NAVAL RESEARCH ADVISORY COMMITTEE

SUPERCONDUCTIVITY

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EXECUTIVE SUMMARY

The remarkable phenomenon of superconductivity has been the subject of intense scientific and technological interest since the initial discovery in mercury below its critical temperature (T_C) of 4.2K. The discovery (around 1960) of superconducting materials capable of supporting high electrical current densities in strong external magnetic fields, and the discovery of the Josephson tunneling effect, accelerated the rate at which potential applications were identified. Many of these applications have since been reduced to practice. The Navy has long recognized the significance of superconductivity and, for this reason, has supported a substantial effort in superconductivity research and development. Nonetheless, progress has been inhibited, in many cases, by the low critical temperatures and the attendant cost and complexity of liquid helium refrigeration.

The dramatic discovery of a class of ceramic oxides exhibiting critical temperatures above 100K has created an extraordinary increase in interest in both scientific and technological aspects of superconductivity. Among the important potential benefits of high-T_C Superconductors (SCs) are operating temperatures at or above the boiling point of liquid nitrogen (77K), and the potential for sustaining higher magnetic field strengths and higher frequencies. The existence of high-T_C superconductors has also renewed speculation on the possibility of achieving "room-temperature" superconductivity.

Based on a review of the Navy superconductivity program, including the current technical status, management, funding levels, and future plans, the panel reached eight broad conclusions.

- The Navy has correctly identified a number of opportunities for revolutionary system advances. Examples are superconductive electric-drive propulsion and its application to radical hull designs, and high sensitivity superconductive Magnetic Anomaly Detection (MAD) of mines, torpedos, and submarines.

- Many opportunities also exist for evolutionary system improvements based on superconductive technologies such as very high-speed integrated electronics, energy storage, launchers, high-Q cavities and electromagnetic shields.

- Most Navy superconductivity applications in systems compatible with liquid helium operating temperatures can be accomplished with relatively mature low-T_C technology.

- The introduction of high-T_C technology could, in principle, offer significant operational advantages, including improved performance in comparison with low-T_C materials, greater refrigeration efficiency, and the potential for achieving semiconductor/superconductor device integration at 77K.

- Although achievements to date are encouraging, high-T_C materials technology is still immature. Significant progress in high-T_C materials science and engineering will be required to realize the full potential of high-T_C superconductors. In particular, the electrical transport properties of bulk specimens (especially in external magnetic fields) fall far short of requirements. The mechanical properties (e.g., toughness and ductility) and chemical stability also require improvement. The best performance has been achieved in thin films, although for many applications surface resistance must be reduced further and acceptable low dielectric-constant substrates must be demonstrated.

- Given the current state of high-T_C materials technology, it is premature to invest significant development effort in enabling technologies (e.g., refrigeration systems and multifilamentary conductor cables) at this time.

- The Navy has played a significant role in superconductivity science and engineering for four decades. The present investment level is fully justified and addresses Navy needs with appropriate technical balance. However, while several focal points are evolving, the materials research and development activities have become fragmented and central authority is still lacking.

- Continued Navy investments in high-T_C technology can have a significant impact on the field. It is reasonable to anticipate that Navy Research and Development (R&D) can produce useful thin-film electronic devices for specialized applications involving sensors, shields, and high-Q cavities. However, even after the requisite materials performance levels have been achieved, many applications, especially those requiring high current density conductor cables, will require sustained investments on a national scale which are beyond Navy means. In those instances, Navy R&D will still play an important role by contributing to the national effort, thereby accelerating the introduction into Navy systems.

The conclusions summarized above have led the panel to make the following recommendations.

(1) Within available resources, the Navy should concentrate the near-term tech-base effort in five areas.

  - Continue support of low-T_C superconductivity research.

  - Resolve materials science and engineering issues (e.g., critical current density (J_C) and surface resistance (R_S)) limiting performance of known high-T_C materials.

  - Initiate advanced technology demonstrations for useful small-scale applications of high-T_C superconductivity.

  - Stimulate invention of new device concepts, not only by extension of low-T_C concepts but also by exploitation of novel high-T_C material properties such as their extreme anisotropy.

  - Encourage research for new classes of superconductive materials with improved characteristics.

(2) While the Navy has been well served by the enthusiasm of its superconductivity community, it is important that a more structured approach guide the evolution of the tech-base effort. Specifically, it is recommend that the Navy:

  - Establish a coordination authority.

  - Establish lead laboratories for promising areas.

  - Discourage unproductive duplicative efforts among Navy laboratories and centers.

- Review the performer balance among universities, laboratories, centers, and industry to ensure optimal access to a broad community of ideas.

- Generate and execute an integrated R&D plan.

(3) While it is not too early to plan for the future, it is essential that near-term efforts not be compromised by premature commitments to large-scale applications. It is recommended that the Navy:

- Continue system-level studies of superconductivity applications aimed at identifying operational advantages and disadvantages, as well as necessary enabling technologies.

- Define a long-range research strategy which incorporates an appropriate balance between sequential and parallel effort, and which relies on cooperation with other government and commercial efforts in areas requiring major investments.

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TERMS OF REFERENCE
SUPERCONDUCTIVITY PANEL

- **EXAMINE USE OF HIGH- AND LOW-TEMPERATURE SUPERCONDUCTIVE MATERIALS IN NAVY APPLICATIONS**

    - **BENEFITS**
    - **BARRIERS**
    - **STRATEGIES**

- **IDENTIFY CRITICAL NEEDS/GAPS IN TECHNOLOGY BASE**

- **ASSESS POTENTIAL CONTRIBUTIONS OF OTHER DOD AND COMMERCIAL PROGRAMS**

- **ASSESS STATUS OF ENABLING TECHNOLOGIES**

- **EVALUATE NAVY R&D EFFORTS AND STRATEGY**

I. INTRODUCTION

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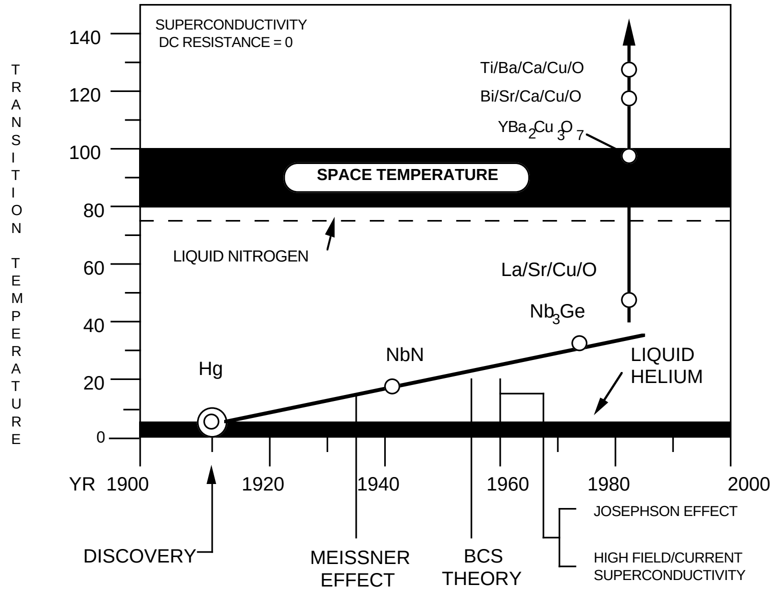
SCIENTIFIC AND TECHNOLOGICAL REVOLUTION



This chart traces progress toward achievement of higher transition temperatures (T_C) beginning with the 1911 discovery of superconductivity in mercury (Hg) at 4.2K. The remarkable properties of superconductors (e.g., zero dc electrical resistance, perfect diamagnetism) are manifestations of quantum phenomena on a macroscopic scale. (See Appendix A for a review of the principal features of superconductivity.) Numerous potential applications have been identified, and many have been reduced to practice. In many cases, however, implementation has been impeded by the high cost and complexity of refrigeration systems needed to maintain operating temperatures below T_C.

The potential impact of high-temperature superconductors has been understood for a long time. Before 1986, progress in that direction was steady but very slow. Scientists had developed binary alloys and metallic compounds with T_Cs as high as 23K (Nb_3Ge). During 1986, however, two Swiss scientists (Bednorz and Müller) discovered a class of superconductive oxides, derived from the insulating ternary compound La_2CuO_4 by fractional substitution of alkaline earths (e.g., Sr) for lanthanum, with T_Cs approaching 40K. Subsequent discoveries in related oxides rapidly pushed T_Cs above 100K. The highest temperature documented to date is near 125K, providing some hope that practical superconductors may eventually be found that will permit operation near room temperature. In the meantime, the existing high-temperature superconductive oxides should have many important uses because of the favorable economics of liquid nitrogen refrigeration for terrestrial applications and passive cooling for space applications.

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HISTORY OF OXIDE SUPERCONDUCTORS

COMPOUND	T_C	LAB DISCOVERED	DATE
TiO, NbO	~1 K	Westinghouse	1964
$SrTiO_{3-x}$	.7 K	NBS	1964
Bronzes			
A_xWO_3	6 K	U.C., San Diego	1965
$A_x MoO_3$	4 K	DuPont	1966
$A_x ReO_3$	4 K	DuPont	1969
Ag_7O_8X	1K	Bell Labs	1966
$LiTi_2O_4$	13 K	U.C., San Diego	1974
$Ba(Pb,Bi)O_3$	13 K	DuPont	1975
$(La,Sr)_2CuO_4$	35 K	IBM-Zurich	1986
$YBa_2Cu_3O_7$	95 K	U Alabama/U Houston	1987
$Bi_2Sr_2Cu_2O_{7+x}$	22 K	U Caen (France)	1987
Bi/Sr/Ca/Cu/O	110 K	Japan	1988
TlBa/Ca/Cu/O	125K	U of Arkansas	1988
(BaK)BiO	30 K	Bell Labs	1988

Superconductivity in metallic oxides was first discovered in a few materials around 1964. Many other superconductive oxides were found during the subsequent decade, but their T_Cs were too low to provide technological competition for non-oxide superconductors such as Nb-Ti alloys and the intermetallic compound Nb_3Sn. The dramatic developments of the recent past began with the observation of a 35K transition temperature in a $(La,Sr)_2CuO_4$ composition. This was followed rapidly by the discovery of $YBa_2Cu_3O_7$ with $T_C \approx 94K$, and a T1/Ca/Ba/Cu/0 composition with $T_C \approx 125K$. No agreement exists currently on the most likely coupling mechanism responsible for the superconductivity in these materials. In the absence of a detailed theoretical understanding, it is not possible to predict the upper limit of T_C. A feature shared by these oxides is a layered structure of copper and oxygen planes, leading to strong anisotropy in electrical and mechanical properties. The observation of the moderately high T_C of ~ 30K in the cubic oxide (Ba, K) BiO_3 leads to the speculation that other, less anisotropic classes of high-T_C oxide superconductors may be discovered.

