerned, one does not really have to have a very massive cylinder because a higher Q value (smaller damping) than is possible with aluminum can be achieved by using a single crystal dielectric. With a higher Q value one can get away with smaller mass. Sapphire, for example, has been proposed for such an antenna. Laser interferometry is yet another technique. Here the displacement between two mirrors is measured by means of a shift of fringes and a sensitivity of $10^{-15}$ m has been achieved. This can certainly be improved. The laser interferometer is a non-resonant antenna, that is, broad-band, and should be capable of detecting frequencies up to more than 20 kHz. (The cylinder antennas are usually designed to detect best at frequencies near 1 kHz.)

Ranging between "free" masses is yet another method which has been proposed for the detection of gravitational radiation. The principal advantage of such a system is the long baseline which is made possible by the use of electromagnetic ranging between the masses. In fact, baselines comparable to the gravitational wavelength can be contemplated, and this can be many thousands of kilometers. Theory says that the antenna strain sensitivity should be proportional to the length of the baseline and this is why the method is attractive. This is also a broad-band detection method and may be applicable to long-period gravitational waves; for example, from one second to days or more. One of the masses could be a satellite and the other the earth. In this case, one would simply have a transponder aboard the satellite and use Doppler ranging to the satellite from the earth. In other suggestions, one might have two drag-free satellites with laser ranging between them. In the former method -- tracking a

single space craft from the earth -- the dominant noise currently is oscillator instability. That is, the frequency stability of the oscillator over the ranging delay time, which can be more than ten minutes for interplanetary distances, is the important factor. Calculations show that a frequency stability to one part in $10^{17}$ would be necessary for a successful experiment. However, no oscillators of such stability exist at the present time. Both the hydrogen maser clock and superconducting cavity oscillators now have frequency stabilities better than 1 part in $10^{15}$, and development is continuing. The present stability of a superconducting cavity oscillator (see Chapter VII) is still well below its theoretically projected limit.

We now turn to a different technique for gravitational wave detection. It can be shown theoretically that a gravitational wave sweeping over the earth, the moon or any other spherical body will excite certain modes of oscillation. However, seismic noise, always present on the earth, may forever prohibit detection of gravitational wave excitation of the earth; a vertical seismometer experiment was only able to establish an upper limit on the radiation intensity. The moon is considerably less noisy. The Apollo 17 crew placed a mechanical gravimeter on the moon, but unfortunately it did not work properly, and no definitive conclusions about gravitational wave detection could be made. Emplacement of a superconducting gravimeter (see Section VI.2.2.) is an attractive alternative.

It is true that certain even oscillatory modes of spherical masses will be able to absorb energy from the incident gravitational wave whereas the adjacent odd modes will not absorb energy. One group (Tuman, 1974), using a superconducting gravimeter, has observed that the earth oscillations do in fact exhibit an asymmetry between the odd and the even modes when they have been excited: the even modes have higher energy content. Earthquake mechanisms are thought to excite both types of modes rather symmetrically. Of course, there can be mechanisms, perhaps deepseated earthquakes, which would give rise to the asymmetry. Nevertheless, it is intriguing to suppose that gravitational radiation is being absorbed. The investigators have been able to estimate the absorption cross-section of the earth for gravitational radiation, and from that have been able to estimate what the intensity of the supposed radiation would be. This intensity turns out to be only an order of magnitude or so less than the intensity that would have had to exist in the Weber experiments of the late 1960's and early 1970's. At present, however, most scientists would not be willing to say that gravitational radiation has thus been detected.

We have found no sentiment whatsoever among the investigators designing and operating Weber antennas for putting these bars into space. They feel that the present techniques for vibration isolation will be sufficient and that the advantage of having a bar floating in space would not offset the complications arising from having the bar essentially out of one's control after it has left the earth. Nevertheless, there are some advantages for a bar in space which, for the record, we will simply point out. Of course the most obvious is freedom from earth noises. For example, the antenna should be completely free from seismic noises and reasonably far away from earth-based electromagnetic interference although it is possible that very large scale electrical storms could affect the very sensitive instrumentation onboard a satellite. In space the unsupported bar would need no vibration isolation. There

are no acoustic paths for a freely floating bar, except the small amount through the helium exchange gas; but such vibrations would be very small and of high frequency -- the bars of course have a low resonant frequency. Furthermore, because the bar is unsupported there would be no bending or torsional modes which could be excited if the bar had supports, thus confusing the results. Supports also induce stresses which can give rise to acoustic processes within the bar. We should point out that there may be considerable future interest in putting a bar in space if the latest generation of low-temperature antennas now under construction prove unsatisfactory in some way.

Sources of gravitational radiation include the gravitational collapse of a star, rotating binary stars, rotating or pulsating neutron stars, and black holes. Objects falling into a black hole should have a peak frequency of about 1 kHz if the object falling in is about 10 sun masses. In all likelihood not all sources have yet been conceived.

## VI.3.2. Equivalence Principle

The equivalence principle states that inertial mass and gravitational mass are the same thing, and is foundational to Einstein's theory of general relativity. The first modern attempt to measure the possible inequivalence was made in 1964 and had a sensitivity of about 3 parts in $10^{11}$. A subsequent experiment pushed the inequivalence limit to 1 part in $10^{12}$. Both experiments were earth-bound. Although it may seem that these are very sensitive tests, there is still a great deal of interest in continuing the measurements, not only as a check of gravitational theories, but because some scientists are now speculating that the weak-interaction force may well violate the equivalence principle. As is well known, the weak-interaction force violates parity conservation, which all other forces obey. The weak interaction is now believed to be consistent with the equivalence principle at the 1% level.

Recently it has been proposed to repeat the earth-bound test in space, with the expectation that the inequivalence limit can be pushed to better than 1 part in $10^{14}$ (Worden and Everitt, 1974), with a theoretical limit between 1 part in $10^{17}$ and 1 part in $10^{18}$. The basic idea is to use two different materials, as in the earth experiments, but shape them in the form of concentric cylinders. These will be placed in space and positioned by superconducting magnets. Inequivalence would result in a small relative displacement of the two masses, which would be detected with a SQUID magnetometer (see Chapter III). There are three advantages of doing the experiment in space. First, the driving acceleration should be three orders of magnitude larger than in the comparable earth-bound case. Second, the experiment would be isolated from seismic vibration, which is the limiting factor in the earth-based experiments. Finally, random gravity gradients due to the motion of large masses near the laboratory are practically eliminated in a satellite. To achieve their most recent design goal of 1 part in $10^{17}$, the investigators propose cryogenic techniques throughout. Lower temperatures will of course result in lower thermal noise and greater sensitivity. Superconducting shielding will be used, and as already mentioned, superconducting magnetic restraints will control the position of the test masses, and a very stable and sensitive position readout will be made by SQUID's. Another advantage of low temperature is that there is better mechanical stability -- thermal expansion and mechanical creep are very much smaller. The problem of levitating the cylinders is much more complicated in the earth's gravitational field than it will be in space. Hence, the space shuttle might be used for

testing that part of the design. (See also Section VI.2.3. on superconducting bearings for further comments on this experiment.)

### VI.3.3. Gravitational Red Shift

The equivalence principle affects electromagnetic radiation and manifests itself there as the gravitational red shift. Two well-known investigators (see, for example, Will, 1974) have asserted that the red shift experiment is not a strong test of general relativity, arguing that the red shift can be deduced from conservation of energy together with elementary quantum theory and the results of other equivalence principle experiments. But this conjecture is not proven and red shift experiments are still considered important. In fact, a measurement of the gravitational red shift to second-order in the solar potential is regarded by many scientists as one of the most important gravitational measurements which could be done.

This is the reason for the interest in a close solar probe. The first-order shift at a distance of four sun radii is $0.5 \times 10^{-6}$, whereas the second-order shift is $5 \times 10^{-13}$, according to general relativity. The elapsed time for a space craft to orbit half-way about the sun, changing its direction by 180°, is sixteen hours, and the clock stability required over this time interval is a few parts in $10^{15}$, which is about at the present limits of the hydrogen maser clock. The relativistic theories which are challenging the general theory of relativity have the same first-order shift but differing second-order shifts, and a good measurement here would be able to eliminate some of the competing theories. A clock with a stability of $10^{-16}$ could be read down to about 1% of the second-order term. Continued refinement of the hydrogen maser might achieve this stability, but the frequency-stabilized laser and the superconducting cavity oscillator also hold promise of extending clock stability to the $10^{-16}$ level (see Chapter VII).

Red shift measurements have already been made in the earth's gravitational potential. The first of the more modern experiments was a measurement over 75 vertical feet and confirmed the predicted red shift to about 1%. Subsequent measurements on board rockets have reduced this to $2 \times 10^{-4}$. Space flights using oscillators with great frequency stability will make possible much greater sensitivity. For example, the European Space Research Organization has proposed placing a hydrogen maser clock on board a space craft in a highly eccentric orbit around the earth. However, it is apparent that if the vehicle has cryogenics on board, an improved superconducting cavity oscillator with yet greater stability might also be used.

### VI.3.4. Geodetic and Mass-Current Precession of a Gyroscope Spin Axis

In 1960, Schiff pointed out that a well-constructed gyroscope placed in an orbiting satellite about the earth, could provide two sensitive tests of the general theory of relativity. Two effects cause a precession of the gyroscope spin axis -- the geodetic effect, which is due to the motion of the gyroscope around the earth, and the motional or mass-current effect, which is due to the rotation of the earth beneath the gyroscope. The motional effect can only be measured with a superconducting gyroscope (see Section VI.2.4); no

other instrument or technique has yet been proposed with the required sensitivity. The gyroscope experiment will also test those theories of gravitation which predict no mass-current drag, in contra-distinction to the general theory of relativity.

VI.3.5.    Measurements of the Gravitational Constant G.    Cavendish Experiments

In Einstein's general theory of relativity, the gravitational constant G is truly a constant, but it is not in several competing theories, the best known of which is Dirac's large-number-hypothesis, which predicts that G decreases in time since the matter of the universe is receding. There are several variant theories, but all place the expected rate of change of G close to the observed rate of the expansion of the universe, which is $5.6 \pm 0.7$ parts in $10^{11}$/year. Occultations of stars by the moon have been observed for some 20 years with the use of atomic time and these observations show that if G and only G among the fundamental constants is changing, then the relative rate of change of G is $-7.2 \pm 3.7$ parts in $10^{11}$/year (Van Flandern, 1976). More recent similar analyses, however, give a larger uncertainty, with the range of possible values for the change in G spanning zero (Calame and Mulholland, 1978). Laser ranging to the moon may someday be able to distinguish between competing theories that assume some change of G, although the earth-moon tidal interactions might complicate interpretation of the results. Radar observations of Mercury would perhaps provide the best means for estimating the possible time variation of G over the next few years. The placement of long-lived transponders on Mercury's surface could improve the measurements.

The traditional Cavendish experiment measures G itself, and at the moment is accurate to only about 3 parts in $10^4$, with a hope of perhaps 1 part in $10^5$. Measurement of the effects of the variations of G are much more accurate as we have seen in the above discussion. Those measurements do not involve superconductivity. However, a new type of Cavendish experiment (already in progress) does involve superconductivity and is hoped to have a precision of a few parts in $10^{12}$/year in measuring the time rate of change of G (Van Flandern, 1976). The idea of replacing the mechanical suspension and torsion forces in the traditional Cavendish experiment by magnetic suspension and torsion has been discussed informally. Whether precision could be significantly improved is not known, and thus it is much too early to discuss whether the alternative theories to general relativity, which predict certain corrections to G, may be checked through measurements of G.

In another proposal a Cavendish apparatus would be orbited in a high eccentric orbit, where the sun's potential can vary by as much as 1 part in $10^7$. The earth's orbit provides a variation of only 1 part in $10^{10}$ in the sun's potential. A Cavendish experiment with a sensitivity of 1 part in $10^{11}$ would be required to detect, with 10% precision, the variations in the local value of G predicted by several gravitational theories (due to the sun's changing Newtonian potential along the earth's orbit). Thus the orbiting Cavendish apparatus would not need to be nearly as sensitive as the earth-based apparatus.

## VI.4.0.  GRAVITY AND ELASTIC PROPERTIES OF THE PLANETS

Measurements of the local gravitational field and its variations are made by seismometers and gravimeters which detect the motion of the surface of a planet.  Most knowledge of the earth's interior has been obtained by studying the motions of the surface in the seismic frequency range (periods of less than about 100 s).  Instruments which measure longer periods are called gravimeters.  Both instruments give several types of information about the planets. For example, the normal modes are thereby elucidated and the amplitudes of the tidal motions can be measured.  The effects of the oceans and the atmosphere of planets having such can be determined.  Just a few years ago, it was hoped that earthquake prediction could be facilitated with seismometers.  Earthquake scientists have recently become more cautious about this, however.  It is possible that a network of superconducting gravimeters (see Section VI.2.2) could be useful.  Until the development of these gravimeters, it was not possible to measure periods of longer than about a day.  The superconducting gravimeter now measures effects such as the fortnightly earth tides (driven by the moon) very accurately ($\sim$ 1%).  The theories of gravitation might also be checked by precise measurement of these tidal periods.  It has been proposed that gravitational radiation might also be detected with use of gravimeters (see Section VI.2.2.).

## VI.5.0.  NAVIGATION

Navigation is perhaps the oldest science, and at the present time uses very many techniques.  We shall mention only those having some application to space technology.

The Navy has, for many years, used navigation satellites to assist its forces in determining their positions.  A recently developed fuller exploitation of the received Doppler signal has reduced error determination of position to about 40 m per knot of ship velocity. The Department of Defense is very active in developing a satellite navigation system for tri-Service capability.  DOD is especially interested in four technical capabilities:  (1) that of maintaining very accurate clocks in space over long periods of time; (2) determining and predicting satellite orbits to within ten feet; (3) predicting and compensating for variable delays in the ionosphere; and (4) eliminating ambiguity or signal degradation caused by multi-path signal transmission.

