Naval Research Reviews

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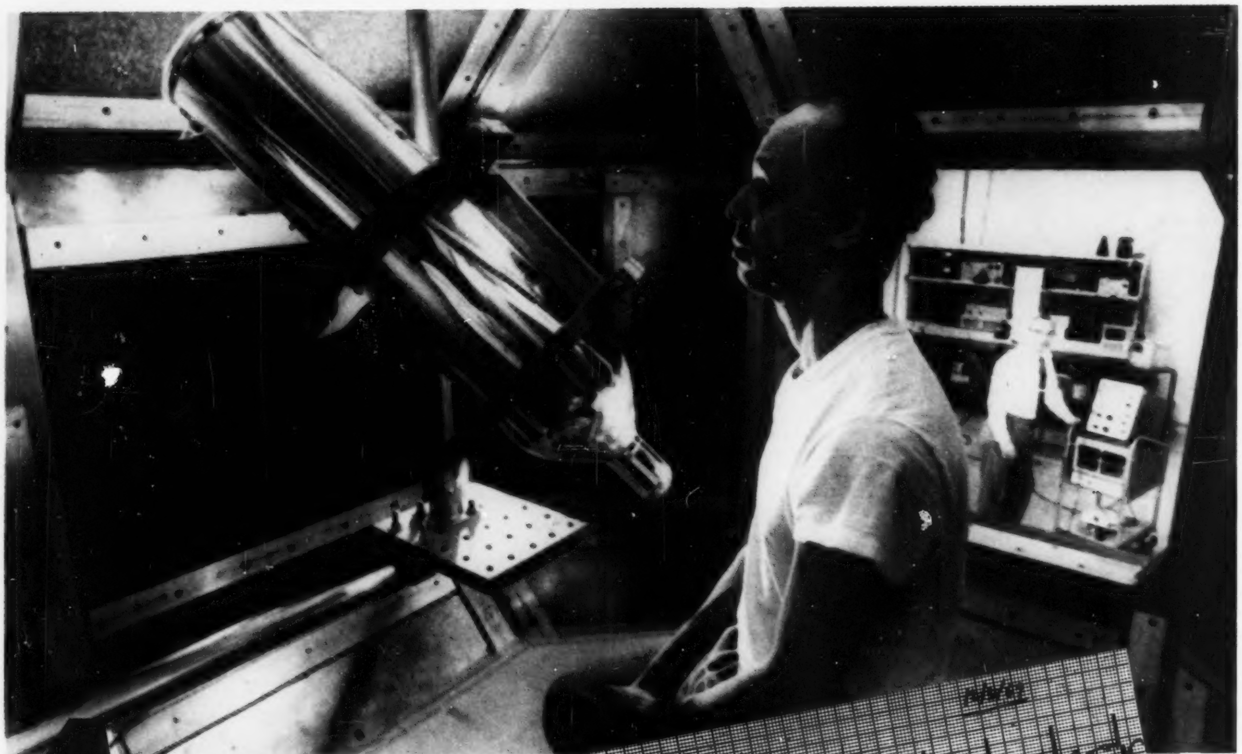
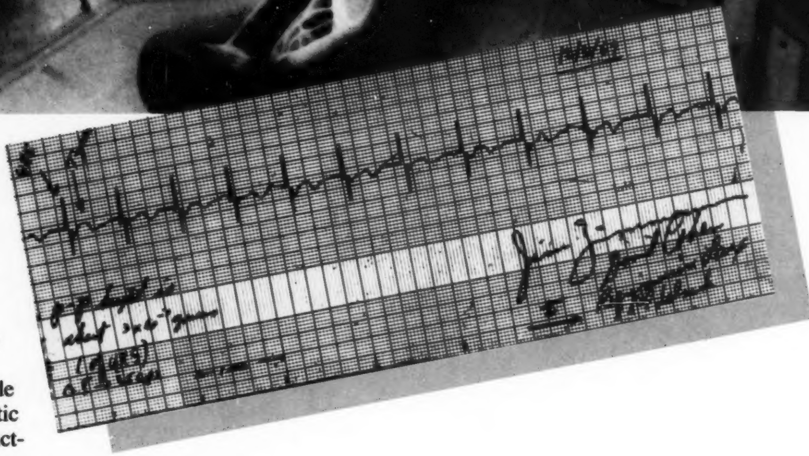
Vol XXXVII

First Biomagnetics SQUID Magnetometer





A magnetic sensor called a "SQUID" (Superconducting Quantum Interference Device) is housed in a liquid helium dewar held near the subject's chest. This device, which was developed by Dr. James Zimmerman of the National Bureau of Standards Research Laboratory at Boulder, Colorado, with Office of Naval Research (ONR) funding, made the first measurements of the magnetic field of the heart using a superconducting magnetic sensor in 1969. The SQUID sensor is housed in a chamber designed and built by Dr. David Cohen of the Massachusetts Institute of Technology with ONR support. The chamber screens out all extraneous magnetic fields, including the earth's own magnetic field. The weak magnetic fields of the human heart can be sensed inside this magnetic field-free chamber. This experiment of 1969 ushered in a new era for biomagnetism which ONR continues to support.

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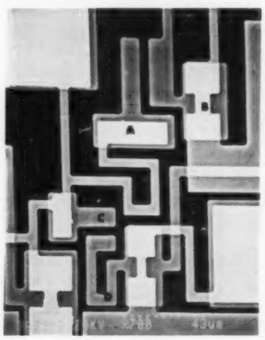

Josephson technology time domain reflectometer circuit built by HYPRES, Inc. of Elmsford, NY. The circuit consists of all-niobium Josephson junctions, interferometers (SQUIDS), capacitors, resistors, inductors and ultra-wide bandwidth transmission lines. Shown are two pulse generators producing seven picoseconds duration pulses and a sampling gate. The circuit, which is magnified 700 times, has minimum features of five micrometers. This circuit is an example of very complex superconducting integrated circuit performing memory, logic, and other functions.

The letters on the micrograph identify selected circuit elements such as a Josephson junction "A," a two junction SQUID, "B," a resistor "C," and an inductor, "D." Photograph is the courtesy of HYPRES, Inc.

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NAV

Applications of

Pin-head size magnetic detectors of submarine signatures and large motors for electric ship propulsion are "cousins"—they both trace their origin back to the phenomenon of superconductivity. Applications of superconductivity span an enormous range of some 30 orders of magnitude in energy. In this paper, we highlight recent developments in large-scale, high-power and in small, low-power applications of Navy interest. The Federal Government annually spends over 15 million dollars for research and development in superconductivity. The Navy provides about a third of this total. These sums are only the tip of a very large and fast growing iceberg. Estimates of the commercial superconductivity market vary from 3 to 9 billion dollars by 1990 and from 11 to 36 billion dollars by the year 2000. There is little doubt that superconductivity is becoming big business!

What is superconductivity? It is often described as a phenomenon of great intricacy, diversity and elegance. These characteristics have assured it a prominent place among the most interesting and challenging fields of science. It has, as well, led to remarkable technological, industrial and military applications. Large scale applications include motors and generators for electric ship propulsion; land-based electric utility power systems containing the highest energy densities; experimental magnetically levitated train (the world's fastest); magnets for nuclear resonance medical diagnostic systems; the world's largest electromagnets for magnetic confinement thermonuclear fusion experiments; and bending and focusing magnets for the world's most energetic particle accelerators. Small scale applications include the fastest switching and least power consuming electronic devices for computer and signal processing applications; the most sensitive magnetic detectors capable of measuring minute magnetic signals emanating from the human heart and brain; the most sensitive and lowest

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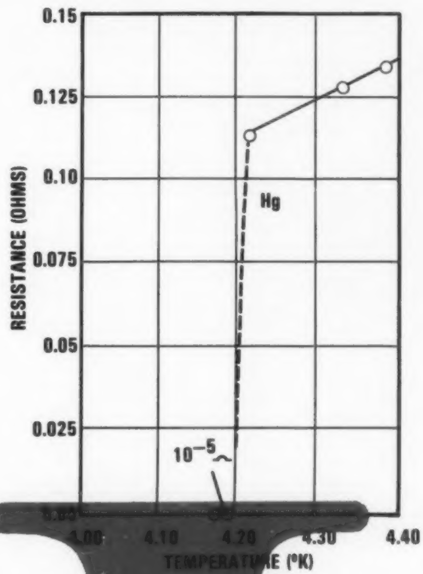
noise detectors of millimeter and infrared radiation and the most accurate electrical voltage standard now used as the U.S. national standard.

The physics which relates to all of these applications, both large and small, is quite simple. In 1911, the Dutch physicist Kamerlingh Onnes noted that as he cooled mercury to the temperature of liquid helium, (4 °K) the electrical resistance of the mercury dropped suddenly from a finite value to zero (Figure 1). He concluded that mercury had passed into a new state, which because of its extraordinary electrical property he called the superconducting state. It has since been discovered that at this low temperature, zero electrical resistance state is widespread among over 1,000 elements, alloys and compounds, including such common metals as lead and tin, as well as a few exotic organic compounds. The temperature at which a material transforms from its normal resistive state to a state of perfect electrical conductivity is called its transition temperature, T_c (transition temperatures have been measured from 0.015 °K to 23 °K).

Another startling property of superconductors is observed if a metal ring made of superconducting wire is put in a constant magnetic field and then cooled below its transition temperature. In the normal non-superconducting state, the magnetic flux lines penetrate through the ring (Figure 2 a). If the metal ring is now cooled to low temperature, a few degrees above absolute zero, the ring becomes superconducting and expels the magnetic field from the body of the ring (Figure 2 b). This is called the Meissner effect, after the physicist who first observed it. In this effect, a current is spontaneously set up in the ring which opposes the applied magnetic field and forces it out. Now if the magnetic field is turned off, a current is induced that circulates around the ring keeping the magnetic field constant inside. If the ring were made of normal metal, this current would quickly decay because of the electrical resistance in the wire. In the

Figure 1

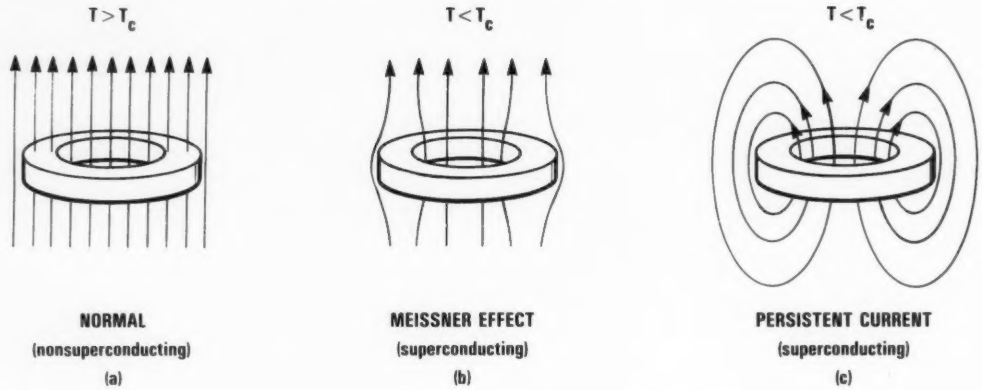
Resistance of mercury versus absolute temperature. This plot by Kamerlingh Onnes marked the discovery of superconductivity



Superconductivity

Figure 2

Meissner effect in superconducting ring cooled in a constant magnetic field



case of the superconducting wire, a persistent current is established and the current continues to circulate, as long as the metal ring is kept cold. (Figure 2 c).* The magnetic field inside the ring remains "trapped" as long as the current persists. This trapped magnetic field has some very unusual properties. First, one cannot change the level of magnetic field in the ring in a continuous manner. One can only trap discrete levels of the magnetic field. In other words, the trapped magnetic field inside the superconducting ring is quantized. It exists only in multiples of a very small fundamental magnetic quantity called a fluxoid. The properties of zero electrical resistance and trapped magnetic flux are used in large magnets and motors as well as in most small scale electronic applications.

