Superconductivity:

Alternative Scenarios for Technological and Business Opportunities

March 1988/R880301

Arthur D. Little Decision Resources
17 New England Executive Park
Burlington, Massachusetts 01803
Telephone 617-270-1200

About Arthur D. Little Decision Resources

Arthur D. Little Decision Resources provides corporate leaders around the world with authoritative information on the businesses and technologies of tomorrow. Through interpretive publications, conferences, and personal consultation, it offers clients continuing access to the insight and expertise of Arthur D. Little, Inc., one of the world's leading management and technology consulting firms. The principal product of Arthur D. Little Decision Resources is Spectrum, a management service that provides an independent perspective on new business opportunities, industry dynamics, technological change, and the competitive environment.

SUPERCONDUCTIVITY;

Alternative Scenarios for Technological and Business Opportunities

D. William Lee
Study Director

Edward J. Cook
Edward T. Peters
Mehmet Rona
Lawrence J. Stratton

Arthur D. Little, Inc.

March 1988

Arthur D. Little Decision Resources

TABLE OF CONTENTS

Page No.

(continued)

TABLE OF CONTENTS

Page No.

HIGH-ENERGY MAGNET APPLICATIONS (continued)

(continued)

LIST OF TABLES

(continued)

LIST OF TABLES

TABLE OF CONTENTS

Page No.

LIST OF FIGURES

(continued)

LIST OF FIGURES

ABOUT THE AUTHORS

Edward J. Cook has an extensive background in the organization and management of applied physics research programs and the development of new products. He has been awarded over twenty patents and has published numerous articles dealing with various analytic and engineering aspects of electron beam and solid state devices. Dr. Cook has had considerable experience in the application of acoustics to a variety of requirements including detection and ranging, telemetry, physical properties measurement, and nondestructive testing. As a member of the Arthur D. Little staff, he has carried out an extensive evaluation of the properties, fabrication, manufacturing capacity and applications for rapidly solidified Nd-Fe permanent magnets.

D. William Lee is a Vice President of Arthur D. Little, Inc., and Manager of the Materials and Applied Physics Section. His technical laboratory activities have involved fundamental studies in the nucleation and growth of single crystals and their electronic and optical properties and applications, and in the superconducting properties of transition metal carbide and nitride fiber and whisker forms. He has participated in a broad range of studies of new product and process development, technical/economic evaluation of material technology, and the strategic implementation of technology. Dr. Lee has led several major projects related to the manufacturing of ceramic products and their use in electronic, electrical, mechanical, and chemical applications.

Mehmet Rona's work at Arthur D. Little, Inc., has included the establishment of a molecular beam epitaxy laboratory. His research activities have concentrated on the physics of thin crystalline films, their epitaxial growth, and their interaction with intense electromagnetic radiation. In this area Dr. Rona has proposed novel techniques for optical components for high-energy laser applications. In addition, he has carried out work on the physics of superconducting magnetic energy storage systems and the materials and design of high-voltage transmission lines. At present, he is involved in the analysis of electrical properties of high-T_c superconductors.

Lawrence J. Stratton has concentrated his work at Arthur D. Little, Inc., in studies and designs of new products in the fields of solid state controls, electric machine design, and systems analysis. Mr. Stratton has been responsible for the design of power conditioning equipment for a rotary reciprocating cryogenic refrigerator, for the design and development of a microprocessor control system for an experimental electric car, and for the development of a superconducting generator. In addition, he has studied utility generation, loading, transmission, lightning, and switching transients on a network analyzer.

Edward T. Peters is a senior staff metallurgist in the Materials and Applied Physics Section of Arthur D. Little, Inc. Dr. Peters specializes in the physical, structural, chemical characterization of materials, and has worked with clients in the areas of failure analysis, process evaluation, product quality and improvement, environmental assessment, and materials specification.

SUMMARY

Conventional superconductor applications were intensively investigated in the years between 1960 and 1980. A major perceived barrier to successful commercialization of the technology was the low operating temperature needed in the operating environment; this required liquid helium cooling. However, the recent discoveries in high-temperature superconductors (HTSC) with critical temperatures of 90 K to 120 K have challenged this barrier and generated a great deal of speculation on the potential impact of superconductivity on technological change.

A significant amount of money and scientific effort will have to be expended before the questions concerning the future impact of HTSC technology are ultimately answered. In the meantime, some insight into the potential opportunities for HTSC technology and the barriers and constraints to its implementation can be found through an analysis of the viability of HTSC technology in applications where it could replace existing technology.