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POTENTIAL SURFACE SHIP APPLICATIONS

HIGH POWER RADAR

AIRCRAFT CATAPULT

HVAC & REFRIGERATION

ELECTRIC WEAPONS

ENERGY STORAGE

MAGNETIC MINE SWEEP

ELECTRIC PROPULSION MACHINERY

POWER CABLES

SHIP SERVICE GENERATORS

HIGH POWER SONAR POWER SOURCES

HIGH SPEED COMPUTER

This illustration depicts schematically the wide range of potentially important applications of superconductive components in surface ships. These applications generally fall into two classes. High-power applications involve low-loss electrical power conversion and transmission, or magnetic field generation based on the ability of certain superconductors to sustain high current densities in moderate to very intense magnetic fields. Electronic applications typically involve magnetic sensors or ultra high-speed electronics based on non-linear superconductive devices (e.g., quantum interference).

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POTENTIAL SUBMARINE APPLICATIONS

MHD
PROPULSION

ENERGY
STORAGE

ADVANCED
SONAR

PROPULSION
MOTOR

PROPULSION
GENERATOR

POWER GENERATION
&
TRANSMISSION

ELECTROMAGNETIC
LAUNCHERS

This illustration depicts schematically a number of potentially important applications of superconductive components in submarines.

II. NAVY APPLICATIONS AND MATERIALS REQUIREMENTS

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HIGH-POWER APPLICATIONS

- **Electric power generation/transmission**
- **Energy storage**
- **Acoustic projectors**
- **Weapon launchers**
- **Catapult**
- **Ship propulsion**
    - **Electric motor drive**
    - **MHD pump jet**

REQUIREMENTS

- **Stabilized multifilamentary conductor cable**
- $J_c = 10^5 - 10^6$ **A/cm**^{2}
- $H_{c2} = 10 - 20T$ **(except 0.1T-1T for power transmission)**

High-power applications of superconductivity exploit the high electrical power densities and efficiencies achievable with zero-resistance conductors. These applications generally involve either the transport of electrical energy or the generation of intense magnetic fields. The energy associated with the magnetic field is used directly in high-density electrical-energy storage applications. Most high-field applications of interest to the Navy, however, such as acoustic projectors, launchers, and motors, involve transformation of the magnetic energy into kinetic energy.

The generation of intense magnetic fields requires bulk conductors with critical current densities (J_C) in the range $10^5 - 10^6$ A/cm^2. For maximum utility, these current densities must be supported in external fields approaching 20T (Tesla). Stability in the presence of thermal and electromagnetic disturbances requires multifilamentary conductor cables incorporating a large volume fraction of high-conductivity normal metal. In addition, the cables must be sufficiently flexible for winding purposes, and possess adequate strength to withstand the large magnetic pressures acting on the windings of a high-field magnet.

Many high-power applications have already been demonstrated with low-temperature conductors. Most notable of these are Nb-Ti and Nb_3Sn high-field magnets operating at liquid helium temperatures. Shipboard implementations, however, have been inhibited by the operational complexities and costs of liquid helium refrigeration. In principle, these impediments could be eliminated by use of high-temperature superconductive technology, although significant technical obstacles still need to be overcome.

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ELECTRONIC/SENSOR APPLICATIONS

PASSIVE

- **Interconnects**
- **Delay Lines**
- **Transformers**
- **Filters**
- **Cavities**
- **EM shields**
- **Antennas**

ACTIVE

- **Josephson Devices**
  - **High-speed logic**
  - **A/D converters**
  - **Mixers**
  - **IR detectors**
  - **SQUID MAD detectors**

REQUIREMENTS

- **Thick and thin films**
- **Low ac surface resistance**
- **Reproducible device characteristics**
- **J_cs ranging from 10^4 (antennas) to 10^6 A/cm^2 (interconnects)**
- **Compatibility with substrates and other materials**

Electronics and sensor applications of superconductivity can be divided into two categories. (1) Passive components exploit the low surface resistance of superconductors, which can extend to very high frequencies at temperatures sufficiently lower than the critical temperature (T_C). (2) Active components exploit the non-linear characteristics of superconductive quantum devices based on Josephson tunneling junctions. (See Appendix A).

Requirements for these applications generally involve superconductive films deposited on low dielectric-constant substrates. The surface of these films must be free of non-superconductive (i.e., normal metal) surface layers. The lower critical field (H_{c1}) must lie above the peak magnetic field strength associated with the intended application. Critical current densities (J_C) may typically fall in the range 10^2-10^5A/cm^2, but may range as high as 10^6A/cm^2 in certain cases.

A number of electronics and sensor applications based on low-temperature technology have been reduced to practice. Examples include Superconductive Quantum Interference Device (SQUID) magnetometers, voltage standards, rf cavities and electromagnetic shields. Extensive development experience has also been gained with high-speed logic devices.

Components using high-T_C superconductive materials potentially offer two significant advantages. First, the higher operating temperatures not only pose far simpler refrigeration requirements, but also provide the potential of integrating superconductor and semiconductor devices on a single chip. Secondly, the higher T_Cs imply larger energy gaps in the superconductive state and hence the potential for significantly higher operating frequencies.

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SQUID MAGNETIC ANOMALY DETECTION

- **Technical approach**
  - **Use five-axis superconducting SQUID gradiometer**
  - **Solve field equations to yield range, bearing and magnetic moment of target**
- **Performance of current sensors limited to 3 x 10^{-4} ℂ/ft (-70db) by approximately 15 separate contributions to noise budget**

APPLICATIONS	**DESIRABLE PERFORMANCE (γ/FT)**	
Torpedo guidance	**3x (10^{-3}-10^{-4})**	**(-50 to -70db)**
Mine hunting	**3x (10^{-4}-10^{-5})**	**(-70 to -90db)**
ASW final localization	**3x (10^{-4}-10^{-5})**	**(-70 to -90db)**
ASW shallow water sensor	**(10^{-5}-10^{-6})**	**(-100 to 120db)**
ASW open ocean search	**(10^{-6}-10^{-8})**	**(-120 to -160db)**

$\gamma = 10^{-5}$ G - 10^{-9} T

A superconductivity application of special importance to the Navy is SQUID Magnetic Anomaly Detection (MAD). Specific applications of interest include torpedo guidance, mine hunting, and submarine detection. The technical approach of choice is a multi-axis gradiometer which, in comparison with a more conventional magnetometer, gains improved background noise rejection at the expense of decreased range (r^{-4} versus r^{-3}) for a dipole field. Thus, a factor of 2 range extension requires a factor of 16 sensitivity increase.

Maximum sensitivities achieved to date in mobile gradiometers using low-T_C SQUIDs appear adequate for torpedo guidance but marginal for mine hunting as well as final ASW localization. More general ASW applications will require significant improvements in sensitivity which is currently limited by a large number of separate contributions to the noise budget.

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SQUID MAGNETIC ANOMALY DETECTION

- **NCSC development of improved device with 3 x 10^{-5} γ/ft sensitivity appears to be:**
  - **Justified by intended applications**
  - **Technically feasible**
  - **Supported by a competent team**
  - **Well structured to accomplish the systematic elimination of noise sources**
- **Application of advanced technology (thin films, etc.) will require funding for industrial participation**
- **Achievement of device with sensitivity of 10^{-6} - 10^{-7} γ/ft is a long term goal which, if achievable, would provide a useful open ocean ASW search capability**
  - **Sensitivity of 10^{-7} γ/ft might provide detection range of 2 miles, and area sweep rate of about 1000 square miles per hour**

Near-term development plans at the Naval Coastal Systems Center (NCSC) call for a next-generation low-T_C gradiometer featuring a 10-fold sensitivity increase. On the basis of current fundamental understanding, this goal represents a sensible evolutionary step in the technology. It appears that a sensitivity of 3 x 10^{-5} ©/ft is technically feasible and fully supported by a very competent, experienced staff and well-structured program plan. Achievement of this goal would broaden the range of accessible applications. In particular, the utility of SQUID gradiometers in ASW would be enhanced significantly.

In order to provide reasonable assurance of success it is essential that industrial participation in the NCSC program be increased. The proposed gradiometer is critically dependent on a number of advanced manufacturing technologies whose realization is paced by industrial developments.

Although it is not possible at this time to establish performance limits which might ultimately be achievable, it is conceivable that sensitivities might reach the 10^{-7} ©/ft levels. At this level, open-ocean ASW search rates of 1000 square miles per hour (depending on submarine depth and magnetic dipole moment) would become possible.

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SQUID MAGNETIC ANOMALY DETECTION

ROLE OF HIGH-T_c SUPERCONDUCTORS

- **Sensitivity in range 10^{-3} - 10^{-4} γ /ft. (i.e., torpedo guidance, mine hunting) may be achievable at liquid nitrogen temperatures**
  - **High-T_c SQUID**
  - **High-T_c cold-side electronics**
- **Sensitivity exceeding 10^{-4} γ /ft (i.e., most ASW applications) requires liquid helium operating temperature**
  - **High-T_c shields**

Missions requiring sensitivities not exceeding 10^{-4} ©/ft would benefit greatly from high-T_C SQUID sensors and high-T_C cold-side electronic components. Operational cost and complexity would be reduced dramatically if the sensor could be operated at liquid nitrogen rather than liquid helium temperatures. Torpedo guidance, mine hunting, and similar applications of SQUID MAD gradiometers would then become extremely promising from an operational point of view.