Nature has created two kinds of superconductors, Types I and II. An external magnetic field applied to a Type I superconductor will quench its superconductivity returning it to the normal resistive state for relatively small values of the applied magnetic field—about 1000 gauss or less. (Permanent iron magnets can sustain magnetic fields up to 15,000 gauss, while the earth's magnetic field is about 0.5 gauss) (Figure 3 a and b). In the case of Type II superconductors, external magnetic fields are also excluded up to about 1000 gauss of less (Figure 3 c). Above that value, the magnetic field does penetrate into the superconductor in the form of single quantum flux bundles. The higher the magnetic field the more bundles of flux penetrate the material. Some Type II materials remain superconducting in this "mixed" state of superconducting and normal regions until about 600,000 gauss (Figure 3 d) when the material finally goes completely normal. The discovery of Type II superconductors, which occurred only some 20 years ago, has made possible large scale applications of superconductivity. Current densities of 100,000 amperes/cm^2 are easily attainable.

Large Scale Applications

When Type II superconducting wire became available, the development of superconducting rotating electric machines began in earnest. Superconducting wire offers significantly higher magnetic fields and much greater current densities than copper wire. Also, it has the intriguing promise of reducing resistive losses to zero. The early projections of high power density, very high efficiency and a factor of ten increase in power for a given size proved difficult to realize.

Superconductors are loss free only under steady direct current (DC) conditions. Changing the magnetic field or changing the current causes eddy current losses and hysteretic losses which result in heating. The alternating current (AC) characteristics of the superconducting wire are the dominating factor in the design of superconducting machines. Today all practical superconducting machines employ superconductors

* Superconducting rings of tin have been made to carry circulating DC currents greater than an ampere for periods of more than a year, disconnected from any battery, without any measureable decrease in curent. The D.C. electrical resistance of superconductors may for all practical purposes thus be assumed to be zero.

only in the DC excitation windings which are well protected from all AC transients. The windings which generate the machine output by magnetic induction are inherently AC and continue to use copper conductors.

Good motor design must also provide for thermal isolation of the superconducting windings. As with all large scale applications of superconductors, the design of rotating machines must consider the stability of the superconducting windings against quenching to the normal resistive state. Today these problems are avoided by using multifilament stabilized conductors (Figure 4).

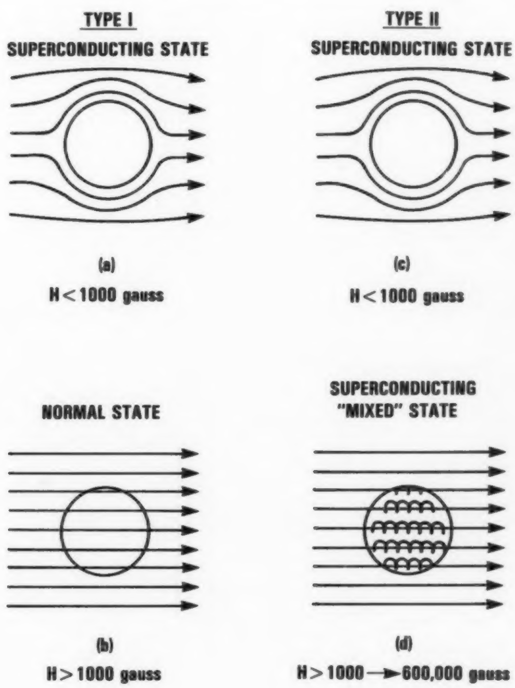
All superconducting machines operate with such high magnetic fields that additional components must be provided to confine the fields to the interior of the machine. This requirement has a major impact on the weight, size and efficiency. The most direct confinement technique provides a ferromagnetic return path for the machine flux. This iron is the component that dominates the size and weight of the machine. If the machine has a rotating field the external stray field is AC, so an eddy current shield can be used to confine the field. This shield is very much lighter than the iron, but it has a high loss. The resultant machine is reduced in efficiency (Figure 5).

Ship Propulsion

The use of electrical machines to connect the prime mover to the ship's propeller allows great flexibility in the location and arrangement of propulsion components. Electric drive with conventional machines also provides propeller speed control. The main impediment to electric drive has been the size, weight, and cost of conventional motors and generators. The use of light-weight gas turbine prime movers has opened the possibility of placing the gas turbine high in the ship for minimum gas ducting and easy replacement. An electric power transmission system is well suited for this application. Also, many radical ship configurations such as those with partially submerged hulls will require electric drives. Superconducting machines have the potential for significant reduction of the size and weight of the drive components, especially low speed motors for direct propeller drive.

Figure 3

Types I and II superconductors in a magnetic field below and above 1000 gauss



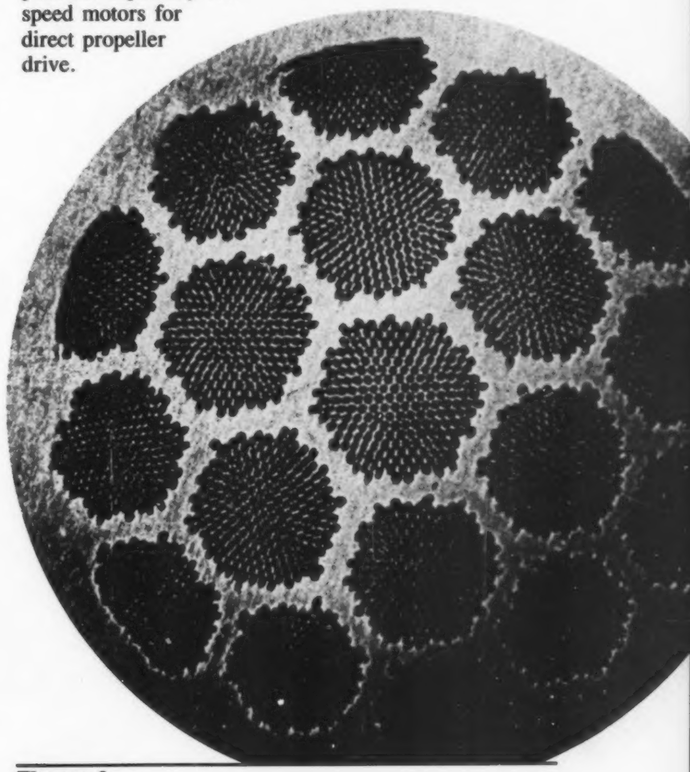


Figure 4

Multifilamentary stabilized superconducting wire

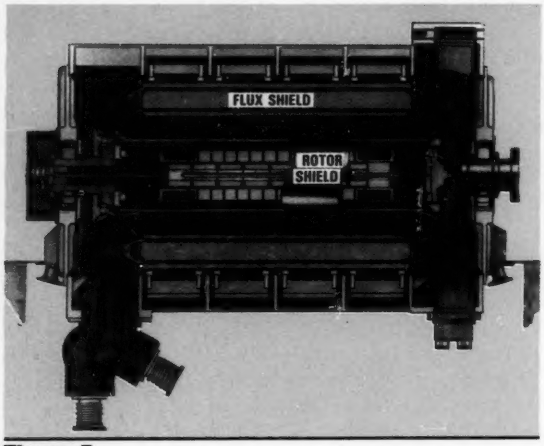
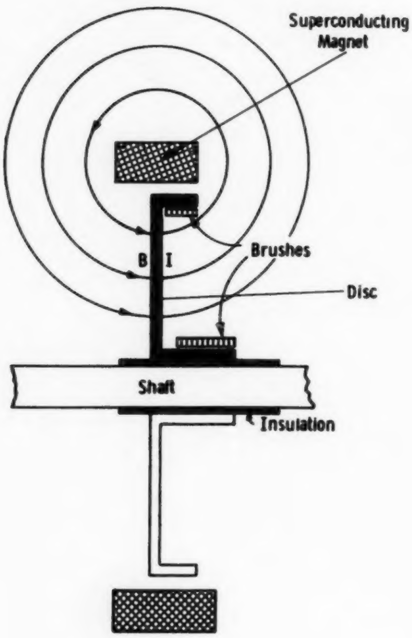


Figure 5

Schematic of a 300 MVA superconducting generator showing the rotor and flux shields

Figure 6

Basic homopolar machine (disc type)



The basic features of a disc-type superconducting homopolar machine are shown in Figure 6. It utilizes a single field winding enclosed within a cryostat to minimize the heat leak to the winding by conduction and radiation. The magnetic field produced by the superconducting winding is a maximum at the inside surface of the winding and, in the bore, falls to a minimum on the axis. The armature consists of a disc with slip-rings near the shaft and at the outside of the disc. Means for collecting the current at the slip rings are provided. It takes the current radially between the outer slip ring and the machine terminals. The useful magnetic field of the machine is that which cuts the disc between the slip rings.

In the drum homopolar configuration, the superconducting field is stationary and is placed inside the rotor drum (Figure 7). The solenoidal field winding and its vacuum enclosure are cantilevered inside the drum from the nondrive-end and through the hollow rotor shaft. Two sets of sliding contact current collectors are required on the surface of the drum. One set feeds the motor current to the drum and the second set takes the current out at the other end of the drum. The stator drum is surrounded by iron to confine the magnetic field within the machine and to serve as a return path for the flux. In this configuration, the magnetic field is a static DC solenoid. This requires a simple superconductor and cryogenic design. The major problem with this design is that current collectors have to carry current of the order of 10,000 amperes, since the machines have voltages of only several hundred volts. Full size drive motors will have to be on the order of 30,000 hp. Superconducting ship drive systems are under development at the David Taylor Naval Ship Research and Development Center, Annapolis. This group has concentrated on developing drum machines with liquid metal current collectors. A 300 hp demonstration system has been used extensively for development work at the Center (Figure 8). A 3000 hp prototype system is now undergoing tests on a small ship.

A similar program is in progress for the British Navy. The British machines are similar to the Annapolis machines except that solid sliding brush-type current collectors are used rather than liquid metal collectors. Extensive work has been done to improve solid brush performance.

Success of the superconducting ship drive programs is dependent on two factors. The first is the performance of current collectors and the second is cryogenic refrigeration. Additional effort is needed to provide reliable small capacity helium cryocoolers of extremely high reliability.

Flight Weight Machines

Advanced systems being developed by the U.S. Air Force will require flight weight superconducting machines with ratings up to 50 MW. These machines have very low

Figure 7

Basic homopolar machine (drum type)

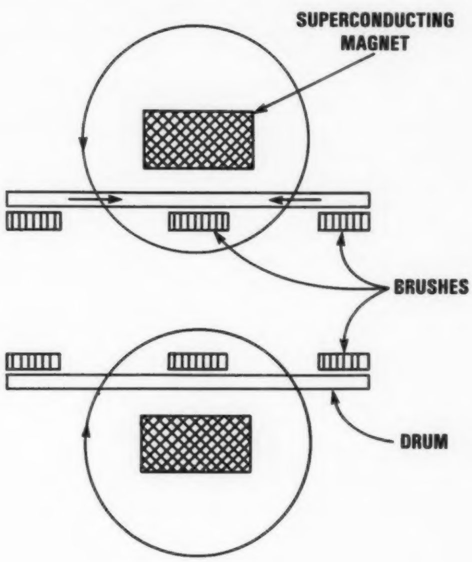
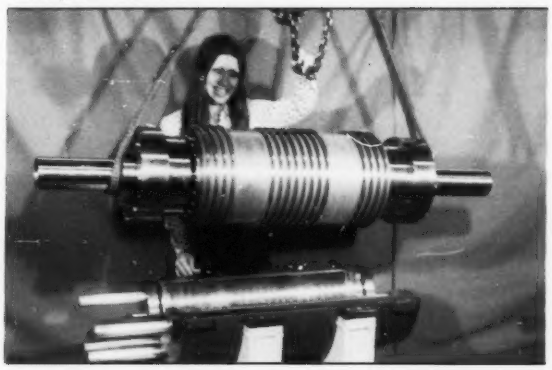


Figure 8

NSRDC/Annapolis 300 HP superconducting drum-type homopolar machine



duty cycles but must operate for extended periods in a stand-by condition and be ready for very rapid power up in the order of one second. One class of application requires voltages of the order of 70 kV. A prototype machine is under construction. It consists of a high frequency synchronous generator with a rotating superconducting field. The machine is presently nearing completion and is scheduled for testing.

