2

Report of the Defense Science Board Task Force on

Military System Applications of Superconductors

October 1988

Office of the Under Secretary of Defense for Acquisition
Washington, D.C. 20301-3140

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE	Form Approved OMB No 0704-0188 Exp. Date Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS NONE
2a. SECURITY CLASSIFICATION AUTHORITY N/A	3. DISTRIBUTION/AVAILABILITY OF REPORT Distribution Statement A. Approved for Public Release. Distribution is unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) N/A	5. MONITORING ORGANIZATION REPORT NUMBER(S) N/A

6a. NAME OF PERFORMING ORGANIZATION Defense Science Board, Ofc of the Under Secy of Def (A)	6b. OFFICE SYMBOL *(If applicable)* DSB/OUSD(A)	7a. NAME OF MONITORING ORGANIZATION N/A
6c. ADDRESS *(City, State, and ZIP Code)* The Pentagon, Room 3D1020 Washington, D.C. 20301-3140		7b. ADDRESS *(City, State, and ZIP Code)* N/A
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Defense Science Board/OUSD(A)	8b. OFFICE SYMBOL *(If applicable)* DSB/OUSD(A)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N/A

8c. ADDRESS *(City, State, and ZIP Code)*
The Pentagon, Room 3D1020
Washington, D.C. 20301-3140

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
N/A	N/A	N/A	N/A

11. TITLE *(Include Security Classification)*
Report of the Defense Science Board Task Force on Military Applications of Superconductors, UNCLASSIFIED

12. PERSONAL AUTHOR(S)
N/A

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
FINAL	FROM N/A TO N/A	88/10/00	51

16. SUPPLEMENTARY NOTATION
N/A

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☑ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE *(Include Area Code)*	22c. OFFICE SYMBOL
Diane L.H. Evans	(202) 695-4158/6463	DSB/OUSD(A)

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

OFFICE OF THE SECRETARY OF DEFENSE
WASHINGTON, D.C. 20301-3140

DEFENSE SCIENCE
BOARD

MEMORANDUM FOR THE SECRETARY OF DEFENSE

SUBJECT: Report of the Defense Science Board Task Force on Military Applications of Superconductors

Attached is the final report of the Defense Science Board Task Force on Military Applications of Superconductors, chaired by Mr. Walter E. Morrow, Jr. This report highlights a number of significant military capabilities, which may emerge through exploitation of superconductors.

The report also defines an aggressive research and development program for the Defense department, leading to early transition of successful superconductor technologies into military systems.

The potential of superconductivity has been the subject of a number of recent studies. Opinions vary widely on this subject, ranging from overstatement to pessimism. I believe that this Task Force report represents a balanced view. At this juncture in the evolution of the new superconducting materials, no one can be sure of the potential; however, this panel believes that the benefits of success from an aggressive R&D program far outweigh the risk of failure. It is clear that Japan believes in superconductivity and is aggressively pursuing materials development as well as the building of an industrial infrastructure. DoD must take the same approach.

I recommend that you read Mr. Morrow's letter and the Executive Summary and that you direct the Department to create the type of development program outlined in the report.

Robert R. Everett
Chairman

OFFICE OF THE SECRETARY OF DEFENSE
WASHINGTON, D.C. 20301-3140

DEFENSE SCIENCE
BOARD

9 September 1988

Mr. Robert R. Everett
Chairman
Defense Science Board

Dear Bob:

Attached is the final report of the Defense Science Board Task Force on Military System Applications of Superconductors. The Task Force believes that the recent discovery of new superconductor materials to be of great significance because of their higher operating temperatures and magnetic fields. The Task Force found military applications of superconductors which offer significant operational performance advantages. In particular, superconducting materials being developed today may permit:

- Space IR sensor arrays with very high resolution and low power consumption
- High-speed miniature digital processors for target detection and identification
- Mine detection systems with very high sensitivity
- Hypersonic tank guns with projectile speeds which ensure penetration of reactive armor and modern composite armor
- Undersea magneto-hydrodynamic propulsion for ultra-quiet submersible operations.

To achieve this potential, a vigorous program of research, development, and demonstrations is needed. Such a program should include: expanded efforts in basic research, including theory; intensive development of high-temperature thin-film materials and high-temperature composite wires and conductors; as well as pursuit of two key supporting technologies: cryogenics and high-strength structural material and development of a number of engineering test models based on superconductor materials to serve as a basis for early transition of high-temperature superconductors into military systems.

We have recommended a five-year R&D program which requires more than double the resources of the FY88 actual expenditures.

In summary, the panel believes that the new superconductor materials represent a major opportunity for DoD in a wide range of applications. The panel has great concern that, without substantial and focused increases in R&D by DoD, U.S. industry will fall well behind the Japanese in this important technology, and DoD may be forced to purchase superconducting components from foreign sources.

I want to thank all of the members of this panel for their contributions to this report.

Sincerely,

Walter Morrow

Walter E. Morrow, Jr.
Chairman
Task Force on Military Systems
Applications of Superconductors

This Page Intentionally Left Blank.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

APPENDIX A - TERMS OF REFERENCE

APPENDIX B - MEMBERSHIP

APPENDIX C - BRIEFINGS PRESENTED TO THE DSB TASK FORCE ON MILITARY APPLICATIONS OF SUPERCONDUCTORS

APPENDIX D - DIRECTIONS OF RESEARCH AND DEVELOPMENT INTO HIGH TEMPERATURE SUPERCONDUCTORS

APPENDIX E - CRYOGENIC TECHNOLOGY

APPENDIX F - A JOSEPHSON 4-BIT MICROPROCESSOR

APPENDIX G - BACK-UP DATA ON JAPANESE FUNDING FOR SUPERCONDUCTIVITY R&D

APPENDIX H - HIGH TEMPERATURE SUPERCONDUCTIVITY FUNDING ($M)

APPENDIX I - GLOSSARY OF TERMS

LIST OF FIGURES

This Page Intentionally Left Blank.

EXECUTIVE SUMMARY

In 1911 a Dutch scientist discovered a class of materials which, at temperatures near absolute zero, could conduct electricity with no resistance and therefore zero loss of power. In spite of the revolutionary potential of this superconducting material, the difficulty in producing engineered materials and in maintaining low operating temperatures precluded practical applications for many decades. The recent dramatic discoveries of high temperature superconducting materials (up to 125 degrees Kelvin) have prompted an intense international surge in superconductivity research and development.

This surge of research and development activity, particularly that of the Japanese, combined with the promise of revolutionary performance improvements in many applications prompted President Reagan to establish a national program in high temperature superconductors. The Defense Science Board was tasked to study the military system applications of superconductors. The attached report presents the findings of this study.

The Task Force found a number of superconductivity applications that could result in significant new military capabilities, including electronics and high power applications. In particular, superconducting materials could enable significant military improvements in:

- *Magnetic Field Sensors* with greatly increased sensitivity for improved detection and identification capability ;
- *Passive Microwave and Millimeter-wave Components* enabling increased detection range and discrimination in clutter ;
- *Staring Infrared Focal Plane Array* sensors incorporating superconducting electronics permitting significant range and sensitivity increases over current scanning IR sensors ;
- *Wideband Analog and Ultra-Fast Digital Signal Processing* for radar and optical sensors ;
- *High Power Motors and Generators* for ship and aircraft propulsion leading to: decreased displacement; drive system flexibility; increased range; or longer endurance on station ;
- *Magnets/Energy Storage* for high power microwave, millimeter-wave or optical generators (e.g., free electron laser); capability for powering quiet propulsion systems ;
- *Electro-Magnetic Launchers* capable of launching hypervelocity projectiles for anti-armor weapons and close-in ship defense weapons ; and
- *Magnetohydrodynamic (MHD) Propulsion* enabling ultra quiet drives for submarines, torpedoes, and surface ships . (U)

As these examples illustrate, superconducting materials have potential for significant military applications. It is important to note that many of the applications have high value for commercial and scientific applications as well. However, an extensive program of basic and applied research and materials development will be necessary to make these applications possible. The present R&D level in the U.S. is below critical mass to achieve the desired applications in a timely way. By comparison, the Japanese effort in superconductors is substantially greater than that of the aggregate U.S. commercial and government effort. If these trends continue, the U.S. may fall so far behind in this field that defense and important commercial applications will be achieved only by using foreign source materials and designs as they become available to the U.S. It is the judgment of the DSB that such dependency on foreign sources is an unacceptable position for the U.S.

We have recommended a significantly expanded superconductor R&D program for the Department of Defense which increases the 1989 effort by 50 percent and triples the current effort by 1992. The Task Force members believe such an aggressive program is required to assure U.S. leadership in the many high leverage superconductivity applications. This recommended R&D effort is balanced between exploitation of old (LTS) materials and development of new (HTS) materials. It includes a vigorous program of building engineering models that will demonstrate the substantial performance advantages achievable with superconducting materials. The demonstration programs recommended include engineering models of a space surveillance system, mine detector, hypersonic tank gun, undersea MHD propulsion system, and a millimeter-wave radar. Most of these efforts involve old (LTS) materials. To achieve the very real cost, weight, and logistic benefits of the new (HTS) materials in these applications, substantially more progress must be made in the U.S. R&D program, particularly in the development of new material processing techniques. We have also recommended the development of improved militarized cryogenic devices, because even the new HTS materials will require cooling. In the near future we do not anticipate room temperature operation of superconducting materials.

In summary, superconductor materials represent a major opportunity to significantly improve performance in important defense missions as well as in commercial applications. To achieve these benefits, we will need to make substantial, focused increases in R&D over a sustained period. While U.S. superconductivity research is competitive with that of other countries, we cannot count on our commercial developments providing this capability for defense. In fact, U.S. industry is already well behind Japanese industry in the development of superconductivity applications.

SECTION 1 INTRODUCTION

The recent dramatic discoveries of high temperature superconducting materials (up to 125 degrees Kelvin as shown in Figure 1-1) have prompted an intensive international surge in superconductivity research and development. As a result, the Defense Science Board was tasked (terms of reference, Appendix A) to study the military system applications of superconductors. The tasking specifically requested:

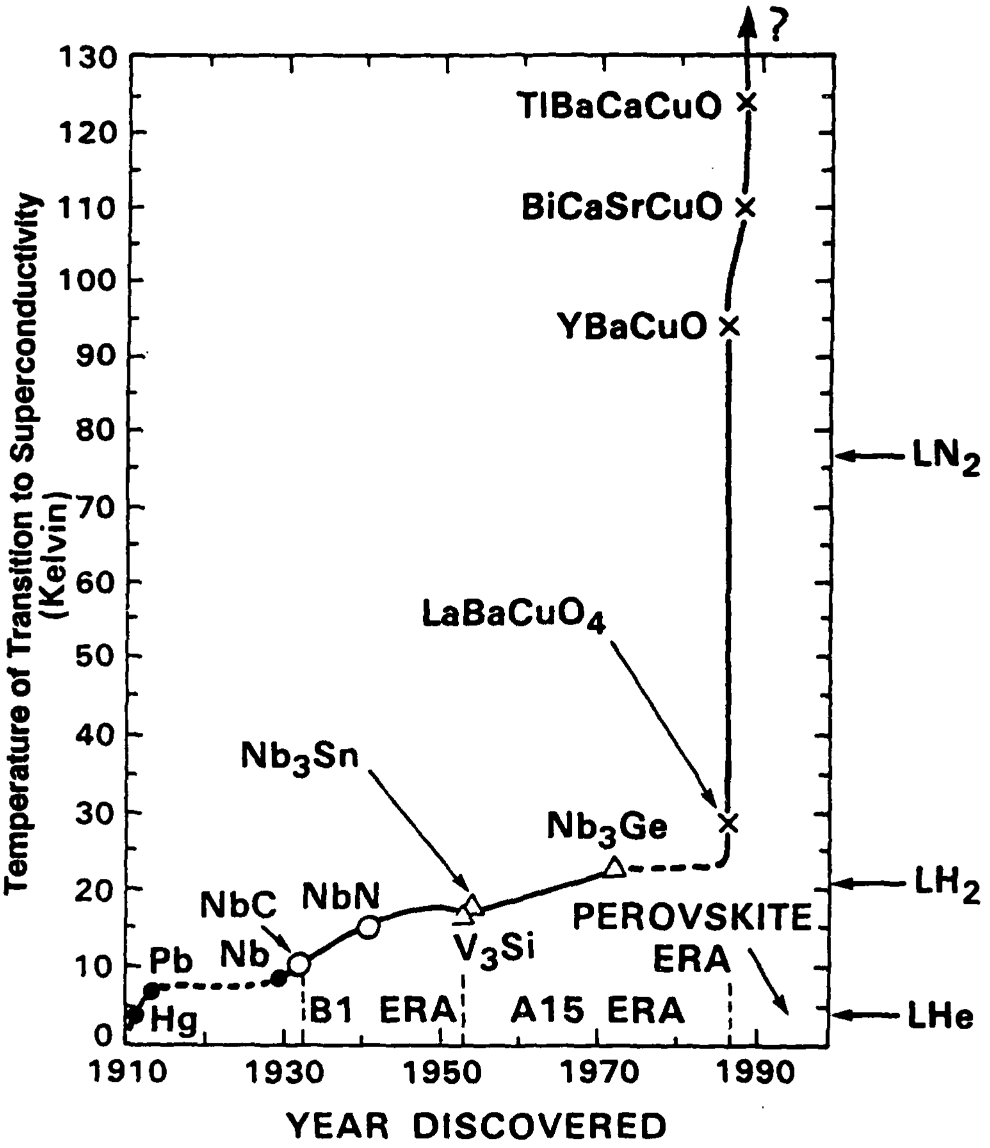
- A review of the current understandings of superconductor physics, as well as the status of materials properties and their processing.
- An evaluation of possible military system applications with emphasis on their potential for significant new capabilities and cost savings.
- Identification of commercial or scientific applications of interest to DoD.
- Identification of supporting technology necessary for realization of military applications.

Task Force membership, Appendix B, heard a variety of presentations, which are listed in Appendix C.

The Task Force concluded that there are some very significant military superconductivity applications which could result in enhanced military capabilities. Some of these are ready for engineering models using low temperature superconductors. However, an extensive program of research and materials development will be necessary to make these applications possible in HTS. Given the current level of foreign investment in this area, there is a substantial possibility that the United States will fall behind in superconducting materials processing capability.

Figure 1-1

TIME LINE FOR DISCOVERY OF SUPERCONDUCTORS



SECTION 2 FINDINGS

The Task Force focused on the following aspects of superconductor technology:

- Superconductivity theory, technology, and materials (both low temperature and high temperature technologies)
- Selected supporting technologies (cryogenics and high strength materials)
- Military applications
- The level of U.S. and foreign research expenditures in high temperature superconductivity

STATUS OF SUPERCONDUCTING THEORY, TECHNOLOGY, AND MATERIALS

A superconducting state is characterized by zero dc electrical resistance and zero internal magnetic field. Materials technology and theory are discussed for two classes of superconductor applications: electronics and high power systems . Electronic applications typically incorporate thin superconducting films and integrated circuit structures. High power applications use a composite, multi-filamentary wire. The technical usefulness of *superconductors* is limited to temperatures not exceeding 0.5 to 0.7 of the superconducting transition critical temperature (T_c), as shown in Figure 2-1. The figure depicts the critical surfaces which bound the current densities, magnetic fields, and temperatures which can be achieved by superconducting materials. The niobium-containing materials were identified and studied by 1950. The current high temperature materials are exemplified by the surface indicated in dashed lines (YBaCuO). Projection of a point in the temperature-magnetic field plane on such a surface defines the highest possible (critical) current density, J_c. It should be noted that, due to their early state of development, there is great uncertainty in levels of current density which can be achieved for the new high temperature materials.

LOW TEMPERATURE SUPERCONDUCTORS (LTS)

LTS materials of interest have T_c's grouped either around 10 degrees K (niobium metal, and niobium alloys) or between 15 and 23 degrees K (mostly niobium compounds). These metallic materials conduct electricity in all directions, thus simplifying the fabrication of conductors. They are used predominantly in polycrystalline form and are capable of sustaining very high current densities.[1]

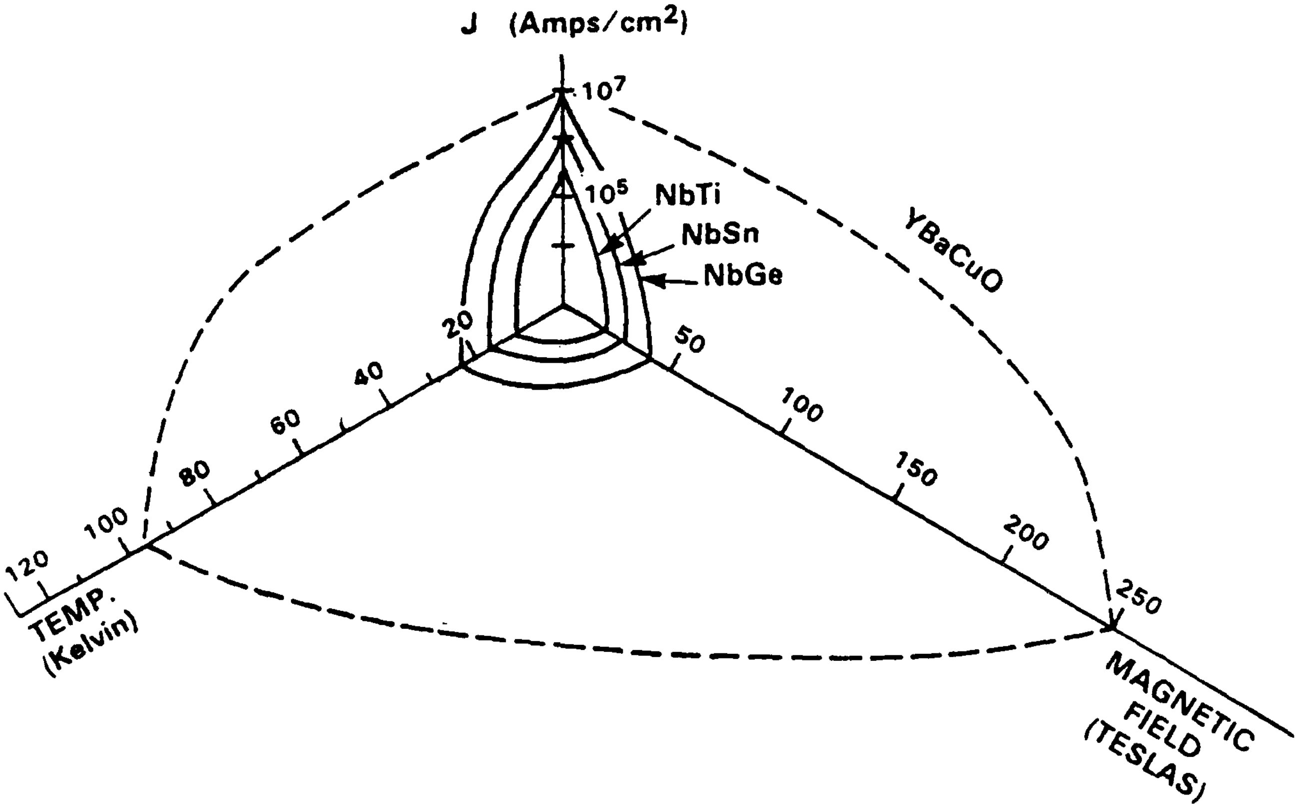
The phenomenon of low temperature superconductivity is well understood using the theory developed by Bardeen, Cooper, and Schrieffer (BCS). The publication of the BCS full

---

[1] $J = 10^6$ to 10^7 A/cm^2 in low magnetic fields and 10^4 to 10^5 in high fields at liquid helium (LHe) temperature, T = 4.2 degrees K).