NASA, of course, has since its inception, been heavily involved in navigation technology. Because of its relevance to other parts of this report, we shall mention here NASA's Orbiting Astronomical Observatory (OAO-C, or Copernicus).  This satellite, launched in 1972, used a 3-axis, precision, inertial grade gyro system.  The drift rates of the gyros were observed in orbit and remained within a band of about 16 arcsec/hour, or about 1 arcsec/hour when the effects of known disturbances were considered.  Regarding deep-space navigation, NASA's MARK-I navigation, involving ground-based radio tracking and flight path control, was adequate to meet the needs of various lunar, Venus, and Mars missions in the 1960's.  During the 1970's, MARK-II navigation involving a combination of ground-based radio and on-board optical measurements, but still utilizing ground-based control, was and is considered adequate for such missions as the Viking in 1975, the Mariner, Jupiter and Saturn missions of 1977, the

Pioneer to Venus mission of 1978, and the Mariner to Jupiter and Uranus mission of 1979. In the 1980's and beyond, however, reaction time becomes more important for many of the advanced missions under consideration by NASA. Examples of these include precision asteroid or comet fly-bys, probe delivery, outer planet satellite tours, and others. It is thus necessary to develop for the 1980's a MARK III navigation system which can use on-board computation and control to avoid both signal propagation delays and certain earth-based delays in data processing and decision making during time-critical mission phases. Thus, autonomous navigation is now becoming important to NASA interests.

Navigation in space depends, among other things, upon the use of accelerometers (see Section VI.2.1.) and gyroscopes (see Section VI.2.4.). We have not encountered any serious recent proposals for improving navigational procedures by introducing superconducting techniques. Nevertheless, it is apparent that should the need be felt in the future, superconductivity has a great deal to offer, both in the greatly improved sensitivity in acceleration measurements and in the directional measurements offered by superconducting accelerometers and gyroscopes. To add some perspective to the projected performance of the superconducting gyroscope, consider the following triangulation. For the base distance between the earth and the moon, the error associated with a drift of 0.05 arc sec per year (projected drift of superconducting gyroscope) is less than 100 m per year.

## VI.6.0.    SUMMARY AND CONCLUSIONS

Superconducting instruments may well play an important role in future experimental tests of gravitational theories. In general, these experiments require performance which is not yet available, and superconductivity is introduced as a technology which might provide the needed advances. It is also interesting that some of the devices needed for the tests are also useful for navigation (gyroscopes, accelerometers, stable oscillators). Thus an investment in fundamental (superconductive) research could ultimately pay dividends in the form of advanced navigational instruments.

The gyroscope-precession experiment (see Sections VI.2.4 and VI.3.4.) constitutes an extremely sophisticated and demanding use of superconductivity. Development is in an advanced stage and the system may fly within the next decade. To be successful the gyroscope stability will have to eclipse that of all others by several orders of magnitude. No doubt a successful flight will lead to interest in navigational applications.

Accelerometers based on superconductivity is another area which deserves attention (see Sections VI.2.1.). The two proposals which seem most promising are the tunable diaphragm and the flux gradient accelerometers. With projected sensitivities (displacement) in the range of $10^{-20}$ m, these devices could find many uses. NASA might want to consider further stimulation of development work which is currently directed toward application as sensors for gravitational wave antennas.

Other experiments which deserve careful study include the proposed test of the equivalence principle (Section VI.3.2.) and tests for changes of the gravitational constant (Section VI.3.5). The superconducting oscillator is a prime condidate for further developmental work as it

offers significant opportunity for improvements in ranging and navigation. Improved ranging, for instance, might offer a means of detecting gravitational waves as they perturb the relative distance between a satellite and the earth. This type of application is discussed in more detail in the following chapter.

## VI.7.0.   REFERENCES

Bertotti, B. (1974). editor, *Experimental Gravitation*.  Academic Press, New York.

Calame, O. and Mulholland, J.D. (1978).  Lunar Tidal Acceleration Determined from Laser Range Measures. *Science 199*, 977-978.

Clauser, M.U. (1965).  Superconducting Inertial Reference System. *U.S. Patent No. 3,176,519*.

Everitt, C.W.F. (1974).  The Gyroscope Experiment. I: General Description and Analysis of Gyroscope Performance.  [see Bertotti, 1974], 331-360.

Fairbank, W.M., Boughn, S.P., Paik, H.J., McAshan, M.S., Opfer, J.E., Tabor, R.C., Hamilton, W.O., Pipes, B., Bernat, T. and Reynolds, J.M. (1974).  Search for Gravitational Radiation Using Low-Temperature Techniques.  [see Bertotti, 1974], 294.

Goodkind, J.M. and Warburton, R.J. (1975).  Superconductivity Applied to Gravity. *IEEE Trans. Mag. MAG-11*, 708-711.

Hendricks, J.B. (1975).  A SQUID Readout System for a Superconducting Gyroscope. *IEEE Trans. Mag. MAG 11*, 712-715.

Hoffman, A.W., Douglass, D.H., Gram, R.Q. and Lam, C. (1976).  Flux Gradient Accelerometer: Tests on a Working Model. *Rev. Sci. Instr. 47*, 1441-1444.

Lipa, J.A., Fairbank, W.M. and Everitt, C.W.F. (1974).  The Gyroscope Experiment II: Development of the London-Moment Gyroscope and of Cryogenic Technology for Space.  [see Bertotti, 1974], 361-380.

Paik, H.J. (1976).  Superconducting Tunable-Diaphragm Transducer for Sensitive Acceleration Measurements. *J. Appl. Phys. 47*, 1168-1178.

Tuman, V.S. (1974).  In Search of Low-Frequency Gravitational Radiation.  [see Bertotti, 1974], 543-572.

Van Flandern, T.C. (1976).  Is Gravity getting Weaker? *Sci. Amer. 334*, 44-52.

Will, C.M. (1974).  The Theoretical Tools of Experimental Gravitation [see Bertotti, 1974], 1-110.

Worden, P.W., Jr. and Everitt, C.W.F. (1974).  The Gyroscope Experiment III: Tests of the Equivalence of Gravitational and Inertial Mass Based on Cryogenic Techniques.  [see Bertotti, 1974], 381-402.

CHAPTER VII

ULTRA HIGH-Q CAVITIES

S. R. Stein

## VII.1.0.  INTRODUCTION

A resonant circuit has a strong response near a certain frequency, called the resonant frequency ($\nu_o$), and a weak response for very different frequencies. Such circuits are needed in order to separate a desired ac signal from signals at other frequencies.  The bandwidth ($\Delta\nu$) is a measure of the selectivity of the resonance.  However, since most applications place requirements on the relative width of the resonance ($\Delta\nu/\nu_o$), the most commonly used figure of merit for a resonator is its quality factor or Q which is equal to $\nu_o/\Delta\nu$.  The Q is defined as the ratio of the energy stored in the resonator to the energy dissipated during one radian of the oscillation.  Thus high Q implies both great selectivity and small power loss.

The first electrical resonators consisted of coupled lumped reactances, the stored energy oscillating between the electric field of a capacitor and the magnetic field of an inductor.  Resonant cavities were introduced by W. W. Hansen in 1938.  They usually consist of a volume of any shape almost completely enclosed by high conductivity walls and are necessary at high frequencies because of the difficulty of fabricating lumped circuit elements. Cavities have the advantage of reasonable dimensions and extremely high Q for the frequency range from 100 MHz to more than 10 GHz.  The factor which limits the Q is the surface resistance of the metallic walls, there being no need to use dielectric materials.  Since the conductivity of metals increases as the temperature is decreased, the Q can be improved by operation at cryogenic temperatures.  The improvement obtained in this manner in normal metals is severely limited by the onset of the anomalous skin effect which halts the increase in conductivity when the electronic mean free path becomes smaller than the skin depth.  For usual microwave frequencies, the rf surface resistance of superconductors is small compared to what can be achieved with normal metals.  It decreases exponentially as the temperature approaches absolute zero, until it is limited by non-intrinsic effects.  At the present, it is possible to obtain Q's in excess of $10^{11}$, which is an improvement by a factor of about $10^7$ compared to a room temperature copper resonator.

The applications of superconducting cavities can be divided into two categories which stress different, but related properties of superconductivity. High power applications such as electron accelerators, proton and ion accelerators, particle accelerators and rf plasma confinement use superconductivity in order to achieve the low levels of power dissipation required for continuous operation.  On the other hand, a variety of low-power applications make direct use of the extremely narrow linewidth.  The cavities can be incorporated into high stability oscillators with unsurpassed performance, which can be used as flywheel oscillators in physics experiments directly involving clocks, or in large systems which require precise timing such as Doppler tracking, satellite navigation, and radio astronomy.  The cavities can be used directly to filter noisy signals, to impedance match between devices having very large impedance differences, and to store energy from very weakly radiating devices. Superconducting cavities can also be used as transducers for a variety of physical quantities.  They make very sensitive displacement detectors since the frequency changes in proportion to length.  They have also been used to measure materials properties in solid

dielectrics, semiconductors and liquid helium, and to measure the thermal expansion of niobium.

In addition to these applications there are also special uses which aren't easily categorized. Of course, superconducting cavities have been and will continue to be an important vehicle for the study of rf superconductivity. They can also be used in certain novel and unique ways such as in cesium frequency standards and electromagnetic gyroscopes.

Extensive general reviews of superconducting cavities have been written by Maxwell (1964) and Pierce (1974). Shorter reviews of applications were written by Hartwig (1973) and Turneaure (1972). This report will stress devices and instrumentation based on superconducting cavities and their applications. The reader may refer to the earlier reviews for more complete background information and to the paper by Barnes, et al. (1971), for a description of the specification and measurement of frequency stability. Since superconducting cavities are common to all the devices and applications and superconducting cavity oscillators are used in most of them, these topics will be discussed first, followed by discussions of specialized devices and applications.

<div align="center">VII.2.0.  SUPERCONDUCTING CAVITIES</div>

## VII.2.1.  Fabrication

The response of a normal metal at room temperature to microwave electromagnetic fields is adequately described by Ohm's law. When the metal is cooled, the conductivity increases as a result of the increase in mean-free path. One is prevented, however, from achieving a very high Q by the anomalous skin effect which occurs when the mean-free path becomes comparable to the skin depth. The behavior of a superconductor is quite different. At microwave frequencies the resistance of an ideal superconductor decreases exponentially as the temperature is reduced below the superconducting transition temperature. In real resonators this behavior does not extend to zero temperature. Instead, a loss mechanism which is independent of temperature is always observed. The result is that the Q of the resonator becomes constant, or residual, below some temperature. Figure VII-1 illustrates this behavior in the case of a niobium resonator in the $TM_{010}$ mode at 8.4 GHz (Turneaure and Weissman, 1968). The intersection of a horizontal line corresponding to a residual Q with the theoretical curve determines the highest temperature at which that resonator may be operated with a Q equal to the desired value.

Microwave resonators in a variety of modes are suitable for use in stable oscillators. However, there are design criteria which are specific to superconducting cavities. Because of the very low losses in the walls of the resonator, minor imperfections such as assembly joints or small amounts of foreign substance such as a surface oxide layer can seriously degrade the Q. Assembly joints may be located where there is no rf current in the desired mode. In the case of niobium, current-carrying joints may be fabricated by electron-beam welding.

Niobium and lead are the two superconductors which have shown the most promise for use in high stability oscillators. These two materials are available commercially in sufficient purity, and techniques have been developed which permit complex resonator shapes to be
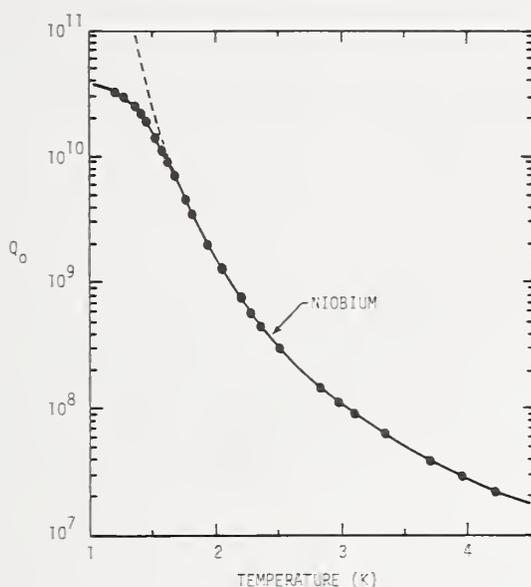
<div align="center">118</div>

Figure VII-1.   The unloaded Q of an X-band $TM_{010}$ mode niobium cavity.
(Turneaure and Weissman, 1968).

fabricated from either material with surfaces which are clean, microscopically smooth, and relatively unstrained. The transition temperature of niobium is 9.25 K, and that of lead is 7.19 K, which means that a required Q can be achieved at higher temperatures than for most other materials.   There are known superconductors with higher transition temperatures than niobium.   Several laboratories are studying $Nb_3Sn$, but the results so far are not as good as for pure niobium.

For the best frequency stability, niobium is the preferred material. Niobium resonators have exhibited the lowest residual surface losses and are unsurpassed in terms of mechanical stability and surface cleanliness.   Q's higher than $10^{11}$ have been achieved.   Two methods have been developed to manufacture the resonator from the bulk metal.   In the first process, a cylindrical resonator is machined in two pieces and assembled by electron-beam welding.   It is then alternately fired in ultra-high vacuum at about 1900° C and chemically polished. More recently a technique has been developed which does not require ultra-high vacuum firing: The surface is prepared by electro-polishing followed by anodizing.   This process potentially makes high-quality niobium cavities available to many more laboratories.   However, there is some evidence that the anodized surface degrades in time and this is a possible disadvantage for oscillator applications.

Lead is an excellent material if the Q needn't be as high as achieved with niobium.   If the cavity mode must be restricted so there is no normal electric field at the walls, Q's in excess of $10^{10}$ may be achieved.   The primary advantage of lead is that high quality surfaces

119

can be made in almost any laboratory using standard electroplating techniques. Unlike niobium, high-quality lead surfaces have not been successfully produced when the resonator has been machined from the bulk material. It has recently been suggested that resonators be fabricated from a solid piece of dielectric such as sapphire by plating the outer surface with a super-conductor. Unpublished experiments indicate that Q's as high as $10^8$ have been obtained by this method. It is possible that resonators made this way may be mechanically more stable than traditional designs but no experimental evidence is available yet.