Fast Discharge Homopolar Generator

Rail gun projectile accelerators require a fast discharge pulse generator. High current homopolar generators are ideally suited for this application. The discharge of the pulse is initiated by dropping the collector brushes onto the spinning rotor. Conventional homopolar machines have been used to date, but superconducting machines promise higher pulse power with faster rise times. A superconducting homopolar machine is under design for this application.

Utility Generators

One of the most promising applications of superconductors is in the field windings of the largest utility power station generators. Superconducting generators appear to be better than conventional machines in sizes above 500 megawatts (MW), with the advantages becoming larger, above 2000 MW, where conventional machines have reached an upper limit. Superconducting machines are expected to push the economy of scale in machine ratings to larger sizes than are practical for conventional machines. The machines are expected to have about one half the losses of conventional machines.

The level of activity in the development of utility superconducting generators has decreased drastically during the last year because of the significant decrease in new power station construction. The Massachusetts Institute of Technology and the Department of Energy developed an advanced concept superconducting generator which is the only currently active utility machine development in the U.S. A 10 MVA machine is currently nearing completion, and a full load test on a utility system is scheduled in 1985. A photograph of the partially complete rotor for this experimental machine is shown in Figure 9.

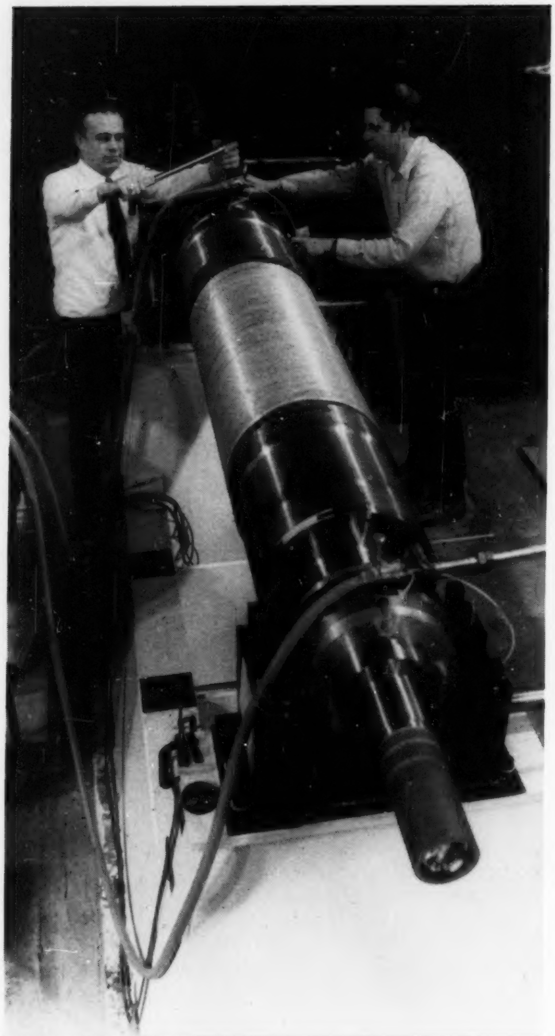
The most aggressive development programs are now in Japan. Three major projects are underway. A joint effort by Fuji and Mitsubishi has produced a 30 MVA machine. Hitachi has constructed a 50 MVA machine and Toshiba has recently started to develop a prototype.

Small Scale Applications

The unique properties of the superconducting state can be employed for a wide variety of electronic devices, circuits and systems with much improved performance capabilities for Naval surveillance, as well as communications and information processing applications. Since superconductivity is only observed at very low temperatures—

Figure 9

Rotor for 10 MVA superconducting generator under development at MIT. (One of the authors, JLS, is on the left)



the highest known transition temperature is only 23° K—the improved performance must be weighed against the requirement for a cryogenic environment. In the case of electromagnetic radiation detection, for example, the improvement over competing room temperature technologies is several orders of magnitude. Thus the cryogenic environment is readily accepted. On the other hand, in superconductive digital signal processing, the advantage over competing semiconductor technologies may not be as great. Thus a careful trade-off has to be made in each specific case before attempting to introduce superconductive electronic equipment in future Naval systems.

Employment of superconductivity in electronic circuits and systems, requires that several properties of the superconducting state be considered beyond those already described. These include (a) the high frequency electrical resistivity, (b) magnetic flux quantization, (c) tunneling, and (d) Josephson effects. These properties result in devices, circuits, and systems which possess very high sensitivity, low loss, low noise, wide bandwidth, extremely fast response, and very low power dissipation.

High Frequency Electrical Behavior

As mentioned earlier in this article, the resistance of a superconductor is zero—or at least vanishingly small—only at DC or very low frequencies, such as in most high field magnet applications. However, at high frequencies, a superconductor exhibits a non-zero but small resistance. With increasing frequency, the resistance increases but is still orders of magnitude less than that of a cooled normal conductor. Only at very high frequencies, 100 GHz to 1,000 GHz, does the surface resistance of a superconductor approach that of normal metals (Figure 10). Thus for frequencies below about 100 GHz, superconducting materials can be used to build very low loss passive circuit elements such as resonant circuits and filters, cavities, and transmission lines.

Resonant circuits and filters are used in electrical circuits as frequency selective components. The average value of the frequency that will pass through a resonant circuit can be adjusted to the desired value by suitably varying the electrical inductance and capacitance; the bandpass of the circuit, that is, the range of frequencies that will pass through the circuit with only minimal attenuation, will depend on the electrical losses within the circuit. Smaller electrical losses will result in narrow bandwidths and thus more frequency selective response for the resonant circuit. With careful design of a resonant circuit and using low resistivity materials such as copper to fabricate these structures, low loss, narrow bandwidth resonant circuits can be obtained. However, with the use of superconductive materials, even lower loss and hence even more frequency-selective resonant filters and circuits can be realized.

Superconductive cavities resonant at several hundred MHz to about 10 GHz have been built that can store very large amounts of electrical energy with very low loss. Such cavities have been used to build high energy particle accelerators. These accelerators produce very intense beams of atomic particles more economically than can be done using conventional technologies. For lower power applications, superconducting cavity stabilized microwave oscillators have been built that have exhibited frequency stabilities better than the hydrogen MASER. The latter is currently used as the stable frequency source in the NAVSTAR Global Positioning System. Superconducting cavity oscillators have stabilities of one part in 10^{15}.

Another application of superconducting cavities in Naval communication systems is as multicouplers for receivers operating in the High Frequency (HF) band (3-30 MHz). In many naval ships, several HF transmitters may feed a common antenna system. Resonant circuits, called multicouplers, are used to match the individual transmitters to the antenna and to provide isolation between the transmitters feeding the same antenna. In typical HF communication applications, transmitter power levels are about 1 kW. To obtain adequate isolation between transmitters, the response of a given multicoupler must be down by a factor of 30 dB (0. 1 percent in power) at the center frequency of any other multicoupler feeding the same antenna. Conventional multicouplers now used at frequencies near 10 MHz have electrical characteristics such that two adjacent transmitters must be separated by at least 750 kHz to insure adequate isolation. Since voice communications require signal bandwidths of about 4 kHz, the use of room temperature resonant circuits as multicouplers leads to inefficient utilization of the frequency region. Superconductive resonant circuits operating in the HF band capable of handling 1 kW of power have been built and evaluated at Naval Research Laboratory. These superconducting cavities have a bandpass of about 5 kHz which is broad enough to easily handle voice communication channels. The frequency-selectiveness of these cavities are narrow enough to provide the specified isolation for transmitters operating with a frequency spacing between adjacent channels of 75 kHz, leading to an improvement by a factor of ten in band utilization. The only known technology that can provide these Q-values and still handle 1 kW of power is superconductive electronics.

In addition to resonant cavities and resonant circuits, superconductivity can be exploited in transmission lines with very useful characteristics. For some electronic applications superconductive microstrip transmission lines have been built which exhibit very low attenuation and nearly zero frequency dispersion for signal frequencies exceeding 100 GHz. This is illustrated in Figure 11 where the calculated attenuation and dispersion are shown as a functions of frequency for microstrip transmission lines fabricated from superconductive lead and from room temperature copper. The attenuation for the superconductive line is orders of magnitude

Figure 10

Surface electrical resistance versus frequency for superconductors and normal conductors at room temperature, 4° and 8° Kelvin.

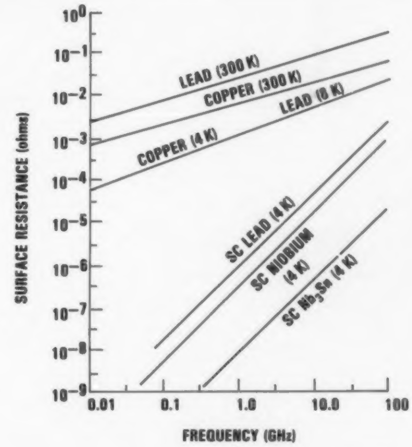
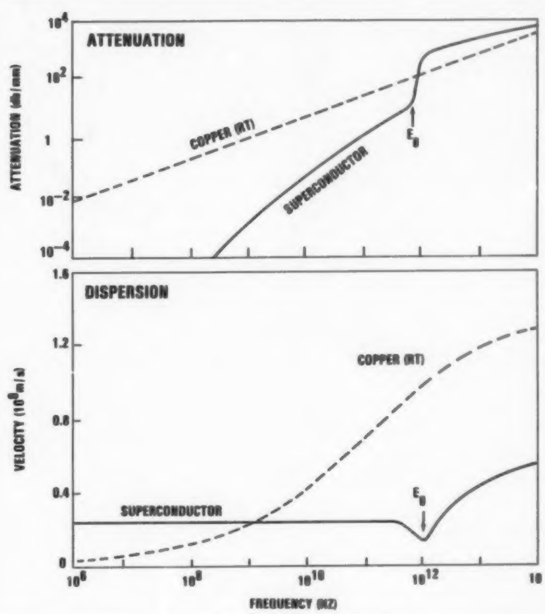


Figure 11

Calculated attenuation and dispersion versus frequency for microstrip lines fabricated from superconducting lead and room temperature copper



smaller than that for the copper lines. The frequency dependence (dispersion) of the phase velocities for signals propagating down the transmission lines is nearly zero for frequencies approaching 300 GHz. Another advantage of superconductive transmission lines is that they can be scaled down in dimensions to about 0.1 micrometer without degradation of their properties. This is to be compared to conventional (normal metal) transmission lines, whose resistance increases as the dimensions decrease and thus their properties dramatically degrade as dimensions are reduced below one micrometer. The increase in (normal metal) losses with miniaturization of interconnecting transmission lines is a very serious problem that will have to be addressed by the semiconductor integrated circuit (IC) community in the near future with the advent of very large scale integrated (VLSI) and more dense circuit technologies. Superconductive transmission lines will be discussed further in the section on superconductive digital circuits and systems.

Magnetic Flux Quantization

Magnetic flux quantization, which is a manifestation of the quantum mechanical nature of the superconducting state, has been mentioned above only in passing. The unit of quantization, which is known as the magnetic flux quantum, is a very small quantity. For example, a superconducting loop 1 cm in diameter in which a magnetic field intensity equal to about one millionth of the earth's magnetic field has been trapped will contain only a single flux quantum. Thus a very high discrimination magnetic sensor would have to be used to resolve the discrete nature of trapped flux in a 1 cm diameter loop within which a field equal to the earth's field has been trapped, for this would correspond to 10^6 flux quanta. However, the discreteness of this trapped flux has been established by a variety of very precise measurements. This concept plays an important role in many of the small scale applications of superconductivity that we will now describe.

Superconductive Tunneling

If two thin superconductors are separated by a very thin insulating barrier region, there will be a finite chance for a current to flow across this barrier if the barrier is sufficiently thin (Figure 12). This phenomenon is known as superconductive tunneling. According to the theory of superconductivity, the quantum mechanical wave function which describes the properties of the superconductor extends slightly beyond the surface of the superconductor into the barrier region. If the barrier is of the order of 1 to 2 nanometers (about four atomic layers thick), then there is a finite probability that electrons will flow across the barrier. The dissipation-less conduction in the superconducting state is associated with "paired electrons" or so-called Cooper pairs which move through the specimen without experiencing any loss mechanisms.