Figure 2-1

OVERVIEW ASSESSMENT



microscopic theory of superconductivity in 1957 was a significant contribution to modern physics. This theory led to the prediction of the Josephson effect, a non linear tunneling process exploited in many electronic devices. This theory also helped guide the development of materials suitable for useful magnets.

For electronic applications at liquid helium temperatures, all-refractory niobium devices and circuits are in a mature state. In contrast to Japan, the U.S. has a limited industrial base for fabricating superconducting LSI circuits for digital application and currently has no design capability for digital circuitry. For electronic applications above 4.2 degrees K and within the lowest threshold of portable closed-cycle refrigeration ($T = 8$ to 10 degrees K), the material of choice is niobium nitride. The technology to produce NbN devices and LSI circuits is not mature but demonstrated to be feasible. Further investment in the industrial fabrication base is required to attain required tolerances and yields.

Ductile niobium titanium alloys allow composite conductors to be fabricated for magnet and machinery applications involving dc magnetic fields up to 6-8 tesla. This technology is mature. The ac applications are limited by unavoidable conductor losses. Niobium tin wires can sustain dc magnetic fields up to 12-16 tesla but are brittle. Although a U.S. industrial base for this technology exists, applications are limited by poor mechanical properties and the cost of supporting structures. Non-ductile superconductors which sustain fields up to 20-30 tesla are known but the feasibility of manufacturing practical wires has not been fully demonstrated. All materials manufacturing capabilities in the U.S. reside in small companies. Few applications are being pursued at the very high field levels due to the excessive mechanical support required to withstand the enormous forces associated with such magnetic fields.

HIGH TEMPERATURE SUPERCONDUCTORS (HTS)

The HTS materials currently under development are cuprates (oxide compounds of copper, an alkaline earth metal and other elements) discovered in 1986 with critical temperatures in excess of 30 degrees K. Due to the very high level of worldwide research effort, the number of these materials and their confirmed T_c's are growing. The highest critical temperature recorded to date is 125 degrees K, in a thallium-based cuprate. The most researched material is $Y_1Ba_2Cu_3O_7$ (YBCO) and its derivatives where Y is replaced by another rare-earth element. Their common T_c is 90-95 degrees K. These HTS are capable of conducting electricity, however, they exhibit strong directional electrical conduction properties. These materials have the ability to sustain extremely high magnetic fields without loss of superconduction.[2] Although single crystals of YBCO are capable of sustaining very high current densities, presently available wires and films of the new HTS materials sustain only low current densities in zero applied magnetic field at 77 degrees K.[3] These current densities fall off rapidly in increasing magnetic fields.[4]

---

[2] (Estimated at 50 to 300 tesla near $T = 0$ degrees K and, in YBCO, up to 20 tesla at the temperature of liquid nitrogen (LN_2), $T = 77$ degrees K)

[3] ($J_c = 3 \times 10^3$ A/cm^2 at 77K in zero field)

[4] ($J_c = 10^6$ to 10^7 A/cm^2 at 77K in zero fields and 0.5×10^6 A/cm^2 in fields up to several tesla.)

In contrast to the LTS case, theoretical understanding of HTS is still poor. The phenomenon was not predicted, and may represent a new physical effect. Greater understanding would further enable the development of useful materials and devices. Further basic discoveries, both experimental and theoretical, can be expected in the next few years. These should have a beneficial (if unforeseeable) impact on development projects.

HTS materials may prove useful for electronics in the form of both single crystal and polycrystalline films. Several thin film fabrication techniques have been demonstrated; others are being researched. For electronic applications, HTS films currently exhibit properties which require further study, such as high microwave losses. The loss mechanism is partially understood, so suitable loss reduction appears feasible. Current films are also characterized by high electronic noise. Noise mechanisms are being investigated and eventual reduction is expected.

Significant effort is required to pursue the capability for design, fabrication, and optimization of today's HTS materials. The HTS materials manufacturing base must be aggressively developed in order to provide the basis for the wide range of potential military and commercial applications. Appendix D outlines the range of materials and manufacturing issues which must be addressed for HTS materials. The U.S. is at a significant disadvantage, particularly with respect to Japan, in that our manufacturing capabilities in advanced ceramics is limited. Most essential is research to determine the nature of current-limiting weak links and to attain high critical currents in polycrystalline materials. Further development of thin film processing capabilities for hybrid (semiconductor plus superconductor) structures is needed. While the materials technology for brittle conductors poses very challenging technical and economic problems, solutions to these problems appear feasible.

The initial high temperature superconductivity developments in basic research materials, and manufacturing sciences needed for military applications are also relevant for commercial applications. In both cases, a strong industrial base for manufacturing materials and components is needed for near-term, cost effective deployment of both commercial and military devices.

STATUS OF SUPPORTING TECHNOLOGIES

CRYOGENIC COOLING

One technology that has limited the previous use of superconductors has been the availability of reliable, long-life, cryogenic coolers. An extensive review of current cryogenic technology is contained in Appendix E. The older materials required cooling to 10 degrees Kelvin or lower. The new materials with critical temperatures between 90 and 125 degrees Kelvin are likely to require cooling to 40 to 80 degrees Kelvin. Since cryogenic cooler efficiency and complexity are strongly dependent on how closely absolute zero is approached, the new high-temperature materials should greatly ease the cooling problem.

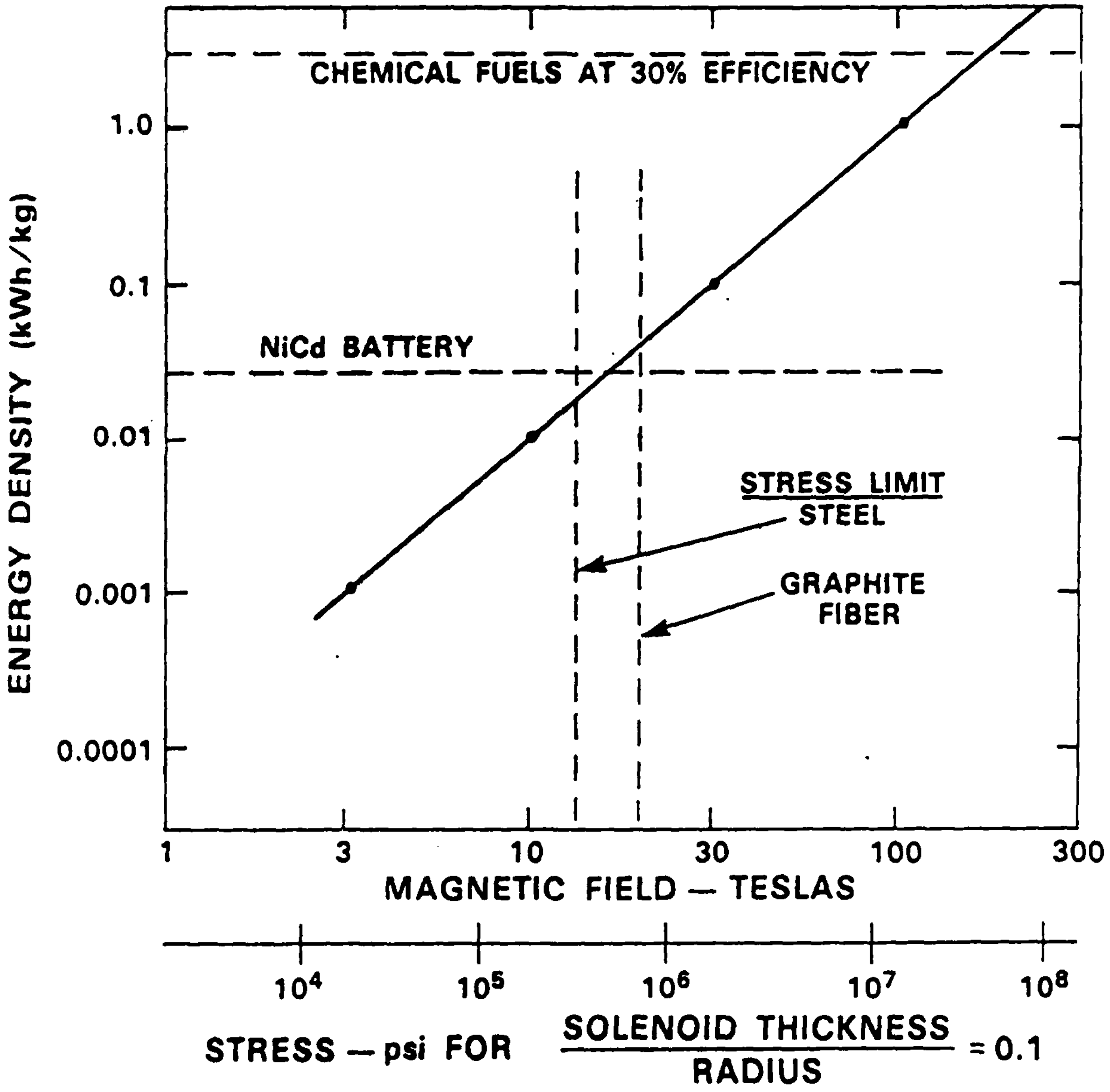
At the present time, coolers (to 4 degrees K) for commercial ground-based applications are available. The availability of low temperature, ruggedized, long-life coolers for military and space environments is much more limited. At higher temperatures (40 to 80 degrees Kelvin), a number of low-power (up to 1 watt cooling capacity) military designs exist which are suitable for electronics applications. The principal deficiency is the lack of proven long life, high-capacity, militarized coolers for high-power applications.

HIGH STRENGTH MATERIALS

Achieving the high current densities and magnetic field levels of many high power superconductor applications will require significant advances in high strength materials. As shown in Figure 2-2, the stress exhibited by magnetic fields above 15 to 20 teslas exceeds even the capabilities of graphite fibers. In fact, mechanical stress levels, not current density, are the principal limiters to high power HTS applications. Any movement to higher field levels will exceed available structural materials capabilities. To make possible such applications, further development of composite superconducting/high strength materials is needed. It appears, however, that certain mechanical constraining structures may also be used. (see Appendix F).

Figure 2-2

MAGNETIC ENERGY STORAGE LIMITS



MILITARY APPLICATIONS OF SUPERCONDUCTORS

INTRODUCTION

Superconductor technology, both for the older low temperature materials and the new high temperature materials, has very wide applicability in both military and civilian products. As shown below, superconductor technology can be applied to a number of important electronic and high power applications.

ELECTRONICS

Magnetic Field Sensors
IR Sensors
Microwave/mmWave Sensors
DC to UHF Sensors
Analog to Digital Convertors
Analog Signal Processors
Digital Data Processors

HIGH POWER

Magnets
Electrical Machinery
Electro-Magnetic Launchers
EnergyTransmission
MHD Propulsion
Energy Storage

Superconductor technology will support a number of important military systems including ballistic missile submarines, ballistic missile defense, anti-armor warfare, advanced air-to-surface missile, and anti-submarine warfare.

ELECTRONICS

Overview

Military and space systems place the greatest demands on the performance of electronic devices, components, and systems. In this performance-driven field, superconductive electronics can have a major impact on sensor, signal processing, and data processing systems. The impact of superconductors in electronics is based on several unique attributes which make possible:

- Ultra-low loss/dispersion transmission lines and filters;
- High speed, low noise, and low power Josephson junction active devices;
- Superconducting quantum interference devices (SQUIDs) used for magnetic and electro-magnetic sensing;
- Monolithic integrated circuits for both analog (microwave and millimeter-wave) and digital components.

Uniquely, ultra high speed, low noise and low power can be realized simultaneously in superconductors.

IR Sensors

Superconductivity's major impact on IR sensors is the reduced power required to cool the signal processing and data extraction components supporting large focal plane arrays. This allows realization of large staring arrays with greater sensitivity and range than the lower performance scanning sensors which they would replace. Superconductors also have the potential to improve detectivity at longer wavelengths, spatial resolution, and large array manufacturability.

Future space based IR focal plane array (IRFPA) sensors will incorporate a large detector array, electronic multiplexing circuits, and a data harness from the cryostat to ambient temperature electronics. Because of the large number of detectors required, signal processing for these sensors is a major technological bottleneck. CMOS A/D converters could consume several kilowatts of power. Equivalent LTS A/D converters, cooled to the 10 degrees K temperature of the IR detectors, could reduce this power requirement by 90 percent. LTS A/D convertors dramatically reduce cooling power requirements and significantly reduce system weight and size (Figure 2-3).

The availability of HTS A/D converter technology will require development of active devices in the new materials systems. Such devices will be important for IR detectors operating at higher temperatures whether semiconducting or superconducting (e.g., HgCdTe at 77 degrees K). The key is to deploy low power A/D converters which can operate at the detector temperature. Projected on-chip power dissipation for these superconductive A/D converters is linear with temperature, but reduction in cooling power more than compensates for this due to signal processing power requirements. Some very large infrared imaging arrays may only be feasible with superconductive A/D converters.

Microwave and MMW Sensors

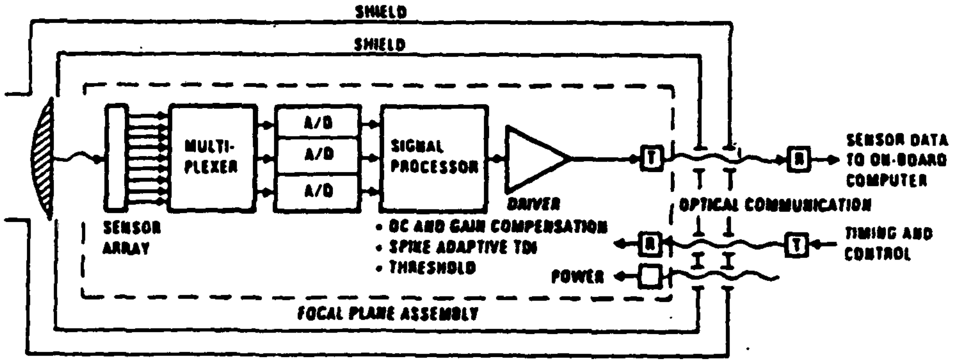
Low noise, low power monolithic receivers incorporating superconductors will have improved range and resolution. These improvements are especially important for space surveillance and communications. While the improved noise figure alone does not justify superconductors for earth or ocean imaging, it is impractical to deploy focal plane arrays of conventional detectors at MMW. With superconductor technologies, multi-band MMW imaging arrays may be feasible. These arrays could provide an all-weather capability, as well as cloud and smoke penetration not available in visible and IR systems; improved spatial and Doppler resolution, and the capability to detect low signature targets. Multi-element MMW focal plane arrays improve signal collection efficiency proportional to the number of array elements.

In a low background space communication link, the improved receiver noise (Figure 2-4) can increase range, reduce power requirements to a level where solid state transmitters become attractive, and/or reduce antenna size and weight. These attributes should enhance system lifetime, autonomy, and security. High temperature superconductor technology could improve the viability of very wideband communications systems. A major impact of HTS will be lightweight passive microwave/MMW components for phased array spacecraft antennas and improved MMIC components such as oscillators.