In contrast to the moderate sensitivity regime, fundamental noise considerations dictate liquid helium sensor temperatures for those applications requiring much higher sensitivities. In the high-sensitivity regime, high-T_C sensors offer no significant advantage over the relatively mature low-T_C materials technology. On the other hand, the effectiveness of low-temperature superconductive shields could be substantially enhanced by use of high-T_C materials.

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SUPERCONDUCTIVITY SHIP PROPULSION APPLICATIONS

- **Superconductive electric drive**
- **MHD pump jets**

Electric propulsion has not been used for Naval vessels since the early 1950s. Electric propulsion was superseded by more compact gas turbine plants which were more energy efficient. If the problems of size and inefficiency that are inherent in conventional electric drive systems could be solved, a wide variety of new propulsion concepts could be explored. These would permit radical improvements in hull design and propulsion placement. If reliable high-T_C superconductive motors and generators were available, revolutionary improvements in ship performance could then be achieved. In the absence of high-T_C technology, marine electric propulsion systems are unlikely to become competitive with more conventional drive trains.

An even more intriguing concept is that of Magneto-Hydrodynamic (MHD) pump jets for propulsion of surface ships and submarines. While MHD propulsion is feasible in principle, the technology required to support it is immature. If the many serious problems associated with MHD (e.g., corrosion, field control, magnetic shielding) can be solved, the availability of high-T_C conductors would result in a significant improvement in the efficiency of such systems.

The advantages of superconductive dc electric motors depend on motor armatures fabricated from suitable type-II superconductors that can produce much stronger magnetic fields at much higher efficiencies (i.e., lower losses) than those using normal metal conductors. Since the torque of a dc motor is directly proportional to the magnetic field strength, motor volume and weight can be reduced greatly by use of superconductive materials.

Because of the relatively low saturation fields of iron, conventional dc motors are designed to operate at fields of about 1 Tesla (i.e., 10,000 Gauss). Superconductive Nb-Ti motors operate at fields of about 7 Tesla. Since the upper critical fields (H_{c2}) of type-II superconductors generally increase with T_c, motors designed to use high-T_c materials might be operable at even higher field strengths.

The use of high-T_c materials in superconductive motors intended for marine applications would permit elimination of liquid helium refrigeration. In addition to reduced system complexity and cost, liquid nitrogen refrigeration would greatly ease the logistical burden of large-scale use of helium at sea.

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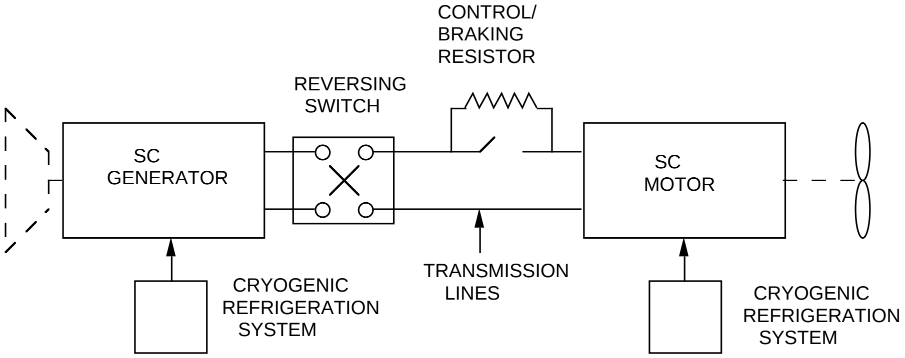
SUPERCONDUCTIVE ELECTRIC PROPULSION
ESSENTIAL TECHNOLOGY



This diagram illustrates the essential technology of a superconductive electric propulsion system. The elements are simply a superconductive generator, and reversing switch, superconductive transmission lines, a speed control/braking resistor and a superconductive motor. The motor, the generator and transmission lines must have cryogenic systems to maintain their temperatures at a fraction of T_C.

The reversing switch is rather more complex than conventional switches, and generally involves a magnetic field that is stronger than the critical field in order to extinguish the current before the switch is opened. The speed control/braking resistor operates at room temperature and allows currents to be dissipated. All superconductive conductors must contain a sufficient cross-section of normal metal so that in the event of a loss-of-cryogen accident, currents are shunted to the normal conductor, thus preventing a catastrophic failure.

Some form of prime mover is still required to turn the generator. In effect, a superconductive electric propulsion system merely serves to couple a prime mover to the propellor shaft. In this mode, it replaces the clutch and gear train that would otherwise be required.

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Programs for the development of superconductive electric-drive motors have been underway for more than 20 years. All designs to date have involved low-T_C materials, principally Nb-Ti. In 1983, the David Taylor Research Center (DTRC) completed the design, construction and testing of the 3,000 HP superconductive motor shown in the photograph. As a next step in the evolution of electric-drive ship propulsion technology, DTRC has proposed to scale up the design to a 40,000 HP motor, again based on low-T_C materials. The most compact conceptual design contemplated would operate at a field of 10 to 15 Tesla. It would weigh only 18,000 pounds and have a diameter of 4.5 feet. In contrast, a conventional dc motor having the same shaft horsepower would weigh approximately 320,000 pounds and have a diameter of 20 feet.

There is little doubt that a reliable 40,000 HP low-T_C dc motor can be built. Its disadvantage would be the requirement for cryogenic helium cooling. In general, widespread shipboard applications of superconductive machinery are likely to depend on the development of high-T_C conductor cables that can support the required mechanical stresses and current densities in external magnetic fields above 10 Tesla.

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The 3,000 HP DTRC motor shown in the preceding chart has been used to drive the small boat shown in this picture.

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APPLICATION FOR SUPERCONDUCTIVITY

ACOUSTIC SIGNATURE REDUCTION

TODAY	FUTURE
CAVITATION - 13 KNOTS	CAVITATION - 20 KNOTS
GEAR NOISE - TONALS	ac MOTOR - QUIET
	dc MOTOR - ULTRA QUIET

Potentially, one of the more important benefits of electric-drive ship propulsion systems is acoustic signature reduction. The placement of drive-shafts and propellers on conventional monohull designs generally results in the onset of cavitation at about 13 knots. In addition, gear noises result in the development of tonals. With compact superconductive dc motors connected directly to the propeller, the propulsor could be optimally placed in a region outside the disturbed fluid region that is created by the flow passing around the ship's hull. The onset of cavitation could thereby be raised to about 20 knots. Since gears would be eliminated, a dc motor would provide for a very quiet propulsion system.

To be completely practical, it appears that the development of high-T_C superconductive electronic drive components is a necessary step in the realization of podded electric drive concepts.

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APPLICATION FOR SUPERCONDUCTIVITY

FLEXIBLE ARCHITECTURE

TODAY

FUTURE

MONOHULL

SWATH

SES

HYDROFOIL

RADICAL HULL DESIGNS WILL DEPEND ON THE DEVELOPMENT OF HIGH-T_C SUPERCONDUCTIVE MOTORS

In the long term, the principal advantage of superconductive electric-drive systems lie in the flexibility offered the Naval architect. Concepts for advanced monohull propulsor systems, Small Waterplane Area Twin Hull (SWATH) ships, Surface Effect Ship (SES), and hydrofoils are all dependent on the availability of a compact motor that can be placed near the propeller. In a very real sense, however, the adoption of radical hull designs, and the realization of the hydrodynamic efficiencies that they will yield, is dependent on the development of high-T_C motors. In principle, high-T_C materials can sustain higher magnetic fields than low-T_C materials. Thus, high-T_C superconductive motors might be capable of developing greater torque for a given weight/volume than their low-T_C analogs, and have the additional critical advantage of operating at liquid nitrogen versus liquid helium temperatures.

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COMPARISON OF MECHANICAL, CONVENTIONAL ELECTRICAL AND SUPERCONDUCTIVE ELECTRICAL PROPULSION

	MECHANICAL	**ELECTRICAL**		
		CONVENTIONAL	**LOW-T_c**	**HIGH-T_c**
Ship Architecture	**Inflexible**	**Flexible**	**Flexible**	**Most Flexible**
Weight & Volume	**Intermediate**	**Largest**	**Smallest**	**Smallest**
Hydrodynamic Efficiency	**Lowest**	**Intermediate**	**Intermediate**	**Highest**
Energy Efficiency	**Intermediate**	**Lowest**	**Highest**	**Highest**

This chart provides a comparison of mechanical and electrical ship propulsion systems. Naval architects have long argued that use of electric motors would result in much more efficient designs. The following are some claimed advantages.

- Propeller placement is not constrained by shaft line, permitting designs with:
    - Reduced wake,
    - Higher cavitation threshold,
    - Ultra-quiet drive,
    - 20 percent less power needed for same speed and tonnage.
- Flexible internal power architecture
- Greater ease in developing propulsion for SWATH-like ships
    - Better seaworthiness
    - Less sea-state limited operation
- Smaller-volume engine room for same hull displacement
    - Enhanced military payload
    - Lower acquisition cost

It is clear that the potential advantages of electric drive can only be realized with superconductive components. The principal difficulties that have militated against their adoption follow.

- Problems with current collectors (i.e., brushes) in large continuous-duty, high-power dc motors.

- Complexities associated with liquid helium refrigeration

    - Engineering problems
    - Back-up systems in case of loss-of-cryogen accidents
      (take home propulsion systems; hotel power system)
    - Logistics problems

It appears that liquid metal (Nak) current-collector technology has advanced sufficiently to assure adequate efficiency and reliability.

Regarding cryogenic cooling problems, it is clear that only high-T_C materials operating at liquid nitrogen (or higher) temperatures offer hope for a totally satisfactory solution. However, without currently unforeseen progress in high-T_C materials and conductor technologies, high-T_C superconductive motor drives for Navy ships will not pass Defense Systems Acquisition Review Council (DSARC) III level reviews before the year 2000.