The pace of research into material compositions, superconducting properties, and materials processing is intense and is being undertaken by many laboratories throughout the world. The full impact and potential of HTSC superconductivity must await the outcome of these R&D efforts. It will be some years before the results of these efforts are commercialized.

This report examines the potential for HTSC applications by assuming certain technological advances in materials and materials processing that will provide selected values for the key superconducting properties of critical temperature, critical field, and critical current. We make the assumption that reproducible films and wires can be fabricated. Further, we consider the cost of HTSC wire and cable and the capital and operating costs for cooling throughout the temperature range from 4.2 K to 77 K (the temperature of liquid nitrogen). These factors then constitute the basis for several scenarios that are used to examine the viability of applications and to project the technical and economic potential of HTSC technology in the business environment.

We categorize the major applications as high-energy magnets, electric power applications, and electronic devices and components. These are commercial sectors in which high-temperature superconductors have been touted as having real promise. Within each sector the acceptance of high-temperature superconductivity faces different problems. In some instances, these problems relate to the cost of refrigeration, while in others they involve compatibility with existing technologies with which the superconducting materials must interface.

The scenarios should not to be viewed as a forecast of HTSC properties or cost, but rather as reasonable projections of the known properties and of material economics based on our experience with similar processing technologies.

The intense HTSC activity worldwide is largely focused on the composition and properties of materials, with only nominal efforts on processing technologies. However, in the longer term, processing and device fabrication will become the key technology areas, and the commercial opportunities will be in value-added products rather than in the production of materials. Although the specific activities of the major participants are proprietary, the interests and R&D direction of important competitors provide some insights into the future of HTSC. Our findings and conclusions regarding the potential for HTSC technology in the major applications are summarized below.

High-energy magnet applications involve a substantial range of performance characteristics from steady state, low-field-strength applications (magnetic resonance imaging -- MRI -- and magnetic separations), through those requiring operation at frequencies of 0.1-1.0 Hz and fields of 5-10 tesla (accelerators and colliders), to those operating at frequencies of 1-100 Hz or greater and at fields of 10-20 tesla or greater (fusion contaminant and pulsed energy sources). If high temperature superconducting wire is developed, the market for high-energy magnets has the potential to reach $1.5 billion by the year 2000.

MRI magnets based on HTSC are expected to cost less than present niobium-titanium magnets under all scenarios and would be particularly attractive if they could be operated at temperatures substantially below the critical temperatures. On the basis of magnet cost, HTSC MRI magnets could economically replace existing superconductor magnets in applications when the field is greater than 0.5 tesla. However, the cost savings are relatively inconsequential when compared with the very high total system price (in excess of $1.5 million), and thus HTSC magnets would have little impact on growth of the MRI market overall.

If magnets with a strength of 2-5 tesla can be operated at 77 K, it is likely that HTSC magnets could replace low-temperature superconductor (LTSC) magnets in industrial separation applications. Commercialization could occur as early as 1995, and the market could grow significantly, to $150 million, by the end of the decade.

HTSC technology is unlikely to impact the market or technology for accelerator or collider magnets since the major new facilities have been planned for the early 1990s, and this is much too soon for the development of adequate HTSC technology.

In the long term (beyond the year 2000), HTSC magnet technology could have a major influence on the design and utilization of fusion devices and pulsed energy systems because of the potential for high-field and high-frequency operation. However, substantial development of the technology will be required. These companies that are technologically oriented and diversified in their manufacture of systems could benefit greatly from these developments. Large scale applications could develop in the power generating industry, the defense industry and the minerals and chemicals industries.

Electric power applications involve large perceived markets for superconductor technology in several major areas: a.c. generators, a.c. transmission cables, energy storage systems, and electric drives for water and land transportation systems.

A superconductor that is able to operate at room temperature would obviate most of the technical and reliability problems of a.c. generators. Assuming low a.c. losses at fields of 7 tesla, we expect that a high-temperature superconductor with a current carrying capacity of 15 amp/mm^2 could be used for a superconductor stator as well as the rotor, resulting in a very efficient (99.5%) machine that has both a low cost and perhaps one-tenth the size and weight of a conventional a.c. generator providing the same power. Such technology would have significant commercial applications. If the a.c. losses of room-temperature superconductors were low enough to permit their use in stators, their impact on electric machinery would be revolutionary, affecting not only generators but also electric motors.