Figure 2-3

SUPERCONDUCTING FOCAL PLANE PROCESSING REDUCES POWER, WEIGHT, AND COMPLEXITY

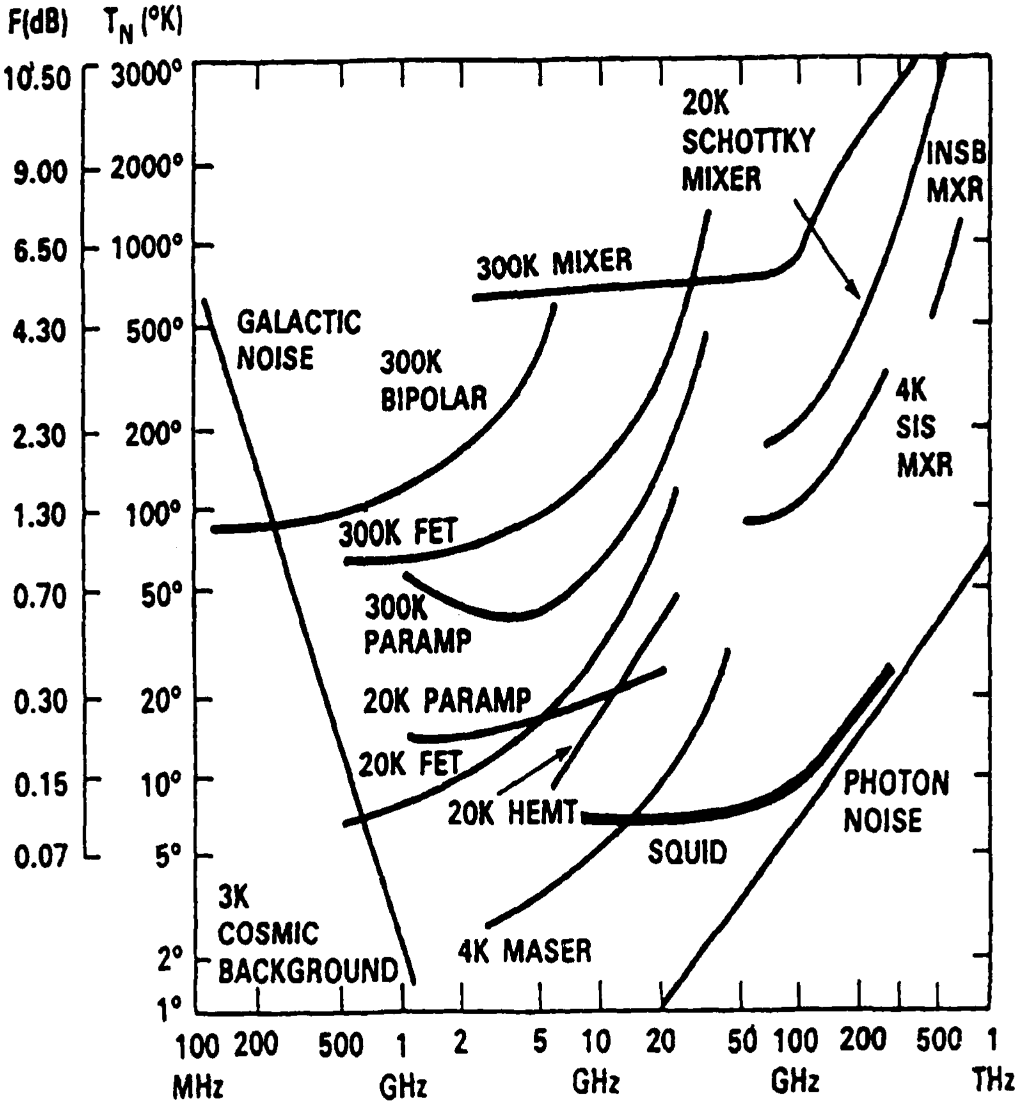
	Number of A/D Converters	Power (W)	Data Lines
VHSIC II/CMOS	5000	2500	20,000 Cu
Nb materials	5000	100	2,000 fiber optics



- Higher speed and lower power dissipation allows faster update times and larger number of array elements using superconducting processing
- Operation of superconducting processor is consistent with cooled detectors
- Use of fiber harness reduces heat load, weight, and size
- Applications for wide area IR or visible surveillance

Figure 2-4

NOISE FIGURE (F) AND NOISE TEMPERATURE FOR VARIOUS DEVICES AND NATURAL LIMITS - 1984



DC to UHF Sensors

The extremely low noise inherent in a superconducting SQUID amplifier permits the use of a very small antenna at UHF frequencies and below while retaining both high sensitivity and wide bandwidth. Applications would include ELF/VLF communication systems and advanced HF receivers as well as compact high gain UHF antennas.

Magnetic Sensors

Low temperature superconducting SQUID magnetometers and gradiometers are already highly developed and commercially available. These low temperature SQUID devices are under evaluation by the Navy for ASW applications and mine detection. Figure 2-5 compares the performance of superconducting SQUIDS with conventional magnetic sensors. At higher temperatures, thermally-generated noise power will be inherently larger than at lower temperatures, eliminating some detector noise-limited applications. The complexity of the logistical support would be significantly reduced which would make currently unattractive remote sensing applications much more practical.

Signal Processing

A/D Converters

Superconducting A/D converters offer significant advantages in speed and power efficiencies over semiconductor devices. Figure 2-6 shows that the predicted performance of superconductive A/D converters exceeds projections of conventional converters in both speed and linear resolution. The development of HTS A/D converters will substantially increase their utility due to reduced cooling, lower overall power dissipation, and improved performance. The significantly lower power will make it possible to deploy multi-channel A/D converters for analysis of multi-GHz spectral systems.

Delay Line Signal Processor

Analog signal processors based on tapped delay lines provide wideband signal processing for wideband radar and communications systems. Superconductor devices have the capability to perform waveform chirp, convolution, correlation, spectral analysis, and matched filtering with bandwidths as high as 20 GHz. Use of new HTS materials will allow integration with semiconductor devices to expand functional performance. The reduced cooling requirement will open deployment opportunities in many wideband radar and intercept systems.

Figure 2-5

COMPARISON OF SUPERCONDUCTIVE MAGNETIC SENSORS WITH CONVENTIONAL MAGNETIC SENSORS

	CONVENTIONAL MAGNETIC SENSOR	LTS MAGNETIC SENSOR	HTS MAGNETIC SENSOR
SENSITIVITY	10^{-5} TO 10^{-8} Gauss	10^{-9} TO 10-^{10} Gauss	SLIGHTLY LESS THAN LTS SENSOR
MEASUREMENT CAPABILITY	Field Strength Only at 10^{-8} Gauss; Not Capable of Measuring Source Strength and Location	Full Field Gradient; Capable of Measuring Source Strength and Location	Full Field Gradient; Capable of Measuring Source Strength and Location

Figure 2-6

SUPERCONDUCTING VS. SEMICONDUCTING A/D CONVERTERS

TECHNOLOGY	BITS (N)	SAMPLING RATE (MSPS)	PWR (mW)
JJ (Counting Type)	12* 6*	10 640	0.020 0.020
CMOS (VHSIC Phase 2 Goal)	12	10	500
SILICON BIPOLAR	6-8	500	8000

TRENDS: SEMICONDUCTOR CONVERTERS - PWR ~ 2^N
JJ CONVERTERS - PWR ~ N

* FURTHER IMPROVEMENT OF 4 BITS (or 16 in speed) EXPECTED

Digital Signal And Data Processing

LTS digital signal processors provide more than a factor of ten increase in processing speed over conventional GaAs logic for the same complexity and at lower power dissipation (Figure 2-7).

Computers can also realize significant performance benefits through application of LTS technology. The shortest response time measured to date is approximately two picoseconds or $2\mathrm{x}10^{-12}$ seconds. This, combined with signal swings of a few millivolts, produces high performance logic circuits that consume very little power.

Fujitsu has reported a four bit microprocessor based on Josephson technology that is ten times faster and consumes 0.002 times the power of a gallium arsenide version of the same microprocessor. (See Appendix G).

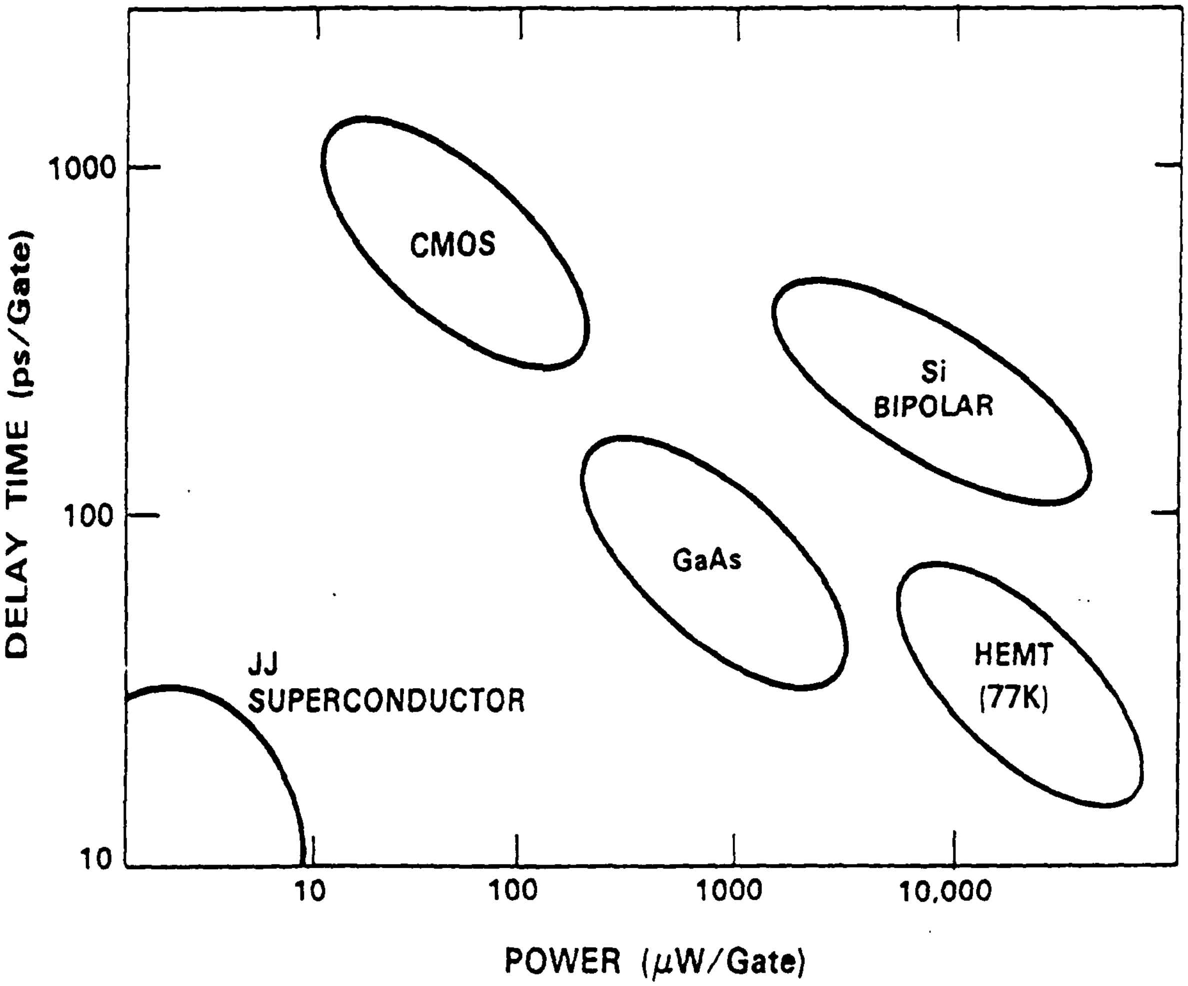
A critical problem in high performance computing is heat removal. For a given heat removal technology the space required per circuit at the systems level increases as the power per circuit increases. Therefore, the transit time or the time to transmit logic signals within the system becomes increasingly important in determining overall system performance. The very low power requirement of a low temperature Josephson technology system is partially offset by the power required to maintain the low temperature. However, the very low power required by even a large system permits the sytem to be built in a very small volume. The greater device speed combined with the shorter transit time will provide greater computational capability in LTS for equivalent total power dissipation (including cooling).

At the present time, approximately ten circuit families based on the Josephson technology, have been reported. All of these circuit families are of the Kirchhoff or threshold logic type. This type of circuit performs logic by summing currents and, as a result, is sensitive to parameter variations. Josephson technology has evolved in this direction because the Josephson device is a two terminal device without power gain.

There is no fundamental reason to believe that a superconducting equivalent of the transistor is not feasible. If such a device can be developed that has power gain with very high performance, it would revolutionize the use of superconducting technology in computing systems. HTS materials show great potential because they may be much more compatible with semiconductor materials than the older superconductors, thus enabling hybrid approaches (superconductors with semiconductors). It should be emphasized, however, that achieving the potential of three terminal devices will require the invention of a fundamentally new device.

Figure 2-7

DIGITAL SUPERCONDUCTING/SEMICONDUCTING GATE/CIRCUIT COMPARISONS



HIGH POWER APPLICATIONS

High power applications will primarily exploit the intense critical magnetic fields that can be generated by high current density superconductor materials.[5] There are many promising application areas for such materials. Superconductor magnetic fields can store large amounts of energy for extended periods of time. They can provide compact, high magnetic field sources for rotating electrical machinery and offer the promise of unconventional electric drive systems for military platforms. Employed in weapons, they can accelerate projectiles to exceptionally high velocities and, as control magnets for electron-beam tubes they can provide high-power sources of millimeter and visible wavelength energy. All of these possibilities include important military applications.

Magnets -- Applications

The earliest superconductor technology applications were high-field magnets used in particle accelerators and energy storage inductors. In operation, energy is fed into the inductor slowly, stored for an arbitrarily long period, and then released on demand. A modest-sized superconducting storage inductor ($3x10^7$ joules) has already been used by the Bonneville Power Administration. A larger scale storage system (10^{12} joules), could meet the high-peak power demands of a ground-based free electron laser or a space-based directed energy weapon. Magnetic energy storage devices with high critical fields could reduce the size and weight of these storage devices as shown in Figure 2-8.

Near term applications of high-field magnets could include superconducting beam control magnets employed in gyrotrons and free-electron lasers for the generation of high-power levels at microwave, millimeter and optical wavelengths.

Electrical Machinery

The quickest payoff in high-power applications will come from the exploitation of superconductor materials in rotating electrical machinery. Substantial weight savings can be realized by eliminating magnetic circuit materials and customary field windings. Already, an experimental 3-megawatt superconducting D.C. motor has been built for ship propulsion and tested at sea. This motor was 33 percent smaller than the equivalent conventionally air-cooled A.C. motor.

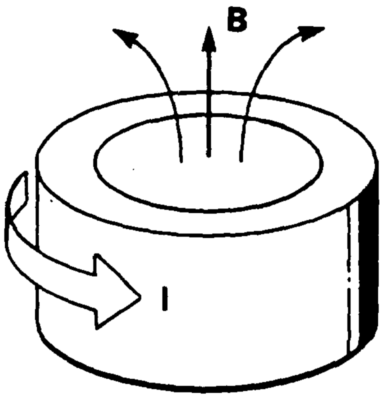
Substantially greater motor size reductions are possible with conventional LTS materials. A superconducting homopolar D.C. motor of 40,000 h.p., employing superconducting shielding, could be built at about one fourth the size and weight of a contemporary A.C. motor. The decreased size and weight and increased electrical efficiency reduce fuel requirements and lead to an overall reduction in propulsion system demand on the ship's resources. A superconducting generator, which may be located remotely from the ship drive motor, will provide an efficient, flexible ship propulsion system. The effect on a destroyer-class ship's performance would be to reduce ship displacement by 14 percent and increase its range by 30 per-

---

[5] Critical magnetic fields have been measured up to 20 tesla (T) at 4 degrees K for conventional LTS and 30 T at 77 degrees K for HTS.

Figure 2-8

MAGNETIC ENERGY STORAGE



$$\text{ENERGY/VOLUME} = \frac{B^2}{2\mu_o}$$

B (TESLAS)	E/V (kWh/m^3)	SPECIFIC ENERGY (kWh/kg)
1	0.15	4 X 10-4
5	3.8	.004
20	60	.045
30	135	.100
NiCd BATTERIES		.030

cent. If the propulsion system were mounted in an external pod, the ship's displacement could be decreased by 25 percent and its cruising range increased by 40 percent.

As illustrated in Figure 2-9, high temperature, high field materials would allow further decreases in weight and size. At this point, the propulsion system would be a negligible fraction of overall ship displacement, and multiple redundant drive systems could be installed.

While the first high-power propulsion applications are likely to be in ships, Figure 2-9 suggests that high-field superconductors could also provide light-weight generators and motors for armored vehicles and, more speculatively, for aircraft propulsion. It must be emphasized that if these systems are to come about, the necessary cryogenic support systems must be developed to withstand the rigors of an operational environment.

Other superconductor propulsion sysems are clearly foreseeable. In Japan Magneto Hydrodynamic (MHD) drives have been built and tested at scale-model level by Kawasaki Heavy Industries. By 1990, Mitsubishi Heavy Industries, in partnership with Toshiba and Kobe Steel, plans to have a 120-ton displacement ship with MHD drive in operational test. In addition to surface ships, MHD drives can also find use as quiet propulsion systems for submarines and torpedoes. Speculating about further term applications, an MHD collector-diffuser and an MHD magnetic nozzle may make feasible a "scramjet" propulsion system for space bodies traveling in an ionized medium. In this concept (Figure 2-10), a combustor operates between two MHD sections, one of which adjusts the flow velocity and temperature to be suitable for combustion, and the other of which provides thrust augmentation. Excess inlet gas energy is removed by the forward section and re-injected as electrical energy into the stream by the aft section. This will require particularly compact and lightweight magnetic field sources.

Launchers

The electromagnetic (EM) mass accelerator concept is some 25 years old and has been explored intermittently. Recently, SDIO has supported EM rail-gun technology for use as a projectile accelerator. The EM accelerator is of interest because it is capable of propelling a large mass to a very high velocity. Unlike chemical propulsion systems, the achievable terminal velocity is not limited by the speed of exploding gas, but rather by the speed of a traveling electromagnetic pulse. Hence, a projectile could be accelerated to act as an effective kinetic energy weapon. EM accelerator applications include: launching close-in ship-defense projectiles against cruise missiles, launching torpedoes from submarines, or as a hypersonic anti-armor weapon which, because its velocity could exceed the sound velocity in protective armor, would be an assured penetrator.

Superconductor materials, whether LTS or HTS, will increase the feasibility of EM launchers as military weapon systems for many of the reasons previously stated in other applications -- lower weight, smaller volume, and higher efficiency. Superconductor materials would be used in the prime power generator, in the energy storage system and in the high speed switch which could employ superconducting thin films.