### VII.2.2. Oscillator Stability

For the purpose of this discussion, the frequency fluctuations of any oscillator based on a superconducting resonator can be separated into two categories: Statistical fluctuations around the center of the resonance and perturbations of the resonant frequency itself. The second category determines an ultimate performance level for any oscillator which is relatively independent of its design. It includes temperature, power level, and mechanically induced frequency shifts. Since most superconducting oscillator research has been performed with solid niobium cavities and the best results have been obtained with these cavities, this discussion of performance will relate most directly to solid niobium resonators fabricated by this technique.

Two independent effects transduce a temperature change of the microwave resonator into a shift of its resonant frequency. Thermal expansion or contraction changes both the mechanical and the electrical length of the resonator while the variation in the penetration of the rf magnetic fields with temperature changes the effective electrical length. The penetration depth varies exponentially with temperature and is the dominant effect above 1 K. The coefficient of the fractional frequency is $6 \times 10^{-9}$/K at 1.75 K and $4 \times 10^{-10}$/K at 1.3 K. Inside of a vacuum can contained within a dewar it is possible to do excellent temperature regulation. With a single-stage regulator drift rates of $10^{-5}$ K/week have been observed while the fluctuations from second to second were too small to be observed. The ease of temperature regulation in a cryogenic environment helps to compensate for some of the added complexity.

Any oscillator system operates with some energy stored in the resonator. Because of the radiation pressure of these fields and the dependence of the surface reactance on the rf field level, there is necessarily a static frequency shift of the superconducting resonator. Some measurements indicate that the frequency offset is proportional to the stored energy. The total fractional frequency shift observed in one experiment was $10^{-11}$ for $10^{-7}$ J of stored energy. The total frequency offset determines the size of the frequency fluctuations which result from oscillator power fluctuations. Frequency fluctuations from this source can be reduced by decreasing the operating power level but only if a lower signal-to-noise ratio can be tolerated, otherwise power regulation is necessary.

The third major perturbation of the resonant frequency of a superconducting cavity results from mechanical strains. For a $TM_{010}$ mode cavity, resonant at 8.6 GHz, the static stress due to the force of gravity produces a fractional frequency shift of $1 \times 10^{-9}$ from the zero strain value. Consequently, changes in either the acceleration of gravity or the

orientation of the superconducting cavity result in frequency shifts of the resonance. For a $TM_{010}$ mode resonator, maintained in a fixed location, the variations in gravity are not significant, but the angular coefficient is $1 \times 10^{-14}$ per arc second. This sensitivity permits many factors to be transduced into short-term, diurnal, and long-term frequency shifts of the resonator. Another possible effect of the stress of gravity on the resonator is creep of the niobium. The creep process is not well understood at these temperatures and has not been measured.

Elastic deformation of the resonator due to mechanical vibrations produces significant fluctuations in the center frequency. Studies of the most rigid solid niobium cavities have shown the frequency stability in an oscillator system to be limited by vibrations for averaging times between 10 ms to 10 s. Some vibrations are coupled to the resonator from the laboratory but the most significant vibrations which have been observed were due to boiling cryogen (liquid nitrogen) used to maintain the low temperature in the dewar.

If the center frequency of the resonance is sufficiently constant, then other sources of noise will determine the ultimate stability of the superconducting oscillator system. The frequency fluctuations about the center of the resonance are highly dependent on the design of the particular oscillator, however a lower limit corresponding to the case where all noise sources are filtered by the resonator can be determined. If the perturbing noise is white, then the phase of the oscillator does a random walk. The one-sided spectral density of the phase fluctuations, in a form appropriate for microwave resonators, is given by

$$S_\phi(f) = \left(\frac{\nu_o}{f}\right)^2 \frac{kT}{2P_a \, Q_E \, Q_L} \quad , \tag{VII-1}$$

where $\nu_o$ is the operating frequency, k is the Boltzman constant, T is the absolute temperature, $P_a$ is the power dissipated in the load, and $Q_E$ and $Q_L$ are the external and loaded Q's respectively. In the case of a superconducting cavity with $Q_E = 10^{10}$, $Q_L = 5 \times 10^9$, $P_a = 10^{-3}$ W, $\nu_o = 10^{10}$ Hz, and T = 1 K,

$$S_\phi(f) = 10^{-20} \text{ Hz}/f^2 \; .$$

The active element in a practical oscillator will dominate the thermal noise. In this case T must be interpreted as the effective noise temperature of the device. Such noise temperatures vary from approximately 20 K for varactor parametric amplifiers to more than $10^4$ K for a transferred-electron device.

Another important limitation on the stability of a superconducting oscillator is additive noise which results from a white noise voltage generator at the output of the oscillator. In an ideal oscillator the additive noise is due to output buffer amplifiers or a user device. The spectral density of the phase fluctuations is

$$S_\phi(f) = kT'/2P_a \; , \tag{VII-2}$$

where T' is the effective noise temperature of the circuitry which sees the output of the oscillator. If the effective noise temperature is 300 K and the available power is $10^{-3}$ W, then

$$S_\phi(f) = 2 \times 10^{-18}/\text{Hz} \; .$$

In this case the additive noise dominates the oscillator spectrum for Fourier frequencies greater than 0.07 Hz. Under the same conditions, the rms fractional frequency fluctuations are given by

$$\sigma_y(\tau) = \left\{ \left[ \frac{8.3 \times 10^{-21}}{\tau^{1/2}} \right]^2 + \left[ \frac{4.3 \times 10^{-20} f_h}{\tau} \right]^2 \right\}^{1/2} \; ,$$

where $f_h$ is the noise bandwidth of the measurement system.

Equations (VII-1) and (VII-2) show that both the random walk of phase and the additive noise can be reduced by increasing the available power; however, this technique is limited by several factors. The nonlinearity of the resonator couples amplitude and phase modulation and may ultimately limit the stability. If this is not a problem, then at some field level the resonator breaks down. Finally, high power levels may exceed the dynamic range of the user device such as a mixer in a super-heterodyne receiver.

### VII.2.3. Oscillator Design

Because of the tremendous stability potential of superconducting resonators a variety of techniques have been used to construct superconducting oscillators (see Fig. VII-2). The goals of this research have varied. Some oscillators have been constructed to illustrate feasibility, some to accomplish modest stability goals for further research on superconducting resonators, and others to achieve the ultimate frequency stability over some range of Fourier frequencies or averaging times. As a result, the achieved frequency stability for each technique is probably a poor indication of its potential performance. Instead of making such a comparison, this chapter will outline some of the advantages or disadvantages of each method from the point of view of achieving the best possible frequency stability.

The techniques discussed in this section use the superconducting resonator in three different ways -- as the sole resonator of an oscillator circuit, as an auxiliary resonator to stabilize a free-running (noisy) oscillator, or as a filter which provides no feedback to the source.

Figure VII-2b illustrates how an oscillator may be realized using a superconducting resonator and a unilateral amplifier. Oscillation can occur when the amplifier gain exceeds the losses and the total phase shift around the loop is a multiple of $2\pi$ rad. Automatic gain control or limiting is necessary in order to produce oscillations at the desired power level. The resonator may be used in either transmission or reflection, but the transmission mode is preferable because the insertion loss of the resonator suppresses spurious modes of oscillation which do not lie in its pass bands. This technique has received considerable attention because of its simplicity. The only element which needs to be located in the dewar is the superconducting cavity which can be connected to the room-temperature amplifier by long lengths of transmission lines. However, this virtue is its major detraction when state-of-the-art frequency stability is desired. Changes in the phase length of the transmission lines produce proportional frequency shifts. If $\Delta\phi$ is the phase change from any source, the fractional frequency shift is
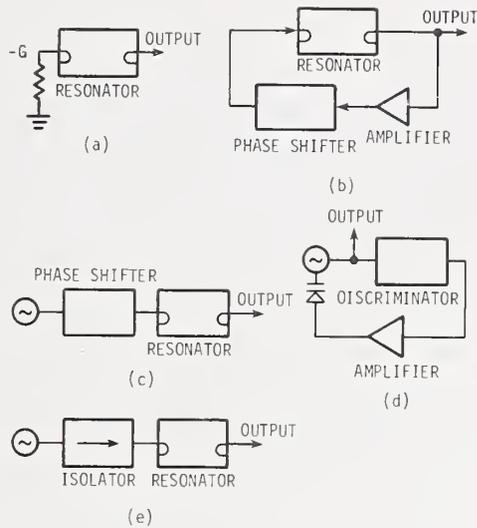
Figure VII-2.  Block diagram illustrating several superconducting frequency
sources:  (a) negative resistance oscillator, (b) loop oscil-
lator, (c) cavity-stabilized oscillator, (d) stabilized-
voltage-controlled oscillator, and (e) passive filter.

$$\Delta\nu/\nu = \Delta\phi/2Q_L \quad .$$ (VII-3)

The phase changes due to factors such as thermal expansion and vibrations are sufficiently
large in a cryogenic system that they totally dominate the short-term stability and drift of
such an oscillator.

One possible solution to this problem is to use an amplifier which functions in the same
low-temperature environment as the resonator and is connected to it by a short rigid trans-
mission line.  It has been proposed to use a cryogenic travelling wave maser in a unilateral
amplifier design.  Alternatives are tunnel diode amplifiers and varactor diode parametric
amplifiers. Both of these devices function by generating a negative conductance at the
resonator frequency.  Since they are bi-lateral, they can simply be connected to the super-
conducting cavity through an impedance transforming network as shown in Fig. VII-2a.  When
the negative conductance of the amplifier exceeds the positive load conductance of the
resonator, oscillation results.  The major advantage of the tunnel diode oscillator is that
it requires only dc bias power for operation.  On the other hand, there are several disad-
vantages.  Shot noise in the tunnel junction limits currently available tunnel diode ampli-
fiers to an effective noise temperature of 450 K at 9 GHz.  In addition, the very low operat-
ing voltage limits the theoretical output power to 1 mW at 10 GHz from commercially available

devices (having peak current less than 20 mA). If other problems were solved, these two difficulties could limit the frequency stability of the tunnel diode superconducting oscillator. In contrast, cooled parametric amplifiers have demonstrated 20 K noise temperatures, and room temperature non-degenerate parametric oscillators have produced more than 100 mW at 9 GHz.

The most widely studied technique for realizing a superconducting oscillator has been the stabilization of a free-running oscillator with a superconducting resonator. One technique for accomplishing this, called cavity stabilization, is shown in Fig. VII-2c. The oscillator is injection-locked by the power which is reflected from the superconducting resonator. The stabilization factor, which is the ratio of the free-running oscillator frequency fluctuations to the cavity-stabilized oscillator frequency fluctuations, is given by the ratio of the Q of the superconducting cavity to the Q of the free-running oscillator. Equation VII-1 shows that the best possible performance reduces to that of an oscillator built with the superconducting cavity as its only resonator. There are two major disadvantages to this technique. First, room-temperature oscillators such as klystrons and Gunn-effect devices have extremely high noise temperatures. And second, the frequency offset from the center of the resonance is proportional to the line length between the oscillator and the cavity, just as in the loop oscillator.

The most successful superconducting oscillator technique to date is the use of active feedback to stabilize a voltage-controlled oscillator. The superconducting resonator is the frequency sensitive element of a discriminator which generates an output voltage proportional to the frequency difference between the oscillator and the center of the superconducting cavity resonance. Although this system also has a long path length between the room-temperature oscillator and the superconducting cavity, it is possible to design the discriminator so that the dependence of the oscillator frequency on this path length is greatly reduced. This is accomplished by using phase-modulation sidebands on the carrier frequency to provide the reference for locating the plane of the detuned short of the superconducting cavity. Despite the fact that this technique also uses a noisy room-temperature oscillator, its performance is not limited by this fact. This is true because in such a system it is possible to greatly multiply the phase vs frequency slope of the resonator by using external amplifiers. In this way, the frequency fluctuations of the free-running oscillator may be reduced until the performance level, determined by the microwave detectors, is reached.

Figure VII-2e shows a superconducting resonator being used to filter the output of an oscillator. This application is particularly important when the oscillator is to be used as a source for frequency multiplication. For example, a state-of-the-art quartz crystal oscillator may be multiplied to 0.5 THz before the carrier is lost in the phase noise pedestal. However, if the same oscillator is filtered by a passive superconducting cavity with loaded Q equal to $2 \times 10^9$, it could in principle be multiplied to 100 THz.

The conclusion of the above discussion is that two types of superconducting oscillators appear most promising for improved stability: stabilization of a VCO and the all-cryogenic oscillator. The fundamental limitations of the two devices are similar so the most important differences at this time are the practical problems of implementation: the VCO stabilization system has all the critical elements outside the dewar where they are readily available for

adjustment and experimentation, but they are necessarily sensitive to problems of temperature
fluctuations and vibration. On the other hand, the active oscillator is compact and totally
contained in the highly controlled cryogenic environment. It will, however, present some new
technical difficulties such as heat dissipation and device parameter fluctuations.

VII.2.4. Oscillator Performance

The best superconducting oscillator frequency stability to date has been obtained by
stabilizing a free-running VCO using the system of Fig. VII-2d. The measured time domain
stability of a single superconducting oscillator is shown in Fig. VII-3 (Turneaure, 1977).
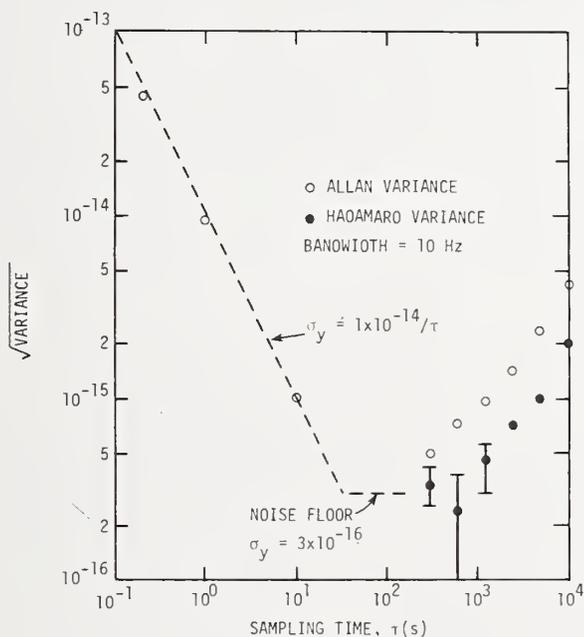


Figure VII-3. The fractional frequency fluctuations of a superconducting-
cavity stabilized VCO (Turneaure, 1978).