The potential for HTSC technology applications in electric power transmission cables will be highly influenced by the infrastructure of the system as it now exists. Although 5-10% of power generated is lost in a.c. transmission, the conversion costs of a d.c. transmission system and the expense of an underground a.c. superconductor-based system are both prohibitive. Even though our analysis suggests that HTSC cables operating at 77 K would have an advantage over LTSC at reasonably low power capacities, the economics and driving forces are not significant enough to stimulate the necessary R&D investment. A room-temperature superconducting cable with low a.c. loss and reasonable current density could possibly be economically configured for overhead a.c. power transmission, thereby reducing transmission losses and/or permitting power transmission over greater distances.

Superconducting magnetic electric storage (SMES) for supplying energy for peak demand periods or for stabilizing electric networks during transient conditions are amenable to technical solutions. The use of HTSC at liquid nitrogen temperatures improves the economics in smaller SMES installations. A market for stabilizing SMES could develop if we assume low a.c. losses that allow rapid charging and discharging. Our scenario analysis shows that room temperature operations would be very favorable for the development of this market.

Although interesting developments in superconducting homopolor electric drives for ships have been demonstrated, HTSC superconductor technology does not address or impact the major technical problems. The near-term implementation of electric drives in ships is expected to involve conventional electric generators and motors.

There is little incentive for the development of high-speed land transportation based on magnetic levitation technology in the United States owing primarily to nontechnical issues such as the cost of right-of-way and the lack of large concentrated mass-transport passenger markets. The development of HTSC does not materially alter this conclusion.

The viability and impact of HTSC technology for <u>electronic devices and components</u> is less dependent upon superconducting properties and operating temperatures than upon factors specific to superconductor physics and the competitive position of present and evolving semiconductor technologies. Therefore, the scenario analysis was not significantly discriminating in this instance.

The lower power dissipation and faster speed of superconducting Josephson junctions (JJs) for logic circuits are an advantage in electronic applications, but the implementation will be difficult because of the two-terminal construction and latching character of JJs. Furthermore, competitive technology such as optoelectronics is evolving rapidly and, once installed, will be difficult to supplant. A major barrier that must be overcome before these markets can be addressed is the development of HTSC material compatible with existing semiconductor processing technology.

While superconductor interconnects provide only marginal improvement in device performance, certain analog devices and sensors are viable in low-volume, high-value, niche applications of HTSC technology.

The potential market for applications of superconductivity to electronics with known devices and implementation techniques is severely limited. In digital electronics, the segment of the present electronics market susceptible to penetration by SC is emitter-coupled logic (ECL). In analog electronics, only a part of the present sensors market is available for superconductivity. Technological breakthroughs may, of course, create new markets as well as address present market segments. However, past experience with superconductivity in digital electronics shows the importance of achieving technical targets within narrow windows of opportunity.

At this point in time, high-temperature superconductivity is an intriguing scientific phenomenon. The task of understanding and developing the underlying theoretical base and the implications of this evolving science for future technology is a formidable and important one. Our analysis supports the conclusion that the technical and economic driving forces for the utilization of HTSC materials are limited even under the assumptions of the most favorable of our scenarios. High-temperature superconductivity is a high-risk technology because of the substantial investment required to develop improved materials in usable shapes and forms with viable processes and to fund the engineering developments required for large-scale applications.

1. INTRODUCTION

by D. William Lee, Sc.D.

The recent spectacular scientific discoveries in high-temperature superconducting (HTSC) material have stimulated not only an extraordinary explosion in research activity but also an equally large amount of speculation concerning the potential impact these developments may have on technology broadly. Substantial investments of money and time will be required to develop this technology. Nevertheless, at this time the potential viability of selected applications can be examined by assuming certain technological advances in materials and properties.

We have devised a scenario analysis that allows us to project those applications in which high-temperature superconductors appear technically and economically viable in comparison with existing low-temperature superconductors (LTSC) and conventional and alternative competing technologies. The applications we have examined will be discussed in more detail in subsequent chapters. These are in three categories: high-energy magnets (the one category with current significant commercial applications), electric power (with potentially the largest applications in generation, transmission, storage, and propulsion), and electronics (with important, but elusive, applications in analog and digital devices, sensors, and interconnects).