Figure 2-9

MOTOR/GENERATOR APPLICATIONS

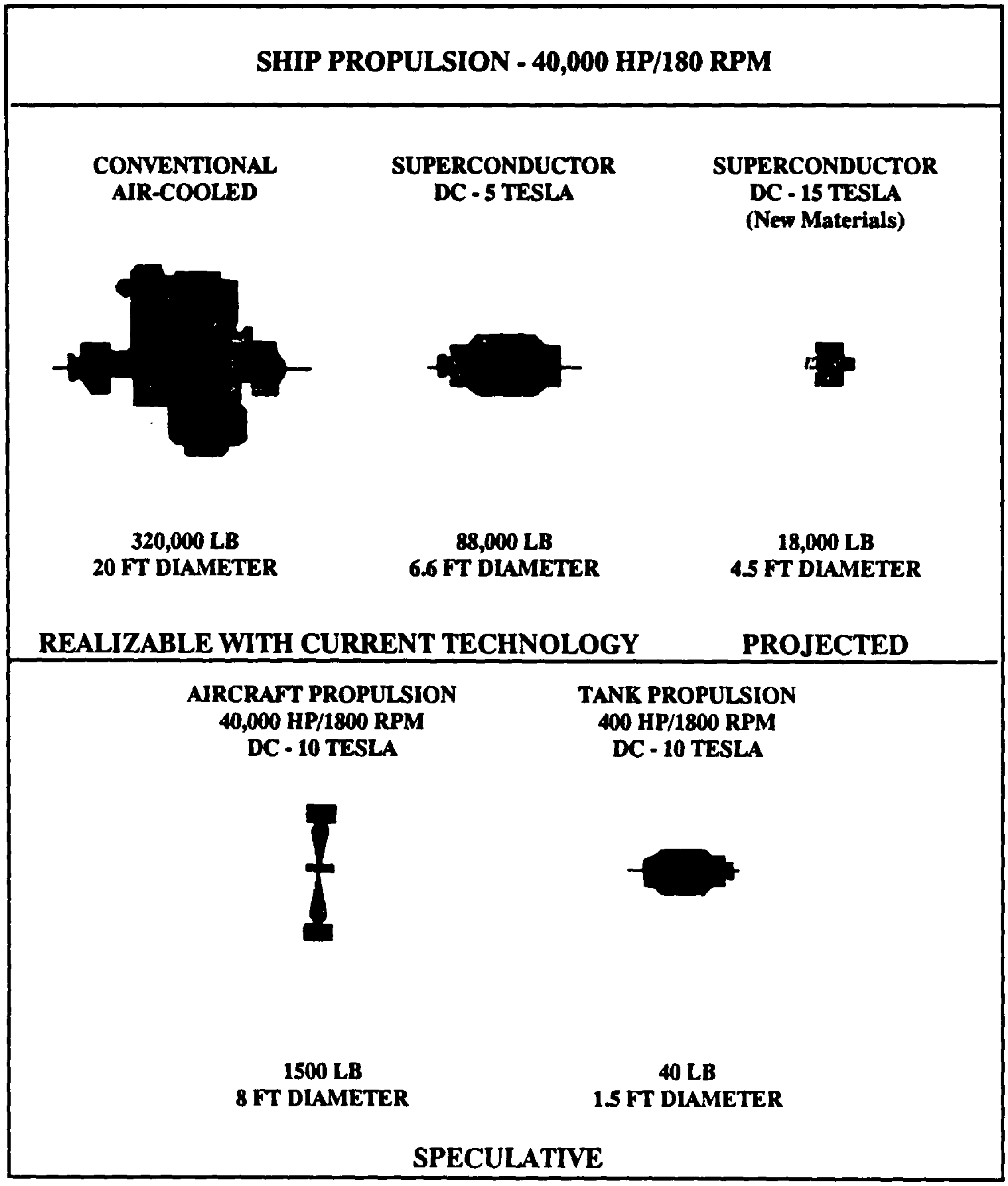
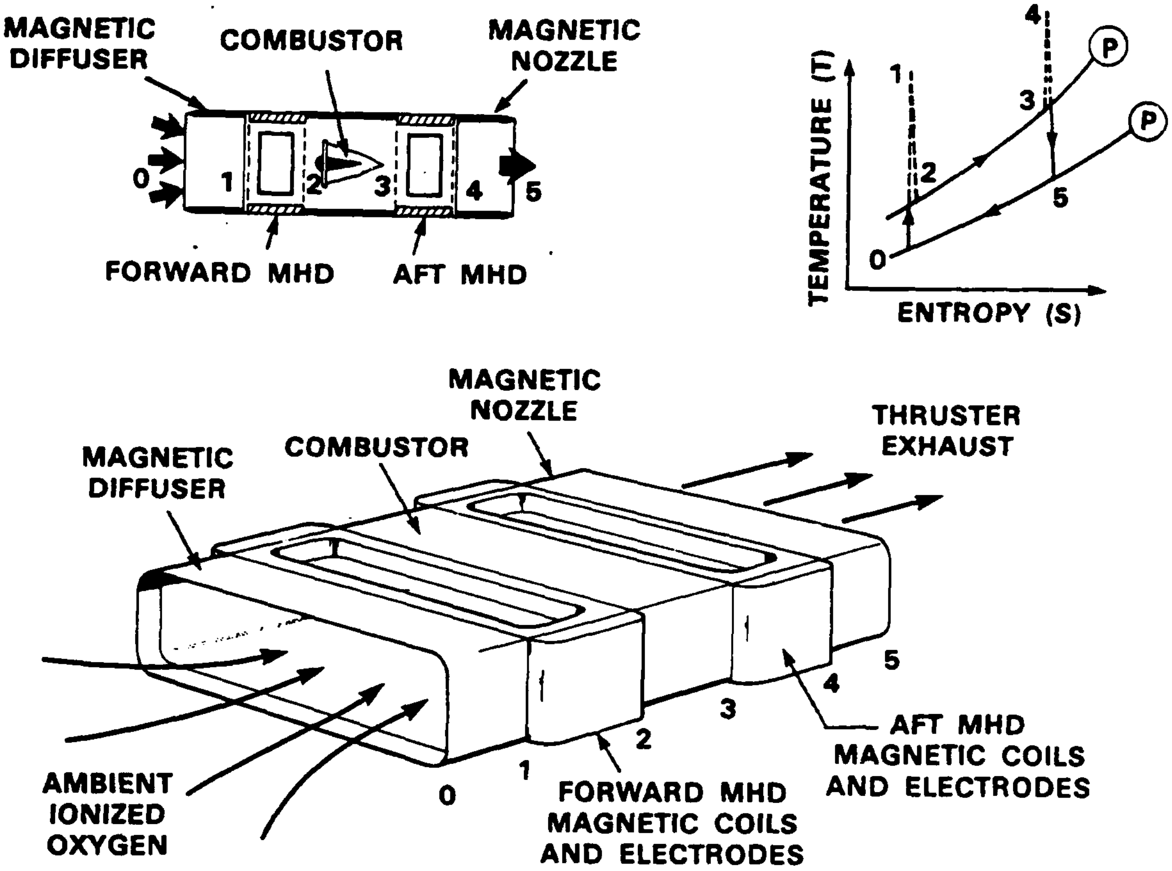


Figure 2-10

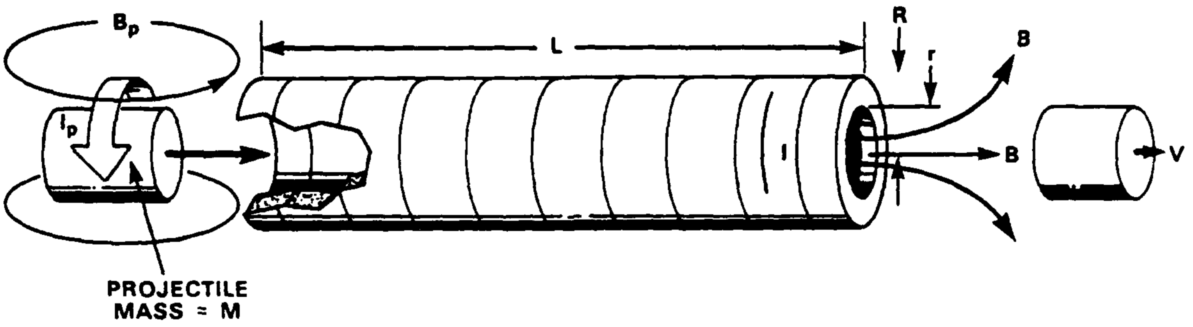
MAGNETICALLY ASSISTED HYPERSONIC RAMJET



High-current density superconductor materials could make feasible a new concept, the superconducting augmented rail gun (an inverse rail gun), in which most of the launch energy is stored in a superconducting field magnet. This eliminates the requirement for a pulsed, high-energy system to achieve the desired acceleration levels. The problem of high current, high speed sliding contacts, which is common to all rail guns, would still remain.

An EM coaxial launcher, which requires no physical contact between the projectile and launcher, has been proposed to get around the sliding contact problem. In a version known as the superconducting quench gun, it could operate very effectively with compact, high-field intensity superconducting elements. In this concept, all the launch energy is stored in a multisection solenoid barrel (Figure 2-11). The magnetic field of each section is very tightly coupled to its immediate neighbor and to the superconducting projectile coil. The projectile coil is accelerated by the solenoid magnetic field and, as it passes the mid-point of each section of the solenoid barrel, the superconducting current flow in that section is quenched. The quench gun directly converts magnetic energy into kinetic energy at high efficiency.

Figure 2-11
MAGNETIC LAUNCHERS



MAGNETIC ENERGY IN PROJECTOR $= \frac{B^2}{2\,\mu_0} \times \pi r^2\ L$

PROJECTILE VELOCITY $V \cong B \cdot r \sqrt{\frac{\pi \cdot L}{\mu_0\,(M)}}$

SOLENOID STRESS $S \cong \frac{B^2 \cdot r}{4 \cdot \mu_0\,(R - r)}$

U.S. AND FOREIGN RESEARCH EXPENDITURES IN HIGH TEMPERATURE SUPERCONDUCTIVITY

With the discovery of high temperature superconductivity, substantial R&D efforts have been undertaken in the U.S., Europe, Japan, and very likely in the USSR. It is very difficult to make estimates of national R&D efforts. 1988 estimates of U.S. and foreign high temperature superconductivity research, as drawn from CIA and NSF inputs to the Task Force, are as follows:

	FY88 FUNDING ($M)	# OF PROFESSIONALS
U.S.		
Government	95	500
Industry	50	250
Japan	135*	1000*
UK	25	300
France	20	200
West Germany	15	150

* See Appendix H for more detailed information. The above estimates for Japan do not include salaries of the researchers. All other funding numbers do include such costs.

U.S. Government funding details are contained in Appendix H. It is estimated that in 1988 approximately 500 professionals are supported by U.S. Government funding. Most of the U.S. industrially-funded research is concentrated in a few large research laboratories (e.g., IBM, AT&T, etc.). In addition, several start-up companies have been formed. The rest of U.S. industry is investing relatively little and maintaining a wait-and-see attitude.

The intensity and emphasis of the Japanese effort is notable. Both basic research and rapid industrialization are emphasized. Single crystal materials with significant current carrying capacity at 2 tesla fields have already been achieved. In contrast to the U.S., Japan is already applying significant effort toward the industrialization of both LTS and HTS. According to a recent OTA report,

> Japanese companies have been more active in pursuing the commercial potential of HTS. They have more people at work, many of them applications-oriented engineers and business planners charged with thinking about ways to get HTS into the marketplace...As the Scientific race becomes the commercial race, Japanese firms could quickly take the lead. Indeed, they may already be doing so.[6]

The European efforts are mainly concentrated in universities and emphasize basic research.

At the present time, it seems clear that high-temperature superconductivity research is geographically widespread and that the U.S. is not the principal focus of research.

---

[6] Commercializing High Temperature Superconductivity, OTA Report Brief, June 1988

Based on these findings, the Task Force came to the following conclusions:

1. The new high-temperature superconductors are of great significance because of their high operating temperatures and magnetic fields.

2. The discovery of high temperature superconductors has rekindled interest in low temperature applications which have not been exploited.

3. There are Superconductor applications of potentially significant military impact, as shown in Figure 3-1.

4. To make these military applications possible, intensive research and development in the following areas will be required:
   - Expanded efforts in superconductor theory and basic research should provide the fundamental understanding of the new materials to guide applied research. Such basic research (theory and experiments) could also lead to the scientific breakthroughs which will make the speculative applications feasible.
   - Thin HTS film fabrication, with emphasis on lower processing temperatures, perfecting surfaces/interfaces, reducing RF surface losses, minimizing electronic noise, and increasing environmental stability, including radiation hardness.
   - HTS composite films/conductors/wires with emphasis on increasing current densities in high magnetic fields to useful levels, minimizing persistent current creep and AC losses, and attaining requisite mechanical strengths and flexibility.
   - Militarized cryogenic coolers with long lifetimes and increased reliability, especially portable, miniaturized coolers.
   - High strength structural materials for magnet support systems.

5. DoD sponsored developments in basic research, materials, and manufacturing processing will provide direct benefit to commercial manufacturing organizations.

6. Some applications of great military significance could be embodied in engineering models in the near future. The following programs, which combine a high degree of significance with a reasonable expectation of technical success, could be started in parallel with the efforts to develop improved high temperature superconducting materials:

Figure 3-1

ELECTRONICS AND HIGH-POWER APPLICATIONS OF SUPERCONDUCTIVITY

MILITARY SIGNIFICANCE	FEASIBILITY*
STARING IR FOCAL PLANE ARRAYS Significant Range and Sensitivity Increases Over Current Scanning IR Sensors	LTS - Low Risk HTS - Medium Risk
MAGNETIC FIELD SENSOR Increased Sensitivity for Detection and Identification	LTS - Low Risk HTS - Medium Risk
PASSIVE MICROWAVE/MILLIMETER-WAVE COMPONENTS Increased Radar Range	LTS - Low Risk HTS - Medium Risk (Phased-Array Antenna)
WIDEBAND ANALOG AND ULTRA-FAST DIGITAL SIGNAL PROCESSING	LTS - Low Risk (Analog) Medium Risk (Digital) HTS - Medium Risk (Analog) Speculative (Digital)
MOTORS AND GENERATORS Ship, Aircraft, and Advanced Vehicle Propulsion with: Decreased Displacement; Increased Range/Longer Endurance; and Drive System Flexibility;	LTS - Low Risk (Ship) High Risk (Armored Vehicle) Speculative (Aircraft)
MAGNETS/ENERGY STORAGE High-Power Generation for Microwave, Millimeter-wave or Optical Generator (e.g., FEL)	LTS - Low Risk HTS - High Risk
ELECTRO-MAGNETIC LAUNCHERS Hypervelocity Projectiles for Anti-Armor Weapons and Close-in Ship Defense Weapons	LTS - Medium Risk HTS - High Risk
MHD PROPULSION Ultra Quiet Drives for Submarines, Torpedoes, and Surface Ships	LTS - Medium Risk HTS - High Risk
MHD DIFFUSER/MAGNETIC NOZZLE High Altitude Hypesonic Propulsion; Orbital Power Generation	Speculative

---

*FEASIBILITY KEY:	Low Risk	Routine Engineering Problems
	Medium Risk	Difficult Engineering Problems, Solvable
	High Risk	Difficult Engineering Problems, May Not Be Solvable
	Speculative	Requires Engineering Discovery

- Space Surveillance System. Build an IR focal plane array demonstrating high resolution and low power consumption by combining detectors using existing extrinsic silicon materials with signal processors employing LTS materials. In parallel, a 6.2 program could develop sensor elements with HTS materials.
- Mine Detector. Build and demonstrate a magnetic field sensor with LTS materials suitable for use as a mine detector. In parallel, a 6.2 program could develop sensor elements with HTS materials.
- Hypersonic Tank Gun. Build and demonstrate an electromagnetic projectile launcher using LTS materials. This launcher should achieve hypersonic velocities capable of penetrating reactive armor and modern composite armor.
- Undersea MHD Propulsion. Build and demonstrate a small scale MHD propulsion systems with LTS materials. This engineering model would be designed to power a torpedo. Later models would be scaled up for submarine applications.
- Millimeter-wave Radar. Build and demonstrate a millimeter-wave radar. This radar would embody HTS materials in its filters, transmission lines, phase shifters and possibly the reflector.

7. Foreign investment in superconductivity research and development is increasing rapidly and significantly exceeds that of the U.S. Japan is currently spending considerably more than the total U.S. effort in superconductivity research and has targeted superconductivity as an important commercial area.

SECTION 4 RECOMMENDATIONS

Based on this evaluation, the following recommendations are made:

- DDR&E should implement a focused plan for superconductivity basic research, (theory and experiments) materials development, and application demonstrations. This plan should include cooperation with industrial organizations in order to build a strong industrial base in the area of superconductivity. This plan should also incorporate substantial funding which increases over the next several years. A model funding profile is shown in Figure 4-1.
- The Services, SDIO and DARPA should implement an aggressive plan for early exploitation of high-temperature superconductivity in electronic applications, including sensors and data processing, as well as weapon and propulsion systems. Initial emphasis should be placed on electronic applications. A suggested funding profile is included under the high-temperature 6.3 lines of Figure 4-1.
- To facilitate the earliest military applications of superconductivity, the Services, SDIO and DARPA should build a number of engineering test models exploiting existing low temperature materials. Estimates for funding of these efforts are shown in Figure 4-1 under the last two 6.3 lines.

Figure 4-1

SUGGESTED DOD SUPERCONDUCTIVITY FUNDING*
(Dollars in Millions)

		88	89	90	91	92	93
6.1	Basic Research including Theory	17	20	20	25	25	30
6.2	Applied Research on Processing of New Materials, Manufacturing Sciences, Cryogenics, and High Strength Composites	22	50	60	70	70	75
6.3	Engineering Demonstrations of Electronics Applications of New Materials (e.g., Magnetic Sensor, IR Sensor, and Microwave Antenna)	13	10	20	30	40	50
6.3	Engineering Demonstrations of High Power Applications of New Materials	0	0	0	0	10	20
6.3	Early Exploitation of High Power Engineering Test Models Using LTS (e.g., Quench Gun, MHD Torpedo for Quiet Propulsion)	22	30	50	70	80	70
6.3	Early Exploitation of Electronics Engineering Test Models Using LTS (e.g., digital signal processing, squids, millimeter-wave sensors)	5	10	10	20	20	15
	TOTAL	79	120	160	215	245	260

* This funding is over and above that being invested by agencies and organizations outside of the Department of Defense

Appendix A

TERMS OF REFERENCE

THE UNDER SECRETARY OF DEFENSE
WASHINGTON, DC 20301

ACQUISITION
DSB

4 DEC 1987

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference--Defense Science Board (DSB) Task Force on Military System Applications of Superconductors

You are requested to form a Task Force to enumerate and evaluate military system applications that may be enabled by the recent progress in high temperature superconductors. These new materials are widely recognized as enabling a technical revolution, and there has been a good deal of speculation about component or device applications.

A review of the recent technology advances will be required, but is not the main focus of this tasking. The core of this Task Force's work will be to develop a list of potential system applications parameterized in such a way that, as the technology advances, we will be able to see which concepts then become viable, and what value they may have to DoD systems. This is a somewhat more open-ended task than many and you are to have considerable latitude in carrying out your investigations. However, I anticipate that the Task Force will:

- Assess the current understanding of the physics involved in high Tc superconductivity and the status of materials processing technology necessary to produce devices. Where possible, project likely advances in critical temperature, critical fields, stability of materials, and ease of manufacture in various configurations (thin films, wires, etc.).

- Enumerate possible system applications and their military impact. Attempts should be made to quantify system performance improvements, and where possible, cost savings.

- Order the potential system applications in terms of necessary superconductor characteristics and in terms of military capability.