Figure 12

(a) Diagram of a tunnel junction; (b) I-V curve of tunnel device

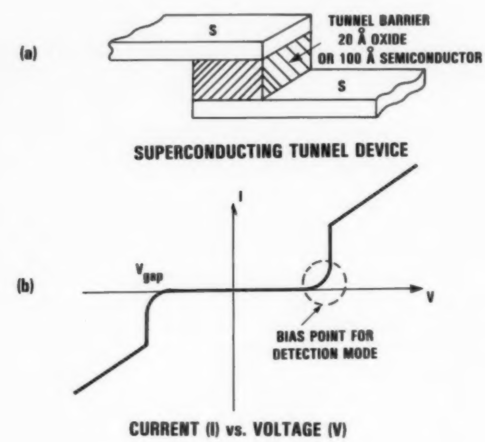
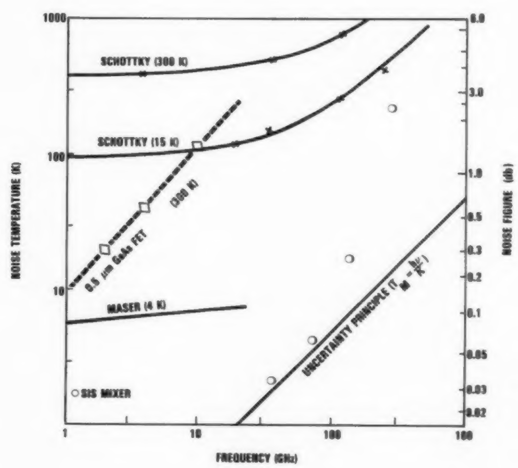


Figure 13

Performance of mixer technologies operating at room and cryogenic temperatures



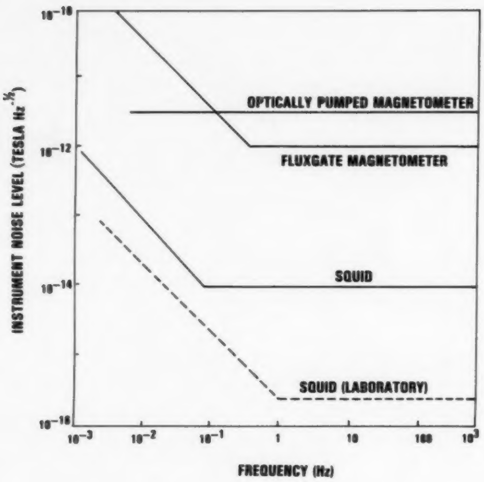
In addition to paired electrons (or superelectrons), conduction across the barrier region can also occur by unpaired electrons or "quasiparticles" (or normal electrons). Quasiparticle conduction is observed when finite voltages are applied across the barrier. As the voltage increases from some very small value, vanishingly small quasiparticle currents will be observed until the applied voltage exceeds some critical value which is characteristic of the superconducting material. This voltage, which is typically several millivolts, is known as the "energy gap voltage" for the device. Once the applied voltage exceeds the energy gap voltage by a small amount, there will be a very abrupt increase in quasiparticle current flow across the barrier. The current-vs.-voltage (I-V) characteristic for such a device is schematically shown in Figure 12 for the case of a tunnel barrier too thick to pass a significant Cooper pair current. The onset of quasiparticle current flow can be very sharp, and there will be a very large non-linearity in the I-V curve at the energy gap voltage. If the device is voltage biased to a voltage slightly below the energy gap voltage, this non-linearity can be used to detect electromagnetic radiation, especially radiation in the microwave and millimeter wave regions of the electromagnetic spectrum. If an electromagnetic signal is incident on such a device, the non-linearity will generate currents at harmonics of the signal frequency including a zero frequency beat or dc current. The magnitude of this current will be proportional to the amplitude of the incident electromagnetic signal. This mode of operation of a non-linear radiation detector is known as the "incoherent" or "direct" detection mode. In another mode of operation, known as the "mixer" mode, the signal power as well as local oscillator power are both incident on the non-linear element. The non-linearity causes currents to flow in the device at frequencies which are the sum and differences of multiples of the two incident frequencies. If there is a filter in the external circuit connected across the non-linear device tuned to the difference or "intermediate" frequency between the signal and the local oscillator, then the resulting configuration is the mixing element for a heterodyne receiver. The superconductor-insulator-superconductor (SIS) device operated in the so-called quasiparticle mode has been evaluated both in the incoherent and in the mixer modes of operation. In the frequency region from about 1 GHz through 100 GHz, the SIS element has exhibited quantum-noise-limited operation, that is, for each microwave quantum incident on the device, one electron appears in the external circuit. Theory states that this is the ultimate performance that can be realized by any passive non-linear electromagnetic radiation detector. No other technology has achieved the quantum limit of operation anywhere in the microwave or millimeter wave regions of the spectrum. Such low noise radiation detectors can play an important role in future Navy communication and surveillance systems. In Figure 13, the performance of various mixer technologies operating both at room temperature and at cryogenic temperatures is compared. The noise temperature for room temperature mixers is about two orders of magnitude higher than for SIS mixers throughout the microwave and millimeter wave regions of the spectrum. There are some conventional technologies which when cooled do give improved performance relative to their room temperature behavior. For frequencies below about 20 GHz, Gallium Arsenide Field Effect Transisters (GaAs FET) amplifiers have good characteristics and are probably adequate for many Navy applications. However, above 30 GHz, all room temperature technologies exhibit noise temperatures greater than 300° K, and thus systems operating at these frequencies and employing these mixers will be amplifier limited. If superconductive mixers and incoherent detectors are used in millimeter wave receivers, it is feasible to obtain systems that are environmental noise limited in almost all situations. Thus in those millimeter wave system applications where the ultimate in low noise receivers are required, superconductive SIS technology will be the technology of choice.

Josephson Effects

The tunneling phenomenon discussed immediately above was concerned with quasiparticle (normal) currents flowing across a superconductor-insulator-superconductor structure. Within the context of that picture, the current across the SIS device is very small for small applied voltages and vanishes when the applied voltage is decreased to zero. In 1962, Brian Josephson, then a young graduate student at Cambridge University in England, theoretically studied the quantum mechanical coupling between paired electrons in the case of two superconductors separated by a thin insulating barrier, in the limit of vanishingly small applied voltages. Josephson showed that for very thin insulators there was a finite probability for the Cooper pairs or superconductors, to tunnel across the barrier from one superconductor to the other. According to Josephson, the current of Cooper pair electrons tunneling across the barrier at zero voltage can be quite large. This result was very surprising as there is no corresponding effect in classical physics. Shortly after Josephson's article was published, the effect he predicted was observed experimentally by a number of researchers. Many hundreds of research papers dealing with this phenomenon were published during the following decades. One of the most intriguing aspects of the Josephson effects is that a very simple physical structure such as two thin superconductor films separated by a thin insulating barrier when cooled to very low temperature could exhibit properties that were uniquely associated with quantum mechanics. In addition to the great interest shown by physicists, technologists showed interest as it appeared that the properties of Josephson tunneling structures could be employed to make classes of very useful and novel devices.

Figure 14

Noise level versus frequency for superconducting and room temperature magnetic sensors



Magnetometers

One of the predictions made by Josephson was that the magnitude of the superconducting current that flowed at zero applied voltage, the so-called "Josephson current", was a very sensitive function of ambient magnetic field. If one or more Josephson tunnel devices or Josephson junctions are incorporated into a superconducting circuit, the total current flowing through this circuit will be a very sensitive measure of the ambient magnetic field. With such a circuit, which is known as a Superconducting QUantum Interference Device or SQUID, connected to an appropriate room temperature circuit, changes in the ambient magnetic field smaller than one billionth of the earth's magnetic field can be detected, that is, magnetic field changes as small as $1:10^9$ of the earth's field!. Thus SQUID magnetometers are about 3 orders of magnitude more sensitive than any other currently available magnetometer technology (Figure 14). Such ultra-sensitive magnetic sensors can be used in a number of Naval systems such as Magnetic Anomaly Detection (MAD) of submerged submarines. In another application of interest to the Navy, scientists at the Naval Research Laboratory demonstrated that a SQUID magnetometer system could detect very weak Extremely Low Frequency (ELF) signals at depths of more than 100 meters below the ocean's surface. Such a system could be employed as the receiving antenna in an ELF communication system in which the submarine could remain in contact with its home port while remaining submerged at operational depths. Several versions of an ELF communication system for submerged submarines have been evaluated.

Josephson Oscillators

A second prediction made by Josephson was that a voltage applied to a SIS device will cause an alternating current to flow in the device. By coupling the device to a suitable high frequency circuit, high frequency radiation can be coupled out of the device. The ratio between the frequency of the induced radiation and the applied voltage has the value of 484 MHz/microvolt. This ratio is a constant independent of voltage and frequency, and thus a voltage biased Josephson device has been used to demonstrate a precisely linear voltage controlled microwave oscillator covering the frequency range from 2 GHz through 20 GHz. The frequency range for such an oscillator depends only on the ability to set and maintain the required voltage and the electrical characteristics of the circuit in which the Josephson elements are imbedded. Oscillators of this type can be extremely useful in a wide variety of electronic countermeasure and spread spectrum systems.

Voltage Standard

The Josephson voltage-to-frequency relationship has been used to establish the voltage standard currently used in metrology. If a high frequency electromagnetic signal is incident on a Josephson device, zero resistance "steps" will be induced in the I-V curve of the device as illustrated in Figure 15. The upper trace (A) is the I-V curve of the device without incident microwave radiation while the lower trace (B) shows the effect of microwave radiation. The spacings between the vertical "steps" induced by the radiation are precisely equal and proportional to frequency of the incident radiation. This ratio of frequency to voltage spacings between the "steps" has been determined to be 483.5940 MHz/microvolt to a precision of a fractional part per million. A voltage standard based on this concept has been adapted by the United States and several other countries as their primary voltage standard for metrological applications.

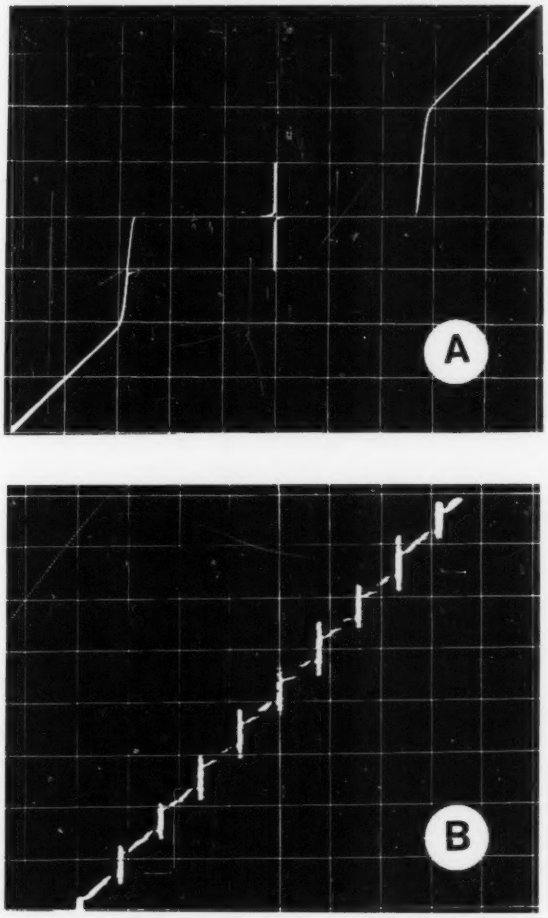
High Frequency Detection

The Josephson supercurrent flowing across a superconductor-insulator-superconductor is an extremely non-linear function of the alternating voltages applied to the device. If two high frequency voltages, a signal voltage and a local oscillator voltage, are applied to a Josephson device, the non-linearities in the characteristics of the device will generate a large number of signals within the device at the sums and differences of multiples of the two incident signals. Hence the Josephson device can be used as the "mixing" element in a heterodyne receiver. Microwave and millimeter wave radiation has been detected with Josephson mixing for signal frequencies from about 1 GHz to above 1,000 GHz.