The rms fractional frequency fluctuations in a $10^4$ Hz bandwidth decrease with averaging time
approximately as $5 \times 10^{-15}$ s/$\tau$, reaching a noise floor of $3 \times 10^{-16}$ for times longer than
10 s. Measurements in the frequency domain indicate that the random component of the phase
fluctuations is white for Fourier frequencies between 10 Hz and 50 kHz: the spectral density
of the phase fluctuations is $S_\phi(f) \simeq 7 \times 10^{-13}$ rad$^2$/Hz. For Fourier frequencies below 300 Hz,
there are several peaks in $S_\phi(f)$ due to coherent frequency modulation of the oscillator by
mechanical vibrations. The largest of these bright lines have rms amplitudes of approximately
$8 \times 10^{-5}$ rad, which is consistent with the stability observed in the time domain. The

125

long-term behavior of the superconducting oscillator was measured via a comparison with an ensemble of cesium frequency standards. The result of a fit to a model including linear drift was a frequency drift rate of $1 \times 10^{-14}$/day for the best-performing superconducting oscillator system.

Although this performance is excellent, there are several applications which need even better long-term or short-term frequency stability. Since factors which now limit super-conducting oscillators do not appear to be fundamental in nature, further research should result in significant progress. The superconducting-cavity, negative-resistance oscillator and the superconducting-cavity maser oscillator provide an opportunity to minimize external perturbations, since all their critical components are contained within the very stable cryogenic environment, perhaps making it possible to come closer to the frequency stability limits determined by thermal noise and the filtering action of the superconducting resonator.

At the present time, throughout the world, there are four groups which actively pursue the development and improvement of superconducting oscillators. There are another three to six groups which are interested or just starting projects. The two active groups in the United States have combined funding of less than \$100 K per year for this research. As a result, progress has been slow since 1974 when a frequency stability of $6 \times 10^{-16}$ was first achieved. A conservative projection of the potential of superconducting oscillators within the next decade would be a stability of $10^{-15}$ at 10 ms with a noise floor of $10^{-17}$. The rate of progress would probably double with increased funding and the involvement of additional researchers in this field.

## VII.3.0. APPLICATIONS

All of the uses of superconducting cavities which will be discussed here result from their low electromagnetic losses. However, substantially different advantages can be gained from this one property. These are applications where it is desirable to reduce the large amounts of power which would be dissipated in conventional devices. A second group uses the very high Q to realize exceptional filter characteristics, such as narrow bandwidth and high ratio impedance transformation. The low losses mean that practically any object placed in a superconducting cavity will determine its performance. Thus many materials properties may be accurately transduced as a frequency with high resolution and low noise. As a result of their state-of-the-art performance, superconducting oscillators are beginning to find a wide variety of applications either directly as clocks, as components of oscillator systems, or in a variety of physics experiments involving clocks and time. Finally, there are some special applications which are rather unique and are discussed separately from all the others.

### VII.3.1. High Power Devices

The performance of conventional linear electron accelerators is limited in the areas of duty factor and accelerated electron-beam current, energy stability, and energy resolution by the power which is needed to maintain the accelerating fields. For the linear accelerator at SLAC (Stanford Linear Accelerator Center), $5 \times 10^9$ W is required for an electron to reach an

energy of 20 GeV in a distance of 3000 m. In order to limit the average energy consumption to acceptable levels, the accelerator is operated with a duty factor of about $10^{-3}$. The power required by superconducting cavities is about $10^6$ times smaller. Taking into account the efficiency of heat extraction at 2 K, which is $5 \times 10^{-4}$, a superconducting accelerator would require only 0.2 percent of the power needed by a conventional machine. The superconducting accelerator could be operated continuously with improvements in all the areas which were mentioned above. Similar advantages are obtained in the case of proton and heavy ion accelerators.

Many accelerators produce secondary particle beams with very high momentum and duty factor. Conventional rf particle separators require as much as 10 MW of rf power for these high-momentum particles, but suitable high-power microwave tubes are not available and the separators must be operated with low duty factor. Superconducting-cavity particle separators would make continuous operation possible. One has been built and installed at CERN.

A potentially very important application which is beyond the present state-of-the-art of superconducting technology is the confinement of high temperature plasmas. The small losses in superconducting cavities could make an important contribution towards achieving the break-even point in the generation of thermonuclear fusion power from an rf confined plasma. The confinement problem requires peak surface magnetic fields of $10^4$ Oe within the microwave cavity; this is one order of magnitude higher than has been achieved to date.

## VII.3.2. Filters

Perhaps the most obvious application of high Q superconducting cavities is as narrow band filters. Below approximately 100 MHz, lumped element resonators are preferred, but at higher frequencies various types of cavities are used: helical structures between 500 MHz and a few GHz; low-order mode structures from a few GHz to 10 GHz or more; and Fabry-Perot resonators at higher frequencies. In addition to the obvious advantage of very narrow bandwidth, for example, 0.1 Hz at 10 GHz, cavities have very pure resonance modes. The geometry can often be chosen so that spurious modes are separated by an octave or more. In contrast, quartz crystal filters have spurious modes usually spaced only 0.1 percent from the desired mode.

Superconducting cavities can be mechanically tuned over a wide range, but the instability introduced by the tuning mechanism counteracts the most important property of the resonators. Very fine, stable tuning can be achieved by controlling the temperature of the resonator -- the total fractional tunability is on the order of $10^{-10}$. Similar tunability can be achieved by coupling an electronically variable reactance to the cavity. Another method which yields a tuning range of $10^{-4}$ is optical tuning by the photodielectric effect. This has been realized by placing a high-resistivity semiconductor wafer in the gap of a quarter-wave reentrant cavity where the rf electric field is very high. When a light beam is directed on the semiconductor, its dielectric constant changes, thereby producing a large shift in the cavity resonant frequency. Step changes in the frequency can be made in less than 10 ms, but the presence of the semiconductor degrades the band-width of the filter: a Q of $10^6$ at 1 GHz has been achieved for such a device.

The narrowband, tunable filters which can be realized with superconducting cavity filters may be applicable to some communications or radar receivers. However, it is more likely that they will be used in highly specialized devices. For example, a superconducting resonator may be used to obtain strong coupling between an evaporated Josephson junction and an electromagnetic field. This is particularly valuable when the junction is used as an oscillator. If such a junction is not incorporated into a resonant structure, the large shunt capacitance shorts out high frequency voltages. The theoretical maximum output power from a Josephson junction is $0.58 \, I_o V$, where $I_o$ is the critical current and V is the bias voltage. Theoretically, a typical junction can emit about $10^{-7}$ W at X-band, but only about one percent of this is observed from waveguide-coupled evaporated junctions. In addition to performing the required impedence matching to the junction, the superconducting resonator also provides narrow-band filtering of the output signal. Unfortunately, this property detracts from the major advantage of the Josephson junction oscillator -- it has a tuning sensitivity $10^5$ times greater than conventional oscillators. In order to preserve this property, it will be necessary to use superconducting cavities with extremely agile frequency tuning.

Superconducting resonators may also be useful as high-ratio impedance transformers for use with superconducting antennas. This application also has the disadvantage of narrow bandwidth. Superconducting antennas are not considered advantageous over conventional devices (at least for today).

### VII.3.3. Transducers

Superconducting cavities make attractive transducers for a variety of quantities because they introduce negligible perturbations and their output is usually in the form of a an easily and accurately measured frequency. Since the frequency of a cavity resonator is approximately inversely proportional to one of its dimensions, it is very natural to use such a resonator to measure changes in that length. The resolution is limited by the frequency instability of the resonator; the best achieved stability of superconducting cavity oscillators corresponds to a random noise level of $3 \times 10^{-16}$ cm. This performance can be improved, in principle, by designing the resonator so the controlling dimension is very small. *It has been predicted that a quarter-wave re-entrant cavity would permit the resolution of $10^{-17}$ cm for a one-second integration time.* However, it has not been demonstrated that the necessary Q can be obtained with such a resonator design. There is an interest today in superconducting cavity length transducers for the detection of gravity waves. In such an experiment, the cavity itself could be used as the antenna, but more likely two cavities would be coupled to a traditional bar antenna in a way which would cancel a substantial fraction of the frequency noise in the exciting oscillator.

Substantial use has been made of superconducting cavities to measure a variety of properties of materials at low temperature. The technique is to place a sample within the resonator and to measure either the frequency or Q as a function of the parameters of interest. The advantage of this technique is that it does not require ohmic contacts and can be used with randomly shaped, powdered or liquid samples. Dielectric constants very near unity and loss tangents as small as $10^{-9}$ can be measured because of the high stability and very low losses of the superconducting cavity itself. Many semiconductor properties have

been measured including relaxation time, lifetime, Fermi level, trap ionization energy, trap density capture cross section, free carrier density and trap population.

Some properties of liquid helium have also been studied this way. The thermal expansion has been measured with a sensitivity, in terms of fractional density change, of $4 \times 10^{-9}$. This sensitivity is sufficient to yield quantitative data concerning the dispersion relation for thermal phonons in liquid helium. The damping of oscillations of the liquid helium through a small orifice can be studied by using the frequency of a superconducting cavity to sense the level of liquid helium within it. This data has been used to study the quantization of vorticity in superfluid helium.

Several interesting and useful devices can be implemented using superconducting cavities. A thermometer can be made for the temperature range from 0.25 to 0.6 K by filling a cavity with $He^3$ vapor in equilibrium with the bulk liquid. Changes in density, which are reflected in frequency changes, are interpreted in terms of the temperature of the gas. The accuracy of such a thermometer is estimated to be 0.2 percent. A nuclear radiation detector can be made by placing a properly doped semiconductor crystal on the stub of a quarter-wave re-entrant cavity. Below 70 K, the charge carriers created by the absorption of radiation are trapped for very long times at sites in the forbidden band. As a result, the frequency of the cavity shifts in proportion to the total absorbed dose. A detector for low levels of light can be implemented in a similar way, only in that case the frequency shift results from the photodielectric effect.

### VII.3.4. Oscillators and Clocks

The excellent spectral purity and medium term stability (up to about one day) of super-conducting oscillators have numerous applications. In the following discussion, these are divided into three categories: oscillators used as components of instruments; oscillators used as clocks to provide timing functions for complex instrument systems; and oscillators used to perform experiments based directly on clock performance.

Oscillators with very good spectral purity (short term stability) are important elements of many instruments and measurement techniques. One example is the use as the starting oscillator for frequency multiplication from microwave to infrared or higher frequencies. The process of multiplication by an integer n increases the phase noise power by $n^2$. This creates a severe practical problem because once the integrated white phase noise becomes comparable to 1 rad, it is no longer possible to identify the coherent signal component. Superconducting oscillators have two important advantages in this application: they can operate at frequencies at least as high as 10 GHz, and theoretically they can produce a signal whose spectral purity is limited by the characteristics of the multiplier. For example, *it has been predicted that a state-of-the-art commercial 5 MHz quartz crystal oscillator may be multiplied to 0.5 THz before the carrier is lost, but the same signal when filtered by a 10 GHz superconducting cavity with $Q = 10^{10}$ can be multiplied directly to 100 THz.*

Certain types of radar also depend critically on the spectral purity of their local oscillator. Return signals from nearby stationary clutter mix with the phase noise sidebands and limit the signal to noise ratio of the true Doppler signal. For example, if a 1 GHz radar has target velocity detection down to 40 m/s and Doppler bandwidth of 10 kHz, then in

order to achieve 80 dB sub-clutter visibility it is necessary to use a local oscillator whose phase noise is more than 120 dB below the carrier for Fourier frequencies greater than 200 Hz.

A third application for short term stable oscillators is as flywheel oscillators in atomic frequency standards. Since the time domain frequency stability, $\sigma_y(\tau)$, cannot improve faster than $1/\tau$, the medium term performance of the standard is limited by the flywheel oscillator if its stability is worse than that of the atomic frequency discriminator at the attack time of the feedback loop. Quartz crystal oscillators do not degrade the performance of current atomic standards, but if expected improvements in these standards are made, then improved flywheel oscillators will be needed and superconducting oscillators are a possible candidate. Flywheel oscillators are also used for autotuning hydrogen masers, a process whereby cavity pulling and spin exchange frequency shifts are simultaneously reduced. Present autotuning systems utilize a pair of masers, one of which could be replaced by a superconducting oscillator, thereby realizing a significant cost reduction.

Superconducting oscillators can also be used to provide time for complex instrumentation and measurement systems such as radio astronomy and radar ranging. The desirability of superconducting oscillators for these applications range from cost savings to the potential for significant improvements in performance.

Very long baseline interferometry (VLBI) using independent clocks may have the following clock performance requirements for certain types of experiments: initial 1 µs synchronization of the start of recording; total time error of less than 1 ns over a five hour observation period to insure that all the data have the same initial offset error; and sufficient coherence to guarantee that the recorded signals can be cross correlated. For a 10 GHz system and an observation time of one hour, the coherence requirement is met by an oscillator with a noise floor $\sigma_y = 5 \times 10^{-15}$. The required noise floor decreases inversely with both the operating frequency and the observation time. The current requirements are met by both hydrogen frequency standards (active and passive devices) and superconducting oscillators. The active masers are very expensive ($\sim$ \$250 K), whereas the other two devices appear to cost only about one-third as much.

Various types of navigation systems need state-of-the-art clocks. Since both the navigation requirements and the techniques are somewhat flexible, it is difficult to place fixed requirements on clock performance. Typical performance goals for two navigation systems are discussed here.

The NASA Deep Space Net (DSN) utilizes a network of radar stations to track spacecraft which have left earth orbit. The current capability of the system is $\sim$ 5 m range resolution and 1 µrad angular resolution. Planners foresee the need for approximately an order-of-magnitude improvement in resolution for some missions which will be flown in the early 1980's, such as the Jupiter Orbiter (JOP). The clock stability requirements depend on the method of range measurement. One approach, which has been suggested, is to replace most of the co-herent (two-way) Doppler ranging with non-coherent (one-way) Doppler measurements. The latter technique, also called wideband VLBI, has the advantage that it substantially reduces the tracking time for accuracy comparable to current coherent tracking methods. However, it places the most stringent requirements on clock performance. When daily calibrations are used, the frequency must be constant to $1.5 \times 10^{-14}$ over one day. Weekly calibrations are

preferable to reduce cost and calibration time, but the frequency stability requirement becomes $3.2 \times 10^{-16}$ over one day.