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MHD PROPULSION

V_{in} V_{out}

A_{out}

A_{in}

C_D - DRAG COEFFICIENT
ρ - DENSITY SEAWATER
A_{in} - INLET AREA
A_{out} - OUTLET AREA
A_{sub} - TOTAL CROSS-SECTION AREA
v_{in} - INLET SPEED
v_{out} - OUTLET SPEED

$$\text{THRUST} = \rho\, A_{out}(v_{out} - v_{in})v_{out}$$

$$\text{DRAG} = (\rho/2)\, C_D\, A_{sub}\, v_{out}^2$$

In principle, MHD pump jets can be adopted for ship propulsion. The MHD thrust is proportional to the product of the magnetic field strength and the electric current flowing transverse to the field. The intense fields achievable with superconductive magnets have created some enthusiasm for this concept, despite obvious technical difficulties. Since the MHD thrust direction is perpendicular to both field and current, the concept requires a dipole field, which is far more difficult to realize in practice than a solenoidal field geometry.

Other potential problem areas have been identified, as well. For example, the electric current is likely to result in the rapid corrosion of electrodes that serve as a current source. The corrosion problem, and the problem of shielding the high magnetic fields that must be employed, have to date rendered the concept infeasible for application to submarine design. For surface ship applications where control of magnetic signature may not be required, such a concept might prove feasible. In any case, MHD ship propulsion is still a rather immature technology that does not appear to have near-term utility.

III. STATUS OF HIGH-T_c MATERIALS TECHNOLOGY

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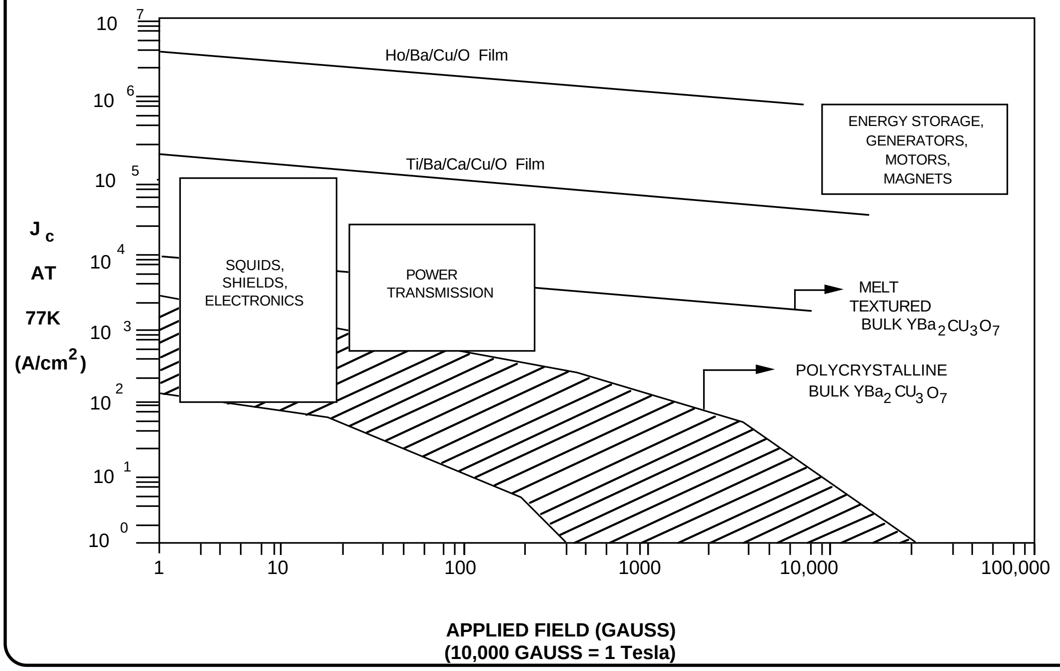
MATERIAL REQUIREMENTS FOR NAVAL APPLICATIONS



Many practical applications of superconductivity require that the superconductor support high current densities in the presence of strong magnetic fields. The chart compares the approximate ranges for critical transport current density (J_C) and magnetic field strength (H) required for major naval application, against high-T_C material capabilities achieved to date at liquid nitrogen temperatures.

Applications involving thin-film structures (e.g., shields) can be explored with existing high-T_C materials technology. On the other hand, applications involving bulk conductors must await significant improvements in materials performance. The relatively low critical current densities and their rapid decrease in external fields, observed in polycrystalline bulk conductors, are an extrinsic property of high-T_C ceramics. The degraded performance has been attributed to current-limiting weak links (i.e., Josephson tunnelling junctions) caused by grain boundaries. This interpretation is supported by the increase in J_C(H) achieved in melt-textured materials. However, to date this technique has not yielded a practical process for large-scale production of long lengths of conductor filaments.

It is noteworthy that commercially available low-T_C superconductors (e.g., Nb, Nb-Ti, and Nb_3Sn) provide complete coverage of applications which are compatible with liquid helium operating temperatures and which do not require larger superconductor energy gaps**.**

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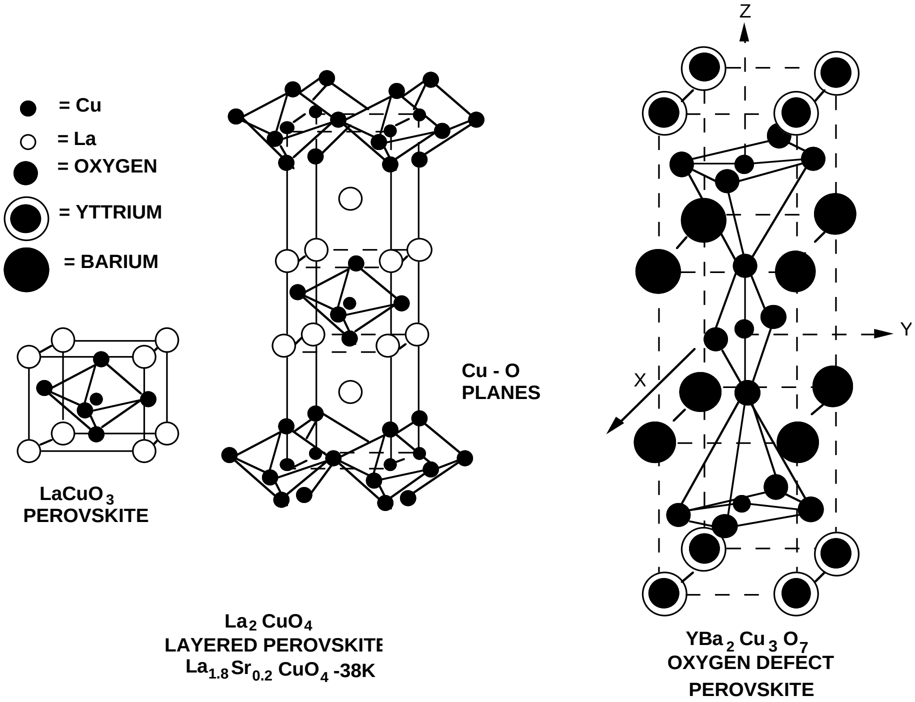
UNIT CELL OF PEROVSKITE STRUCTURES



The crystal structures of the high-T_C ceramic oxide superconductors are derived from the perovskite structure and feature planes of copper and oxygen atoms. The characteristic layered atomic arrangement of high-T_C materials gives rise to highly anisotropic electrical and mechanical properties. For example, electrical transport favors the quasi two-dimensional Cu-0 conducting planes. This behavior contrasts with the essentially isotropic properties of conventional low-T_C materials. In addition, the high-T_C materials are brittle and thus lack the ductility which is desirable for applications involving appreciable strains during fabrication.

The two-dimensional character of these ceramic oxides appears responsible for flux-lattice "melting" phenomena observed in some cases at temperatures well below T_C. Since the practical limits to high critical current densities in strong external magnetic fields are set by the strength of flux pinning, any flux-lattice instabilities would have a deleterious effect on maximum achievable transport current densities.

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PHYSICS/CERAMICS LIMITATIONS MAY PREVENT HIGH TRANSPORT CURRENT

LOW-T_C METAL SUPERCONDUCTORS

ξ = 100-1,000 Å

►| |◄ 10-20 Å (GRAIN)

►| 10^5 Å |◄

HIGH-T_C CERAMIC SUPERCONDUCTORS

ξ = 20-40Å

►| |◄ 50-100 Å

►| 10^5 Å |◄

A fundamental limitation of currently known high-T_C superconductors is their short coherence length (Ω). This characteristic length establishes the minimum distance over which superconductive properties can change appreciably. In practical terms, it is the shortest distance over which superconductivity can be quenched. In low-T_C superconductors this distance is typically much greater than the width of grain boundaries. For this reason, supercurrent transport in these materials is not perturbed significantly by grain boundaries or other small-scale crystal imperfections. Because of their short coherence lengths, which are typically comparable in magnitude to grain-boundary widths, the opposite is true for the high-T_C oxide superconductors. In this case, crystal imperfections tend to produce transport current-limiting weak links. Moreover, since the width of flux-pinning centers must be of order Ω for maximum effectiveness, pinning centers in the high-T_C oxides will have to be constrained to unusually small dimensions.

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BULK/CABLE

This illustration identifies schematically a few of the many problem areas which need to be addressed before manufacturable high-T_C conductor cables suitable for high-power applications can be realized. Of fundamental importance is the development of processing techniques which avoid the current-limiting weak links caused by grain boundaries and other imperfections, while providing flux-pinning centers of adequate strength. Requirements for positive control over current, and stability against electromagnetic perturbations (including fail-safe operation in the event of catastrophic quenching of superconductivity) dictate cable designs consisting of large numbers of small-diameter (typically 10-micrometer) superconductive filaments imbedded in a high-conductivity matrix of normal metal such as copper. The superconductive cables must also have sufficient mechanical flexibility and strength to tolerate the stresses and strains inherent in their intended applications (e.g., magnet winding). Alternatively, it is possible that the final shape can be obtained in the ceramic's "green" state, followed by thermal treatment of the ceramic (i.e., react in place). Finally, it will be necessary to provide low-resistance electrical contacts to the cable.