Although the Josephson device is a very good detector of high frequency radiation, it is not good for low noise. Josephson mixers and detectors are about a factor of 10 poorer in noise performance then are superconductive quasiparticle SIS mixers described earlier. Thus when low noise superconductive receivers are used, the mixing element is most commonly operated in the SIS and not the Josephson mode.

Figure 15

The current-voltage curve for a Josephson device without incident microwave radiation (A) and with incident radiation (B)



Josephson Digital Applications

In the sections above which described quasiparticle tunneling and Josephson tunneling, it was shown that a superconductor-insulator-superconductor (SIS) device has two branches to its I-V charactersitics, the zero voltage Josephson branch and the finite voltage branch. If while the device is in the zero voltage state with a supercurrent flowing through it, the current is raised above some threshold value, the device will switch very rapidly from the zero voltage state into the finite voltage state (Figure 16). The intrinsic value for the time to switch the device is about 0.1 picosecond (10^{-13} seconds) while in a real circuit, the switching will be slowed to about 10 picoseconds due to the electrical time constants of the device and the circuit in which it is located. Hence Josephson devices can be employed as "switches" in digital applications by causing, in a controlled manner, the "switching" of the device from the superconducting (zero voltage) state to the normal (finite voltage) state. The SIS device is inherently a two-state device and can be used to represent "0's" and "1's" in conventional digital terminology. (The device can be reset from the finite voltage to the zero-voltage state by lowering the drive current to zero and then reapplying it.)

Not only is the Josephson device a very fast digital switch, it also dissipates very little power. As was mentioned earlier, the nominal value for the energy gap voltage is several millivolts while the currents are usually less than 1 milliampere. Thus when the device is in the finite voltage state, it will dissipate about 10^{-6} watts while it will have zero dissipation when it is in the superconducting Josephson state. Hence the power dissipated by an SIS digital device will be of the order of 1 microwatt and probably less if the device is in the zero voltage state during part of the machine cycle time. The product of power dissipated multiplied by the switching time is a figure of merit frequently used in comparing various digital technologies. Its value for a Josephson device is two to three orders of magnitude smaller than for any current or projected semiconductor technology (Figure 17).

Another essential component for a digital circuit is a memory cell for storing information in the form of 0's and 1's. A memory device can be configured using the principle of magnetic flux quantization by a superconducting loop containing Josephson devices. The Josephson devices function as "magnetic flux turnstiles" controlling the motion of magnetic flux quanta into and out of the superconducting loop. The information stored in the cell is either a "0" or a "1" depending on whether zero or one magnetic flux quantum is trapped in the cell. This type of memory is nonvolatile; when the power is turned off, the information will remain stored provided the memory chip is maintained at temperatures below the transition temperature of the superconducting material.

Another crucial element of a complex, high density digital technology is of the thin film wiring or interconnections, used to connect the various gates on a microelectronic

Figure 16

Switching of a Josephson device from zero-voltage state to finite voltage state

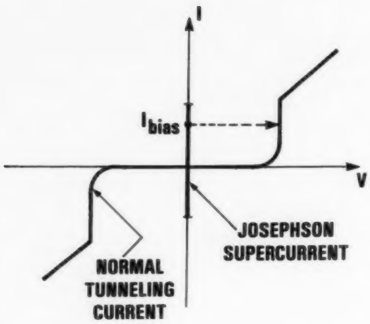
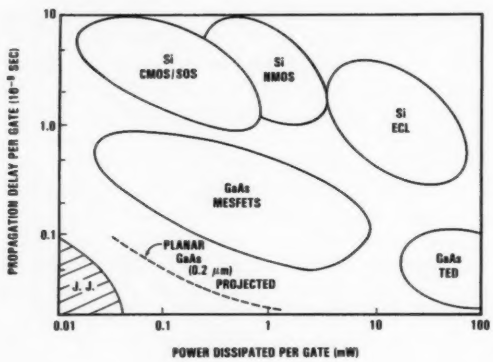


Figure 17

Power dissipation versus propagation delay for various digital technologies



chip*. As was pointed out earlier, superconductive transmission lines can be fabricated that have very low attenuation and nearly zero dispersion up to frequencies exceeding 100 GHz. That is, these transmission lines will permit pulses with time constants of 10 picoseconds to propagate with zero dispersion and very low loss. Since Josephson devices involve voltages of the order of several millivolts, it is also feasible to terminate these transmission lines which will minimize the problem of reflections associated with fast pulses propagating up and back along these lines. Superconductive transmission lines with characteristic impedances of the order of 10 ohms can be fabricated; and since the characteristic voltage swing of a Josephson's device is several millivolts, the power dissipated in these terminating resistors will be of the order of microwatts comparable to the power dissipated by Josephson digital devices. Thus, Josephson technology has the additional advantage of terminated transmission lines, something that cannot be realized for semiconductor technologies where voltage swings are of the order of volts.

The feasibility of building a high-performance, high-density computer using Josephson technology was undertaken by IBM in the US and, more recently, by a consortium of companies in Japan. It has been demonstrated that the necessary logic and memory functions can indeed be implemented in Josephson technology, and that several discrete chips can be integrated into a "package" suitable for extension to a computer with a large number of chips and boards. The IBM activity was terminated last year following a decision as to the commercial future of the Josephson computer. The speed advantage of a factor of 2 to 3 over conventional technologies was not judged to be sufficiently great to overcome the hurdles associated with the introduction into the commercial marketplace of a totally new computer technology, especially a cryogenic one. The decision by IBM appears not to have been a technological one but rather commercially motivated. The activity in Japan is continuing at a level of effort of about 100 man-years per year.

The system advantage of Josephson technology relative to conventional technologies is illustrated in the following comparison. The CRAY-I computer, which is state-of-the-art for high performance supercomputers, has about 200,000 gates, and has a machine cycle time of 12.5 nanoseconds. The central processing unit (CPU) of the CRAY-I has a volume of two meters in diameter and two meters high and consumes about 150 kW of electrical power. A Josephson computer with the same number of logic gates would dissipate only about 5 watts at 4 °K and would have a machine cycle time of about 2 nanoseconds, about five times faster than the CRAY-I. Five watts of refrigeration at 4 °K requires about 5-10 kW of electrical power at room temperature. Thus the Josephson computer would not only be a factor of five faster than the CRAY but the overall power requirements

* A gate is that portion of a computer circuit which permits or inhibits the passage of an electronic signal.

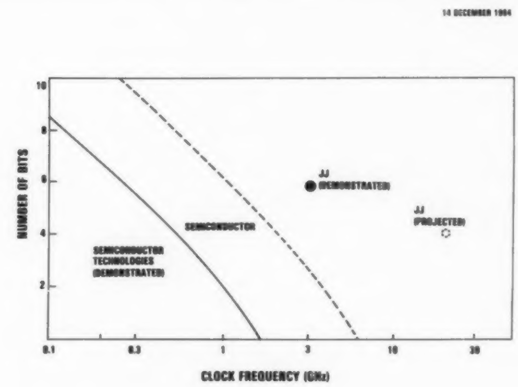
(power from the mains) would be at least a factor of ten smaller. The overall size of a Josephson computer with the same computational capabilities as the CRAY-I would be a cube about 10 cm on edge, exclusive of the cryogenic enclosure which might be only as large as a four drawer letter size file cabinet. In addition, this cryogenic refrigeration system might be capable of servicing a number of Josephson computers, and thus staging should be fairly easily accomplished. The final chapter to the story of high performance computers has not yet been written; but when it is, Josephson technology will certainly play an important part.

Analog-to-Digital Converters

In many systems of interest to the Navy, it is highly advantageous to transform incoming analogue signals, such as radar pulses, into digital format, "0's" and "1's", prior to detailed analysis by digital computers. The National Bureau of Standards, Boulder, Colorado, has pioneered in the use of Josephson devices as digitizing elements in analog-to-digital (A/D) converter circuits, and has demonstrated 6 bit resolution at sampling rates as high as 3 gigasamples/second. No other known technology has demonstrated A/D conversion at any level of resolution for sampling rates greater than 1 gigasample/second although there is some activity in GaAs technology to develop a converter that will operate at gigasample sampling rates. A comparison of various A/D conversion technologies is given in Figure 18.

Figure 18

Comparison of various A/D conversion technologies



The potential for Josephson digital technology is very great. At its present stage of development, Josephson technology has shown a definite advantage in terms of high speed and low power dissipation compared to existing semiconductor technologies. This level of performance has been demonstrated using rather large feature size - 2.5 to 5 micrometers - while much of the semiconductor results were obtained using 1 micrometer or smaller feature sizes. Superconductive Josephson digital technology continues to show great promise while still in a formative stage when compared to well established semiconductor technologies.

Refrigeration

Superconductivity is inherently a low temperature phenomenom. The highest transition temperature yet observed for any metal, alloy or compound is only 23° K. Therefore to use superconductive electronic systems, it is essential to provide a cryogenic environment to maintain the temperature of the superconductor below its transition temperature.

Open-Cycle Cooling

In this technique, the specimen is immersed in a liquid cryogen, either helium (boiling point, 4.2° K), hydrogen (boiling point, 20.4° K), or nitrogen (boiling point, 77° K). The liquid is usually stored in a dewar which is thermally insulated thermos-bottle-type container with a vacuum in the space between the walls. To extend the storage time for cryogens such as helium and hydrogen, a double dewar system is commonly used with the dewar containing the lower boiling point cryogen immersed in a dewar containing a higher boiling point cryogen. A variation of the open cycle dewar system which does not require a higher boiling point cryogen to reduce losses has been used extensively in recent years. In this configuration, the dewar is a double walled container with a fill tube connecting the cryogen reservoir to the room temperature outer wall of the container. A shield of highly (thermally) conducting material is placed in the vacuum space surrounding the cryogen reservoir and is thermally connected to a point along the fill tube where the temperature is midway between the boiling point of the cryogen and room temperature, but slightly closer to that of the cryogen. When thermal equilibrium is established, the radiation shield assumes a temperature intermediate between room temperature and the bath temperature and thus energy radiated into the cryogen reservoir is dependent on the temperature of the radiation shield and not on room temperature. With suitably designed radiation shields, a dewar of this type, which is commonly called a "superinsulated" dewar, can store cryogens such as helium or hydrogen very efficiently. A dewar of this type designed by J.E. Zimmerman of the National Bureau of Standards, Boulder, Colorado, is shown in Figure 19. The outer dimensions of the dewar are 30 cm long and about 8 cm in diameter.

Figure 19

Dr. James Zimmerman and the dewar he designed at National Bureau of Standards, Boulder, Colorado

It has a capacity of about one liter of helium. With a superconducting SQUID magnetometer immersed in the helium reservoir, one liter of helium will maintain the magnetometer at a temperature of 4.2° K for about 24 hours, a length of time suitable for a many field applications.

For longer periods of operation without the necessity for refilling, superinsulated dewar have been built with very large helium reservoirs. An early dewar with a large liquid helium reservoir is shown with a Figure 20. The outer dimensions are 2 meters in length and about 0.8 meters in diameter and the helium reservoir has a capacity of 180 liters. This dewar was capable of maintaining a superconductive sensor at 4.2° K for a period of over 100 days. Today's improved materials and design concepts have extended the performance of this type of dewar system.

Closed Cycle Refrigeration Systems

Cooling can be obtained by various machines in which a working fluid, usually helium gas, is compressed and then allowed to do work in moving a piston in a cylinder. By a proper sequence of such operations done repeatedly, one point in the machine is cooled below room temperature while heat is rejected to the environment at some other point in the machine. A single stage piston-in-cylinder machine can provide cooling down to about 40-60° K, a two stage machine down to about 10° K and a three-stage cooler can produce cooling at temperatures down to about 4° K.

The theoretical efficiency of a closed cycle refrigerator is given approximately by the ratio of the cold temperature divided by the temperature at which heat is rejected to the environment. For a cryocooler operating at 77° K and rejecting heat at room temperature, 300° K, the theoretical efficiency is 26 percent, that is, about 4 watts of work must be done at room temperature to produce 1 watt of cooling at 77° K. A practical cryocooler with a cooling capacity less than several watts achieves only about 5 to 10 percent of ideal behavior and hence requires about 40 to 80 watts of electrical (or thermal) energy at room temperature to provide 1 watt of cooling at 77° K. Correspondingly, a 4° K cryocooler has a theroretical efficiency of about 1.4 percent and a realized efficiency of 0.07 to 0.14 percent. That is to say, approximately 1,000 watts of energy must be expended at room temperature for each watt of cooling required at 4° K. This is the penalty one must pay to operate superconducting equipment near 4° K.