- Identify those system applications that will be unique to the military and those which, as they are developed for commercial interests, will assist the military. Suggest ways in which we might develop the uniquely military components and systems, as well as ways in which we might cooperate with industrial development.

- Identify what supporting technologies (those not directly related to superconducting materials) will need development in order to realize each system application.

- Make recommendations on how DoD, and in particular DARPA, should pursue development in these areas.

The Director of DARPA and the Deputy Under Secretary of Defense for Research and Advanced Technology will co-sponsor this Task Force. Mr. Walt Morrow, Jr., has agreed to serve as Chairman. Dr. Kay Rhyne of DARPA will be the Executive Secretary. LCDR George A. Mikolai, USN, will be the DSB Secretariat representative. It is not anticipated that your inquiry will need to go into any "particular matters" within the meaning of Section 208 of Title 18, U. S. Code.

Robert C. Duncan

Robert C. Duncan
Assistant Secretary of Defense
(Research & Technology)

Appendix B
MEMBERSHIP

MEMBERSHIP

CHAIRMAN

Mr. Walter E. Morrow, Jr.
MIT Lincoln Laboratory

VICE CHAIRMAN

Dr. William J. Perry
H&Q Technology Partners

MEMBERS

Dr. Philip B .Allen
State University of New York at Stony Brook

Dr. Richard N. Herring
Ball Aerospace

Dr. Donald C. MacLellan
MIT Lincoln Laboratory

Dr. Aleksander I. Braginski
Westinghouse R&D Center

Mr. Joseph Logue
Consultant

Dr. William H. Press
Harvard University

Dr. Arnold H. Silver
TRW Space and Technology Group

EXECUTIVE SECRETARY

Dr. Kay A. Rhyne
DARPA/MSD

MILITARY ASSISTANT

LCDR George A. Mikolai, USN
DSB/OUSD(A)

GOVERNMENT ADVISORS

Dr. Ted G. Berlincourt
Office of Deputy Under Secretary of Defense
Research and Advanced Technology

Dr. Bernard Paiewonsky
Office of Secretary of Air Force

Mr. Ronald Vaughn
Office of Chief of Naval Operations

Dr. Donald Gubser
Naval Research Laboratory

Dr. Clarence Thornton
Director, U.S. Army Electronic
Technology Laboratory

Dr. Harold Weinstock
Air Force Office of Scientific Research

Appendix C
BRIEFINGS PRESENTED TO THE DSB TASK FORCE ON MILITARY APPLICATIONS OF SUPERCONDUCTORS

LISTING OF SPEAKERS FOR THE DEFENSE SCIENCE BOARD TASK FORCE ON MILITARY APPLICATIONS OF SUPERCONDUCTORS

Name/Organization	Topic
January 19-20, 1988	
Dr. Aleksander Braginski Westinghouse R&D Center	"Properties of Technologically Useful Superconductors"
Dr. Richard Withers MIT Lincoln Laboratory	"Signal Processing Applications of Conventional Superconductors."
Dr. David Clarke *IBM*	"Processing and Properties of High T_c Superconductors."
Dr. Ted Berlincourt ODUSD/R&AT	"Large Scale Superconductivity Applications in the Department of Defense"
Dr. Sadeg Faris Hypres, Inc.	"Dawn of the Third Electronics Revolution Based on Superconductivity"
Dr. David C. Larbalestier University of Wisconsin	"Processing, Fabrication and Properties of Helium Temperature Superconductors"
February 24-25, 1988	
Dr. Clyde Northrup SDIO	"High Temperature Superconductors for Strategic Defense Systems"
Dr. B. van der Hoeven IBM, TJ Watson Research Center	"Josephson Technology Development Line"
Dr. H.J. Paik University of Maryland	"Superconducting Inertial Instruments for Gavity Survey and Navigation"
Dr. Kay A. Rhyne DARPA	"The New $Bi_2(SrCa)_3Cu_2O_{8+\delta}$
Dr. Phillip Allen *State Univ. of NY, Stony Brook*	"Developments of Theories and their Role in Exploiting Superconductivity"
Dr. Gary Kekelis Naval Coastal Systems Center	"Status of Superconducting Gradiometry"
Dr. Peter Kemmey DARPA	"Opportunities in Electromagnetic Launcher and Pulse Power Systems Using High Temperature Superconductors"
Dr. Arnold Silver TRW Space and Technology Group	"Superconductive Sensor andd Signal Processing Technology"

Name/Organization	Topic
Dr. Fernand Bedard National Security Agency	"Electronic Applications of Superconductivity"
March 17-18, 1988	
Dr. Michael Superczynski David Taylor Research Center	"Superconductivity Machinery and Energy Storage"
Dr. Harold Weinstock AFOSR/NE	"Air Force Research and Development Plan for Superconductivity"
Dr. Charles Hogge Air Force Weapons Laboratory	"Air Force Superconductor Applications"
Dr. Gerald Iafrate Army	"High Temperature Superconductivity... Issues, Novel Concepts, and Army Applications"
Dr. Gerald P. Dinneen Honeywell, Inc.	"Corporate Overview on Superconductivity"
Dr. Richard Withers MIT Lincoln Laboratory	"Lincoln Laboratory High Temperature Superconductivity Applications Assessment"
William Duggleby, Donald Lundy CIA	"Research and Applications of Non-U.S. High Temperature Superconductivity Work"
April 14-15, 1988	
Dr. Glenn Pennisten Alpha Partners Inc.	"The Commercialization of Superconductor Technology"
Dr. Alex Malozemoff IBM	"Issues and Commercialization of High Temperature Superconductivity"

Appendix D

DIRECTIONS OF RESEARCH AND DEVELOPMENT INTO HIGH TEMPERATURE SUPERCONDUCTORS

DIRECTIONS OF RESEARCH AND DEVELOPMENT INTO HIGH TEMPERATURE SUPERCONDUCTORS

1. Introduction

Section 2 of the DSB Report summarizes the status of superconducting materials. The purpose of this Appendix is to define in a concise manner the more important HTS materials and manufacturing issues in the two classes of applications: military electronics and high power systems. The R&D directions with the greatest need of DoD support are also identified. A few general issues and ensuing R&D directions are common to both classes of applications and these are discussed first. Exploration of these general problems will be best addressed by the search for new materials. This activity is most appropriate for academic, long range, low-level research programs, both theoretical and experimental. The National Science Foundation and the DoD Offices of Research are suitable conduits of support for a majority of such programs.

2. General Issues

2.1 *Operating temperature*: in almost all applications the operating temperature is 0.5 to 0.7 T_c. The desired operation at liquid nitrogen (77K), and eventually room temperature, mandates a search for higher T_c materials with a goal of attaining about 150K. The successive HTS discoveries which raised T_c from about 80K to 125K in the past two years suggest that further T_c increases might be expected. Both thallium and bismuth compounds that are more stable in air than YBCO have been found with critical temperatures greater than 100K. Development of an applicable theory of HTS superconductivity mechanism could provide clues for novel, higher T_c materials.

2.2 *Range of superconducting interactions*: in all oxide HTS materials this range is extremely short and often comparable to the distance between adjacent atoms. Consequently, small defects and imperfections disrupt superconductivity. For example, the transfer of high electric current density between grains (crystallites) of such ceramic materials is most severely limited by imperfect grain boundaries. Defective film surfaces and interfaces make prospects for the operation of HTS Josephson tunnel junctions uncertain.

2.3 *Directional properties:* all HTS cuprate crystals have highly directional (anisotropic) magnetic field and electric current carrying capability. There is a potential for developing devices which exploit the anisotropic nature of the materials. The search for HTS materials having field and current capabilities independent of direction (isotropic) is still desirable. The most recent discovery of such a material, a Ba-K-Bi-oxide, with a T_c approaching 30K indicates that work along these lines might be a fruitful part of such an R&D program.

2.4 *HTS theory development.* As noted in section 2 of this report, theoretical understanding of HTS is poor. Although R&D can proceed without a full theoretical basis, this lack of understanding inhibits the development of new materials and processes. Theoretical research efforts should be supported as a part of DoD's HTS program.

2.5 *Refinement of Processing Methods.* Since the new superconducting materials with critical temperatures greater than 90K have four or more components, their deposition as thin films has been challenging. A large variety of techniques must be evaluated for appropriate properties.

All cuprate HTS materials discovered and investigated to date exhibit qualitatively a similar behavior, so that the priority objectives/directions for applied R&D are relatively common to all such materials. Present issues and deficiencies define the practical goals for the investigation and optimization of properties and processes which are listed below for the two classes of applications. The foremost requirement in these investigations is to acquire basic understanding of the material deficiencies.

3. HTS Materials for Electronics

Superconductors, both LTS and HTS, are used in electronics mostly in the form of thin film and layered film structures which also incorporate nonsuperconducting films of insulators, semiconductors and normal conductors. Material requirements are to a large degree common to low and high power electronics. The identified obstacles to HTS utilization are the high radio frequency (RF) losses, high electronic noise and the film surface/interface superconductivity degradation. The weak links between grains can be either utilized (in granular films) or eliminated by epitaxial, single crystal film deposition.

3.1 Objectives for Electronic Materials Investigation:

3.1.1 Maximize critical current density and flux pinning in epitaxial HTS superconductor films for active devices to attain and exceed 10^7 A/cm^2 at 77K. Maximize flux pinning in granular HTS films in order to obtain 10^6 A/cm^2 at 77K.

3.1.2 Reduce low-field RF loses in HTS epitaxial films and film substrates to at least two orders of magnitude lower level than in copper at the same frequency and temperature. Increase the RF surface magnetic penetration field to approach the superheating critical field.

3.1.3 Reduce the low frequency (l/f) noise energy in HTS epitaxial and granular films to a target level of less than 10^{-30} Joule/Hz at 77K and 1 Hz.

3.1.4 Attain superconductivity at HTS film surfaces and interfaces comparable to that inside the film and demonstrate tunneling into these surfaces.

3.1.5 Determine mechanism of inter-grain coupling and opto-electronic nonequilibrium effects in granular HTS films.

3.1.6 Explore effects in HTS films which might lead to new functional devices, especially three-terminal transistor-like devices.

3.1.7 Search for optimized substrate materials and buffer layers for HTS films (epitaxial/nonepitaxial, having low rf loss, chemically and thermally compatible to minimize interdiffusion and strains).

3.2 Objectives for Electronic Materials Fabrication Process Development

3.2.1 Develop HTS film deposition methods insuring:
(a) an ultra-precise composition control, (e.g., O_2 content)
(b) stabilization of highest-T_c structural phase,
(c) epitaxial, single crystal film growth with specified crystal orientations,
(d) granular film growth with controlled inter-grain coupling,
(e) reproducibility, versatility and high throughput at a lowest capital investment level.

3.2.2 Attain lowest possible deposition and processing temperatures for HTS films and multilayers with a target temperature not to exceed 500 C.

3.2.3 Attain integration of HTS superconducting films with semiconductors, insulators and metals to fabricate hybrid electronic circuitry.

3.2.4 Develop micron and sub-micron scale patterning of HTS films and multilayers.

3.2.5 Develop techniques for fabrication of electrical contacts in integrated circuits.

4. High Power Applications

In high power, low frequency and direct current (DC) applications, the most important embodiment for the LTS and HTS superconductor is a composite conductor in the form of a multifilamentary wire, tape and cable. Composites must include normal metal matrix or cladding for cryostabilization and mechanical support. The biggest obstacles to fabricating such HTS conductors are the presence of weak links between grains of bulk, polycrystalline materials which limit the current density to very low values, the anisotropy of critical field and current density, the brittleness of the HTS ceramics and the incompatibility (reactivity) with economically viable stabilizers: copper and aluminum.

4.1 Objectives for Conductor Material Properties Investigation

4.1.1 Increase critical current density in bulk polycrystalline aggregates (to a target level of at least 10^5 A/cm^2 at 77K in magnetic fields of 10 to 12 tesla and at least 10^6 A/cm^2 below 1 tesla) and minimize glassy behavior by attaining clean, defect-free grain boundaries.

4.1.2 Determine detailed phase diagrams, oxygen diffusivity data and other physico-chemical properties of HTS compounds.

4.1.3 Determine mechanical properties (elastic constants, Young's modulus, hardness etc.) and thermal properties of HTS single crystals and polycrystalline aggregates over a wide temperature range.

4.1.4 Determine and optimize electromagnetic and thermal properties, especially alternating current (AC) losses and stability, of HTS composite conductors having the minimum required current density at specified field intensity.

4.2 Objectives for Conductor Fabrication Process Development.

4.2.1 Develop methods for fabricating crystallographically oriented (textured) HTS wires and tapes with clean, defect-free grain boundaries.

4.2.2 Develop methods for fabricating/pulling single crystal HTS fibers, fiber or tape coatings and fiber or tape substrates in suitable diameter or thickness ranges.

4.2.3 Develop methods for fabricating HTS composite wires and tapes with economically viable normal metal stabilization.

4.2.4 Develop methods for fabricating HTS composite wires and tapes with mechanical composite reinforcement sufficient for handling and high-field operation of brittle ceramic fibers and coatings.

4.2.5 Develop HTS magnet conductors in geometries other than wire or tape (e.g. a Bitter-type configuration).

4.2.6 Develop methods for joining HTS composite wires.

4.2.7 Explore alternative methods of HTS conductor fabrications to optimize reproducibility, quality control and ease of manufacturing at lowest unit cost and capital investment.

Efforts 4.2.3 to 4.2.7 will deserve high priority after a sufficiently high current density in wires, long fibers or tapes is demonstrated.

Appendix E
CRYOGENIC TECHNOLOGY

SECTION 1

SUPERCONDUCTORS AND THEIR CRYOGENIC REQUIREMENTS

The three important characteristics of the superconducting state are the critical temperature (T_c) (the temperature below which the superconducting state occurs), the critical magnetic field (H_c), and the critical current density (J_c).

It is well known that temperatures above T_c quench superconductivity. Perhaps it is less well known that the superconducting state is also quenched by an external magnetic field, $H > H_c$, or an electrical current, $J > J_c$ or a combination of the three parameters.

The highest temperature possible for the transition to the superconducting state, T_c, occurs when both H and J are zero. For useful values of H and J, the operating temperature of the superconductor must be less than T_c. A useful guideline is that the absolute operating temperature, T, should be about one-half the transition temperature. This temperature level provides useful values of H and J, as well as a margin below T_c to accommmodate any localized transient heating of the superconductor that might occur. (The actual relationships among T, H, and J are complex, but the above rule is nonetheless a handy guide.)

Accordingly, the ordinary (Type II) superconductors with T_c in the 20K range could typically be usefully operated at 10K. *Since no stable, liquid refrigerant exists* at 10K, the operating temperature is usually lowered to 4K, the temperature of liquid helium.

By the same rule, the new class of superconducting compounds, with T_c at about 90K, would be useful superconductors if cooled to 45K. Cooling to the temperature of liquid hydrogen, 20K, may not be unreasonable because hydrogen is much less expensive than the 40K liquid refrigerant, Neon.

Similarly, the yet undiscovered room temperature (300K) superconductors, in order to accommodate a useful magnetic field and electrical current, would be cooled to 150K. For practical reasons, the temperature of liquid nitrogen, 77K, would probably be chosen.

Therefore, superconductors, old, new, and yet undiscovered, require cryogenic temperatures (4K, 20K, and 77K, respectively) to have useful properties.

The balance of this appendix discusses our present ability to create such a cryogenic environment. The discussion is divided into ground-based systems and space-based systems. These two categories are then divided into large-scale and small-scale systems. It will be seen that cryogenics is a mature technology and poses no particular obstacle for operating any superconductor, old or new, at any desired temperature. Table 1 provides a list of some current, extensive reviews of cryogenic cooling technology.

Table 1

REVIEWS OF CRYOGENIC STATUS

1. Smith, Joseph L., Robinson, George Y., and Iwasa Yukikazu, "Survey of the State of the Art of Miniature Cryocoolers for Superconducting Devices," prepared under the office of Naval Research, Contract N0001483K 0327. (Not published in the open literature)
2. Daunt, J.G. and Goree, W.S., "Miniature Cryogenic Regrigerators," Report to ONR under contract NONR-263(70), July 1969.
3. Crawford, A.H., "Specifications of Cryogenic Refrigerators", Cryogenics, February, 1970.
4. "Applications of Closed-Cycle Cryocoolers to Small Superconducting Devices," NBS Special Publication 508, Eds. Zimmerman, J.E. and Flynn, T.M., April 1978.
5. "Refrigeration for Cryogenic Sensors and Electronic Systems," NBS Special Publication 607, Eds, Zimmerman, J.E., Sullivan, D.B,, and McCarthy, S.E., May 1981.
6. Walker G., Cryocoolers, Vols. I and II, Plenum Press, 1983.

SECTION 2

CRYOCOOLERS

A cryocooler is a refrigerating system capable of achieving temperatures in the cryogenic range, generally considered to be less than 120K. Cryocoolers are often rated by the available refrigeration capacity measured in watts. To be meaningful, however, it is necessary to specify not only the refrigeration capacity but also the temperature at which the refrigeration is available. A cryocooler having a capacity of 1W at 4K (Liquid helium temperature) is very different than a cryocooler having a capacity of 1W at 77K (Liquid nitrogen temperature). Thus, the level of refrigeration (4K - helium, 20K - hydrogen. 77K - nitrogen) is specified, as well as the capacity at that level (usually in watts).

Another important parameter is the power input or work required to achieve refrigeration, usually measured in watts of input power per watt of useful refrigeration ($W_{input}/W_{cooling}$). This figure is closely related to the efficiency of the refrigerator. The efficiency of presently available cryocoolers range from a minimum of less than one percent to a maximum of near 50 percent. Efficiency depends more on the scale of the machine than on the temperature level or thermodynamic cycle employed and, therefore, the size of the cryocooler is important to this discussion.

The small machines used for electronic applications have the lowest efficiencies. This is because nearly all the refrigeration generated is consumed in cooling the low-temperature parts of the machine itself. The surplus or useful refrigeration available from these units is very small--only fractions of a watt. Applications requiring a larger useful refrigeration load use larger, more efficient systems. The highest efficiencies are found in large machines used for liquefiers and range from 20 to 50 percent of the Carnot value. (The Carnot value is the thermodynamic limit of the best that can be done.)