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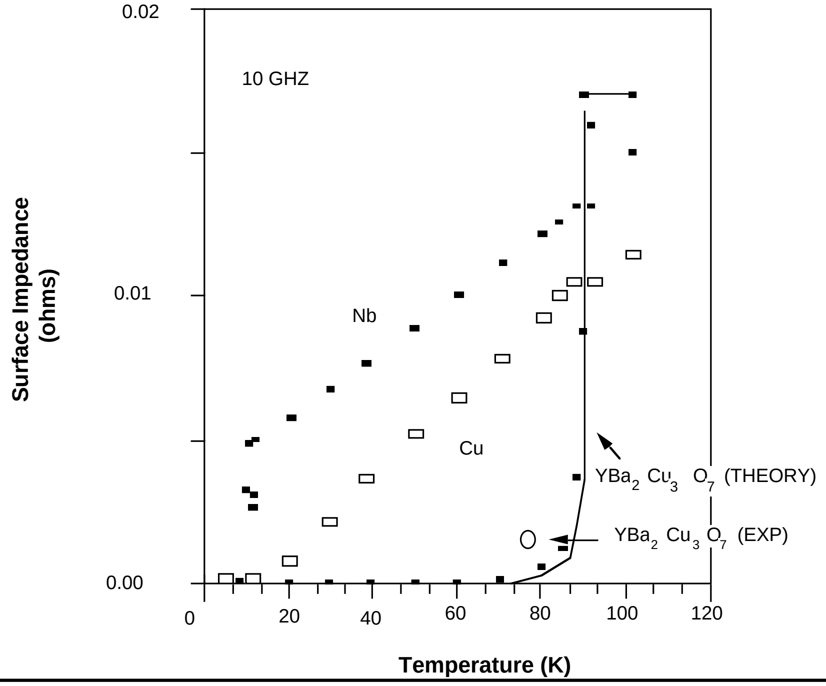
SURFACE IMPEDANCE VERSUS TEMPERATURE



Since the energy gap in a superconductor is proportional to the critical temperature, high-T_C materials can, in principle, support supercurrents to very high frequencies. Under the assumption that the high-frequency properties can be described by conventional BCS theory, the expected behavior is illustrated by the theoretical curve for $YBa_2Cu_3O_7$ shown in the chart. Despite considerable progress, however, experimental results to date still fall far short of predictions. Nonetheless, it is reasonable to anticipate significant improvements in high-frequency surface resistance with further advances in processing. As indicated by the experimental data plotted in the chart, some thin films of $YBa_2Cu_3O_7$ already exhibit large increases in conductivity over copper at liquid nitrogen temperatures and frequencies as high as 10 GHz.

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SUMMARY OF HIGH-T_c OBSTACLES TO BE OVERCOME

- **Materials technology is still immature and further progress is required and possible**
  - **J_C (H) in bulk specimens is too low**
  - **rf surface resistance is too high**
  - **Environmental stability and materials compatibility issues require attention**
  - **Mechanical properties require improvement**

- **T_C is marginal for many 77K applications**
  - **An operating point $T/T_C < 0.5$ is desired**

- **There is a lack of theoretical understanding**
  - **Pairing mechanism**

This chart summarizes the principal materials technology areas in which further progress is required.

IV. NAVY PROGRAM BUDGET AND MANAGEMENT

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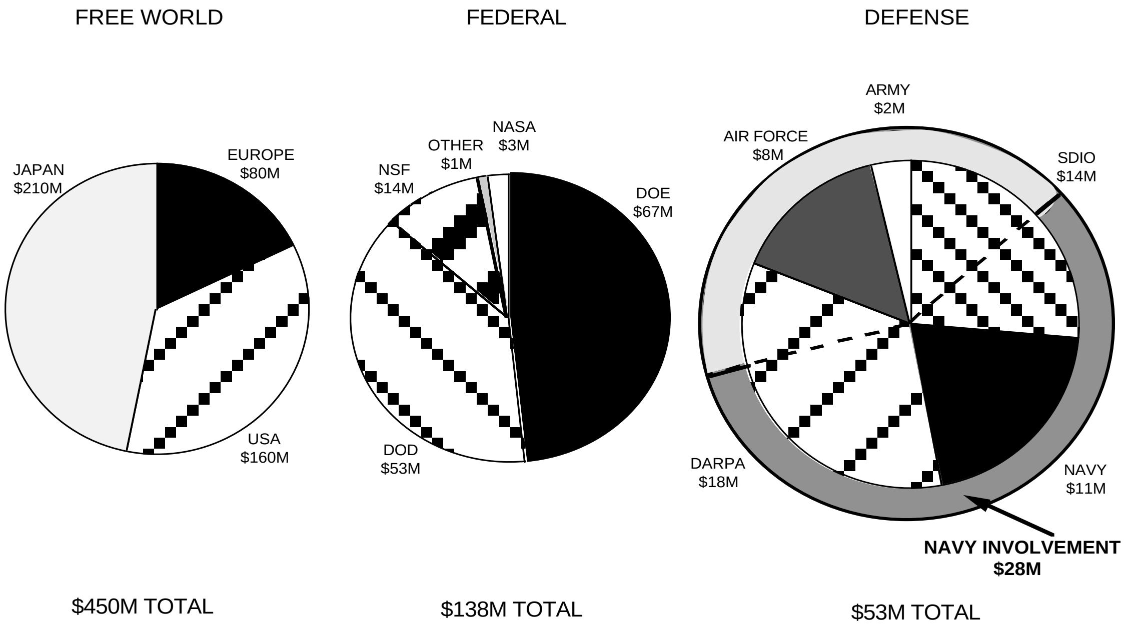
FUNDING IN FY 1988 (ESTIMATES)



The discovery of high-T_C superconductors has led to substantial R&D investments throughout the free world, and presumably the Soviet block as well. This chart provides a rough indication of the distribution of FY 1988 investments. Japan has been the leader in terms of spending rate, exceeding that of the U.S. by about 40%. It appears that the Federal Government has dominated U.S. spending, although current estimates of U.S. industrial activity are not entirely reliable. The Departments of Energy and Defense have represented nearly 90% of Federal Government spending.

The Department of the Navy has played the most significant role among the services in superconductivity research. In addition to its own programs, the Navy has had joint management responsibility for about half of both the Defense Advanced Research Projects Agency (DARPA) and Strategic Defense Initiative Office (SDIO) superconductivity programs.

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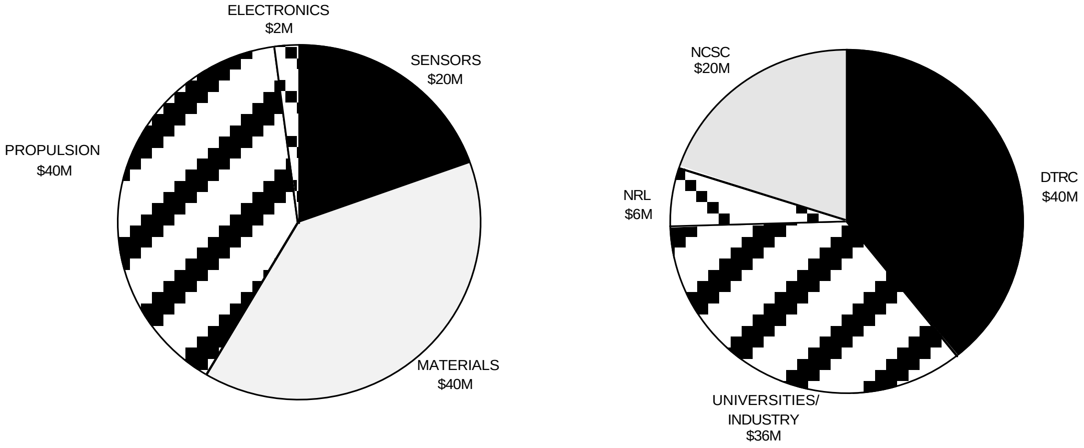
HISTORIC NAVY SUPERCONDUCTIVITY RESEARCH CUMULATIVE FUNDS (FYs 1970-1985)



AREA

PERFORMERS

The Navy has maintained a continuing, long-term effort in superconductivity focused primarily on materials research. It has also supported two major exploratory development programs: Magnetic Anomaly Detection (MAD), and superconductive electric-drive ship propulsion. The Navy's materials research has been conducted principally by the Naval Research Laboratory (NRL) and universities. MAD has been developed by NCSC and ship propulsion by DTRC.

The effectiveness of the Navy's superconductivity programs is well documented by a number of important contributions, some of which are highlighted in Appendix B.

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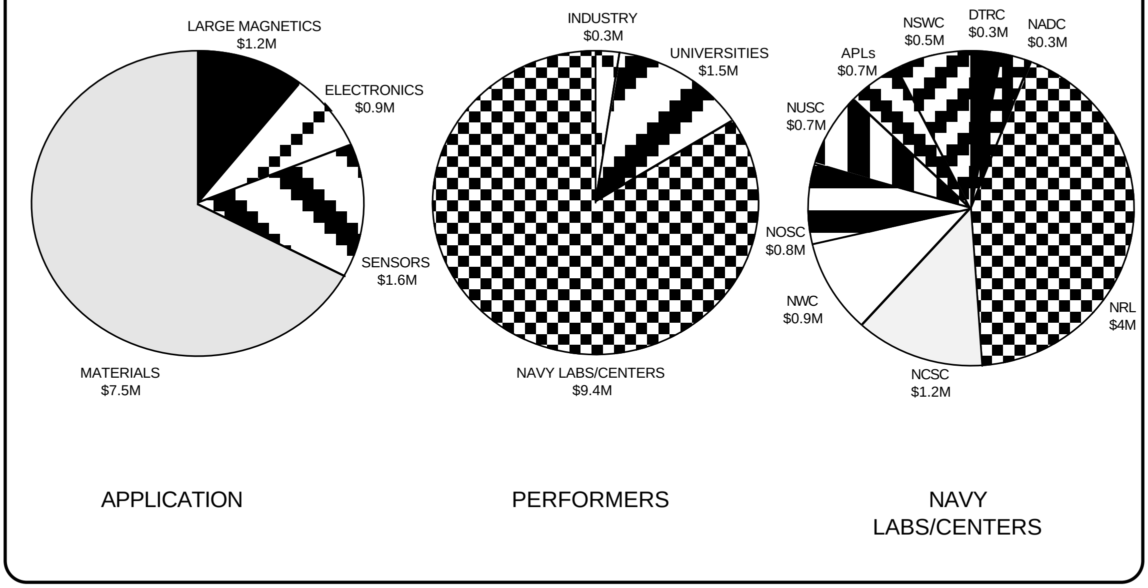
FUNDING (FY 1988)



In FY 1988, the scope of the Navy effort in superconductivity expanded greatly. The distribution of funding became more diverse, with most Navy laboratories and centers engaging in high-T_C superconductivity research. As a result, materials-related work can be found in virtually all facilities and a broad range of potential applications are being evaluated.