An experiment has been proposed to use the DSN to detect gravitational waves. The passage of a gravitational wave pulse past the earth and spacecraft produces an identifiable signature in the range information. This experiment places the strictest stability requirements on the frequency standards. To do a feasibility experiment the frequency stability must be $3 \times 10^{-16}$ for the duration of the experiment, 40 s to 4000 s. This can be achieved with a state-of-the-art superconducting oscillator system. An experiment, sufficiently sensitive to detect theoretically predicted gravitational pulses, would require frequency stability of $3 \times 10^{-18}$. It is probable that a superconducting oscillator using a cavity with $Q = 10^{11}$ would eventually be capable of reaching this performance level.

The Global Positioning System (GPS) is a multisatellite system intended to provide earthbound navigation with a precision of 10 m. Each satellite carries high-stability clocks which need to keep time to 10 ns over 10 days. Several hydrogen frequency standards are being developed for this purpose. Depending on future system requirements, superconducting oscillators could become desirable for this application.

There are several fundamental physics experiments which are based directly on superconducting oscillator performance. Two of these, a red shift experiment and a fundamental constants experiment, are performed by comparing the frequency of a superconducting oscillator to the frequency of an atomic standard based on a hyperfine transition such as cesium or hydrogen. In the red shift experiment, one looks for a term in the frequency ratio that has a period of one solar day. Because of the earth's rotation in the sun's gravitational field, various theories of gravity predict

$$\frac{\nu_{hyperfine}}{\nu_{superconducting}} = A\left[1 + 10^{-12} \left(\Gamma_o - \frac{1}{2} T_1\right) \cos\left(2\pi t/1 \text{ solar day}\right)\right],$$

where $\Gamma_o$ and $T_1$ are zero for any metric theory of gravity such as the general theory of relativity. With available standards it would in principle be possible to set an upper limit of $10^{-3}$ on $\Gamma_o - \frac{1}{2} T_1$. The Eotvos experiment already places a limit of $10^{-8}$ on $\Gamma_o$ and may place a limit on $T_1$.

If instead of analyzing the data for diurnal effects, they are fit to a linear drift model, then the same experiment may be analyzed to yield an upper limit on the time rate of change of the fine structure constant. The ratio of the frequencies of a hyperfine standard to a superconducting oscillator is

$$\frac{\nu_{hyperfine}}{\nu_{superconducting}} = Bg \left(\frac{m}{M}\right) \alpha^3 ,$$

where m is the mass of the electron, M is the mass of the nucleus and g is the gyromagnetic ratio of the nucleus; B is a constant. By comparing a superconducting oscillator to a cesium standard for 12 days it has been determined that $(1/\alpha)(d\alpha/dt)$ is less than $4 \times 10^{-12}$/year with 68 percent probability. The quality of this experiment was determined by the data link connecting the laboratories where the standards were located. Significant improvements may result from a comparison of superconducting oscillators and hydrogen standards in the same

laboratory. Although astronomical and geophysical measurements have set a tighter upper limit, they have the disadvantage of averaging possible changes over periods on the order of 10 percent of the age of the universe.

A laboratory experiment has been proposed to use a superconducting resonator excited by a superconducting oscillator to measure the Lense-Thirring effect -- the dragging of inertial frames by a rotating mass. A toroidal superconducting waveguide is centered on the rotation axis of an axisymmetric object. The wave travelling in the same direction as the rotating body takes less time to complete one round trip than the counterrotating wave. As a result, the interference pattern rotates around the waveguide. For a 5000 Kg mass with 50 cm radius rotating at an angular velocity of $2 \times 10^3$ rad/s, the angular velocity of drag has been estimated to be $2 \times 10^{-20}$ rad/s. The required waveguide Q is $5 \times 10^{16}$ and the stability of the exciting oscillator must be $1 \times 10^{-17}$. This stability is probably achievable, but it is difficult to say whether such high Q's can be achieved. There are many other problems at least as difficult as these, making this experiment extremely problematic.

## VII.3.5. Special Devices

Occasionally superconducting cavities can be used to solve some unusual problems. One example of this is the reduction of the "cavity phase shift" problem in cesium beam frequency standards. At the present time, the most significant limitation in the accuracy of cesium beam frequency standards is the extent to which the phase difference of the rf fields in the two interaction regions can either be nulled or measured. If superconducting cavities were used, the variations of the microwave phase across the apertures of the cavities would become very small and it would be possible to measure the intercavity phase shift with high precision. This approach is not being tried at the present time.

Another novel suggestion is a superconducting cavity gyroscope. One possible configuration is the toroidal microwave cavity which was described earlier in the discussion of the Lense-Thirring effect. The position of the nodes in such a cavity experiences a phase shift proportional to the rotation speed of the cavity and the frequency of the exciting radiation. This is just the Sagnac effect which is used today in laser gyroscopes. Because of the difficulty in optical detection of fringes, laser gyroscopes are constructed today in the form of ring oscillators. These devices must be biased in order to overcome a dead zone at low rotation rates; systematic errors introduced by the bias degrade the performance of the gyroscope. The superconducting version of such a gyroscope is less sensitive by a factor of $10^4$ to $10^5$ because of the wavelength difference. However, this is offset by the fact that it is possible to detect a much smaller fraction of a fringe at 10 GHz than at visible frequencies. Consequently, it may be possible to construct a Sagnac-type gyroscope (using superconducting cavities) which operates in the interferometric mode with no dead zone and is competetive in sensitivity with the best mechanical gyroscopes.

## VII.4.0.  SUMMARY AND CONCLUSIONS

There are desirable applications for superconducting cavities with Q's up to $10^{17}$ and for superconducting oscillators with stabilities as good as $3 \times 10^{-18}$. The best Q achieved to date is $5 \times 10^{11}$ and the best stability is $3 \times 10^{-16}$. Since it is generally possible to find the center of a resonance line to one part per million, it is reasonable to expect that a stability of $2 \times 10^{-18}$ will be achieved using present technology, and this might be accomplished within ten years.

The most intriguing potential space application of these oscillators is their use for ranging. The possibility that gravitational radiation might be detected by more sensitive ranging to a drag-free satellite should warrant careful consideration.

Cavity-stabilized oscillators must surely be considered if large improvements are needed by NASA's Deep Space Net or the Global Positioning System. Present performance of the superconducting oscillator is impressive, but the potential for improvement puts this system into a class of its own.

Most work in progress on these oscillators is directed toward application of the devices to real problems without concern for further major improvements in performance levels. Stimulation of work toward improved performance will have to be driven by applications which require such improvement. This might be considered by NASA if oscillator (clock) improvement is rated as a high-priority task.

## VII.5.0.   REFERENCES

Barnes, J.A., Chi, A.R., Cutler, L.S., Healey, D.J., Leeson, D.B., McGunigal, T.E., Mullen, J.A. Jr., Smith, W.L., Sydnor, R.L. Vessot, R.F.C. and Winkler, G.M.R. (1971). Characterization of Frequency Stability. *IEEE Trans. Instrum. Meas.* *IM-20*, 105-120.

Hartwig, William H., (1973). Superconducting Resonators and Devices. *Proc. IEEE 61*, 58-69.

Maxwell, E. (1964). Superconducting Resonant Cavities. In *Progress in Cryogenics, Vol. 4*, (ed. K. Mendelssohn), Academic Press, New York, 124-158.

Pierce, J.M. (1974).  Superconducting Microwave Resonators. In *Methods of Experimental Physics, Vol. 2*, (ed. R.V. Coleman), Academic Press, New York, 541-595.

Turneaure, J.P. and Weissman, I., (1968). Microwave Surface Resistance of Superconducting Niobium. *J. Appl. Phys. 39*, 4419-4427.

Turneaure, J.P. (1972). The Status of Superconductivity for RF Applications. In *Proc. 1972 Applied Superconductivity Conference*, Anapolis, Maryland, 621-630.

Turneaure, J.P. (1978). From paper by Stein and Turneaure. *Proceedings, Conference on Future Trends in Superconducting Electronics, AIP Spec. Pub.*, to be published.

APPENDICES *

* Roman numerals refer to the chapter associated with the particular appendix.

APPENDIX I.A.

COMMENTS ON CRYOGENICS IN SPACE

The use of superconducting devices in space requires cryostats to maintain stable low operating temperatures. Two cryogenic space vehicles, for IRAS and for the Stanford relativity experiment, are currently in the final design stages. Both of these use evaporating liquid helium to maintain low temperatures. This will probably be the conventional approach to cryogenics in space for several years to come.

It is generally agreed, however, that ultimately small closed-cycle refrigerators (cryocoolers) must be developed for both space and terrestrial applications of superconducting devices. The reasons for this opinion are technical, economic, and undoubtedly, intuitive, and it would be beyond the scope of this report to discuss them here. "Applications of Closed-Cycle Cryocoolers to Small Superconducting Devices" was the subject of a conference held recently in Boulder (Zimmerman and Flynn, 1978). The proceedings of this conference are available as NBS Special Publication SP-508. The document is the first of its kind in combining papers on the current state-of-the-art of superconducting devices and of closed cycle cryocoolers, as well as up-to-date thinking about combining the two technologies.

To summarize, present practice (and for some time to come) is to use liquid-helium or possibly solid-hydrogen, cryostats in space. Within five or ten years, perhaps, one may envision versatile space-qualified closed-cycle cryocoolers capable of long unattended continuous or intermittent operation. The remainder of this section is a discussion of a third possibility for cryogenics in space, namely passive radiation cooling. Radiation cooling has already been used for infrared sensors operating at 50 K or above, but here we will consider the possibility of achieving temperatures in the neighborhood of 10 K or below.

A number of authors observe that the stellar radiation in our galaxy has about the same magnitude as the 2.7 K cosmic background. They estimate that the zodiacal light also has about the same magnitude. Unless there are other heat sources of greater magnitude not taken into account, it follows that a black body in interstellar space should reach an equilibrium temperature of no more than 4 or 5 K. Throughout most of interplanetary space, the equilibrium temperature should be almost this low if the body is effectively shielded from the sun, if it is not too close to a planet, and if unforeseen heat sources such as heating by micrometeorite impacts are not too large. Shielding from the sun and reflection of sunlight and re-radiation from the planets will be discussed below. The equilibrium temperature of a body can be lowered if its surface can be made a good reflector at the sub-micrometer wavelengths of solar and stellar radiation, but a good absorber (i.e., emitter) at the sub-millimeter wavelengths of blackbody radiation at a few K.

The possibility of radiation cooling should not be taken too seriously without further study of the thermal heat loads and mechanical design. Although it seems that radiation cooling of superconducting devices may be possible in interplanetary and deep space probes, the requirements of such a mechanism are probably not compatible with "ordinary" spacecraft. In this regard, it may be noted that the two cryogenic vehicles currently contemplated, namely the Infrared Astronomical Satellite (IRAS) and the Stanford relativity experiment, are already

highly specialized to satisfy the requirements of the low-temperature devices, suggesting that similarly specialized spacecraft may also be conceived.

For satellites operating near the earth or other planets, it is hardly conceivable that radiation cooling can be effected. The alternatives are liquid-helium or solid-hydrogen cooling, or closed-cycle cryocoolers, as noted above.

The numerous disadvantages of liquid and solid cryogens and cryocoolers (high-cost, power requirements, complexity, unreliability, vibration, etc.) are strong incentives to consider radiation cooling in any situation where it might conceivably be made to work.

If the cold package (incorporating thin-film SQUID's and other microcircuitry, for example), is envisioned to be a thin plate, for large radiating surface and small mass, the time rate of change of temperature at low temperatures may be approximated as

$$\frac{dT}{dt} = \frac{2\sigma T^4}{dDC_V}$$

$$C_V = (1943 \ J/mol\text{-}K)\,dDT^3/\theta^3$$

where $\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W/m$^2$K$^4$), d is the thickness, D is the molar density, $C_V$ is the specific heat, and $\theta$ is the Debye characteristic temperature of the material, and the approximation is good for T considerably smaller than $\theta$, but not so small that the electronic (or other) terms in the specific heat become comparable to the lattice term. For a black aluminum plate 1 mm thick, the cooling time constant is about nine hours, so the plate would effectively cool off in less than two days. The cooling rate would be considerably greater above 100 K, and smaller below 10 K, since $\theta$ for aluminum is about 375 K, and the electronic specific heat is appreciable at very low temperatures.

The power radiated by a black surface at 10 K is 0.57 mW/m$^2$, or 1.1 mW/m$^2$ for both sides of a thin plate. A SQUID operating at a bias power level of $10^{-10}$ W would therefore require a radiating area of only 1 mm$^2$ at 10 K.

The prospects of radiation cooling a superconducting device in the neighborhood of the earth or any of the inner planets seems remote. The power radiated and reflected by the earth is of the order of

$$P_s \frac{\omega}{4\pi} = \frac{1300}{4} \frac{W}{m^2} \frac{(8000)^2/4}{93^2 \times 10^{12}} = 5.2 \times 10^{-7} \ W/m^2$$

where $\omega$ is the solid angle, and the expression is evaluated at a distance of one orbit radius away (93 $\times$ 10$^6$ miles). Thus, in most of interplanetary space the sun would be the main heat source, of the order of 1 kW/m$^2$ at the earth's orbit. This would have to be reduced by a factor of 10$^7$ or so if the superconducting package is to be radiation-cooled to 10 K. A reflecting disc used as a sunshade would reduce the power by the factor (1-r) and also by a factor proportional to the solid angle intercepted by the disc at the package. Both factors may easily be of the order of 10 or greater. As few as three or four discs in series should provide the necessary shielding.