Two type of closed cycle refrigerators developed with Navy support for use with superconductive electronics are shown in Figures 21 and 22. Shown in Figure 21 is a three stage refrigerator built by the Army Night Vision Laboratory. It is based on a design concept employed in single stage refrigerators used to cool infra-red (IR) detectors to temperatures near 77° K. This cryocooler weighs about seven kilograms and requires 150 watts of electrical power at room temperature to produce about 0.1 watt of cooling in the vicinity of 10° K. This refrigerator is built with metallic parts

Figure 20

Ms. Freda Cox of Naval Research Laboratory shown with large helium reservoir

and thus is not suitable for use with ultra-sensitive superconducting magnetic sensors. A cryocooler which probably can be used with sensitive magnetometers (Figure 22) was built using non-metallic and non-magnetic materials such as nylon and fiberglass. The refrigerator, which is about 1 meter long and weighs about 20 pounds, requires about 50 watts of electrical energy, can provide about 0.01 watts of cooling at 10° K and has an ultimate operating temperature of about 7.5° K. It can be used to cool superconductive magnetic sensors made of niobium, which has a superconductive transition temperature of 9.2° K. Considering the materials used in its construction, this cryocooler should have a very small magnetic signature and thus should not degrade the performance capabilities of the cooled sensor.

Hybrid Refrigerators

There are a number of operating situations where one would like to use a liquid helium reservoir to cool the electronic equipment but would like to have a longer time between helium replenishing than can be realized with an open cycle dewar system. Besides extending the operating time, a hybrid system can insure that the electronic package will be maintained at operating temperature for a limited time even if there is an interruption in electrical power. One method for accomplishing this is to thermally anchor the radiation shields surrounding the liquid helium reservoir to the two cold stations of a two-stage cryocooler which are usually operated near 70° K and 20° K. The heat intercepted by the radiation shield thus loads down the two-stage cooler but does not contribute to the heat load on the helium bath.

Figure 21

Three stage refrigerator built by the Army Night Vision Laboratory

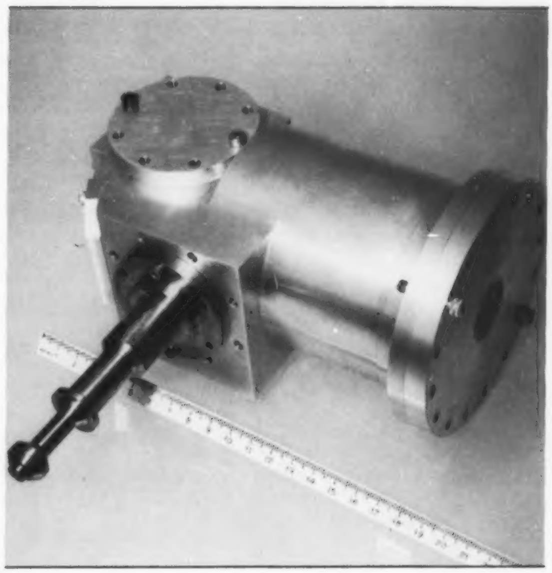


Figure 22

Diane F. Ulibarri of NBS/Boulder with the 8° K cryocooler built of non-metallic and non-magetic materials

This type of hybrid cryogenic system can reduce the boil-off rate of a 50 liter helium reservoir to about 0.25 liters/day compared to a loss rate of about 1 liter/day for a comparably sized superinsulated helium dewar. Because of the physical proximity of a mechanical refrigerator to the helium reservoir, this type of hybrid system probably will not be suitable for use with ultra-sensitive magnetic instrumentation. This type of hybrid system is frequently used with high field superconducting magnet systems.

There are other operational situations where it would be desirable to use a hybrid system to extend the time between replenishing helium, but where the magnetic signature or the vibrational spectrum of the mechanical refrigerator might degrade the performance of the electronic system to be cooled. For this case, one may anchor the electronic equipment to a thermal ballast such as a sealed off volume of helium or a mass with a very large heat capacity at temperatures near the desired operating temperature. A closed cycle cryocooler can be used to cool the thermal ballast and, hence, the electronic equipment down to the desired operating temperature. When the electronic equipment is to be operated, the mechanical closed-cycle refrigerator is switched off. The temperature of the equipment would be allowed to increase gradually at a rate which depends on the heat capacity of the combined ballast and equipment package and on the heat leaks into the system. When the temperature of the equipment reaches some maximum tolerable value, or when the electronic measurement is over, the mechancial closed cycle refrigerator is turned on again to lower the temperature of the equipment and the thermal ballast. This type of hybrid system is proposed for cooling those electronic packages which need be operated for a small portion of the duty cycle.

The technology of cryogenic refrigeration down to temperatures of 4° K and below is well established and is not an obstacle to the deployment of superconductive electronic in naval systems. However, for each specific application, some development activity will be required to interface the electronic package in an optimal manner to a suitable cryogenic system.

Navy Programs in Superconductivity

Research and development programs in superconductivity and cryogenics are performed at more than thirty government, industry, and university laboratories under Navy support. These programs are sponsored by the Office of Naval Research, the Naval Systems Commands, and individual Navy laboratories. In this section, we present brief summaries of individual projects in these programs.

The Navy is one of several government agencies which actively support R&D in superconductivity. Rough estimates of the total U.S. Government support for superconductivity for 1984 are shown in Table 1.

Table 1

U.S. Government Sponsored R&D in Superconductivity, Fiscal Year 1984.

1. Navy	$ 5,000,000
2. Air Force	$ 2,500,000
3. Dep't of Energy	$ 6,000,000
4. National Science Foundation	$ 1,800,000
Total	$15,300,000

The Navy divides its R&D programs into categories. We are concerned with those labelled 6.1 and 6.2. "6.1" includes "all effort of scientific study and experimentation directed toward increasing knowledge and understanding in those fields of the physical, engineering, environmental and life sciences related to long term national security needs." "6.2" includes "all effort directed toward the solution of specific military problems, short of major development projects."

Table 2 is a summary, by subject area, of the Navy's FY 84 superconductivity programs.

Table 2

Navy Funded R & D in Superconductivity FY 84

	Total (thousands of dollars)
SQUIDs/Magnetometry	1,190
Other Devices	1,060
Materials	1,090
Theory	220
Large-scale Application	200
Refrigeration	990
Miscellaneous (conferences, state of the art reviews)	250
Total	5,000

SQUIDS/Magnetometry

The SQUID magnetometry area includes all work related to the development and use of Superconducting Quantum Interference Devices (SQUIDs) for the measurement of extremely weak magnetic fields. The Navy's 6.2 SQUID efforts are centered around the development of field deployable SQUID gradiometers and magnetometers by the Naval Coastal Systems Center in Panama City, Florida. See Table 3.

Devices

Device R & D is concerned with the use of Josephson junctions for microwave, high speed signal processing, and computer switching applications. These devices are aimed at exploiting the high speed, low-noise, low-power properties of superconducting Josephson junctions. See Table 4.

Table 3

SQUIDs/Magnetometry

Organization/Contact	Description
Naval Air Development Center Warminster, PA 18974 A. O'Chadlick (215) 441-1993	SQUID magnetometer development.
Naval Coastal Systems Center Center Panama City, FL 32407 G. Kekelis (904) 234-4281.	Develop field deployable superconducting gradiometers.
Navy Ocean Research & Development Activity NSTL Station, MS 39529 K. Smits (601) 688-4607	Use superconducting gradiometer to measure geomagnetic noise at land sea interface.
Sperry Corp. P.O. Box 43525 St. Paul, MN 55165 D. Fleming (612) 465-3841	Study 1/f noise in thin film Jospehson devices and SQUIDs.
TRW Applied Technology Division One Space Park Redondo Beach, CA 90278 A. Silver (213) 535-2500	Integration of a planar thin film magnet sensor with a miniature cryocooler

Table 4

Other Devices

Organization/Contact	Description
Goddard Institute for Space Studies 2880 Broadway New York, NY 10020 A. Kerr (212) 678-5562	Evaluate SIS mixers at 115 GHz.
HYPRES, Inc. 175 Clearbrook Road Elmsford, NY 10523 S. Faris (914) 592-1193	Fabricate all-refractory millimeter wave SIS mixers and mixer arrays.
National Bureau of Standards Electromagnetic Technology Division 325 Broadway Boulder, CO 80303 C. Hamilton (303) 497-3740	Investigate track and hold circuits for improved Josephson junction analog to digital converters.
Naval Surface Weapons Center Silver Spring, MD 20910 D. Jablonski (202) 394-2674	Electronic simulation of SIS mixers; study chaos in Josephson devices.
TRW One Space Park Redondo Beach, CA 90278 A. Silver (213) 535-2500	Design, fabricate, and test low-noise microwave and millimeter wave SQUID parametric amplifiers.
University of California Department of Physics Berkeley, CA 94720 T. Van Duzer (415) 642-3306	Study the properties of Josephson junction high speed analog-to-digital converters.
University of California Department of Electrical Engineering Berkeley, CA 94720 P. Richards (415) 642-3027	Study millimeter wave Josephson effect detectors and mixers.
Cornell University School of Engineering and Applied Physics Ithaca, NY 14850 R. Buhrman (607) 256-3732	Study the properties of submicron tunnel junctions.
MIT Lincoln Laboratory Analog Device Technology Group Lexington, MA 02173 R. Ralston (617) 863-5500 ext. 7866	Study the RF properties of high transition temperature thin film superconductors.

Table 5

Materials

Organization/Contact	Description
National Bureau of Standards Electromagnetic Technology Division Boulder, CO 80303 F. Fickett (303) 497-3785	Study the effects of low-level magnetization on properties of materials used in cryoelectronics.
Naval Surface Weapons Center Silver Spring, MD 20910 A. Divecha (202) 394-1290	Use modified "Bronze process" to fabricate multi-filamentary superconducting wires for high current applications.
Stanford University Department of Applied Physics Edward L. Ginzton Laboratory Stanford, CA 94305 M. Beasley (415) 497-1196	Study tunneling and Josephson coupling through coupling deposited amorphous semiconductor barriers.
Stanford University Edward L. Ginzton Laboratory Stanford, CA 94305 C. Quate (415) 497-0213	Use scanning vacuum tunneling microscopy at cryogenic temperatures to study superconducting materials, metal surfaces, and dielectric films.
Westinghouse R&D Center 1310 Beulah Rd. Pittsburgh, PA 15135 A. Braginski (412) 256-3552	Study A15/rare-earth oxide and Mo-Re/Oxide interfaces; fabricate tunnel junctions with artificial rare-earth barriers and niobium counter electrodes.
Yale University Dep't of Engineering and Applied Science New Haven, CT 06520 D. Prober (203) 436-1470	Study superconducting properties of thin metallic, amorphous, and granular films.
Naval Research Laboratory Code 6634 Washington, D.C. 20375 S. Wolf (202) 767-2395 D. Gubser (202) 767-2600	Fabricate high T_c superconducting thin films, microstructures, and composites; develop materials for SQUID magnetometers and gradiometers.
Naval Research Laboratory Code 6854 Washington, D.C. 20375 M. Nisenoff (202) 767-3099 E. Cukauskas (202) 767-3247	Fabricate high transition temperature superconducting thin film devices and circuits.

Materials

Materials research involves the metallurgy and physics of superconductors and the development of practical techniques for fabricating superconducting materials and devices. The number of research efforts in this area reflects the importance of materials to almost all applications of superconductivity. To date, many of these applications have been hindered by materials related problems. The development of superconducting computers, micro- and millimeter wave components, gradiometers, and other devices has been seriously affected by problems related to the metallurgy of the oxide tunnel barriers in Josephson junctions. The Navy-supported superconducting materials research is addressing these problems. For the devices area, the goals are high transition temperature and all-refractory materials. A major area of interest is niobium-nitride. Its high transition temperature permits operation using miniature closed cycle refrigerators. See Table 5.