Space-based cryocoolers differ from ground-based systems in several important respects. Aerospace cryocoolers must be able to withstand the high acceleration and vibration spectrum of a rocket launch, and have the ability to operate in any orientation and in a zero or low gravity. The reliability and long-life of aerospace cryocoolers assume an importance not found in ground applications.

Thus, a useful distinction is to classify cryocoolers according to ground-based or space use. Ground-based systems are divided into large and small applications. Space-based systems are usually small--10W or less.

SECTION 3

GROUND-BASED SYSTEMS

LARGE SYSTEMS

Industrial uses of cryogenics are spectacular and commonplace, and most frequently at the 77K (nitrogen) or 90K (oxygen) levels. Uses include food freezing (McDonalds uses $50M/yr of liquid nitrogen), sewage treatment (many cities use oxygen produced on site from liquid air to speed up treatment), breathing oxygen for hospitals obtained from liquid oxygen storage, and the production of chemicals (anti-freeze) and steel from liquid oxygen. Cryogenics is a routine industrial tool currently found in the Yellow Pages of the telephone directory.

Such industrial cryogenic systems as these are routine product lines of Air Products and Chemicals, Inc., Linde Division of Union Carbide, the AiResearch Co., and others.

Hydrogen for industrial and aerospace use is routinely stored as a liquid at 20K, strictly as a convenience. Texas Instruments' Stafford, Texas plant uses the country's largest commercial liquid hydrogen storage tank to supply hydrogen gas for semiconductor processing. NASA and the USAF each have 1,000,000 gallon liquid hydrogen storage tanks, supplied by a network of hydrogen liquefiers. Liquid hydrogen (20K) technology is "off-the-shelf" from such firms as Air Products and Linde.

The status of large-scale liquid helium facilities is perhaps even more surprising. Most large high-energy accelerators use helium-cooled superconducting magnets simply because: (1) it is cheaper to do so, compared to the electric power required for normal conductor magnet; and (2) to achieve higher levels of magnet performance. Table 1 shows a partial list of these facilities. At present, these facilities have a combined capacity of 82.5 kW at 4K. When complete, the Superconducting Super Collider (SSC) will bring this total to 114 kW of refrigeration capacity at 4K. Large-scale helium refrigerators are produced by Koch Process Systems, CTI Cryogenics, CVI, Air Products, Linde, and others. It is a fact that the large-scale production of helium temperatures is a routine, commercially available technology.

SMALL SYSTEMS

The first major requirement for small ground-based cryocoolers was brought about by the need to refrigerate ground-based parametric amplifiers to 4K for use in the satellite communication network. Several units meeting this requirement were developed and built by A.D. Little, based on the Gifford-McMahon (G-M) cycle, with a Joule-Thomson (J-T) circuit.These units produced a few watts at 3.8 - 4K. Further development in amplifier performance led to an amplifier which would perform satisfactorily at 20K. As a result, the major market for the Gifford-McMahon, closed-cycle, 20K cooler evolved. Cryogenic Technology, Inc. has produced close to 1,000 of these units, which are in continuous operation in the satellite communications network. This basic Gifford-McMahon cooler is also produced by Cryomech, Inc.

Table 1
SOME LARGE-SCALE CRYOGENIC SYSTEMS FOR LOW-TEMPERATURE SUPERCONDUCTORS

NAME	LOCATION	OPERATIONAL	CRYOGENIC CAPACITY	NAME
Fermilab Tevatron	Batavia, IL	1983	24 kW at 4 Kelvin 5000 L/hr Liquid He 63000 L Liquid He Storage 254,000 L Liquid N2 Storage	
Mirror Fusion Test Facility (MFTF)	Livermore, CA	MFTF-A 1982 MFTF-B 1985	10.5 kW at 4K 500 kW at 77K	MFTF-B: 1.05 x 10^6 kg magnets at 4.35K 900 m2 of cryopanels at 4.35K 10 days to cool system to 4K
Joint European Torus (JET)	Oxon, UK	YES	500 W at 3.8K 20 kW at 77K	
Tore-Supra Experimental European Fusion Tokomak	France	1986	300 W at 1.75K 700 W at 4.0K 10.7 kW at 80K	50000 kg at 1.8K 120000 kg at 4.5K 20000 kg at 80K
International Fusion Superconducting Magnet Test Facility (IFSMTF)	Oak Ridge, TN	1983	1.4 kW at 4K	360000 kg at 3.8K 20 days to cool system to UK
Brookhaven National Lab (BNL)	Upton, NY	1985	24.8 kW at 3.8K	
Electron-Proton Collider HERA Deutsches Electrones Synchrotron	Hamburg, FRG		20.3 kW at 4K 20 kW at 40-80K	
Superconducting Super Collider (SSC)		NO (1991)	31.5 kW at 4.15K 48.2 kW at 20K 390 kW at 84K	$5x10^7$ kg mass coded to 4K

and by Air Products, Inc. These two companies, as well as Cryogenic Technology, Inc. (CTI Cryogenics), have built a number of G-M units for specific applications with the addition of a J-T loop to provide a final stage of refrigeration at 4K. Units of this type have also been furnished by Cryosystems, Inc. and by Cryogenic Consultants, Ltd. in England. Installations include cooling of computer systems and cooling of superconducting magnets for magnetic separation processing and NMR experiments.

The next major use to evolve was that of cooling infrared (IR) detectors. The initial requirements for IR detectors were 0.25 - 2W at 80 K. A number of manufacturers become involved in producing refrigerators for this level of refrigeration. Thousands of open cycle J-T units have been produced as well as several thousand integral Stirling and split Stirling refrigerators. These units are used for cooling military IR detectors and are produced both in the United States and abroad. For instance, each Bradley Fighting Vehicle uses eight separate cryocoolers for IR systems.

This requirement for large numbers of coolers for infrared detectors in the military system led to development of a common module cryocooler meeting specific size, weight, and performance requirements. These units are manufactured by a number of companies abroad in order to serve their own government defense systems. These companies, in addition to CTI Cryogenics and Air Products, Inc., include Hughes Aircraft, Texas Instruments, H.R. Textron, and Magnavox in the U.S.; Telefunken Co. in Germany; L'Air Liquide and A.B.G. Semca in France; Hymatic in England; Philips in Holland; Ricor Ltd. in Israel; and Galileo Corporation in Italy.

The third major commercial use is that of Cryopumping. Cryopumping produces a high vacuum by condensing residual gases on cryogenically cooled panels. A number of G-M and Stirling cycle refrigerators were installed on cryopumping systems in the early 1970's. However, the market did not fully develop until coolers were required for semiconductor production.

The general range of cooling required for cryopumping systems is 50 - 65W at 80K and 5W at 12 - 15K. Closed cycle refrigerators for cryopumps in this range are produced by CTI Cryogenics, Air Products, and CVI, Inc. In addition, the major vacuum equipment companies produce their own refrigerator systems. These include Balzers High Vacuum, Varian, Inc., and Sargetn Welch, Inc., in the U.S.; L'Air Liquide in France; Leybold-Heraeus in Germany; and Osaka Oxygen Industries, Suzuki Shokan Ltd., Ulvac Cryogenics, Inc., and Toshiba Corp. in Japan.

Although there are no companies producing many refrigerators meeting the requirements of 1W at 4K with a reasonable efficiency and size suitable for cooling small superconductive devices, the major manufacturers listed above have the capability to develop such systems.

Ground-based cryocoolers, large scale or small scale, for use at 4K, 20K or 77K, are virtually "off-the-shelf." (See Table 2.)

Table 2

COMMERCIALLY AVAILABLE, SMALL-SCALE CRYOCOOLERS

Temperature Range:	4-5K	10-20K	20K&80K	80K	80K
Cooling Capacity:	1-4W	1-5W	4W&60W Cryopumping	0.25-2W Closed Cycle	1-2W J-T
MANUFACTURER					
Air Products and Chemicals	X	X	X		X
Rearch				X	
Balzers High Vacuum			X		
Cryomech, Inc.		X	X		
CTI-Cryogenics	X	X	X	X	
Cyrosystems, Inc.	X	X	X	X	
CVI, Incorporated			X		
Hughes Aircraftt Co.				X	
MMR Technologies					X
Magnavox				X	
Sargent Welch			X		
Texas Instruments				X	
H.R. Textron				X	
Varian			X		

SECTION 4

SPACE SYSTEM CRYOGENICS

Cryogenic cooling and storage have been used in space instruments for over twenty years. The cooling needed is typically for temperatures below the boiling point of liquid nitrogen (77K), and for heat loads of ten watts or less. The primary need for cooling is for IR detectors for astronomy, and for surveillance; X-ray and gamma-ray detectors have also been cooled. The storage of cryogenic fluids for the atmosphere of manned spacecraft and for power production in fuel cells is a major use dating back to the late 1950's. Many additional cryogenic applications continue to appear.

Three basic refrigeration methods are used to meet these cooling requirements: (1) passive thermal radiation to space, (2) storage of cryogenic fluids or solids, and (3) active refrigerators.

Passive radiation to space is a simple and reliable method of producing small amounts of cooling. This method has limited applications because the amount of cooling obtainable is very small at cryogenic temperatures--typically fractions of a watt. The practical limit is that the radiator becomes very large and heavy for larger loads.

Storage of fluids or solids has been the mainstay for cryogenic cooling in space. This method employs highly insulated storage tanks. The cooling temperatures obtained range all the way down to less than 2K in the case of superfluid helium storage.

Many cryogenic materials have been used to produce cooling by using the heat of vaporization to absorb heat loads. The practical limitation of cryogenic storage is that the size and weight become large for long-duration missions and for high heat loads.

Active, closed-cycle refrigeration systems (cryocoolers) do not suffer from the severe size and weight limitations of the other methods. Electrical power is used to produce continuous cooling. The limitation of space cryocoolers is availability. Such coolers have been under development for about 30 years. Although some types have been developed and successfully flown, other types still require significant development. The space cryocoolers under development usually fall into three categories: regenerative or Stirling coolers, reverse Brayton coolers, and J-T coolers. Table 3 gives a summary status.

Development of a long-life space cryocooler has been an elusive goal because of fundamental problems relating to contamination and wear.

Stirling coolers were used in space to cool gamma ray detectors to about 80K in the P78 satellite. These coolers were built by the Philips Corporation and employed a linear drive mechanism to achieve several years of operation. Degradation in performance occurred during the mission in the form of steadily rising cooler temperature.

Table 3

SUMMARY OF SPACE COOLERS

Small scale 1-2W, 65-75K

- A few watts at 75K is feasible
- Several such systems are in test:

Joule-Thomson (JTB)	65K/2W	Concept Test
Joule-Thomson (JTJ)	65K/2W	Concept Test
Linear Stirling	65K/2W	In Test
Tactical Stirling	65K/1W	Off-the-Shelf

Small scale (1-2W), 10K

- 10K is about the lower temperature limit achievable by regenerative cycles
- 10K and lower feasible for recuperative cycles. Some systems in test:

Rotary Reciprocating Brayton	10K/1W	In Test
Turbo-Brayton	10K/1W	In Test
Vuilleumier	15K/1W	Qualified

Small scale (1-2W), 4K

- Not feasible for regenerative cycles.

Large scale (10s of W), 4K

- Not attempted

A very promising development of a Stirling type refrigerator is taking place in Great Britain at Oxford University and the Rutherford Appleton Laboratories in conjunction with British Aerospace Corporation. Operational times of about 20,000 hours have been achieved, and this machine has been slated for use in several space systems. The limitations of Stirling coolers are that temperatures below about 20K are difficult to achieve with acceptable power input requirements.

Brayton coolers are being developed for temperatures below 10K and higher cooling loads. The AiResearch Corporation is developing such a cooler using multistage turbomachinery. The Arthur D. Little Company is developing a Brayton cooler that uses positive displacement (piston and cylinder) principles.

Both the Stirling and Brayton coolers have moving parts in the cold regions of the machines that generate vibrations. These vibrations are often unacceptable in sensitive space instruments.

Additional benefits accrue to the J-T approach in comparison to the Stirling and Brayton machines as a result of the fact that J-T coolers produce liquid cryogens. High, short-term peak heating loads, and variable heating loads, can be absorbed at the constant temperature of the boiling liquid refrigerant. This is not possible with other systems that produce only a cold gas, and is sometimes very important to space instrument cooling.

Appendix F

HIGH STRENGTH MATERIALS

HIGH STRENGTH MATERIALS

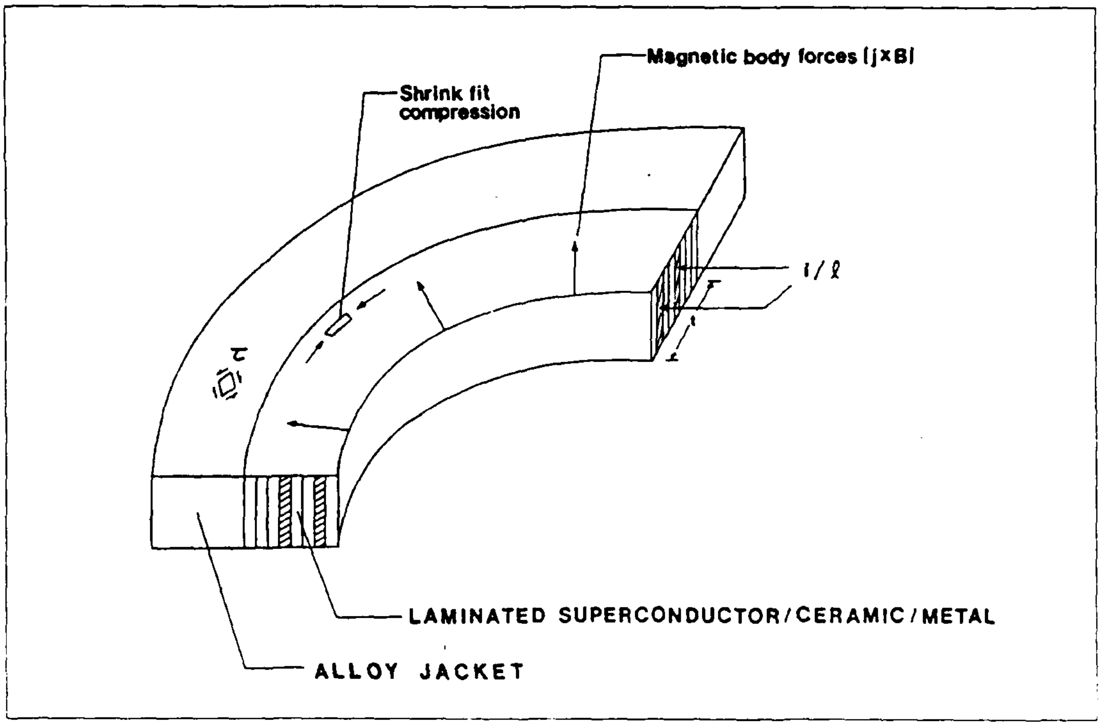
High temperature superconductors are brittle materials with low tensile strength but good compressive strength. Superconducting magnets utilizing such materials thus require designs that minimize the stresses that develop as a result of the j x B body forces. It may be possible to form a superconducting composite using a high strength material to withstand the stresses associated with large magnetic fields. However, the highest strength material known, graphite fiber, lacks the strength required for the high fields anticipated.

A stress-free condition can be achieved if the forces are counteracted by a stiff constraining medium. An example is presented for a cylindrical solenoid geometry consisting of laminated superconductor, constrained by a stiff composite shell (Figure F-1).

The materials selected for the laminate should have a high elastic modulus and high yield strength so that the stress generated in the superconductor is small. The laminate should also include a protective layer of metal adjacent to the superconductor to minimize the effects of quenching.

By applying a shrink-fitting high strength alloy jacket to the laminate, the high compressive strength of the superconductor can be exploited.

Figure F-1
STRUCTURAL SUPPORT FOR HIGH FIELD APPLICATIONS



Appendix G

A JOSEPHSON 4 BIT MICROPROCESSOR

A JOSEPHSON 4 BIT\ MICROPROCESSOR*

SEIGO KOTANI, NORIO FUJIMAKI, TAKESHI IMAMURA, AND SHINY HASUO

FUJITSU LIMITED

10-1, MORINOSATO-WAKAMIYA, ATSUGI, 243-01, JAPAN

TEL: 0462-48-3111 / EXT. 2411
FAX: 0462-48-3896

A 4-bit microprocessor -- the first microprocessor to use Josephson devices -- will be described. The circuit was fabricated using 2.5 - μm all-niobium Josephson technology, utilizing $Nb/AlO_x/Nb$ Josephson junctions. 5011 Josephson junctions are contained on a 5.0 x 5.0 mm die. The microprocessor was operated with clocks of up to 770 MHz under worst-case conditions, dissipating 5 mW.