Heat conduction along the supports to the cold package can be made small if one envisions an open structure with the cold package supported only by members in tension (i.e.,

wires or cords). For example, a mass of 1 kg at 4 K might be supported by six spun nylon cords, extending off in various directions to give kinematic stability, tied to an intermediate assembly at 20 K. If each cord is 10 cm long and each is calculated to break at 10 G loading (10 kg), then the total cross-sectional area of the six cords should be 0.7 $mm^2$, and the total heat flow is 6 $\mu$W. For comparison, the heat radiated by a black surface is 570 $\mu$W/$m^2$ at 10 K and 14 $\mu$W/$m^2$ at 4 K. For spun glass with the same loading the heat flow would be about 9 $\mu$W and for stainless steel about 60 $\mu$W. The data from which these were calculated are from a technical report edited by R. Stewart and V. Johnson (1961). For nylon, glass, and stainless steel, the thermal conductivity integrals from 4 to 20 K were given as 0.008, 0.020 and 0.16 W/cm, respectively. Tensile strengths were taken as 9 x $10^6$, 14 x $10^6$ and 18 x $10^6$ g/$cm^2$.

It is envisioned that the cold package, in the form of a thin plate, and the sun shields would be spaced along an axis pointed toward the sun so that each shield completely intercepts the radiation from the next warmer shield which would otherwise impinge on the cooler shields.

There are various ways by which the cold package and the sun shields can be rigidly assembled by tension members only. For example, the shields might be conical, with the apex of each cone extending somewhat inside the rim of an adjacent cone, and appropriate cords, like the spokes of a bicycle wheel, connecting the two.

We conclude this commentary by stating the obvious -- if superconducting devices are to be used in space in any number of applications, a large development effort on cryocoolers or other means of maintaining low temperatures will be required. It is suggested that a modest beginning of the effort should be encouraged now.

# APPENDIX II.A.

## TERRESTRIAL APPLICATIONS OF SUPERCONDUCTING MAGNETS

Superconducting magnet applications here on earth are subject to some boundary conditions which are more severe than exist for aerospace uses. Of course, the inverse is also obviously true, but those conditions have already been discussed at some length. On earth, nearly all of the tasks proposed for superconducting magnets are capable of being carried out by normal magnets, albeit with enormous expenditures of energy. Furthermore, the economics of capital investment versus operating cost cloud the issue somewhat, as does the (well justified) conservative attitude of much of our industry, and occasionally, a psychological reluctance to get involved with a "new" technology. Also, it is still true that operation of a large superconducting magnet facility requires a much greater competence on the part of the staff than a similar system of normal magnets would. The major difference is the necessity of using various cryogens to cool superconducting magnets, and this situation seems unlikely to change in the near future. With our current knowledge, and given the perversity of nature, it seems that a commercially viable room temperature superconductor is not in the cards for a long, long time.

The discussion here is not intended to cover all projects, there are too many, but to give an idea of the very wide range of applications in which superconducting magnets are being used.

## II.A.1.  Existing Magnet Applications

In this section we discuss systems which have been built and used. In most cases the use is either in scientific laboratories or is very experimental. There are no "every day" commercial uses of superconducting magnets. In nearly all cases, the conductor is NbTi.

*High Energy Physics Magnets*

This application pretty much accounts for all the large superconducting magnets in the world. It has been the major source of money for conductor development and of personnel for all phases of the superconductor business. Even so, the great majority of machine and beam control magnets are still normal.

The higher field strengths and lower energy consumption available with superconductors has recently led to the construction of several very large systems, such as the Energy Doubler at Fermilab and others which are described in the next section, since they are not yet completely operational.

Large superconducting dc dipoles have been built and operated since about 1973 at Brookhaven National Laboratory. One such, a two-module 8° bending magnet has a 3.5 T central field and stores a total of 300 kJ. The magnet is cooled by a 75 W refrigerator. Another large system is the high energy beam line at Argonne National Laboratory which was operational in 1976. It has ten superconducting dipoles and two superconducting quadrupoles. The magnets are contained in four separate cryostats with a total length of > 13 m. The dipoles operate at 2.6 T and the quadrupoles give gradient fields of 0.31 T/cm.

A muon channel magnet system was put into operation in 1974 at the Swiss Nuclear In-
stitute. It is an 8 m long iron-clad solenoid. Cooling for the magnet is by forced flow of
supercritical helium. The sixteen coils in the system store a total of 1.6 MJ and give a 5 T
central field. This system has proven to be nearly maintanence-free over several years of
operation.

The ability of superconductors to create quite large fields (1-2 T) throughout very
large volumes has been exploited in the construction of four large bubble-chamber magnets.
These dc magnets are simple coils heavily stabilized with copper. The two largest of these
are the one at the National Accelerator Laboratory (4.27 m ID, 3.0 T @ 5.0 kA, 400 MJ) and
the CERN-BEBC magnet (4.72 m ID, 3.5 T @ 5.7 kA, 830 MJ).

Many other superconducting high energy physics magnets have been made that have had only
limited success and have not yet been accepted to any degree by the machine users. In this
category are a number of very sophisticated pulsed dipoles and quadrupoles. They have shown
a significant sensitivity to thermal and mechanical shock, as well as a tendency to "train"*
excessively. In nearly all instances magnets for high energy physics research are manufac-
tured in-house. The industrial capability is so limited at present that this is a matter of
necessity.

A related application of superconductors has been in the shielding of charged particle
beams from the machine fields through 2-4 m segments of their path. This technique has been
employed at CERN to lead particles into the bubble chamber through the large magnet. In this
application, the beam travels in a superconducting tube which excludes flux from its interior
by the Meissner effect, thus creating a permanently field free region.

*Fusion Energy Devices*

A large superconducting magnet was built and put into operation in 1971 as a plasma
physics mirror confinement experiment at the Lawrence Livermore Laboratory (LLL). It is
called a "baseball" magnet. The name arises from the shape of the coil winding, which looks
like the seam on a baseball. The magnet stores about 10 MJ, has a 1.2 m "bore" and a maximum
field at the conductor of 5.5 T.

Other smaller superconducting plasma physics devices have been built at Oak Ridge National
Laboratory (IMP), NASA-Lewis (Bumpy torus, 12-3 T coils) and a small (0.5 m bore) mirror at
NASA-Lewis (8.8 T). Two devices, using superconducting rings levitated by normal and super-
conducting magnets, were developed at Princeton and LLL. Most of these are described in the
proceedings of the 1972 Applied Superconductivity Conference.

---

\* Training, also mentioned in Section II.3.4, involves multiple excursions into the normal
state as the magnet is first energized. Usually a large amount of liquid helium is vaporized
in the process. After each of these "quenches" the magnet can be energized to a higher
field. Magnets showing 20 - 50 quenches before reaching maximum field are not rare. After
reaching field the magnet usually can be discharged and recharged without training as long as
it is not warmed up.

*Research Magnets*

For sheer numbers, this class of magnets is probably the largest. Nearly all physics research laboratories have a superconducting magnet of some sort. The magnets tend to be relatively small in size and to be simple solenoids or to have a Helmholtz configuration. Typical is 2-5 cm bore, 7-10 T, 20-30 kg, 100-200 A at full field. They are now wound from multifilamentary wire, usually NbTi, but multifilamentary $Nb_3Sn$ is slowly appearing on the wire market. Unlike their earlier counterparts, these magnets boast charging times to full field of less than a minute and show very little in the way of training. The construction of these magnets for sale is a tough business and only a very few small companies exist at present.

In this group one should also include the very large magnets at places like the National Magnet Laboratory. The largest continuous field magnets yet made (25.4 T and 30.1 T) were recently (1976) constructed there. They are both hybrids which consist of a large superconducting coil with a water-cooled copper coil insert.

*Motors and Generators*

Several medium size (to $\sim$ 3 MW) superconducting motors, both ac and dc, have been built and operated since the first 50 hp motor was made in 1966. To our knowledge only one has actually been put into service in a real system. The Fawley motor, a 3250 hp dc (2.4 MW) device, was first tested in 1971 and operated a water pump with some success for an extended period of time. Both the U.S. and British Navies (and likely others) are interested in superconducting propulsion systems as they offer a great amount of flexibility in control as well as reduced weight. These systems are usually dc. The largest presently under construction, for delivery in 1977, is a 2.2 MW (3000 hp) homopolar system for the U.S. Navy. To our knowledge, no machinery has yet been installed on a ship, although the British were planning a test in 1977.

Another marine application which has been proposed and tested with a small normal magnet system, is a magnetohydrodynamic engine in which an electric current induced through the sea water interacts with a magnetic field to propel a large (2000 ton displacement) submarine to quite high speed, $\sim$ 90 km/hr is projected.

Many words have been published on the feasibility and desirability of superconducting ac generators. They would be about half the size and one-quarter the weight of their normal counterparts. The largest of the normal devices ($\sim$ 2500 MVA) is now limited by size -- any larger and it won't fit under the railroad bridges. In spite of all this only a few superconducting machines have been built (it isn't easy), and only one, the 3 MVA MIT alternator has been run in a power grid, and that as a synchronous condenser. The application of superconducting generators in the power system appears to be a long ways off.

*Magnets for MHD*

As we have already mentioned, magnetohydrodynamic power generation on a large scale is a natural application for superconducting magnets. The magnets are of large size, and thus relatively easy to wind compared to the airborne systems, and the fields required at present are not inordinately high ($\sim$ 4 - 5 T), although it has been suggested that higher field

devices might help the economies significantly.  Unfortunately there are other serious problems with MHD that have kept it from power plant applications.  A large magnet, finished in 1976, for the USSR by Argonne National Laboratory has just been used in the U-25 MHD facility in Moscow.  The magnet system is ∿ 4.4 m long with a magnetic length of 2.5 m.  The maximum on-axis field is designed to be ∿ 5 T and the magnet stores 20 MJ.  A recent NASA-Lewis study has considered a system of similar energy but with somewhat reduced size and weight.

An earlier, smaller magnet was built some years ago by AVCO, but it appears that it was never used in an actual MHD system.  The worldwide effort in large MHD systems is significant.  Whether they will see widespread use or not depends in large part on the future of fission reactor systems.  If fission systems are de-emphasized, MHD offers a possible replacement at perhaps slightly higher total cost.

## Industrial Magnets

Superconducting magnets appear to be well suited for numerous jobs of ore separation, or even scrap recovery, due to the availability of large high field and high field gradient regions which allow a large throughput of material, but they have been little used in spite of some effort (primarily by the MIT National Magnet Laboratory) to convince the industry of their usefulness.  In fact, the only magnet of this sort, of which we are aware, is a relatively small one used to remove iron oxide discoloration from kaolinite which is used for coating printing papers.  The mineral industry is not greatly interested yet, but as the quality of the taconite ores decreases, the higher fields will begin to seem more desirable.

Separation of nonferromagnetic scrap by eddy current induction is a grand idea, but experiment has shown that the strong size dependence of the force experienced by a piece of scrap seems to preclude this approach at least for the near future.

## Medical Applications

The use of large, high gradient magnetic fields, produced by more or less portable superconducting magnets, to steer magnetically tipped catheters through the cranial arteries has led to the possibility of repairing aneurysms, etc., inside the brain.  These and other clever applications of magnets have been used successfully by a team consisting of members of the staffs of the National Magnet Laboratory and Massachusetts General Hospital.

## Levitated Transport

Superconducting magnets offer the possibility of levitating an already moving vehicle above a track which may be made up of other magnets or possibly a pure metal in which induced eddy currents create the repelling field.  This "guided flight" removes the constraints imposed by wheels and axles, making speeds in excess of 600 km/h feasible.  The Japanese National Railway in 1972 operated a model large enough to carry people (3.5 tons), and the Germans (Siemens, Erlangen) have also run a vehicle of significant size on a circular track. The work on such systems in the U.S. has nearly completely vanished for a couple of reasons: mass transit, regardless of speed potential doesn't have a real good reputation in the U.S. for some obscure reason; and the suspension system requires such a large amount of feedback control in order to produce an acceptably smooth ride that it may not be practical in reality.

## II.A.2. Applications in the Near Future

Clearly, the more promising of the applications just described will be evolving as time goes on. In addition, there are a few superconducting magnet applications which appear almost certain to become reality within the next decade. In fact some of them are already well along in construction but have not yet been put into service.

### *High Energy Physics Magnets*

A number of large accelerator and storage ring systems have been proposed and a few are under construction. Two, which are progressing well at present, the Energy Doubler at Fermi Lab and the Experimental Superconducting Accelerator Ring (ESCAR) at the Lawrence Berkeley Laboratory will serve to give a feeling for the scale of such projects.

The Energy Doubler will use 1000 (!) large superconducting magnets (800 dipoles and 240 quadrupoles) in a 6 km tunnel. The magnets have NbTi windings and the dipoles have central fields of $\sim$ 4.5 T. A large number of prototype magnets have already been built and tested.

The ESCAR system will use 24-4 T NbTi superconducting dipoles each $\sim$ 1 m long. They are now in production at the rate of about one a month. Tests of a pre-production prototype were very successful.

These two examples should serve to indicate that this business of superconducting magnets is not just someone's wild dream. Large complex magnets can be built successfully in large numbers. Refrigeration systems adequate to cool these monsters are now available. A detailed description of these and many other high energy physics experiments using superconducting magnets is given by Reardon (1977).

### *Fusion Energy Devices*

Magnetic confinement of the hot fusion plasma ($\sim 10^8$ K) in a toroidal configuration has proven to be one of the more promising approaches to achieving net fusion energy production, but the plasma physics and the machines both have a long way to go. At present it seems certain that high fields with large volumes will be necessary, and that requires superconducting magnets. The USSR has a fusion device of the tokamak design which uses superconducting magnets, but to our knowledge it has never operated successfully. A large mirror machine physics experiment (MFTF) is being constructed at the Lawrence Livermore Laboratory. It uses a heavily stabilized (8:1, Cu:SC) NbTi conductor. The maximum field at the conductor will be 7.5 T and the stored energy in the magnets will be 500 MJ. The magnets have a fairly complex winding geometry called a yin-yang pair.