Refrigeration

Refrigeration is concerned with the development of small closed-cycle cryocoolers for superconductivity applications. The need to cool superconductors to their operating temperature of near 4° K is viewed as a hurdle to the practical application of superconductivity. The promising results obtained with high transition temperature materials such as niobium-nitride have led to the development of minature closed-cycle crycoolers designed specifically for use with superconducting devices. See Table 6.

Table 6

Refrigeration

Organization/Contact	Description
Jet Propulsion Lab California Institute of Technology 4800 Oak Grove Dr. Pasadena, CA 91130 E. Tward (213) 354-6581	Develop four stage closed cycle Joule-Thompson crycooler and integrate with a commercial SQUID
MMR Technologies 1400 Stierlin Rd. Suite A-5 Mountain View, CA 94043 W. Little (416) 962-9620	Develop compressors for very low power Joule-Thompson Crycoolers.
National Bureau of Standards Electromagnetic Technology Division Boulder, CO 80303 J. Zimmerman (303) 497-3901	Develop small Stirling cycle crycocoolers for use with Josephson devices.

Large-Scale Applications

Large-scale applications include superconducting motors, generators, magnets, magnetic actuators, and cavities. They are usually large in size and utilize the large current carrying capacity of bulk superconductors.

The largest of the projects described in Table VII involves the development of superconducting machinery for application to ship propulsion systems. The Naval Ship Research and Development Center's propulsion program is directed at replacing the conventional turbine-gear systems used on ships with electric drive systems. In this approach, an electric generator-motor combination replaces the mechanical gearing between the ship power plant and the propellor shafts. This approach offers major advantage in terms of reduced size and weight of the entire ship propulsion system, as well as considerable flexibility in the location of the main power plant for the ship.

The other projects described in Table 7 are "medium" scale applications. They involve the use of bulk superconductors carrying large amounts of electrical current, but the devices under development are considerably smaller in size than a typical superconducting motor or generator.

Table 7

Large-Scale Applications

Organization/Contact	Description
Naval Ship Research & Development Center Annapolis, MD 21402 M. Superczynski (303) 267-2149	Develop superconducting machinery for ship propulsion systems.
Naval Underwater Systems Center New London, CT 06320 B. Von Winkle (202) 440-4346	Study superconducting coils for acoustic transducers.
Stanford University High Energy Physics Laboratory Stanford, CA 94305 A. Schwetterman (415) 497-2650	Development of compact electron accelerator using superconducting cavities.

Theory

Theoretical research includes studies aimed at either developing or verifying models which describe the properties of superconducting materials and devices. The projects reported in Table 8 are all concerned with theoretical aspects of superconductivity. However, with the exception of the studies of superconducting thin films at the Unversity of California, all of the projects include complementary experimental work.

Table 8

Theory

Organization/Contact	Description
Harvard University Division of Engineering and Applied Physics Cambridge, MA 02138 M. Tinkham (617) 497-3391	Study fundamental processes in superconducting thin film microstructures.
National Bureau of Standards Electromagnetic Technology Division Boulder, CO 80303 R. Kautz (303) 497-3391	Theoretical and experimental characterization and measurement of chaotic noise in rf-driven Josephson junctions.
State University of New York Department of Physics Stony Brook, NY 11794 J. Lukens (516) 246-6119	Extend high precision test of Josephson equation; investigate planar S-N-S junctions; study three terminal S-N-S devices.
University of California Lawrence Berkeley Laboratory Berkeley, CA 94720 V. Kresin (415) 486-6991	Study thermodynamic and electromagnetic properties of thin films with strong electron phonon coupling.

Projects at Harvard, the National Bureau of Standards, and the State University of New York address various theoretical aspects of superconducting thin films and thin film devices. The results obtained from these studies are of considerable scientific interest, as well as useful to those researchers involved in the development of practical superconducting devices.

The second project in this section concerns the subject of chaotic behavior in Josephson systems. The study of chaos in nonlinear systems is a fast growing research area. Josephson junctions, because of their extremely nonlinear behavior, can be used to demonstrate chaotic behavior. Work at the National Bureau of Standards is directed at investigating this topic to assess its possible impact on the development of Josephson microwave devices.

Conclusion

In much of the foregoing, attention has been directed toward the exciting *promise* of the many and varied applications of superconductivity. It is important to emphasize, however, that *in numerous instances that promise has already been realized.* In these cases, superconductivity is the acknowledged, operative, in-place technology of choice. In some of the applications, advantages in technical performance tip the balance in favor of superconductivity. In others, economic factors are dominant. In still other instances, superconductivity provides unique capabilities for which there are no conventional counterparts. In this final section, some examples of these in-place superconductivity applications are briefly noted. It will be evident that members of the public at large are already encountering superconductivity both first hand and indirectly.

At a pace which can only be described as explosive, patients seeking medical diagnosis are entering the high-magnetic-field regions of superconducting magnets, only a scant few centimeters distant from ultracold superconducting cables. There, through the magic of magnetic resonance techniques, millimeter scale details of the interiors of their bodies are analyzed and precisely imaged. In other instances, medical examinations are conducted by means of SQUID magnetometers and gradiometers, which are used to detect the faint magnetic signals which emanate from the heart and from the brain. At a more distant level, citizens on the West Coast owe the high stability of the electric power which energizes their toasters and TV sets to a 30 megajoule superconducting magnetic energy storage device installed in the Pacific Northwest to damp previously troublesome 0.3 Hz oscillations. The quest for new natural resources has also been furthered by superconductivity, as geologists make routine use of SQUID magnetometers and gradiometers in their geomagnetic surveys. Ores discovered through their surveys can today be processed in superconducting magnetic separators.

In attempts to tame thermonuclear fusion for electric power generation, scientists and engineers at Lawrence Livermore Laboratory are utilizing an enormous (400 ton) superconducting magnet in plasma confinement experiments. In related fusion power experiments, plasma heating is achieved by means of the world's highest power millimeter wave generators, so-called gyrotron tubes, in which electrons are forced to execute orbits by magnetic fields supplied by superconducting magnets. (Such millimeter wave tubes may of course be adapted for military millimeter wave communication and surveillance systems).

In a purely scientific application in high energy particle physics research at the Fermi National Accelerator Laboratory, superconductivity is utilized on a grand scale. There, more than one thousand large particle beam bending and focussing superconducting magnets, with their associated refrigeration systems, stretch throughout the full four-mile circumference of the world's highest-energy particle accelerator, the 800 GeV Tevatron. This system marks a true milestone in superconductivity technology for it demonstrates in a most convincing way the large scale feasibility not only of superconductivity, but of the required refrigeration as well. To duplicate the Tevatron's performance using conventional magnetic technology would be prohibitively expensive both in capital costs and in operating costs.

The successes of superconductivity technology, only a few of which have been recounted above, should leave little doubt that we are entering an era in which this remarkable technology will have profound impact on broad sectors of the public interest. The challenge to the Navy is to identify and utilize those applications which offer higher-performance Navy systems at acceptable cost.

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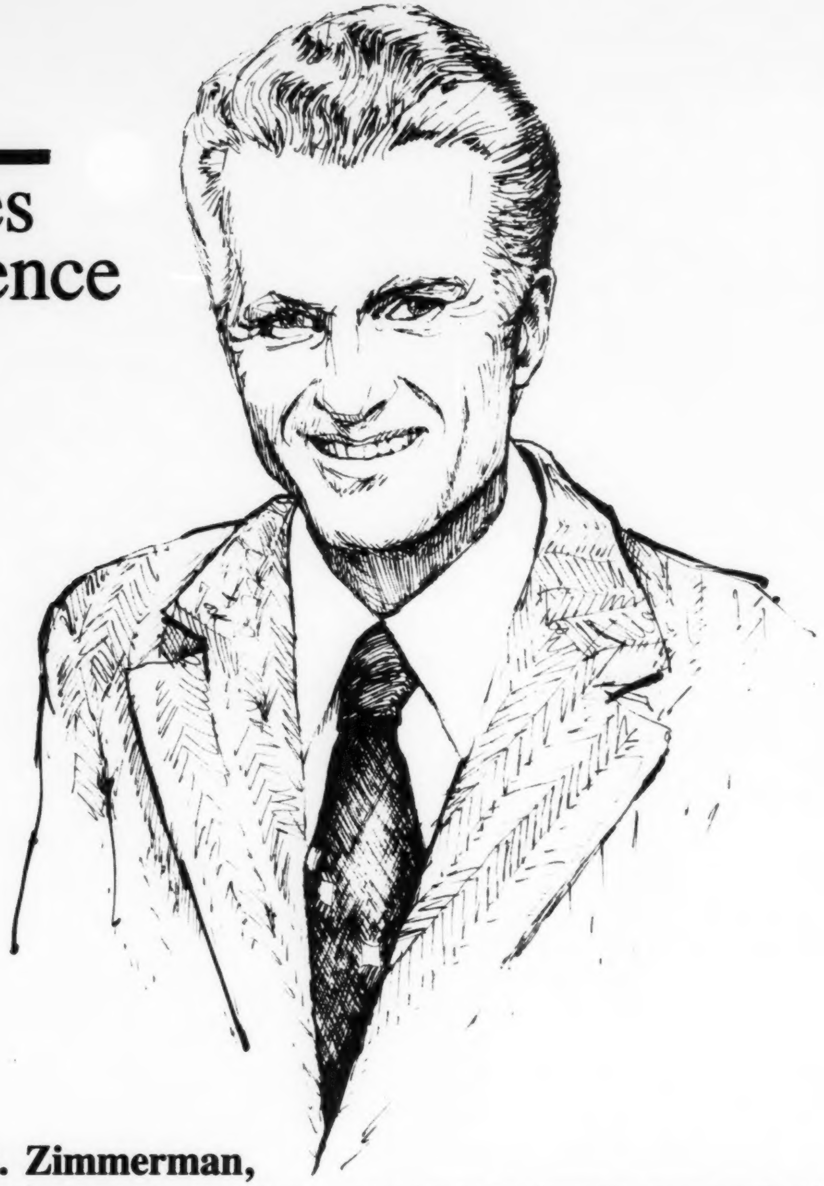
Profiles in Science



Dr. James E. Zimmerman,

is a physicist with the Boulder Laboratories of the National Bureau of Standards, Boulder, Colorado. He has been an ONR investigator for seventeen years. Shortly after the discovery of the Josephson effect, Dr. Zimmerman developed the use of small area contacts as Josephson junctions in superconducting quantum interference devices (SQUIDs). He has written about 100 papers and holds several patents on the design and operation of these devices. He pioneered in their applications to geomagnetism and to magnetic anomaly detection in measurements as diverse as the effect of the solar eclipse of 1973 on the equatorial electrojet, the interaction of the Alaska Pipeline with the aurora borealis, and geothermal prospecting. In collaboration with Mr. Edgar Edelsack of the Office of Naval Research and Dr. David Cohen of the Massachusetts Institute of Technology, he used a SQUID magnetometer for biomagnetic measurements of the heart in 1969, an event which triggered an explosion of research in biomagnetism. He has been associated for ten years with the Medical Center of the University of Colorado researching evoked magnetic responses of the human brain. In recent years, he has promoted the development of new concepts in cryogenics, particularly closed-cycle cryocoolers, for SQUIDs and other low-power superconducting devices. Dr. Zimmerman received a Department of Commerce Gold Medal with Dr. Robert Kamper of the National Bureau of Standards in 1975 and the Samuel W. Stratton Award, the Bureau's highest award for scientific achievement, in 1979. He was recently made a Fellow of the National Bureau of Standards.

Research Opportunities in Superconductivity*

M. Tinkham, Harvard University,
M.R. Beasley, Stanford University,
D.C. Larbalestier, University of Wisconsin,
A.F. Clark, National Bureau of Standards,
D.K. Finnemore, Iowa State University

The science of superconductivity is not one whose development is limited by the lack of ideas. It is limited by the need for consistent support and for major new facilities to prepare and characterize the materials and physical structures necessary to further basic research and advance the technology. Impressive foreign capabilities in both fundamental understanding and technological skills exist today. A commitment to long term, broad based, multi-agency support is required for the U.S. to maintain its status in this field and to nurture its technological promise, both immediate and long term. While the field of superconductivity may not be alone in such claims, this fact in no way makes the situation less urgent.