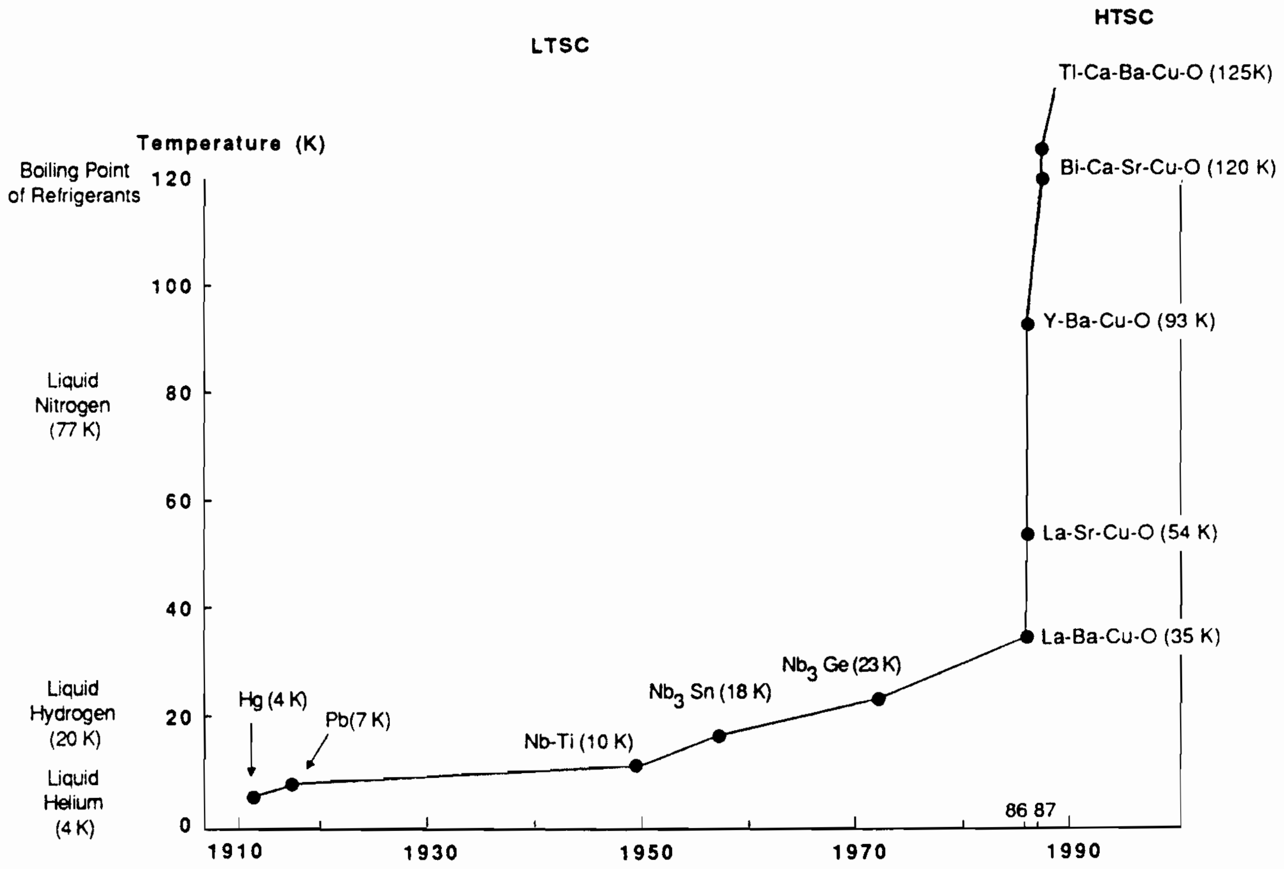
BACKGROUND, RATIONALE, AND OBJECTIVES OF OUR ANALYSIS

The activity and interest in superconductivity within the past 12 months has been a rather fantastic phenomenon. Slightly more than a year after the announcement of the discoveries by Muller and Bednorz, the first indication of a 30 K transition temperature was quickly confirmed. This was extended to a higher transition temperature at higher pressures. Then, within a few months, the 90 K-plus transition temperature discoveries were announced. Over the past several months further advances have been announced and confirmed in new composites (Figure 1). This pace is very startling considering the long search for higher transition temperatures.