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NAVY SUPERCONDUCTIVITY PROGRAM

- **Long-term low-temperature superconductivity effort (6.1)**
- **Two major programs**
  - **Magnetic anomaly detection (6.2; 6.3A in FY 89)**
  - **Electric drive ship propulsion**
- **Many new high-T_c initiatives (IR/IED)**
  - **Opportunity driven**

At the present time (FY 1988), Navy interests in superconductivity are being pursued along the following general directions.

(1) The Office of Naval Research (ONR) and NRL are continuing their fundamental studies (at the 6.1 level), with much of the effort focused on low-temperature physics and materials science.

(2) Two major application programs (6.3A) are focusing on early exploitation of superconductivity for MAD and electric-drive ship propulsion. In both cases the immediate emphasis is on use of relatively mature low-T_C materials technologies.

(3) Numerous high-T_C R&D initiatives are being launched at many facilities. These efforts are largely undifferentiated, and are best described as opportunity driven.

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MANAGEMENT AND COORDINATION

- **Navy directly manages or influences 50% of total DoD investment**
- **At DoN level, coordination under purview of CNR**
  - **ONR - DARPA management "Tiger Team"**
  - **ONR technical management team**
  - **Industry briefing of Navy programs 2/88**
  - **OCNR - DNL 'Naval Consortium for Superconductivity'**
- **At DoD level, ODUSD (R&AT) provides coordination**
  - **Series of meetings of all DoD superconductivity management held late Spring--early Summer 1987**
- **Meeting of DoD superconductivity managers held 2/88.**

The Navy recognized from the beginning that the rapid increase in the number of organizations participating in superconductivity R&D necessitates a substantial increase in management effort. Initial steps in this direction have concentrated on establishing relatively informal coordination procedures, emphasizing information exchange rather than management control. The Naval Consortium for Superconductivity has been especially effective in that regard.

V. CONCLUSIONS

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CONCLUSIONS

1. Opportunities have been identified by the Navy for revolutionary system advances.

- **Superconductive electric-drive propulsion/radical hull shapes**
- **SQUID Magnetic Anomaly Detection (MAD)**
  - **Mine hunting : required sensitivity greater than $10^{-5}\gamma$ /ft**
  - **ASW : required sensitivity greater than $10^{-6}\gamma$ /ft**

Several applications of superconductivity technology have been identified for components, but two areas provide opportunities for revolutionary systems advances, or may provide new capability or improvements which are at least a factor of ten better. Superconductive electric-drive propulsion promises significant savings in volume, weight, and fuel consumption for conventional mono-hull designs. When these advantages are combined with radical hull shapes, revolutionary new capabilities for sea-keeping and acoustic signature reduction are possible. Similarly, the potential for factors of 100 to 1,000 improvement in SQUID MAD sensitivity offers hope for revolutionary advances in mine hunting and open-ocean ASW search systems.

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CONCLUSIONS (CONT.)

2. Opportunities exist for evolutionary system improvements based on superconductivity technologies such as:

- **Very high-speed integrated electronics**
- **Energy storage**
- **Launchers (torpedoes, aircraft, decoys)**
- **High-Q cavities**
- **Shields**

Superconductivity technology has the potential to significantly improve the performance of many components of Navy systems. The reduced thermal noise and increased electron mobility may provide improvements in very high-speed integrated circuits. The superior electric-transport properties of superconductors could permit advances in storage of electromagnetic energy in usefully small volumes, provide the large fields required by electromagnetic mass accelerators for weapons and aircraft, and yield advances in electromagnetic shielding to reduce signatures and improve sensor performance. Reduced bulk and surface resistance properties may lead to much higher performance in resonant cavities. One application of such cavities would be in the Global Positioning System (GPS) where a superconductive cavity has the potential to increase clock stability by an order of magnitude. While some effort is being directed toward the use of superconductors in electrically small antennas, it is not yet clear that these will provide the directionality required for missile seekers.

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CONCLUSIONS (CONT.)

3. Relatively mature low-T_C superconductivity technology can satisfy most Navy applications in systems compatible with liquid helium operating temperatures

- **Nb-Ti cable technology for applications requiring fields to ~ 6T is commercially available, and large-scale applications have been successful**
- **Nb_3Sn cable technology, while less mature, has been used in small-scale applications above 10T**
- **Numerous low-T_C electronic devices (active and passive) have been fabricated in recent years, and some Josephson-junction devices are commercially available**

Relatively mature low-T_C technology is capable of providing performance adequate for many Navy system applications, provided those systems can tolerate the added complexity associated with liquid helium refrigeration. Low-T_C cables suitable for high-performance magnets, motors, and power transmission components are available commercially. Certain electric devices are also available. Many of the evolutionary advances cited in the previous conclusion are, therefore, within reach. Stated differently, for many practical applications the primary advantage of high-T_C superconductors lies not in fundamental materials performance, but rather in the operational convenience afforded by higher temperatures.

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CONCLUSIONS (CONT.)

4. High-T_C technology could, in time, offer significant advantages.

- **More efficient refrigeration**
  - **Reduced capital and operating costs**
  - **Reduced cryogenic engineering complexity**
  - **Reduced machinery cool-down times**
  - **Simplified logistics/training/maintenance**
  - **Increased time on station**
  - **Passive cooling in space**
- **Improved performance at 4K (i.e., reduced T/T_c)**
  - **Improved magnetic shielding**
  - **Higher J_c**
  - **Lower rf losses**
- **Semiconductor/superconductor integration compatibility at 77K**

If high-T_C devices can be successfully developed and fabricated, they could provide several significant advantages. The most obvious of these is the impact on the complexity and energy efficiency of the refrigeration system. Liquid nitrogen refrigeration systems require far less in terms of complexity of design, precision of manufacture, and cost of operation. These lead to reductions in logistics, training, and maintenance. Nitrogen's higher boiling point (77K) means less time is required to cool systems from ambient temperature (300K), and its larger heat of vaporization implies longer time on station for systems that simply rely on a reservoir of coolant.

In addition, if high-T_C devices are operated at liquid helium temperatures, they may prove superior to their low-T_C counterparts. Superconductive properties such as critical current density (J_C), critical magnetic field strength (H_C), and surface resistance (R_S), all improve as operating temperature is decreased below T_C. Therefore, these effects may significantly improve the performance of magnetic shields, magnets, motors, and high-frequency components. The other benefit derived from operating at 4K is reduced thermal noise which can be important in some sensor and electronics applications.

High-T_C devices, operating at liquid nitrogen temperatures offer another intrinsic benefit. These temperatures are more compatible with Si or GaAs integrated circuits. Thus, the opportunity exists to integrate superconductive devices with associated semiconductor circuits and elements.

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CONCLUSIONS (CONT.)

5. Although achievements to date are encouraging, significant progress is required to realize the potential of high-T_c superconductivity technology.

- **Materials technology is still immature**
  - **J_c(H) in bulk specimens must be increased and processes leading to acceptable conductor cables must subsequently be developed**
  - **rf surface resistance in films must be reduced**
  - **Environmental stability and materials compatibility issues need attention**
  - **Mechanical properties (e.g., toughness; ductility) require improvement**
  - **Maximum T_c achieved is still marginal for many 77K applications, and discovery of superior superconductors is therefore of great importance ($T/T_c < 0.5$ is desired)**

- **Theoretical foundation remains inadequate**
  - **High-T_c pairing mechanism must be understood to assist search for new materials**
  - **Influence of crystal defects on flux pinning and weak-link behavior must be understood to guide effort to increase J_c(H)**
  - **Effects of imperfections on surface resistance must be understood for rf applications**

The performance levels achieved to date in high-T_C superconductors fall far short, in general, of what are believed to be the intrinsic limits. A principal conclusion of this study is, therefore, that substantial R&D effort is required before the utility of high-T_C superconductivity can be fully assessed. Needed improvements include critical current densities (J_C) in bulk conductors, rf surface resistance (R_S) in thin films, materials stability and compatibility, as well as mechanical strength and ductility. Since superconductive properties generally degrade rapidly as temperatures increase above $T/T_C \sim 0.5$, operation at liquid nitrogen temperatures (77K) may be marginal for all of the presently known high-T_C oxides ($T_C < 125$K).

The theoretical understanding of high-T_C superconductivity must be improved significantly. Theoretical guidance is desirable in the search for new materials, and may be essential in achieving the required performance improvements in known materials.

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CONCLUSIONS (CONT.)

6. It is premature to invest significant development effort in enabling technologies.

- **None of the enabling technologies (refrigeration, conductor cables, brushes, etc.) are on the 1988 critical path.**
- **When materials with appropriate characteristics are developed, wire/cable technology will become a critical-path item.**

At the present time, material limitations are the pacing obstacles on the critical path to high-T_C applications. For this reason, investments in most enabling technologies deserve lower priority than investments in materials R&D. Enabling technologies such as multifilament conductor cables and refrigeration systems will, however, become critical-path items as materials exhibiting the required properties approach reality.

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CONCLUSIONS (CONT.)

7. For four decades the US Navy has sustained a significant role in advancement of the science and technology of superconductivity; continuing rapid progress fully justifies the present investment level.

- Current program addresses Navy issues, and distribution over technical areas seems appropriate
- Materials activity is fragmented, and many efforts are subcritical or premature
- No central authority exists
  - No integrated program plan
  - 50% of lab/center expenditures are discretionary
- Navy superconductivity consortium is facilitating information exchange
- Focal points are evolving
  - NRL: materials
  - NCSC : SQUID/MAD
  - DTRC: propulsion
  - NWC: rf devices
- Awareness of other agency programs is good

Navy-funded R&D has been a significant contributor to the advancement of superconductivity science and technology since World War II. The Navy laboratories and centers consequently possess much valuable experience and competence. Current efforts are well oriented toward Navy use, and the two major low-T_C development programs (MAD and electric-drive ship propulsion) have achieved significant milestones. Concurrently, Navy research is appropriately concentrated on materials science and engineering issues. However, in the absence of central authority, the material efforts have become fragmented. Many Navy laboratories and centers have, in the recent past, directed discretionary (IR/IED) funds to examine opportunities for high-T_C materials exploitations. In some cases, this has led to premature focus on specific applications. Without an integrated program plan to coordinate the individual efforts, the Navy is unlikely to achieve the desired near-term progress in high-T_C materials technology.