Superconductivity is a *ready technology*. The National Accelerator Laboratory has recently activated more than 1000 6-meter-long superconducting magnets in its Tevatron, which should allow the U.S. to leapfrog ahead in high energy physics while saving about $5 million per year in power costs. Whole-body NMR, made possible with superconducting magnets, has just barely tapped its potential in medical diagnostics and is anticipated to be a $2 billion industry in two years. Superconducting microcircuits form a class of the world's most sensitive electromagnetic instruments, approaching the quantum limits of measurement from dc to far-infrared frequencies. Superconducting circuits for high speed signal processing exceed the performance of competing technologies.

Superconductivity is a *future technology*. The essential role of superconducting magnets in magnetically confined plasmas for controlled thermonuclear fusion is well known. The widely accepted belief that future ultra-fast computers must ultimately operate at cryogenic temperatures, almost certainly involving superconductivity in some fashion, is in no way diminshed by the recent reduction in the industrial Josephson junction (JJ) computer effort in the U.S.

Superconductivity is producing a stream of *new ideas* which show significant promise for future advances. Phenomena in ternary compounds, artificially structured materials, inhomogeneous superconductors, organics and superconducting device structures of various sorts indicate a long range potential for new science, more usefulness and wider applicability as superconductivity extends its limits.

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*Excerpted from a report on the Workshop on Problems in Superconductivity sponsored by the National Science Foundation and the Office of Naval Research, Copper Mountain, Colorado, August 22-23, 1983

Superconductivity is a *unique tool* for the study of phenomena in many fields of science. Superconductivity provides unique capabilities to test fundamental internal mechanisms with simple external measurements for understanding basic physics problems and problems in materials science. Moreover, superconducting instruments provide uniquely sensitive means for making many physical measurements.

The electronic applications of superconductivity have many dimensions. It is especially important to clarify the opportunities and needs in this area. Roughly speaking, superconducting electronics can be divided into four categories: ultrasensitive instruments and electromagnetic detectors; fundamental standards; microwave and high-speed signal processing applications (both digital and analog); and large, high-performance computers. Superconductivity continues to be relevant for high-performance computers in the long run. A new type of device will probably be required, however.

Superconducting devices in the remaining categories, on the other hand, continue to exhibit significant advantage over their competitors. Particularly promising in the near future appear to be systems applications built around fast JJ analog-to-digital converters and high-speed analog signal processing devices (e.g., converters and correlators). At the same time, advances in superconducting instruments and detectors are impacting significantly in basic science, e.g., medical science (SQUIDS for magnetoencephalography) and radio astronomy (SIS mixers).

In support of the present technology and as a scientific base for new device structures and concepts, great opportunity appears to lie in better understanding tunneling barriers. These barriers are the single most critical part of the fabrication of any superconducting device involving tunneling. It must be accomplished with extremely close control and reproducibility. Presently our scientific understanding of the actual chemical and physical structure, and the physics of the tunneling process itself in real barriers is very primitive. By comparison to the effort spent studying the electrodes, barriers have received much less attention overall.

At the same time, whole new approaches to forming tunneling barriers based on artificial barriers (amorphous Si, oxidized Al, etc.) have emerged in recent years and proven very successful. Along with this have come new fabrication processes such as the selective niobium anodization process (SNAP) and selective niobium etching process (SNEP) approaches. These whole-wafer approaches, in which a junction is formed over the whole wafer and then subsequently patterned into the desired small structures, is fundamentally different from the standard Si0 mask/ lift-off patterning approach. In principle it appears superior. This approach needs further development to ascertain its true potential. Similarly, the rapid advances that have occurred recently in making all-refractory integrated circuits need to be further continued. All-refractory circuits will ultimately be desired and appear to be a real possibility if they are aggressively pursued. Here we are definitely behind the Japanese, at least in the sophistication of the circuits that have been built in an all-refractory fashion.

The situation with all-high-T_c circuits capable of operating with small closed-cycle cryogenic refrigerators is more complicated. Such circuits are of perhaps crucial importance for the smaller scale superconducting electronic applications where only a few devices or chips are involved and the technical and economic penalty of refrigeration is most significant. Very good tunnel junctions incorporating high-T_c base electrodes can be made, but high-T_c counterelectrodes have proven more difficult. The problem lies in forming a high-quality film at sufficiently low substrate temperatures so as not to damage the underlying barrier. The two most likely candidate materials are one of the A15 superconductors or NbN. Success will depend on a combination of lowering the deposition temperature required for counterelectrode formation and/or raising the temperature that barriers can withstand.

At the present time, NbN is the most advanced in that it can be deposited at relatively low temperatures with $T_c > 10K$. All-NbN tunnel junctions have been made in Japan and in the U.S. but their characteristics, and indeed the T_c of the counterelectrode, will have to be improved before high operating temperature superconducting electronics becomes a real possibility. High T_c SNS Josephson devices already exist but are likely to have more limited application than tunnel junctions. They are superior for some applications, however, and should continue to be developed. Finally, we note that the practical reality of superconducting electronics capable of operating with a small refrigerator is intimately tied to developments in minature cryogenic refrigerators. Developments in this field need to be watched carefully and attempts need to be made to package and interface the circuits on the refrigerators as appropriate.

Another area of great opportunity in superconducting electronics is new devices, particulary a three-terminal transistor-like device. The introduction of such a device would greatly open up the variety and nature of the applications which are possible. It is almost certainly a sine qua non for any new approach to a general purpose, high-performance superconducting computer. The QUITERON is one possibility, but it has definite limitations. Other approaches based on nonequilibrium superconductivity are imaginable and should be investigated. Radically new approaches should also be encouraged. What is desired is a tunneling triode or FET-like device with high speed, low power and high gain. Vortex file memory devices are also of interest. New circuit concepts and applications are always possible and could have great impact. Finally, the physical and technical limits to microminiaturization of all superconducting devices and circuits needs to be explored as one looks to future applications and needs.

Executive Summary
of the Naval Studies Board Task Group on Superconductive Electronics*

Recommendations

The two decades since the invention of the Josephson junction have seen extensive development of superconductive electronics throughout the world. The present annual, worldwide expenditure is $30 million to $40 million. The Office of Naval Research (ONR) has been one of five U.S. government agencies sponsoring significant fundamental research and development in the field. The ONR investment has yielded considerable progress in ultrasensitive magnetic sensors, millimeter-wave detectors, and extremely high-speed, analog-to-digital (A/D) converters.

The purposes of this Task Group on Superconductive Electronics are to (1) evaluate the future viability of superconductive electronics and compare its prospective utility in Navy systems with competing semiconducting technologies and (2) make recommendations concerning present and future Navy basic and applied programs in superconductive materials, devices, and systems.

The key characteristics that make superconductors of importance to Navy systems are (1) sensitivity of detection of magnetic and electromagnetic fields (even at millimeter wavelengths) limited only by quantum-mechanical effects, i.e., ultimate sensitivity; (2) nearly lossless transmission lines that can be incorporated into integrated circuits to achieve performance not possible with other electronic circuits; (3) lowest noise levels of any circuit, including both analog and digital types; (4) logic circuits that switch in less time by a factor of 2 than the best semiconductor devices while operating at two-three orders of magnitude lower power level; (5) persistent current in superconducting loops for memory applications.

The advantageous Navy systems applications include submarine detection and location, extremely-low-frequency (ELF) underwater communication, millimeter-wave and infrared imaging systems, millimeter-wave broadband communication and radar systems, and signal processors. The advantages accrue through increased sensitivity of passive detectors, greater resolution in imaging systems, receiver front ends with lower minimum detectable signal levels, and signal-processing circuits with greater bandwidths.

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* Excerpted from the 1984 report, "Superconductive Electronics," of a special task group of the Naval group of the Naval Studies Board of the National Research Council.

In most of these applications, the demonstrations of high performance of the various components (magnetometer sensors, millimeter-wave mixers, local oscillators, amplifiers, A/D converters) have been done at low levels of integration. An exception was the IBM project, where circuits with 1-kbit memory and 1000 logic gates were demonstrated. Also, system interconnections were shown to be satisfactory. (This aspect of the competing GaAs-based systems remains a problem area.) A number of institutions have developed or are developing the capability of making sufficiently large superconductive integrated circuits to permit combinations of smaller circuits in all the enumerated applications in order to achieve greatly enhanced performance. An example would be cryogenic electronic control circuits for magnetometers. Another would be the integration of a complete superconducting receiver—mixer, local oscillator, IF amplifier, and possibly an A/D converter—to achieve ultimate sensitivities.

Status of Superconductive Electronics

United States

The ten industrial laboratories engaged in research and development on superconductive electronics are AT&T Bell Laboratories, Controlled Data Corporation, Hughes, HYPRES, IBM, Quantum Design, S.H.E. Corporation, Sperry, TRW, and Westinghouse. The total number of full-time equivalent (FTE) professionals is about 60. The IBM effort is now directed toward devising a new cryogenic millivolt transistor, the Bell work is concerned with junction technology, the present task at HYPRES is a high-speed sampler, and the remaining groups are working on or toward signal-processing applications.

Six government laboratories are involved in superconductive studies. These are the National Bureau of Standards (NBS) at Boulder and Gaithersburg; Naval Research Laboratory (NRL); Naval Surface Weapons Center (NSWC), White Oak; Naval Coastal Systems Center (NCSC), Panama City, Florida and Laboratory for Physical Sciences, College Park, Maryland, with a total of about 20 FTE professionals.

In addition, there are several university groups working on or toward superconductive small-scale integration (SSI) or medium-scale integration (MSI) circuits: University of California, Berkeley, the Universities of Wisconsin and Utah, and MIT/Lincoln Laboratories. Materials and device studies and work on analog applications involving small circuits are in progress at the following universities: Stanford, California at Berkeley, Arizona, Minnesota, Louisiana, Vanderbilt, NYU, Columbia (Goddard), Yale, SUNY at Stony Brook and Buffalo, Case Western, Cornell, Virginia, Maryland, and Rochester, with an FTE of about 60 including graduate students.

The total effort in the United States is about 140 FTE professionals and graduate students.

Japan

Government agency supported work is a part of the so-called "supercomputer" project. The Electrotechnical Laboratory (ETL) has the monitoring function as well as conducting research of its own. The industrial groups are supported significantly by company funds as well as a government-funded organization called MITI. The MITI support for the eight-year project period, 1982-1990, is reported to be $100 million to $150 million. High Electron Mobility Transistor (HEMT) and Josephson technologies are to be compared until 1986, and a machine is to be demonstrated by 1990 with the chosen technology. The NTT project is aimed toward digital signal processing. The total industrial effort (including ETL) in Japan involves nearly 100 FTE professionals. They have devised several logic families, set new records for logic circuit speed, developed both Pb-alloy and Nb-based fabrication technologies, and demonstrated LSI logic and memory circuits. Their projects dwarf in accomplishments those of the industrial groups (outside of IBM) in the United States.

There are efforts in at least two other government laboratories directed toward millimeter-wave receivers.

About 12 university groups are supported by the Ministry of Education. Of these, about four are working on various types of digital circuits, with the rest on device physics, materials, superconductive quantum interference devices (SQUIDs), and millimeter-wave detection. Most of the student participation is through undergraduate thesis projects. It is reasonable to take the FTE for universities at about 60 including professors, research associates, and students.

The total effort in Japan on superconductive electronics is about 170 FTE professionals, about 20 percent larger than the U.S. effort.

Western Europe

The work in Western Europe is carried out by 3 small industrial groups, 7 national laboratories, and about 20 university groups. It is estimated that there are about 100 FTE professionals. Their work includes device physics, circuit modeling. SQUIDs, magnetometers, voltage standards, millimeter-wave detection and mixing, and digital circuits. The emphasis is strongly directed toward analog applications.

Eastern Bloc

It is known that there are groups in Moscow, Kharkov, Kiev, Jena, Warsaw, and Sophia, but the relation of work reported in publications to work in progress is uncertain so that no accurate estimates of activity can be made.

Summary

It is estimated that the total worldwide effort in superconductive electronics is about 450 full-time equivalent researchers with an annual expenditure of $30 million to $40 million.

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