A program at Oak Ridge National Laboratory (ORNL) called the Large Coil Program, is funding the construction by three industrial contractor teams of three superconducting coils of the type to be used for the toroidal field coils in large tokamak devices. The purpose of the project is to prove that such coils can be made successfully and to provide coils for tests of a large toroidal magnet facility. They are not expected to be used in an actual fusion device. Several foreign countries have also agreed to contribute coils to the program. The coil design is flexible within certain guidelines. The magnets are to be D-shaped with a 2.5 x 3.5 m winding bore and produce a field of 8 T at 10-16 kA current. The windings will be heavily stabilized. Two of the coils are using NbTi conductor with poolboiling of

helium as the cooling mode; the third will use $Nb_3Sn$ and be cooled by forced flow of super-critical helium. The coil deliveries are presently scheduled for installation in a test stand at ORNL in early 1980.

## Energy Storage Magnets

A number of inductive energy storage systems using superconducting magnets have been built and tested recently, but they are included here rather than in the previous section because, to our knowledge, they have never been used in an actual application. The largest systems now built and tested are at the Los Alamos Scientific Laboratory (LASL). There started out to be three of them, one was quite successful. They store about 300 kJ in a 2.2 T NbTi magnet operating at 10 kA. Charge and discharge times are 30 s and 10 s respectively. Coils ($\sim$ 0.5 MJ) are being developed for plasma heating by induction in fusion devices; capacitor banks now serve this function, but will be impractical for much larger machines. Similar coils are proposed for providing the large pulses of energy required by high power laser systems in a variety of applications.

Giant underground superconducting magnet systems storing $10^6$ - $10^7$ MJ have been the subject of detailed designs by the University of Wisconsin and LASL. These large systems are primarily proposed for peak-shaving utility applications.

## Magnets for MHD

Superconducting magnets for full scale MHD power plants are now being studied at the National Magnet Laboratory with Department of Energy Funding. Two magnets of this class, one for an Engineering Test Facility (ETF) and an actual Base Load (BL) plant magnet were designed by Magnetic Corporation of America. Both magnets have a 6 T field at the channel and $\sim$ 9.8 T at the windings. NbTi at $\sim$ 4.2 K seems to be the conductor choice for both designs. The ETF magnet is 7.0 m long and stores 483 MJ, and the BL magnet is 16.0 m long and stores 4.5 GJ. In both cases the magnet system is $\sim$ 65% structure and the specific weight is 656 kg/MJ for the ETF magnet and 437 kg/MJ for the BL magnet.

## Medical Applications

A large toroidal superconducting magnet system to allow the use of mesons in cancer therapy has been constructed and tested at the Stanford Linear Accelerator Center (SLAC), but to our knowledge it has not yet been used in treatment. A similar system is being developed at the Swiss Nuclear Institute.

## Industrial Magnets

It has been shown at the National Magnet Laboratory that it is possible to remove a range of pollutants from water by "seeding" it with fine magnetic particles and then passing it through a mesh of fine ferromagnetic fibers (steel wool) located in a modest magnetic field. The non-magnetic impurities are collected by the magnetic seeds which, in turn, are magnetically removed. Again the high field volume necessary for an acceptable throughput requires that the magnets be superconducting. As best we can tell almost nothing has been done on this system recently, but there is no indication that there is any problem with the concept.

## II.A.3. Applications in the Far Future

Clearly, anything suggested here must be taken with much skepticism, so we will keep it short. It seems certain that fusion energy in one form or another will become a major source of power after the turn of the century and, at present, it seems that superconducting magnets will be used for plasma confinement in these devices. Other applications, such as the control of chemical and biological reactions of various sorts are possible, but so much needs to be learned that no prediction is possible. One development which would, of course, change much of the way we look at high field applications would be development of a viable high temperature superconductor, but that doesn't look very promising.

Much concern has been expressed over the continuing availability of helium, since the major source is natural gas, and there is no longer a U.S. program of conservation. The "experts" apparently cannot agree on whether or not this could become a problem in the far future. One could probably assume that it will, although development of superconductors capable of high field operation at liquid hydrogen temperatures, is a very real possibility and would result in a much lower demand on the helium reserves.

APPENDIX II.B.

CURRENT APPLICATIONS OF SUPERCONDUCTING MAGNETS IN SPACE

In this appendix we present a description of the few superconducting magnet systems which have actually been built for application in space or near to it.

II.B.1.  Operational Superconducting Magnet Systems

In this description of actual systems we go into somewhat greater detail than in earlier sections because:  (1) there are so few magnets that doing so is no problem, and (2) the relative simplicity of the systems which work is encouraging and needs to be stressed.

*Orbital Systems*

The only two superconducting magnet systems to achieve earth orbit were small coils flown by the USSR on Cosmos 140 in 1967 and on Cosmos 213 in 1968.

The first of these was a very small (12 cm$^3$ field volume) double solenoid with a maximum field of $\sim$ 1.4 T in a more or less conventional, nitrogen-shielded transport dewar cooled with 6.5 $\ell$ of supercritical helium.  The flight lasted for a total of 32 hours.  It was observed that introduction of a very small artifical gravity (about 0.001 g), directed opposite to the normal direction, caused increased boiloff due to cold fluid entering the dewar throat and warm gas in the magnet region, but the magnet did not quench.  The magnet was charged and put into a semipersistent mode prior to launch.  Some conclusions from this flight were:  that, (1) the large static and vibrational loads at launch did not affect the solenoid in any adverse way; (2) supercritical helium could be used as a coolant with no real problems and; (3) small gravitational forces can seriously affect the operation of the system.

The second flight carried a larger split coil with a 1.7 T central field in a 10 cm bore, used as a magnetic analyzer for cosmic radiation.  The system mass was 16.6 kg and the container was similar to the one flown previously.  The superconductor used in both systems was the alloy 65-BT (probably NbTi).  In this experiment the dewar was filled with two-phase helium, and overpressure by the boiloff during flight (which only occurred when the satellite began rotating six hours into the flight) was used to create the supercritical phase.  At some point, $\sim$ 17 hours into the flight, the magnet apparently quenched.  The conclusion seems to be that the dewar system needs to be carefully constructed to operate well both in weight-lessness and under the complex conditions imposed by the flight.  There seemed to be no problem with the magnet itself.  The experiments are described by Anashkin, et al. (1969).

*Balloon-Borne Systems*

The use of superconducting magnet spectrometers on high altitude balloon flights has become about as routine as anything gets in this business.  The first flight was made in 1969.  Nearly twenty successful flights have been made in this country involving four different magnets.  The magnets tend to be simple coils of rectangular cross section wound from NbTi which is stabilized with copper.  The systems are quite similar.  In one, the central

147

field is $\sim$ 3.0 T. The system uses a nitrogen-shielded liquid helium dewar holding about 80 ℓ of helium and will operate for about one day without refilling. The total package weighs 150 kg and is designed to take 5 g shocks from any direction.* The magnet current is 120 A at full field and the magnet is charged, prior to flight, from a 2 V battery source. Charging and transfer to persistent mode is a slow operation requiring several hours. Stored energy in the magnet is 576 kJ. These systems have been described recently by Golden (1975).

## Magnet Systems in Rockets

Two superconducting magnet systems have been investigated for use on rocket flights. To the best of our knowledge only one was flown. That one was built at AVCO for flight on an Apache rocket. The NbTi magnet was a small end-corrected solenoid with a 7 cm bore and 15.3 cm long. It developed 3.0 T central field at 55 A current. It was to be charged before launch and put into persistent mode for at least a two-hour period. The coil was to be able to withstand 50 g acceleration without quenching. The system mass was to be less than 23 kg. In the course of the program a smaller test coil was actually subjected to 37 g's at frequencies from 100–2000 Hz without quenching. Rumor has it that the actual coil was tested to 50 g's and delivered to NASA-Goddard.

## Magnet Systems in Aircraft

No such systems have actually been flown. In the text of Chapter II we discussed some of the problems of very specialized military systems. Otherwise, in general, there is every reason to believe that any system which will work in the laboratory will work on board an aircraft.

## Summary: Operational Systems

Very few superconducting magnet systems have operated in space. Those that have were relatively small in size, not complex in design, and operated at fields well below the capability of the conductor. The cooling systems were quite conventional. For the most part, no changes from conventional magnet design were made. Limited testing indicates that acceleration and vibration are not severe problems for these heavily stabilized magnets.

There is no question but that modern superconducting magnet systems are capable of performance under much more demanding conditions than those already encountered. If such high-performance systems are to be actually used, and the chances are that they will, now is the time to begin to evaluate what the limits of performance in space applications truly are. Comparison of the parameters of the magnets just described with those of the existing terrestrial magnets in Appendix II.A. should be sufficient to convince even the most skeptical that superconducting magnets represent a basically untapped source of potential assistance for a large number of space activities.

---

* In fact, one of the Lawrence Berkeley Laboratory balloon magnets maintained its field through a descent which ended in a crash on a mountainside, severely damaging the gondola shell.

II.B.2.   Systems That Almost Made It

Much of the history of superconducting magnet applications in or near space involves a
series of rather heartbreaking scenarios in which good magnets were built, or almost built,
and tested, but never flown for reasons having nothing to do with the magnet which in nearly
all cases was perfectly adequate for the proposed task.  Here we describe these magnets, but
space does not allow much of a discussion of the reasons behind their failure to fly.

*Orbital Systems*

A prototype magnetic spectrometer magnet was designed and built to be used on the High
Energy Astronomical Observatory (HEAO) series of flights.  The first of the three flights
in this series has been launched, the second goes in 1978 and the third a year later.  There
will be no superconducting magnets on any of these flights since it was decided to use a
smaller launch rocket, which resulted in the removal of the heavier of the planned experi-
ments.  The dewar system was designed for a hold-time of one year and, in fact, has since
proven to be capable of this extended containment in ground-based tests.  The NbTi magnet
itself and several rewound versions are described by Pope, Smoot, Smith and Taylor (1975).
Apparently only one coil was built; two are needed for the spectrometer.  It produced a field
of 7.0 T at the winding with a current of $\sim$ 120 A and a stored energy of $\sim$ 750 kJ.  The magnet
mass was 150 kg and the coil had an inner diameter of 68 cm and was 9.5 cm long.

A smaller (30 cm), but similar, magnet system was being developed at Marshall for shuttle
applications, but it now seems unlikely that this system will actually be used on any immediate
flight.

*Balloon-Borne Systems*

A large magnet with a complex saddle shape was built about 1967 by the Lawrence Liver-
more Laboratory (Taylor, et al., 1967) and successfully tested at that laboratory.  It had a
1.1 T central field, a 1 m bore, a maximum current of 870 A and a stored energy of 1.2 MJ.
The coil and dewar weighed 1630 kg.  Aluminum alloy was used as the structural material to
minimize the weight.  This magnet is probably a reasonable representation of the breed.  The
distribution of mass is as follows:  coil form 20%; helium container 8%; conductor 31%;
structural shell 17%; dewar 24%.

*Magnet Systems in Rockets*

A coil was to be made at LASL for an ionized plasma experiment in about 1972.  The
magnet was quite large (275 kg, 43 cm bore, 3.5 T), but the forces were low (less than 6 times
the force produced by gravity).  Modeling and test coils indicated that such a system would be
possible, but it was apparently never built.

APPENDIX IV.A.

JOSEPHSON TUNNELING LOGIC

Josephson tunneling logic is based on individual switching devices called Josephson junctions (after Brian Josephson who first theoretically predicted their properties). Such a junction is formed by two superconducting electrodes separated by a thin insulating layer, only a few tens of angstroms thick. To achieve its remarkable properties the junction must be cooled to low temperatures (4 K) so that the junction electrodes are superconducting.

A Josephson junction has a time-averaged current-voltage (I-V) characteristic as shown in Fig. IV.A-1. The dashed line shows the I-V curve of the junction when it is not super-conducting. Not shown in this characteristic are oscillations in the current which occur at
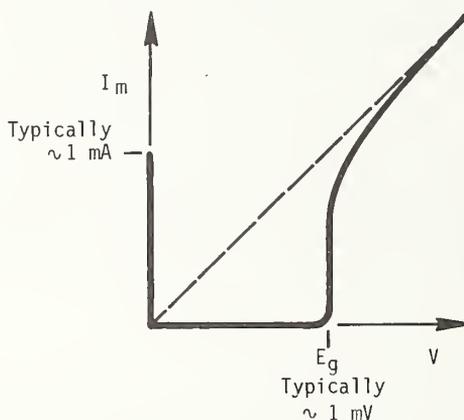


Figure IV.A-1. Time-averaged current-voltage characteristic of a Josephson junction. the dashed line is the I-V curve of the junction when it is not superconducting.

frequency $f = \frac{2e}{h} V$, where V is the average voltage across the device, e is the charge on an electron, and h is Planck's constant. That typical oscillations are at very high frequency is clear since $\frac{2e}{h} = 484$ GHz/mV. For our purposes these oscillations are at such a high frequency that they can only be observed if extreme care is taken. These oscillations must, however, be considered in careful analysis of high-speed device operation.

A particularly unique feature of the Josephson junction is its ability to carry current with zero voltage drop. We see this reflected in the portion of the I-V curve along the current axis. When biased at points along this portion of the curve the device dissipates exactly zero energy. It is a superconductor.

There is a maximum zero-voltage current $I_m$. If we try to raise the junction current above $I_m$, voltage will appear across the junction. At average voltages above zero, but below

the upward bend in the I-V curve at $E_g$, the junction carries very little current. Above $E_g$, the I-V curve approaces the linear one of a non-superconducting junction, a pure resistance.

To see how such a junction is operated as a switching device -- a Josephson tunneling gate -- one attaches it to the bias supply as shown in Fig. IV.A-2. The gate is the "X."
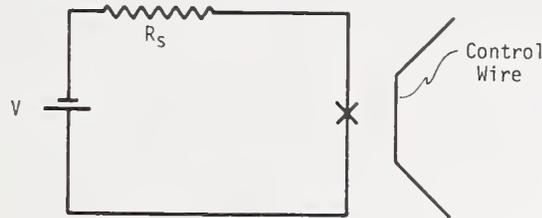


Figure IV.A-2. Bias supply for Josephson gate.