The establishment of a Navy consortium has greatly facilitated information exchange during the formative stages of the high-T_C effort, thereby contributing to the gradual evolution of specific technical focal points among program participants. In general, awareness among Navy program managers of superconductivity programs funded by other Federal agencies appears excellent. Involvement in the management of DARPA and SDIO high-T_C superconductivity programs has been a major factor in gaining this understanding.

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CONCLUSIONS (CONT.)

8. Continued Navy investments can impact future developments in the high-T_C field.

- **Navy R&D can produce useful thin-film electronic devices for specialized applications such as sensors, shields and cavities**
- **Navy R&D in other high-T_C areas can contribute to national efforts, thereby accelerating the introduction into Navy systems**
  - **High magnetic field bulk material applications will require sustained investments on a national scale**
  - **Large-scale superconductive electronics applications, such as high-speed digital logic, will most likely be paced by commercial developments**

Even at present investment levels, the Navy program can have a significant impact on evolving high-T_C technology. Using its own resources, the Navy can anticipate success in developing thin-film devices for a number of specialized applications involving sensors, electromagnetic shields, and rf cavities. However, for many of the most significant applications of high-T_C technology, substantial progress will require resources on a scale not available to the Navy. An example of a program goal requiring national-level commitments is the development of high-T_C conductor cables for high-field applications. Similarly, the development of high-T_C large-scale integrated digital logic devices will most likely be paced by industry, as has been the case for silicon devices.

Given its record of past accomplishments, the Navy can play a significant role even in national-scale efforts. Navy involvement will contribute measurably to a growing high-T_C technology base, and will accelerate the introduction of the technology into Navy systems.

IV. RECOMMENDATIONS

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RECOMMENDATIONS

1. Near-term technical effort.. Within available resources, the Navy should concentrate its tech-base efforts in five areas.

- Continue support of low-T_C superconductivity research.
- Resolve technical issues (J_C , R_S) limiting performance of known high-T_C materials. Initiate advanced technology demonstration for useful small-scale applications of high-T_C superconductivity.
  - Magnetic shields
  - High-Q cavities
- Stimulate invention of new device concepts.
  - Not by extension or analogy
  - Based on novel material properties (e.g., anisotropy, semiconductor compatibility)
- Encourage search for new classes of superconductive materials with improved characteristics.
  - T_C ; J_C (H); R_S (f)

In the near term, the Navy superconductivity effort should concentrate on systematic extensions of the technology base. It is essential, however, that any expansion of high-T_C research not be supported at the expense of productive low-T_C research. The high-T_C effort should address the critical technical issues limiting the performance of known superconductive ceramic oxides (e.g., J_C, R_S), while attempting to demonstrate selected small-scale applications. At the same time, innovative device ideas should be stimulated which exploit some of the special characteristics of the high-T_C oxides. Finally, a continuing search for new high-T_C material classes should be encouraged.

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RECOMMENDATIONS (CONT.)

2. Management of near-term efforts. While the Navy has been well served by the enthusiasm of its superconductivity community, it is important that a more structured approach guide the evolution of the tech-base effort.

- **Establish a coordination authority**
- **Establish lead labs for promising areas**
- **Discourage unproductive duplicative efforts among Navy laboratories/centers**
- **Review performer balance among universities, laboratories, centers, and industry to ensure optimal access to a broad community of ideas**
- **Generate and execute an integrated R&D plan**

As the challenges and opportunities of the high-T_C field come into clearer focus, it will become increasingly important to adopt a more structured approach to managing the Navy program. Initially, a stronger coordination function should be defined. Duplicative near-term efforts among the Navy laboratories and centers should be minimized by assignment of lead-laboratory roles for the most promising technology areas. It is also timely to review the current balance among university, laboratory, center, and industrial performers to assure that the broadest range of innovative ideas is brought to bear on the Navy superconductivity program.

Steps should be taken to reach agreement at the earliest opportunity on an integrated R&D plan to provide effective guidance and assure needed coordination. The plan should have flexibility to encourage innovation, and should be updated at regular intervals to maintain its utility.

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RECOMMENDATIONS (CONT.)

3. <u>Planning for future applications</u>. Near-term efforts must not be compromised by premature commitments to large-scale applications; however, it is not too early to plan for the future.

- **Continue system-level studies of superconductivity applications**
  - **Identify operational advantages and disadvantages**
  - **Identify necessary enabling technologies**
- **Define a long-range research strategy which:**
  - **Incorporates an appropriate balance between sequential and parallel research effort**
  - **Relies on cooperation with other government and commercial efforts in areas requiring major investments (e.g., wire/cable)**

It is of critical importance that the contributions of the near-term R&D effort not be compromised by premature transition to large-scale demonstration projects. Nonetheless, it is prudent even at this early stage to analyze more fully the various potential applications as a first step toward developing future plans. In particular, high-level systems engineering studies should be pursued which are aimed at evaluating operational advantages and disadvantages of competing approaches and identifying the necessary enabling technologies.

A long-range strategy should be adopted which strikes a sensible balance between orderly sequential efforts on one hand, and more risky parallel efforts on the other where justified by large pay-off potentials. Planning for applications requiring major investments should take advantage of cooperation with other Government and commercial R&D efforts.

APPENDIX A
TECHNICAL BACKGROUND

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FUNDAMENTAL SC PROPERTIES

ELECTRICAL RESISTANCE

The loss of electrical resistance in certain materials at temperatures below a critical temperature gave issue to a rich field of physical research which continues to this day. The resistance of a superconductor is strictly zero below T_C only at zero frequency (dc). Its behavior at a series of increasing frequencies (f) is shown in the figure. At a given frequency, the resistance increases as the temperature is increased. This is in accordance with the simple picture that the current in a superconductor is carried by the combined action of two fluids: "normal" electrons and "superconducting" electrons. The former absorb the electromagnetic energy at f and transfer that energy to the crystal lattice resulting in dissipation and, thus, finite resistance. The latter are able to respond to the applied radiation without the accompanying power dissipation. Since the number of normal electrons decreases exponentially with decreasing T, the dissipation (and, thus, resistance) follows suit. Conversely, the number of superconducting electrons increases as the temperature is lowered, and thus the strength of the superconducting properties (e.g., H_C, J_C) increases as T approaches zero.

The other point to be made about the resistance is that it increases as f^2, and for $hf \geq e\Delta$, behaves almost as if the superconductor were completely normal. The preponderance of practical applications of superconductivity (lossless electrical power transmission, low-loss rf conductors, filters) depend on the resistance being as close to zero as permitted by these laws.

Superconductivity vanishes if the amplitude of the applied current is generally converted into a critical current density defined as $J_C = I_C/A$, where A is the cross-sectional area of the current path. The J_C is in turn decreased by the presence of an external magnetic field, H. The destruction of J_C (and, thus, superconductivity) by H is shown in the figure on the right.

There are two important length scales in superconductivity. The first is the depth that an applied magnetic field will penetrate the surface of a superconductor which is called the penetration length, labeled ¬. The other length, Ω , is called the coherence length and describes the distance required for the density of electrons to change completely from superconducting to normal.

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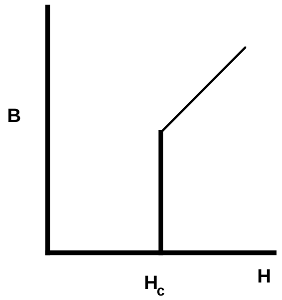
FUNDAMENTAL SC PROPERTIES

MAGNETIC FLUX EXPULSION: TYPE I SC

MEISSNER EFFECT

$\lambda/\xi < 0.707$



The behavior of a type I material in an external magnetic field H is shown in this figure. Above T_C, when the material is normal, the applied field H completely penetrates the interior of the sample. Expressed in terms of the magnetic field inside the sample, B, the applied field (H) and the magnetization (M) the normal state is characterized by B = H and M = 0. When a type I material is cooled below T_C, however, permanent shielding currents flow on its surface (to a depth lambda). These surface currents generate a magnetization and thus a field in the interior of the sample which precisely cancels the applied field. Mathematically, we say that perfect magnetic shielding has occurred: That is, B = 0, and H = 4πM. the currents flow at the expense of some of the energy gained in the superconducting state. As H is increased, larger currents must flow at increased cost to the superconducting state. At the particular field value H_C at which the energy needed to sustain the currents equals the energy gained by the superconducting state, the state is abruptly destroyed. At fields above H_C, the material is again normal.

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MAGNETIC FLUX EXPULSION: TYPE II SC

$\lambda / \xi < 0.707$

This figure shows the behavior of a type II material in an external magnetic field. Just as is the case for a type I superconductor, the material is normal above T_C: $B = H$ and $M = 0$. Below T_C and for small H ($H<H_C$), a type II superconductor behaves identically to a type I superconductor. Above a critical magnetic field, H_{c1}, however, a type II superconductor does not abruptly return to the normal state. Instead, a type II superconductor permits the field to penetrate its interior in the form of a multitude of localized "threads" of magnetic field lines. In the region occupied by each magnetic field line the material is normal, but the region just outside the core is still superconducting. Indeed, a supercurrent circulates around each thread. For this reason, the magnetic thread with its normal core surrounded by supercurrents is often referred to as a vortex. As the magnetic field is increased above H_{c1}, the number of vortices increases at the expense of intervening superconductor regions. Finally, when the whole sample is filled with vortices at an applied H_{c2}, the sample has reverted completely to the normal state.

The results are summarized in the right side of the figure. This curve illustrates another common feature of type II superconductors: hysteresis. That is, flux lines which are admitted into the interior of the sample as H is increased between H_{c1} and H_{c2} are trapped at lattice imperfections and are not free to move. Thus, when the external magnetic field is removed, the trapped field lines do not leave the sample, and a residual field remains.