In addition to stimulating tremendous activity in the scientific world, these new discoveries have caused much speculation regarding the impact that they could have on industry and society. The technical community has been exploring superconductivity for over 25 years. In the period from 1960 to 1980 there was tremendous technical activity in superconductivity, including the building of prototype hardware to explore the usefulness of that technology. Throughout this period it was generally perceived that the very low transition temperature of 4.2 degrees above absolute zero (4.2 K), requiring operation in liquid helium, was the major barrier to commercialization of superconducting technology. The new transition temperatures have removed that barrier, and the potential to operate some of these applications at the temperature of liquid nitrogen temperature (77 K) means a reduction in capital and operating costs, reduced complexity of the systems, and greater reliability. People quickly saw opportunities for greater

FIGURE 1

SUPERCONDUCTIVITY MATERIALS DEVELOPMENT TO DATE



Key

Ba: Barium
Bi: Bismuth
Ca: Calcium
Cu: Copper

Ge: Germanium
Hg: Mercury
La: Lanthanum
Nb: Niobium

O: Oxygen
Pb: Lead
Sn: Tin
Sr: Strontium

Ti: Titanium
Tl: Thallium
Y: Yttrium

Sources: Nikkei High Tech Report 2(12), 1987; and Arthur D. Little, Inc., estimates.

efficiency in electric power generation, storage, and transmission. The potential now also exists for smaller mechanisms for electric propulsion for sea and land transportation with improved performance. In electronics, the possibility of actually using Josephson junction technology could mean faster processing of digital signals and the capability to design and use electronic devices with higher-density packing. High-power magnets for high-energy physics research and for industrial uses such as magnetic materials separation may now become economically viable.

However, some words of caution in the forecasting of new technology are in order. In 1975 a NATO conference on superconductivity, involving a prestigious group of scientists and engineers, compiled some projections on the commercial possibilities for the low-temperature application of superconducting materials (niobium titanium and niobium tin). They predicted at that time that, with the exceptions of fusion containment and transmission line applications, most large machinery applications of superconductivity would be commercially available today (see Table 1). Clearly that has not been the case. Furthermore, the major commercial application of superconductivity today, magnetic resonance imaging (MRI), was neither mentioned nor conceived of in 1975.

Based on our experience in materials development technology and the introduction of new systems, we believe the commercialization of the high-temperature superconductors as we now imagine them will be many years off. Perhaps a decade will pass before we see useful products. We believe the basic data needed to understand high-temperature

TABLE 1

STATUS VS. EXPECTATION OF COMMERCIALIZATION OF SUPERCONDUCTIVITY

	1975 Projections	Present Status (1987)
High-Energy Physics	-	Limited
Fusion Containment	2000	None
Magnetohydrodynamics	1985	None
Magnetic Storage	1980	None
Generators/Motors	1980	None
Transformers	?	None
Transmission Lines	1990	None
High-Speed Transportation	1980	None
Industrial Separation	1980	Very Limited
Interconnects	-	None
Logic Devices	-	None
Sensors	-	Limited
Analog Devices	-	Very Limited
Magnetic Resonance Imaging	-	Largest

Source: Adapted from J. Powell, Superconducting Machines and Devices, NATO Advanced Study Institute Series, 1973.

temperature superconductivity and to develop useful products will require a substantial investment of money and scientific personnel. The known high-temperature superconducting materials are particularly intractable; they are much more difficult to work with than niobium titanium and at least as difficult as niobium tin (which is not truly a commercial product material, even today). New technology will be required to manufacture useful forms of the new HTSC materials.