When biased on the zero voltage part of the I-V curve, as shown by point a in Fig. IV.A-3.A, all of the voltage V supplied by the battery drops across the source resistance $R_s$. No voltage appears across the junction.
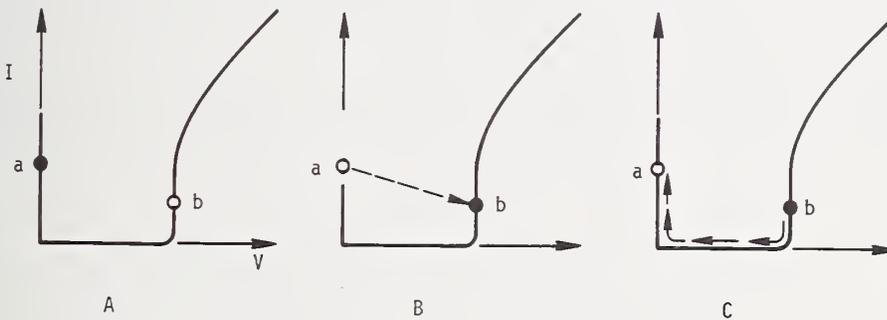


Figure IV.A-3. Operation of Josephson gate (latching).

To cause the junction to switch, one applies a magnetic field to it, which reduces $I_m$ (to be explained in greater detail later) below the junction current at point a. In practice the magnetic field is produced by passing a current through a control wire (usually a thin film) directly above the junction. The current through the wire is called the control current. Once $I_m$ is reduced below a, that point becomes unstable and the junction switches to point b along the dashed line as shown in Fig. IV.A-3B. If the control current is reduced, $I_m$ returns to its original value, but the junction remains at point b. The junction is said to "latch" at point b. To return to point a, one reduces the voltage V, essentially to zero,

and then raises it again. The path followed by the junction is shown in Fig. IV.A-3C. It is also possible to construct "non-latching" junctions which return to point a as soon as the control current is reduced and $I_m$ rises.

Josephson tunneling gates of the type described above can have remarkably fast switching times: as fast as a few picoseconds from point a to point b. Measured switching times from a to b are limited by present measurement techniques to around 30 ps. Switching times of about 80 ps have been achieved for switching from a to b and back to a.

In addition to rapid switching (and perhaps more important) the Josephson tunneling gate offers exceptionally low dissipation. At point a, no power whatsoever is dissipated; at point b, typical dissipation is of order (1 mA) x (1 mV) = $10^{-6}$ W. This is three to four orders of magnitude lower than the dissipation of most semiconductor devices. A revealing comparison was given in Fig. IV-2 (in Chapter IV). Low power is crucial when large numbers of devices are combined to form a large computer or even when smaller numbers of devices are assembled for ultrafast measurements.

Thus we have seen how the state of a Josephson gate can be changed by a control current passing through a wire which is electrically separated from the junction itself. A latching junction can be returned to its original state (point a) by momentarily reducing the bias. Non-latching junctions return directly to their original state when the control current is reduced.

Two questions remain. How does one perform logic and how does one transfer the result of a logical operation to a succeeding junction? To begin with performing logic, one notes that, as shown in Fig. IV-3 (in the main text of Chapter IV), two or more control lines may be placed above a junction. The maximum zero-voltage current $I_m$ through the junction is determined by the sum of the magnetic fields produced by the control currents. Thus, $I_m$ is determined by the sum of the control currents.

One next needs to examine how $I_m$ depends on the control currents (or equivalently the magnetic fields they produce). We have illustrated this dependence in Fig. IV.A-4. It can
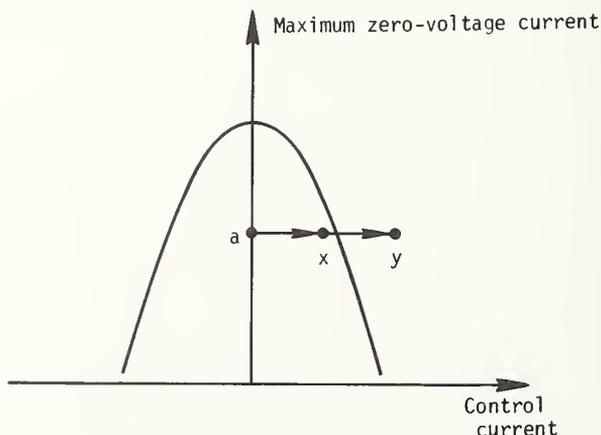


Figure IV.A-4. Operation of Logic

152

be seen that a control current of either polarity will reduce $I_m$. Let us assume that the amplitudes of the control currents are described by the arrows in Fig. IV.A-4. If the junction is biased at point a, applying a control current through one control wire moves the system to point x. The junction does not change state because x is still less than the maximum zero-voltage current. However, if control currents are applied through both control wires simultaneously, the state of the system moves to y. The junction does switch, since the maximum zero voltage current $I_m$ has been reduced below the operating current of point a. We can make a truth table of the results:

| Control Current 1 | Control Current 2 | Junction Switches? |
|-------------------|-------------------|--------------------|
| No | No | No |
| Yes | No | No |
| No | Yes | No |
| Yes | Yes | Yes |

It can be seen that the output of the junction (its state) is the logical "and" of the input control currents. Thus logic has been directly performed by a single Josephson tunneling gate.

It is also possible in an analogous manner to perform a logical "or" by making a junction in which the curve shown by Fig. IV.A-4 is skewed. Logical "not" can also be performed in a somewhat more involved way. Thus, all fundamental logical functions can be performed, making possible the construction of computers and digital instruments.

The final subject, not yet discussed, is the method by which the state of a junction may be transferred to a subsequent junction. As illustrated in Fig. IV.A-5, the junction is connected to a terminated transmission line. Part of the transmission line rises above the
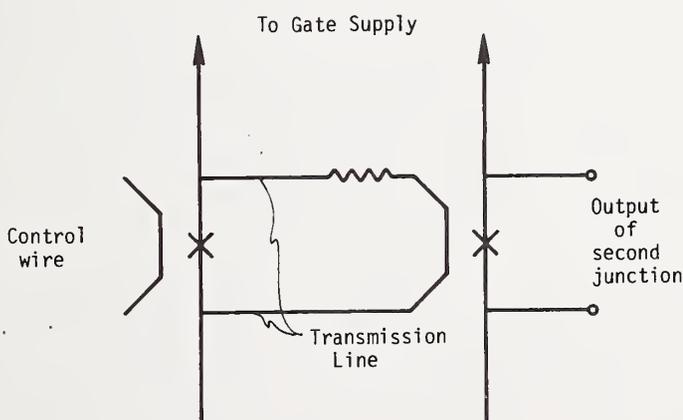


Figure IV.A-5. Transfer of information to subsequent junctions.

next junction and is a control wire for that junction. When the first junction switches to b, a time-averaged voltage appears at the ends of the transmission line and a current therefore propagates down it, acting as the control current for the next junction. The second junction therefore switches to point b. The resistance in the transmission line terminates it and dissipates the magnetic energy stored in it, if the first junction switches back to state a. Thus, the control current for the second junction drops back to zero whenever the first junction reverts to a state a.

APPENDIX IV.B.

JUNCTION FABRICATION TECHNOLOGY

Josephson tunneling logic devices have become serious candidates for a variety of applications to measurements and computers because of substantial progress which has recently been made in fabricating reliable junctions. The progress has been principally in two areas: the use of alloys for the electrodes, and improved barrier formation techniques.

Josephson junctions for practical use need to be made of superconductors which have transition temperatures above the boiling temperature ($\sim$ 4 K) of liquid helium at atmospheric pressure. Thus further cooling by pumping on the helium is unnecessary. There are only two elemental superconductors which meet this criterion: lead and niobium. Niobium is difficult to work with because it oxidizes so readily, making control during barrier formation difficult. Thus, for the moment, lead is the most used material.

Lead junctions suffer substantially because, after lead is cooled with liquid helium, it undergoes compressive stresses when it is rewarmed. These stresses lead to the growth of hillocks or bumps in the lead films. The hillocks are of more than sufficient size to destroy the insulating barrier in the junction. Thus lead junctions, once cooled, are destroyed if allowed to rewarm. This clearly renders them useless for field application.

On the other hand, lead alloy junctions have been demonstrated to be resistant to hillock growth, and to survive repeated cooling and heating without failure. The lead alloy is deposited through sequential evaporation of thin films of pure materials. The layered film which results is then homogenized by heat treatment at modest temperatures of about 70° C. Presently preferred materials are lead, alloyed with indium and gold.

Fabrication of reliable barriers depends both on the use of the alloy films and on the method of oxidation. The alloy described above forms an oxide which is enriched in indium compared with the composition of the alloy. The second electrode is made of materials which do not react with oxygen as readily as indium, thus inhibiting migration of indium in the barrier into the second electrode. The presently preferred materials for this alloy are lead and gold. The indium oxide barriers, formed using these alloys appear to have a lower barrier height than pure lead. Thus, for a given tunneling current density the indium barrier can be thicker than that for pure lead, a desirable result which enhances long term stability of the barrier.

Oxide layers can be produced in a controlled way using an rf sputtering process. One slowly sputters away the surface of the first electrode, in an oxygen atmosphere. At the same time, because of the presence of the oxygen, the surface continually reoxidizes. Eventually a dynamic equilibrium is reached in which the rate of sputter removal of the surface equals the rate at which the surface reoxidizes. Because the process is very sensitive to changes in the sputtering conditions such as rf voltages and oxygen pressure, these parameters can be used as sensitive controls of the resulting oxide thickness. Time is not an important parameter, since as soon as dynamic equilibrium is attained, there are no further changes in the oxide thickness.

To make complete integrated circuits, one must also be able to deposit resistors and insulators for crossovers and microstrip lines. The resistors are made from $AuIn_2$, an intermetallic which is present in the superconducting alloy, so that interdiffusion between resistor and superconductor is not substantial. Two types of insulator are commonly used. Niobium is often used as a ground plane and then anodized to form a $Nb_2O_5$ insulating layer on its top surface. SiO is used in other places where insulators are needed (e.g., between junction and control lines, at stripline crossovers, etc.).

## REFERENCES

Anashkin, O.P., Kurnsova, S.S., Konyakhina, S.S., Lagarikev, A.A., Razorenov, L.A., Sidvakina, T.M. and Fradkin, M.I., (1969). Trial of Superconducting Magnetic System with Field H ≈ 20 kOe on Board an Artificial Earth Satellite. *Kosmitcheside Issledovaniya* 7, 786-793. Translation available as N71-11903.

Golden, R.L. (1975). Superconducting Magnets for Space Flight. In *Research Goals for Cosmic-Ray Astrophysics in the 1980's*, European Space Agency ESRO SP-109, 91 (available as N76-12934).

Pope, W.L., Smoot, G.F., Smith, L.H. and Taylor, C.E. (1975). Superconducting Magnet and Cryostat for a Space Application. *Adv. in Cryo. Eng.* 20, 47-60.

Reardon, P.J. (1977). High Energy Physics and Applied Superconductivity. *IEEE Trans. on Magnetics MAG-13*, 704-718.

Stewart, R.B. and Johnson, V.J. (1961). A Compendium of the Properties of Materials at Low Temperature (Phase II). *WADD Technical Report 60-56, Part IV*, Wright Patterson Air Force Base, Ohio.

Taylor, C.E. Nelson, R.L., Henning, C.D., Taylor, A.R. and Harvey, A. (1976). A Lightweight, 1-Meter-Diameter, 11 kG, Superconducting Magnet System for a Balloon-Carried Cosmic Ray Experiment. *Proc. 2nd Int. Conf. on Magnet Tech.*, 617, (Rutherford Laboratory, Chilton, Berks, England).

Zimmerman, J.E. and Flynn, T.M. (1978). *Applications of Closed-Cycle Cryocoolers to Small Superconducting Devices*, National Bureau of Standards Special Publication SP-508.

| U.S. DEPT. OF COMM.<br>BIBLIOGRAPHIC DATA<br>SHEET | 1. PUBLICATION OR REPORT NO.<br><br>NBSIR 78-885 | 2. Gov't Accession<br>No. | 3. Recipient's Accession No. |
|---|---|---|---|
| **4. TITLE AND SUBTITLE**<br>The Role of Superconductivity in the Space Program:<br><br>An Assessment of Present Capabilities<br>and Future Potential | | | **5. Publication Date**<br>May 1978 |
| | | | **6. Performing Organization Code**<br>724 |
| **7. AUTHOR(S)**<br>D.B. Sullivan, editor | | | **8. Performing Organ. Report No.** |
| **9. PERFORMING ORGANIZATION NAME AND ADDRESS**<br><br>NATIONAL BUREAU OF STANDARDS<br>DEPARTMENT OF COMMERCE<br>WASHINGTON, D.C. 20234 | | | **10. Project/Task/Work Unit No.**<br>7240187 |
| | | | **11. Contract/Grant No.**<br>NASA Contract No.<br>A-437018(JM) |
| **12.** Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*<br><br>National Aeronautics and Space Administration<br>400 Maryland Avenue SW<br>Washington, D.C. 20546 | | | **13.** Type of Report & Period<br>Covered |
| | | | **14.** Sponsoring Agency Code |

**15. SUPPLEMENTARY NOTES**

**16. ABSTRACT** *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report describes the results of a study designed to assess the role which superconductivity might play in the U.S. Space Program. The study was performed by members of the staff of the Boulder Laboratories of the National Bureau of Standards. Six technical subject areas were considered; high field magnets, magnetometers, digital electronics, high-frequency detectors, instruments related to gravitational studies and ultra high-Q cavities. The study identifies a number of applications of superconductivity which are of potential interest to NASA. Wherever possible, the devices are related to specific types of space missions.

**17. KEY WORDS** *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Computers; digital electronics; gravitational studies; high-Q cavities; infrared detectors; magnetometers; magnets; microwave detectors; space; superconductivity.

| **18. AVAILABILITY**     [x] Unlimited | **19. SECURITY CLASS**<br>(THIS REPORT) | **21. NO. OF PAGES** |
|---|---|---|
| [ ] For Official Distribution. Do Not Release to NTIS | UNCLASSIFIED | 163 |
| [ ] Order From Sup. of Doc., U.S. Government Printing Office<br>Washington, D.C. 20402, <u>SD Cat. No. C13</u> | **20. SECURITY CLASS**<br>(THIS PAGE) | **22. Price** |
| [xx] Order From National Technical Information Service (NTIS)<br>Springfield, Virginia 22151 | UNCLASSIFIED | $8.00 |