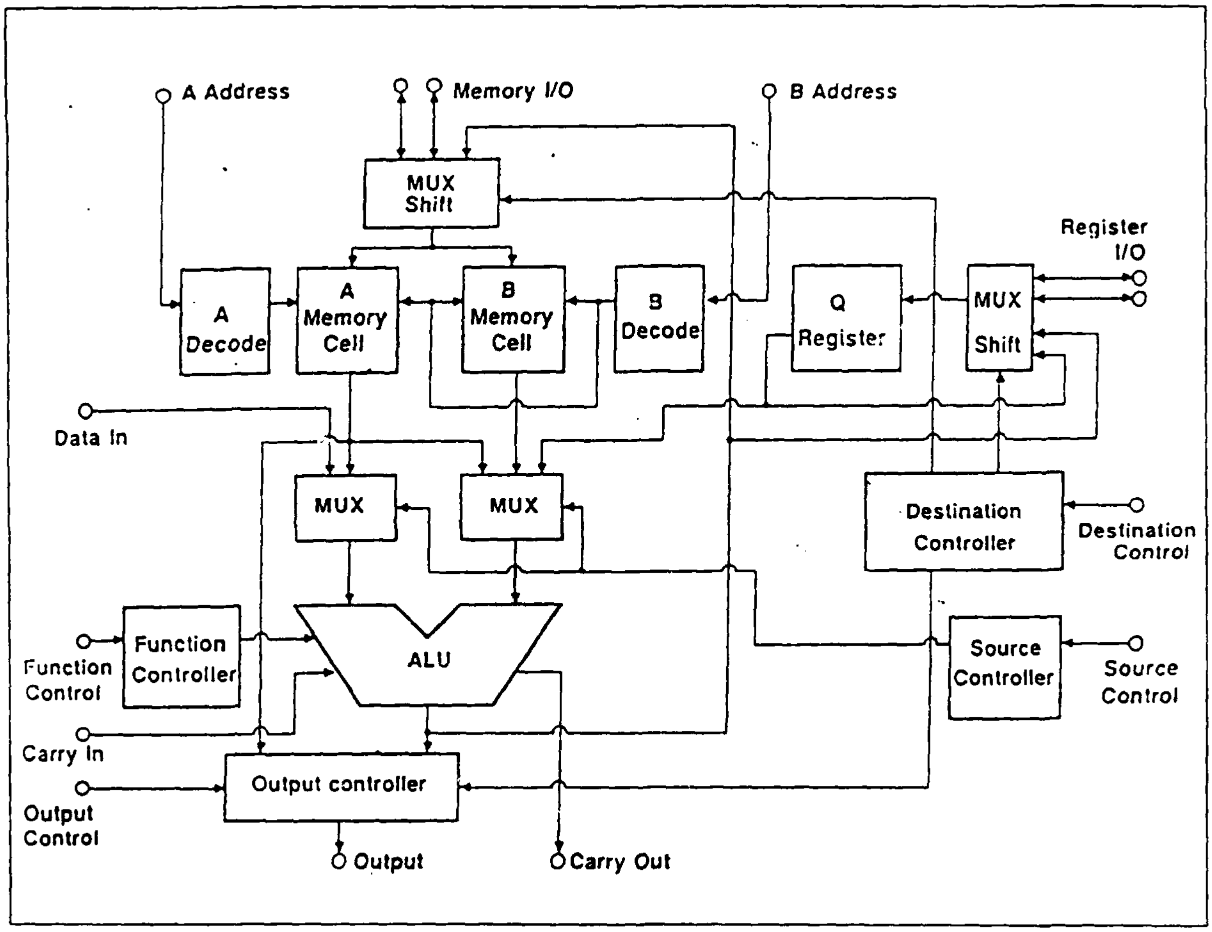
Josephson gates offer superb high speed operation and low power dissipation. More than ten types of logic gates have been reported. We proposed a gate, which we called the modified variable threshold logic (MVTL) gate,1) for Josephson LSI circuits. The MVTL OR gate was 46 x 31μm^2 and the unit cell was 112 x 79μm^2; each unit cell was composed of three gates, two MVTL OR gates and one single-junction AND gate, so this unit cell performs an (A + B) (C + D) logical operation. 2.5 μm diameter Josephson junctions were used in these gates. We demonstrated its high-speed,2) and applied it for a 16-bit arithmetic logic unit (ALU).3) We then designed the microprocessor.

This was the first instance of applying Josephson devices to a microprocessor, so we wanted to verify the feasibility of the chip in comparison with a typical microprocessor constructed with semiconductor devices. We selected chip functions that were similar to those of the Am 2901 microprocessor made by Advanced Micro Devices Inc.4) This microprocessor has come to be regarded as the standard four-bit microprocessor slice. The fastest operation of this microprocessor has been achieved using GaAs devices; a 72 MHz clock with a 2.2 W power dissipation.5)

Figure 1 is a block diagram of our microprocessor. It has a dual memory set which is used as a 16-word by 4-bit two-port RAM with a RAM shifter, an eight-function ALU, a Q register with a Q shifter, and several controller. This circuit is driven by three-phase power; ϕ_1, ϕ_2, and ϕ_3.6) Their waveforms are sinusoidal with dc offsets and their phases fare separated by 120 degrees. The three-phase power has the advantage of preventing the racing phenomenon in the logic circuit, and a Josephson timed inverter (TI) can be fabricated easily if the power is used as the timing signal. Dual-rail logic was adopted in the ALU and controllers of the microprocessor, and complement signals are made from the input signals by TIs powered by $\phi 1$. Decoding operations are run in gates powered by ϕ_1, reading memory data by ϕ_2, and modifying and writing data by ϕ_3.

Figure 1

BLOCK DIAGRAM OF MICROPROCESSOR



In this microprocessor, the critical path is the route of the carry signal transmitted from LSB to MSB in the ALU and then the sum signal transferred from the ALU to the RAM. After detail design, the number of gates which have to switch sequentially along the path proved to be 41, with an interconnecting line length of 15 mm. MVTL gates operate with a sub-ten ps gate delay in actual circuits, [3] and the propagation delay in interconnecting lines is about 8 ps/mm. By rough estimation, the critical delay time seems to be 0.5 ns and the duty ratio of the sinusoidal power is 1/2, so the maximum clock frequency was estimated to be 1 GHz.

The process is summarized in Table 1. This fabrication process is almost the same as that reported previously.2) The circuit consists of $\mathrm{Nb/AlO_x/Nb}$ Josephson junctions, Nb wiring, Mo resistors, and $\mathrm{SiO_2}$ insulators. Both the minimum junction diameter and line width are 2.5 um. The interconnecting lines are 4 um wide. The critical current density of the fabricated Josephson junction was 2300 $\mathrm{A/cm^2}$, this being slightly higher than the optimum design value (2100 $\mathrm{A/cm^2}$). The measured operating margin was ±34% for the MVTL OR gate and ±32% for the unit cell.

Table 1

PROCESS SUMMARY

JOSEPHSON JUNCTION	$\mathrm{Nb/AlO_x/Nb}$
JUNCTION MINIMUM DIAMETER	2.5 um
MINIMUM WIDTH	2.5 um
INSULATOR	$\mathrm{SiO^2}$
RESISTOR	Mo
WIRING	Nb

Figure 2 is a photograph of the fabricated chip with unit locations. The specifications of the chip are given in Table 2. The basic gate is MVTL, as mentioned above, and the total number of gates is 1841. Six power pads are provided, three for sinusoidal power and the others for dc offsets. The number of signal pads is 32; 8 for address, 14 for data, and 10 for control. 52 ground pads are used to suppress the deviation of the chip-ground level from the package-ground level.

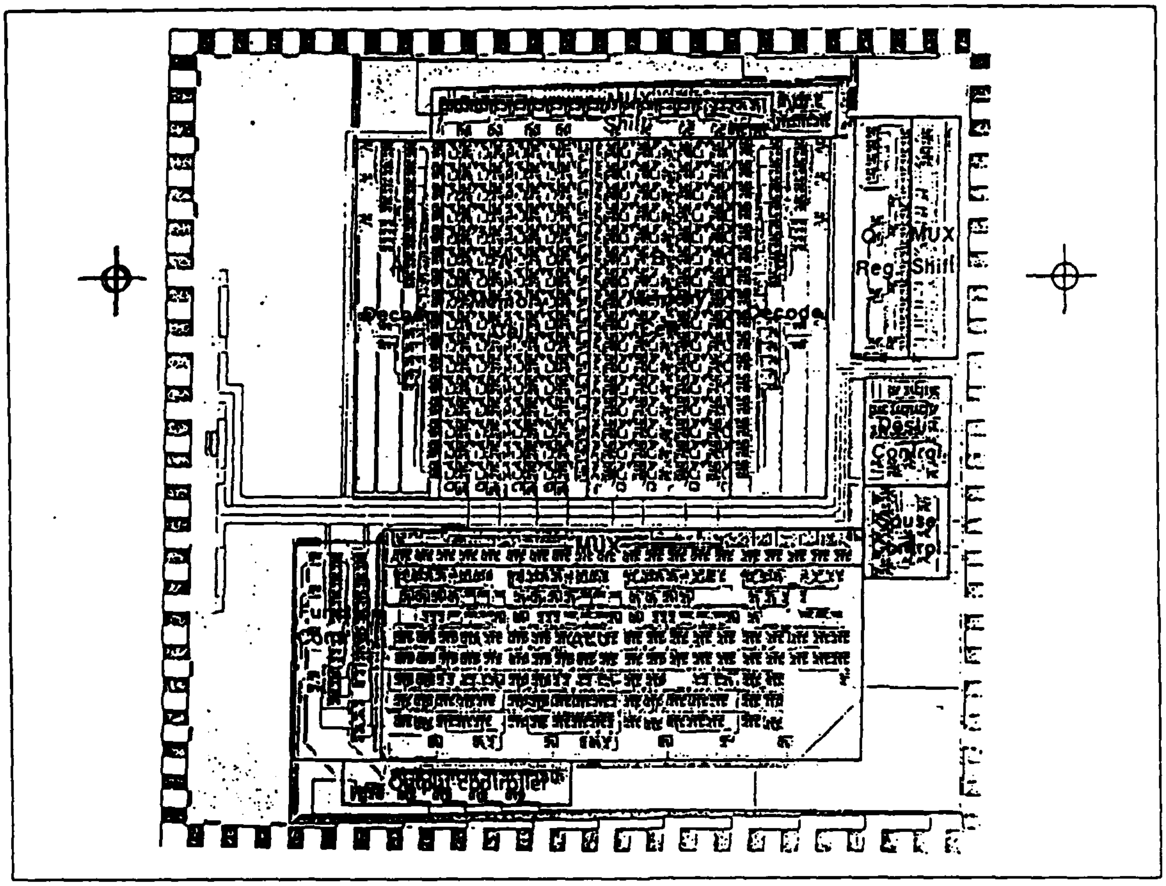
Table 2

CHIP SUMMARY

DIE SIZE	50 x 50 mm
MEMORY	16-word by 4-bit two-port RAM
# ALU FUNCTIONS	8
BASIC GATE	MVTL
# GATES	1841
# JUNCTIONS	5011
POWER (3-PHASE SINUSOIDAL)	5mW
# SIGNAL PADS	32
# PWR/GND PADS	58
CLOCK FREQUENCY	770MHz

Figure 2

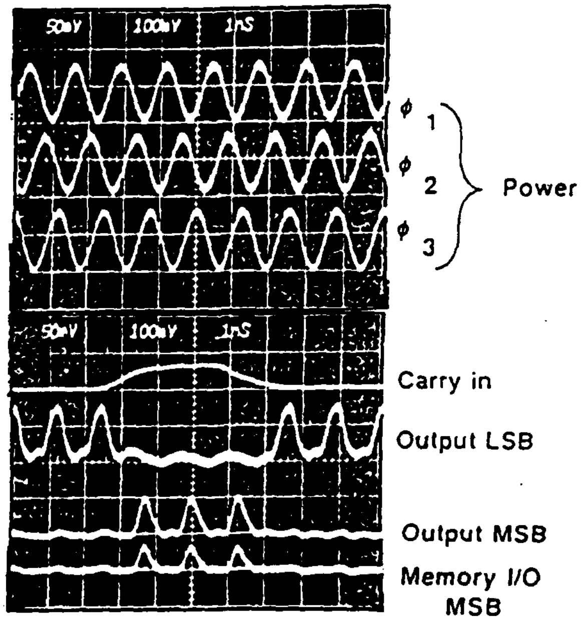
PHOTOGRAPH OF MICROPROCESSOR



All experiments were performed with the chip immersed in liquid He. All functions and source combinations were confirmed with an operating margin of ±16% at a clock frequency up to 100 MHz which was limited by the maximum clock of the word pattern generator. The operation along the critical path of the chip was tested using the high-speed pulse generator, and Figure 3 shows the results obtained at the maximum clock frequency (770 MHz). The same waveform was obtained for the MSB signals of output and memory I/O, thus confirming correct operation. The reason for the amplitude difference in these waveforms is that the timing of the sum signal arriving at the memory is later than that of the signal at the output controller. The power has a sinusoidal waveform, so the bias power of the memory I/O gate at its switching timing. The power was consumed at the OR gate supply resistors, and the value was obtained from the bias level. The gate power dissipation was 3.6 μW/gate, and the total power of the chip was 5 mW.

Figure 3

CLOCK WAVEFORMS AT 770 MHz



We verified that the Josephson microprocessor operated with a one-order faster clock and three-orders less power than a semiconductor microprocessor.

---

* The present research effort is part of the National Research and Development Program on "Scientific Computing System", conducted under a program set by the Agency of Industrial Science and Technology, Ministry of International Trade and Industry.

References:

1) Fujimaki, N., Kotani, S., Hasuo, S. and Yamaoka, T., "9 ps Gate Delay Josephson OR Gate with Modified Variable Threshold Logic," Japan. J. Appl. Phys., vol.24, p.L1; Jan., 1985.

2) Kotani, S., Imamura, T. and Hasuo, S., "A 2.5-ps Josephson OR Gate," IEEE IEDM Technical Digest; Dec., 1987.

3) Kotani,S., Fujimaki, N., Imamura, T., and Hasuo, S., "A 1 ns Josephson 16b ALU," IEEE ISSCC DIGEST OF TECHNICAL PAPERS, p.60-61; Feb., 1987.

4) Mick, J., "Am 2900 Bipolar Microprocessor Family," IEEE Proceedings of the Eighth Annual Workshop on Microprogramming, p.56-63; 1975.

5) Hendrickson,N., Larkins, B., Bartolotti, R., Deming, R., and Deyhimy, I., "A GaAs Bit-Slice Microprocessor Chip Set," IEEE Proceedings of the GaAs IC Symposium, p.197-200; Oct., 1987.

6) Fujimaki, N., Kotani, S., Imamura, T., and Hasuo, S., "Josephson 8-bit Shift Register," IEEE J. of Solid-State Circuits, vol.SC-22, p.886-891; Oct. 1987.

Appendix H

BACK-UP DATA ON JAPANESE FUNDING FOR SUPERCONDUCTIVITY R&D

The Tokyo Office of the
U. S. National Science Foundation

米国国立科学財団 東京事務局

Report Memorandum #152 April 18, 1988

JAPANESE GOVERNMENT AND CORPORATE FUNDING FOR SUPERCONDUCTIVITY R&D

Summary: In JFY 1988 the Japanese Government will spend over 9,049 million yen ($72.4 million) and Japanese corporations will spend at least 11,511 million yen ($92 million) on superconductivity R&D. Much of the government budget and seventy percent of the corporate funds will be for high temperature superconductivity. Largely separate from these funds, Japanese corporations have contributed considerable amounts of money to join the new International Superconductivity Technology Center (ISTEC), a private foundation engaged in R&D on high temperature superconductivity, initiated with guidance from MITI. The total of such funds so far committed, though not necessarily completely handed over, is 5,420 million yen ($43.4 million). (Caution should be excercised in interpreting ISTEC funds as 1) in contrast to the government and corporate funds reported herein, the ISTEC funds largely consist of one-time initial donation, much of which will probably be used for capital expenses, and 2) in that ISTEC is in principle open to international participation. See section on ISTEC below for further details.)

GOVERNMENT

Mr. Makio Hattori, Director for Material Research and Development, R&D Bureau, Science and Technology Agency (STA) of Japan has provided the following information on Japanese Government's FY'88 budget for superconductivity R&D as approved by the National Diet on April 7, 1988, with corresponding figures for FY'87 given for comparison. Corporate R&D figures are from a recently concluded survey by the NSF Tokyo Office. (Figures for both government and private sector are in million yen and include both low temperature and high temperature superconductivity. Current exchange rate is 125 yen to the dollar.):

	(In Million Yen)	
	FY1987	FY1988
Science and Technology Agency (STA)		
(1) Multicore Project:	0	2,044
(2) R&D on Superconducting coils (Japan Atomic Energy Research Inst.):	1,109	678
(3) ERATO Project on Magneto-flux Logic Research (Research Development Corp.:	377	395
(4) Others	97	75
Subtotal of STA:	1,583	3,192
		($25.5 mil.)

Ministry of Education, Science and Culture (MONBUSHO)	FY1987	FY1988
(1) Grants-in-Aid for Scientific Research:	(563)	(*Undecided)
[*Note: Proposals for grants are still under review, and to be decided in May]		
(2) R&D Equipment Procured by Funds under Special ACcounts for National Schools:	527	1,775
Subtotal of Monbusho:	527	1,775
		($14.2 mil.)
Plus "Grants":	(563)	(?)

Ministry of International Trade and Industry (MITI)

(1)	R&D Projects on Basic Technologies for Future Industries:	71	1,123
(2)	National R&D Program (the Large Scale Project):	350	440
(3)	R&D on Energy Conservation Technologies (the Moonlight Project; Primarily for Development of Low Temperature or Traditional Superconducting Power Generator Systems):	100	1,652
(4)	Surveys/Studies on Matters RE Superconductivity:	0	182
(5)	Specific International Joint Research Project:	0	14
(6)	Others:	35	17
	Subtotal of MITI:	556	3,428 ($27.4 mil.)

Ministry of Transport (MOT)

R&D on Magnetic Levitation Railway Systems:	295	597

Ministry of Posts and Telecommunications (MPT)

R&D on Superconducting Telecommunications Systems:	358	57
GRAND TOTAL:	2,960	9,049 ($72.4 mil.)
(Plus Monbusho Grants:	(563)	(?)

(Monbusho's scientific research grants will be decided in May.)

With respect to MITI's budget, MITI officials contacted by the NSF Tokyo Office expect that most of the funds allocated for the "Basic Technologies for Future Industries" program will be allocated through the New Energy and Industrial Technology R&D Organization ("NEW NEDO") for contract research by industries, including about 400 - 500 million yen expected to be provided to the International Superconducting Technology Center (ISTEC) for contract research although exact yen amounts are yet to be decided.

CORPORATE EXPENDITURES

A recent survey by the NSF Tokyo Office of Japanese corporate superconductivity R&D indicates that 41 leading corporations spent 8,671 million yen ($59.96 million @ 144.61 yen per dollar) in JFY 1987 and that they expect to expend 11,511 million yen ($92 million @125 yen to the dollar) in JFY 1988. Seventy percent of the corporate funds are for high temperature superconductivity.

ISTEC

The International Superconductivity Technology Center, a newly established private foundation initiated under the guidance of MITI, to conduct R&D in high temperature superconductivity, so far has attracted 45 Japanese companies as full members, meaning that they may partake in the activities of both the Center (symposia, workshops, etc.) and the Labroatory. The initial one time donation for joining both is 2 million yen for the Center and 100 million yen for the Laboratory. The annual fees for the Center and Laboratory are 2 million yen and 12 million yen respectively. In addition, fifty Japanese corporations have joined just the Center, for which the initial donation and annual fees are 2 million yen and 2 million yen respectively. Thus, in total, Japanese corporations have committed 5,420 million yen ($43 million @125 yen/dollar) including 4,690 million yen in donations and 730 million yen in first year dues. However, the initial donation may be spread over two years at 60% and 40% respectively. A portion of the initial donation will be used for capital expenses such as buildings and equipment. Other portions will be used for the research, though just how much in each category is uncertain. Corporate funds for ISTEC are largely separate from corporate expenditures as reported above. In addition, ISTEC is in principle open to membership by foreign companies. So far one foreign affiliated company, IBM Japan, has joined the Center (as opposed to the Laboratory). No foreign company has as yet joined as a full member, though some are reportedly considering doing so.