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QUANTUM PHENOMENA

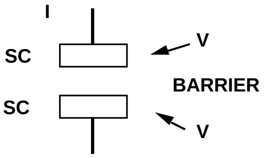
(A) MAGNETIC FLUX QUANTIZATION

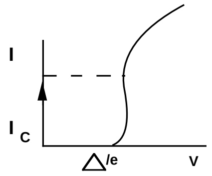
SC RING

FLUX QUANTIZED: N ϕ_0 = N2 X10^{-7} G cm^2

FLUX TRAPPED

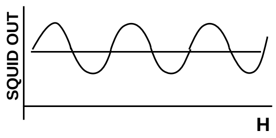
(B) JOSEPHSON JUNCTION





(C) SQUID = RING + JOSEPHSON JUNCTION

JOSEPHSON JUNCTION PERMITS FLUX JUMPS



We now consider the behavior of a superconductor with a hole in it (e.g., a superconducting ring). If we apply an external magnetic field to the ring when $T>T_C$, then cool it below T_C, and subsequently remove the field, we find that the total magnetic flux f (i.e., the integral of the magnetic field over the total area of the hole) is quantized. That is, $\Diamond = n f_0$, where n is an integer and the flux quantum f_0 = h/2e = 2.07x 10^{-7} Gauss-cm^2 is a very small quantity.

Consider next the Josephson junction (shown at the center of the figure) which is a device formed by separating two superconducting regions by a very narrow insulating barrier. For such a device, electrons may tunnel from one side to the other only in pairs. The current (I) which flows through the device as a function of the voltage (V) applied across the junction is shown in the inset. A remarkable feature is that current can flow up to a critical value I_C with V = 0, at which point the voltage becomes discontinuously finite. The switching time is extremely short and has been used for high-speed applications of Josephson junctions such as computer logic elements and analog-to-frequency converters.

Finally, suppose we insert the Josephson junction into the ring. Such a device is called a Superconducting Quantum Interference Device (SQUID), in which the junction permits the flux lines to pass, one by one, in and out of the ring. The output of the device is periodic in f_0 and thus offers unparalleled sensitivity to magnetic field.

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PROPERTIES OF SOME LOW-T_c SUPERCONDUCTORS

MATERIAL	T_c (K)	J_c (A/cm^2)	H_c (o) (T)	H_{c2} (o) (T)	MECHANICAL PROPERTY
			TYPE I		
Hg	**4.2**	**10^4**	**0.05**	**-**	**soft, ductile**
Pb	**7.2**	**10^5**	**0.08**	**-**	**soft, ductile**
			TYPE II		
Nb	**9.2**	**10^6**	**-**	**1**	**ductile**
Nb-Ti	**9.2**	**10^6**	**-**	**11**	**ductile**
NbN	**16**	**10^6**	**-**	**18**	**brittle**
Nb_3Sn	**18**	**10^7**	**-**	**21**	**brittle**

In this table we summarize some of the important properties of superconductors with T_C as high as 18 K. The first two are type I superconductors. They are ductile and can be easily drawn into long wires. These materials can withstand only very low magnetic fields and moderate current densities. Consequently, coils wound from them cannot be used to generate high magnetic fields. By contrast, the type II superconductors shown here are very much "stronger." For example, the compound Nb_3Sn has a much higher T_C, can carry much more current and can withstand magnetic fields at $T/T_C<<1$ of 210,00 Gauss (21 T)! This material is brittle, however, which complicates the construction of magnets. Nevertheless, this material has been used to generate magnetic fields as high as 15 T.

APPENDIX B
HISTORY OF NAVY ACTIVITIES IN SUPERCONDUCTIVITY

ONR ACTIVITIES IN SUPERCONDUCTIVITY

1965	INITIATED SUPERCONDUCTIVE ELECTRONICS PROGRAM.
1966-1980	SUPPORTED SQUID DEVELOPMENT AND PHYSICS OF JOSEPHSON JUNCTIONS AT U OF VIRGINIA, NBS, HARVARD.
1969	FIRST MEASUREMENT OF THE MAGNETIC SIGNATURE OF THE HEART USING SQUID (NATIONAL MAGNET LABORATORY).
1970-1980	DEVELOPMENT OF SUPERCONDUCTIVE MICROWAVE AND MM WAVE DETECTORS AND ELECTRONICS AT UC, BERKELEY AND YALE.
1968-1972	DEVELOPMENT OF ASW USING SQUID AT NCSC.
1972-PRESENT	MEASUREMENT AT NYU OF EVOKED RESPONSES FROM THE BRAIN USING SQUID.
1980-1985	SUPPORT WORK ON SUPERCONDUCTIVE DIGITAL SIGNAL PROCESSING COMPONENTS AND CIRCUITS AT UC, BERKELEY AND NBS.
1985-1987	SUPPORT ESTABLISHMENT OF FIRST US NbN INTEGRATED CIRCUIT TECHNOLOGY AT HYPRES.
1980-1988	DEVELOPMENT AT NBS, NRL, AND IN INDUSTRY OF LOW-VIBRATION, LOW-NOISE REFRIGERATORS FOR SQUID APPLICATIONS.
1967-PRESENT	SPONSORED MANY TOPICAL CONFERENCES, MEETINGS, AND WORKSHOPS ON SUPERCONDUCTIVITY, JOSEPHSON JUNCTIONS, AND REFRIGERATION.

HIGHLIGHTS OF NRL FUNDAMENTAL SC RESEARCH

1950	DISCOVERED NEW CLASS OF SUPERCONDUCTING SEMICONDUCTORS GeTe WHICH HELPED SET THE STAGE FOR HTS
1960	SHOWED IMPORTANCE OF LONG RANGE ATOMIC ORDER ON T_c OF A15 SYSTEM
1970	PIONEERS IN DEVELOPMENT OF J_c AND HIGH FIELD PERFORMANCE OF V_3Ga
1970	DEVELOPED SELF-CONSISTENT BAND STRUCTURE CALCULATION WHICH PERMITTED CALCULATION OF SC T_c. SHOWED THAT FIRST-PRINCIPLES CALCULATION COULD BE USED TO DESCRIBE REAL MATERIALS
1970	PIONEERING MEASUREMENTS IN PHYSICS OF JOSEPHSON JUNCTIONS
1970	DEMONSTRATED JOSEPHSON JUNCTION BEHAVIOR IN GRANULAR FILMS
1980	EXTENSIVE STUDIES OF PROPERTIES OF 2D THIN SC FILMS
1980	HTS: NBS/NRL INELASTIC NEUTRON SCATTERING GAVE PHONON SPECTRUM HTS: NBS/NRL X-RAY PHOTOEMISSION STUDIES HTS: NRL NEW MATERIALS T1/Sr/Ca/Cu/O
1975 - 1977	NRL DEVELOPED PROTOTYPE SUPERCONDUCTIVE SQUID ANTENNA FOR SUBMARINE COMMUNICATIONS

HIGHLIGHTS OF NAVY
APPLIED SC PROGRAMS

1972 - 1988 SQUID MAD DEVELOPMENT AT NCSC

- 1975 MARK I SYSTEM BUILT & TESTED
  - -40 db (10$^{-2}\gamma$/FT) IN MOTION
- 1979 MARK II SYSTEM BUILT & TESTED
  - -60 db IN MOTION
- 1983 MARK III SYSTEM BUILT & TESTED
  - -EXPECTED -80 db IN MOTION
  - -EXTENSIVE DEPLOYMENT FROM SHIP AND AIRBORNE PLATFORMS: -60db
- 1983 - 1988
  - -IDENTIFIED AND ELIMINATED SEVERAL NOISE SOURCES WHICH DEGRADED MARK III PERFORMANCE
  - -EXPECT -80db WITH REFURBISHED MARK II (MARK IV) 6.3A MADAM DEVELOPMENT

HIGHLIGHTS OF NAVY
APPLIED SC PROGRAMS

1970 - 1988 ELECTRIC SHIP PROPULSION DEVELOPMENT AT DTRC

- 1970 - 1982 DESIGNED, BUILT, TESTED 400HP SYSTEM (MOTOR, GENERATOR, CRYOGENIC SYSTEM)
- 1974 - 1984 DESIGNED, BUILT, TESTED 3000HP SYSTEM (MOTOR, GENERATOR, CRYOGENIC SYSTEM) INSTALLED ON SHIP FOR SHIPBOARD TESTS
- 1984 - 1988 CONTINUE DEVELOPMENT OF LARGER SYSTEM

APPENDIX C
ACRONYMS

APPENDIX C

ACRONYMS

ac	alternating current
A/D	Analog/Digital
APL	Applied Physics Laboratories
ASN	Assistant Secretary of the Navy
ASW	Anti-Submarine Warfare
BCS	Bardeen, Cooper, and Schrieffer
CNR	Chief of Naval Research
DARPA	Defense Advanced Research Projects Agency
db	Decibel
dc	direct current
DNL	Department of Navy Laboratories
DoD	Department of Defense
DoE	Department of Energy
DoN	Department of the Navy
DSARC	Defense Systems Acquisition Review Council
DTRC	David Taylor Research Center
EM	Electro-Magnetic
GPS	Global Positioning System
HP	Horsepower
HVAC	Heating, Ventilation and Air Conditioning
IED	Independent Exploratory Development
IR	Independent Research
J_c	Critical Density
K	Kelvin
MAD	Magnetic Anomaly Detection
MHD	Magneto-Hydrodynamic
NADC	Naval Air Development Center
NASA	National Aeronautics and Space Administration
NCSC	Naval Coastal Systems Center
NOSC	Naval Ocean Systems Center
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSWC	Naval Surface Warfare Center
NUSC	Naval Underwater Systems Center
NWC	Naval Weapons Center
OCNR	Office of the Chief of Naval Research
ODUSD (R&AT)	Office of the Deputy Under Secretary of Defense (Research and Advanced Technology)
R&D	Research and Development
rf	radio frequency
R_s	Surface Resistivity
SC	Superconductor
SDIO	Strategic Defense Initiative Office
SES	Surface Effect Ship
SQUID	Superconductor Quantum Interference Device
SWATH	Small Waterplane Area Twin Hull
T	Telsa
T_c	Critical Temperature