Comment: The figures for the government and private sectors represent substantial increases over JFY 1987 levels. For the government sector they are even higher than forecast in September last year by the main Japanese agencies. Most of the government increases can be assumed to be for high temperature superconductivity, with the exceptions of the Moonlight Project and the Magnetic Levitation Railway Systems. (An undefined amount of new money for the Moonlight Project will be used for high Tc superconductivity, although the bulk will be for conventional superconductivity.) For the corporate sector, 70% of the expenditures are for high temperature superconductivity. (The results of the NSF corporate superconductivity survey will be made available in May.)

NOTE: This report was compiled by Masanobu Miyahara, Scientific Affairs Advisor, NSF Tokyo Office, through interviews with several Japanese government and academic authorities.

NSF/T:MMiyahara

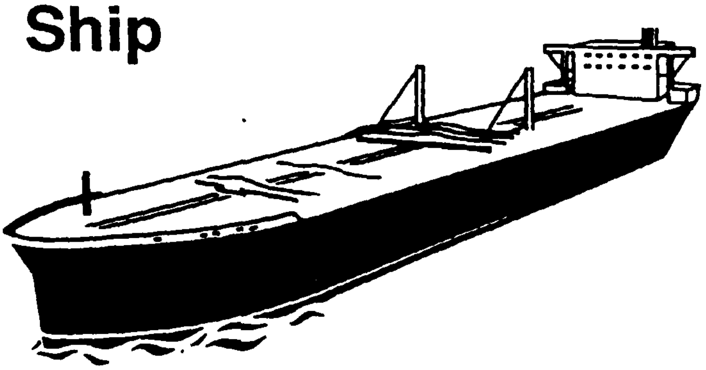
FOCUS ON JAPAN

REPORTS ON JAPANESE DEVELOPMENTS IN SUPERCONDUCTIVITY

Volume 1, Number 2
May, 1988

Council on Superconductivity for American Competitiveness

Oceangoing Ship Planned



Mitsubishi Heavy Industries, Toshiba and Kobe Steel will team up on an oceangoing, superconductor-driven ship due to be ready in 1990. Research on the prototype vessel will be paid for by the Japan Foundation for Shipbuilding Advancement, an industry association.

The goal of the project will be to develop and evaluate superconducting coils and to determine the most appropriate architecture for oceangoing superconducting vessels.

Plans call for the construction of a 22-meter, 150-ton vessel with no propeller. The two power units on board will be capable of generating 8,000 newtons of power (expected speed is 8 knots).

Mitsubishi Heavy Industries will be responsible for one of the superconducting magnets, with Toshiba supplying the other. Kobe Steel will provide helium refrigeration equipment.

If completed on schedule in 1990, the ship will be the first of its kind in the world. Total cost is expected to be in the area of $40 million.

Nikkei Sangyo Shimbun, March 11, 1988, page 13.

Non-Crystalline Ceramics Made

In a world first, a group led by Professor Kazumasa Matsushita of the Technological University of Nagaoka has produced non-crystalline superconductors.

The group discovered that superconducting glass ceramics can be produced by melting and then rapidly cooling BSCCO (Bismuth, Stronuum, Calcium, Copper, Oxygen) materials.

Continued on page 3

R&D Funding Up 300%

Japan is increasing its funding of superconductor research by an average of 300 percent over 1987's budget, recognizing the technological and financial rewards inherent in the development of applicable superconductors.

In a special insert, *Focus on Japan* details the nearly $57 million budget that propels Japan's superconductor research. These are final figures for fiscal 1988, which started in April.

Japan's large-scale government research and development programs normally start out small, with support increasing as the projects take off. This year, for example, the superconductivity budget for the Ministry of International Trade and Industry rose 620 percent over last year's numbers.

The chart on the back of the pullout shows the relationship between the various ministries and their projects. The June issue of *Focus on Japan* will feature the comparable United States government budget.

Fiscal 1988 Superconductivity Budgets of Japanese Government Agencies

I. Ministry of International Trade and Industry

*(*indicates new item)*

Project Title	Million Dollars	Remarks
*Superconducting Materials	2.36	To national research institutes
	3.30	To private industry and the International Superconductivity Research Center 5 themes—materials, devices, etc.
Organic Superconductivity	0.48	To national research institutes
*High-Energy, High-Flux Materials	2.50	Wire for electric power
Josephson Computer Technology	0.82	To national research institutes
	2.55	To consortium of private companies
Cable, Power, Generators	0.52	To national research institutes
	10.88	To consortium of private companies
	1.32	Administrative expenses
Joint International Research	0.12	Research with U.S. NBS on SQUID, etc.
Ultra-low Temperature Electronics	0.13	Electrical properties of metals
Energy Storage	0.35	Agency of National Resources and Energy
Rare Earth Technologies	1.05	Agency of National Resources and Energy
total	26.38	620% increase over fiscal 1987

II. Science and Technology Agency

Project Title	Million Dollars	Remarks
New Projects		
National Research Institute for Metals	8.38	Theory, thin films, evaluation
National Institute for Research in Inorganic Materials	3.75	New materials, crystals, analysis of crystals
Institute of Physical and Chemical Research	0.95	Micro process technology, structural analysis
Japan Atomic Energy Research Institute	2.25	Theory database, neutron-beam analytic system
Power Reactor and Nuclear Fuel Development Corporation	0.20	Survey on applications for nuclear power
National Space Development Agency	0.25	Survey on space applications
Research and Development Department	0.03	Overall coordination
Continuing Projects		
National Research Institute for Metals	0.53	Ultra-low temperature equipment
Research Development Corporation of Japan	3.04	Promotion of innovative research
Japan Atomic Energy Research Institute	5.22	Superconducting coils
Special Atomic Power Research Grant	0.05	Superconducting wire, to National Research Institute for Metals
total	24.55	201% increase over fiscal 1987

III. Ministry of Education

Project Title	Million Dollars	Remarks
Scientific Research Grants		
Intensive Area Grants	——	Mechanisms of superconductivity Grants to 20 researchers *Amount undecided*
Special Project Grant	0.69	Tanaka's group at Univ. of Tokyo (total $1.98 million)
Special Research Projects	0.50	Superconductivity and the New Electronics (total $0.85 million)
Special Project	——	Nuclear fission, magnets, high density current Amount undecided

Special National Appropriations for Education

1. Laboratory in material properties at Materials Science Department, Tohoku University
2. Ceramics center at Tokyo Institute of Technology

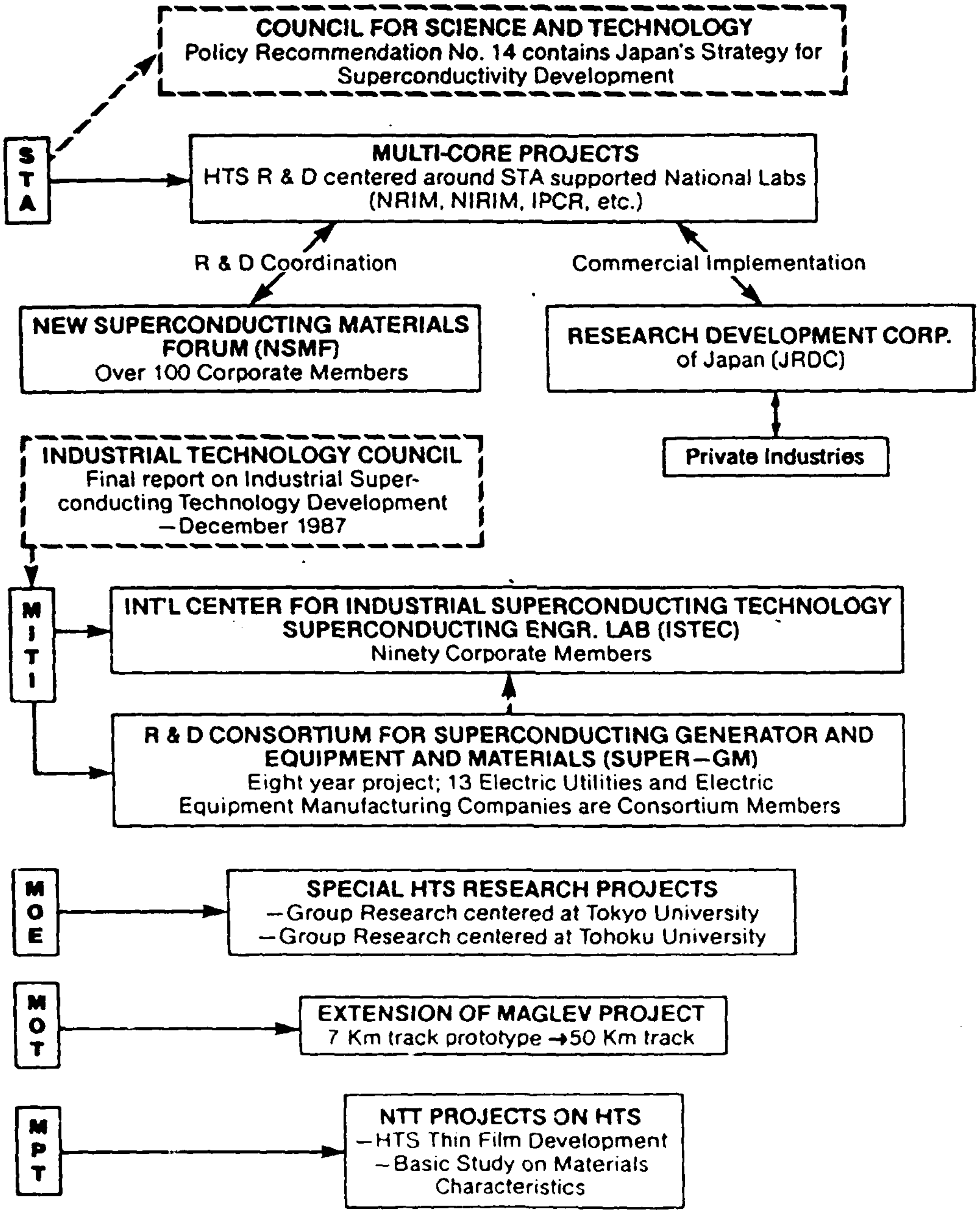
IV. Ministry of Transportation

$1 million for superconductivity-related part of Maglev railway project

V. Ministry of Posts and Telecommunications

$440 thousand for research in high-speed telecommunications. The goal is development of a mixer that can handle THz frequencies. Half to Radio Research Laboratory, half to industry. A six-year project.

JAPAN'S SUPERCONDUCTIVITY R & D AND COMMERCIALIZATION PLAN *(FY 1988)*



STA

COUNCIL FOR SCIENCE AND TECHNOLOGY
Policy Recommendation No. 14 contains Japan's Strategy for Superconductivity Development

MULTI-CORE PROJECTS
HTS R & D centered around STA supported National Labs (NRIM, NIRIM, IPCR, etc.)

R & D Coordination

Commercial Implementation

NEW SUPERCONDUCTING MATERIALS FORUM (NSMF)
Over 100 Corporate Members

RESEARCH DEVELOPMENT CORP.
of Japan (JRDC)

Private Industries

INDUSTRIAL TECHNOLOGY COUNCIL
Final report on Industrial Superconducting Technology Development
—December 1987

MITI

INT'L CENTER FOR INDUSTRIAL SUPERCONDUCTING TECHNOLOGY SUPERCONDUCTING ENGR. LAB (ISTEC)
Ninety Corporate Members

R & D CONSORTIUM FOR SUPERCONDUCTING GENERATOR AND EQUIPMENT AND MATERIALS (SUPER—GM)
Eight year project; 13 Electric Utilities and Electric Equipment Manufacturing Companies are Consortium Members

MOE

SPECIAL HTS RESEARCH PROJECTS
—Group Research centered at Tokyo University
—Group Research centered at Tohoku University

MOT

EXTENSION OF MAGLEV PROJECT
7 Km track prototype → 50 Km track

MPT

NTT PROJECTS ON HTS
—HTS Thin Film Development
—Basic Study on Materials Characteristics

Appendix I

HIGH TEMPERATURE SUPERCONDUCTIVITY FUNDING ($M)

HIGH TEMPERATURE SUPERCONDUCTIVITY FUNDING ($M)

	LTSC FY87	HTSC FY87	LTSC FY88	HTSC FY88
Department of Defense	8.6	16.5	27.	50.9
Army	--	0.3	--	1.9
Air Force	1.3	3.7	1.6	4.6
Navy	2.3	6.8	3.4	10.3
SDIO	5.0	2.0	22.0	12.9
DARPA	--	1.5	--	20.7
NSA	--	0.2	--	0.5
BTI	--	2.0	--	--
Department of Energy	28.5	12.53	39.4	27.16
Basic Energy	27.70	10.4	39.23	15.34
Fusion Energy	--	--		
High Energy and NuclearPhysics	--	--		
Defense Depts	1.63	6.67		
Office of Conservation & Renewable Energy	0.6	0.3	--	4.85
Office of Fossil Energy	0.2	0.2	0.28	0.3
National Science Foundation	2.0	11.7	3.0	14.5
Department of Commerce (NBS)				2.8
NASA			4.2	0.5
Department of Transporation				--
Department of Interior		0.1		0.1
National Institute of Health		0.005		0.26

Appendix J

GLOSSARY OF TERMS

GLOSSARY OF TERMS

AC - Alternating current

A/D Converter - Analog-to-digital converter. This device is used to transform analog signals into digital signals.

Anisotropy - A state in which a quantity, such as electric current, or spatial derivatives thereof are dependent upon direction.

ASW - Antisubmarine Warfare

C^3I - Command, control and communications intelligence

Coherence Length - The characteristic size of a Cooper pair.

CMOS - Complementary metal oxide semiconductor

Cooper pair - The paired electrons that are believed responsible for the phenomenon of low temperature superconductivity and may play a role in high temperature superconductivity.

DARPA - Defense Advanced Research Projects Agency

dB - Decibels

DC - Direct current

DDR & E - Director, Defense Research and Engineering

DRAM - Dynamic Random Access Memory

ECCM - Electronic counter-countermeasures

ELF - Extra Low Frequency. A slightly lower frequency than VLF; less than 10 KHz

EM - Electromagnetic

EM Launcher - An electromagnetic device used to accelerate projectiles to high speeds. A railgun is one example.

EO - Electro-optic

FEL - Free Electron Laser

FET - Field Effect Transistor

GaAs - Gallium arsenide. The fastest conventional electronic devices are GaAs devices.

Gauss - A measure of magnetic field strength. The Earth's geomagnetic field averages about one-third of a Gauss.

GHz - Gigahertz or billions of cycles per second.

H_c - Magnetic critical field, or the magnetic field above which superconductivity is quenched.

HEMT - High electron mobility transistor.

HF - High Frequency

hp - Horsepower

HTS - High Temperature Superconductor

IC - Integrated Circuit

IFPA/IRFPA - Infrared Focal Plane Array. IFPA's are used for IR sensors. The frequencies for infrared are 3 - 300 THz.

IR - Infrared radiation

J_c - Critical current density, or the amount of current a superconductor is able to carry.

JJ - Josephson Junction (see below)

Josephson Junction - A superconducting electronic device.

K - Degrees Kelvin. Zero degrees Kelvin is equivalent to -273 degrees Celsius or -459 degrees Fahrenheit.

LSI - Large Scale Integration

LTS - Low Temperature Superconductor

MHD - Magnetohydrodynamic. MHD Drive has been proposed as an advanced superconductive propulsion technique.

MHP - Magnetohydrodynamic power

MHz - Megahertz or millions of cycles per second.

Micron - One micrometer or one one-millionth of one meter.

MMIC - Millimeter-wave integrated circuit

MMW - Millimeter-wave. This corresponds to frequencies of 40 - 100 GHz.

MOPS - Millions of operations per second.

NPB - Neutral Particle Beam.

POM - Program Objectives Memorandum.

R&AT - Research and Advanced Technology

RF - Radio Frequency. This is a broad frequency band, from 100 MHz to 100 GHz, encompassing several types of electromagnetic wave, including microwave and millimeter-wave.

RPM - Revolutions per minute

SAW - Surface Acoustic Wave

SDIO - Strategic Defense Initiative Office

SECDEF - Secretary of Defense

SMES - Superconducting Magnetic Energy Storage

SQUID - Superconducting Quantum Interference Device. This device is used extensively in magnetic sensors, such as mine detection devices.

SSTS - Space Surveillance and Tracking System

T_c - The transition temperature or temperature at which a given material becomes superconducting.

T_N - Noise temperature

Tesla - Ten thousand Gauss are equivalent to one Tesla. Large permanent magnets typically have field strengths of 1 - 5 Tesla.

THz - Terahertz or trillions of cycles per second.

UHF - Ultra High Frequency, 0.3 - 1 GHz.

USD(A) - Under Secretary of Defense for Acquisition

VLSI - Very Large Scale Integration

VHSIC - Very High Speed Integrated Circuit

VLF - Very low frequency. Corresponds to frequencies of 10-30 KHz.

Superconductive Materials

BiCaSrCuO - Bismuth Calcium Strontium Cuprate, a high temperature compound. Difficult to produce because of the toxicity of strontium.

$LaBaCuO_4$ - Lanthanum Barium Cuprate, one of the first high temperature superconductors.

Nb - Niobium, a low temperature superconductor.

NbC - Niobium copper, a low temperature compound.

NbN - Niobium nitride, a low temperature compound.

Nb_3Ge - Niobium germanium, a low temperature compound.

Nb_3Si - Niobium silicon, a low temperature compound.

Nb_3Sn - Niobium tin, a low temperature compound.

TlCaBaCuO - Thallium Calcium Barium Cuprate, one of the most recently discovered high temperature compounds. It has a T_c of 125 K.

YBaCuO - The superconducting material currently receiving a high degree of research attention. The full compound is YBa2Cu3O7-x, also known as YBCO.

1-2-3 - This sequence of numbers refers to the chemical composition of the above mentioned cuprate superconductors, YBaCuO.