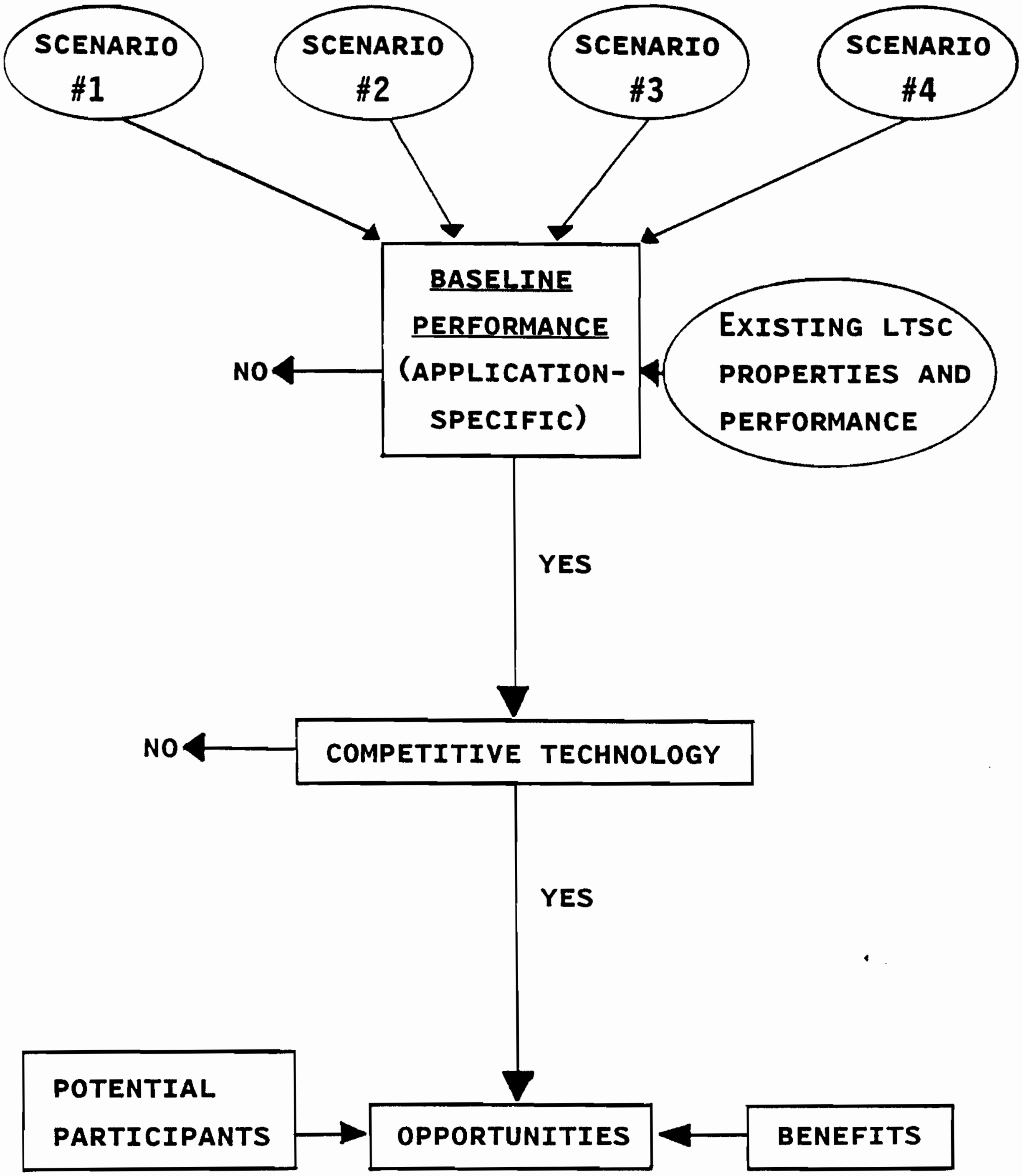
Nonetheless, Dr. John Rowell of Bell Laboratories (holder of the original patent on Josephson junctions) said at a July 1987 White House conference that it would be useful to demonstrate, at least on paper, the advantages of superconductivity at 77 K in various applications assuming the conventional properties of these materials. We agree, and we have extended this concept to include potential operating temperatures near room temperature and materials with improved properties.

With that objective in mind, we have carried out an analysis using present and projected properties of high-temperature superconductors to examine the technical feasibility of some key applications. We considered the economic competitiveness of these new materials compared with existing low-temperature superconductor materials technology and with prevailing competitive conventional technology already in use. Based on this analysis, we project what we believe are the commercial opportunities, when they might occur, and who would be involved.

Figure 2 is a scheme illustrating the logic of our approach. We have established four scenarios based on different assumptions and

FIGURE 2

ESTABLISHMENT OF SCENARIOS



Source: Arthur D. Little, Inc.

extrapolated values for properties and behavior of the materials. We developed scenarios based on various sets of assumptions to provide a basis for projecting the potential opportunities for high-temperature superconductors. The baseline for our analysis was the status quo with respect to low-temperature superconductor technology and economics. Our scenarios for high-temperature superconductors were based on a series of operating temperatures and critical transition temperatures and two levels of critical field and critical current properties. We considered the cost of both low-temperature and high-temperature superconducting composite wire in each scenario and analyzed the economics of refrigeration that would be required across the range of operating temperatures. The properties assumed in the scenarios are not meant to be forecasts or predictions as to future properties of HTSC materials but rather are assumed properties for the purpose of the analysis.

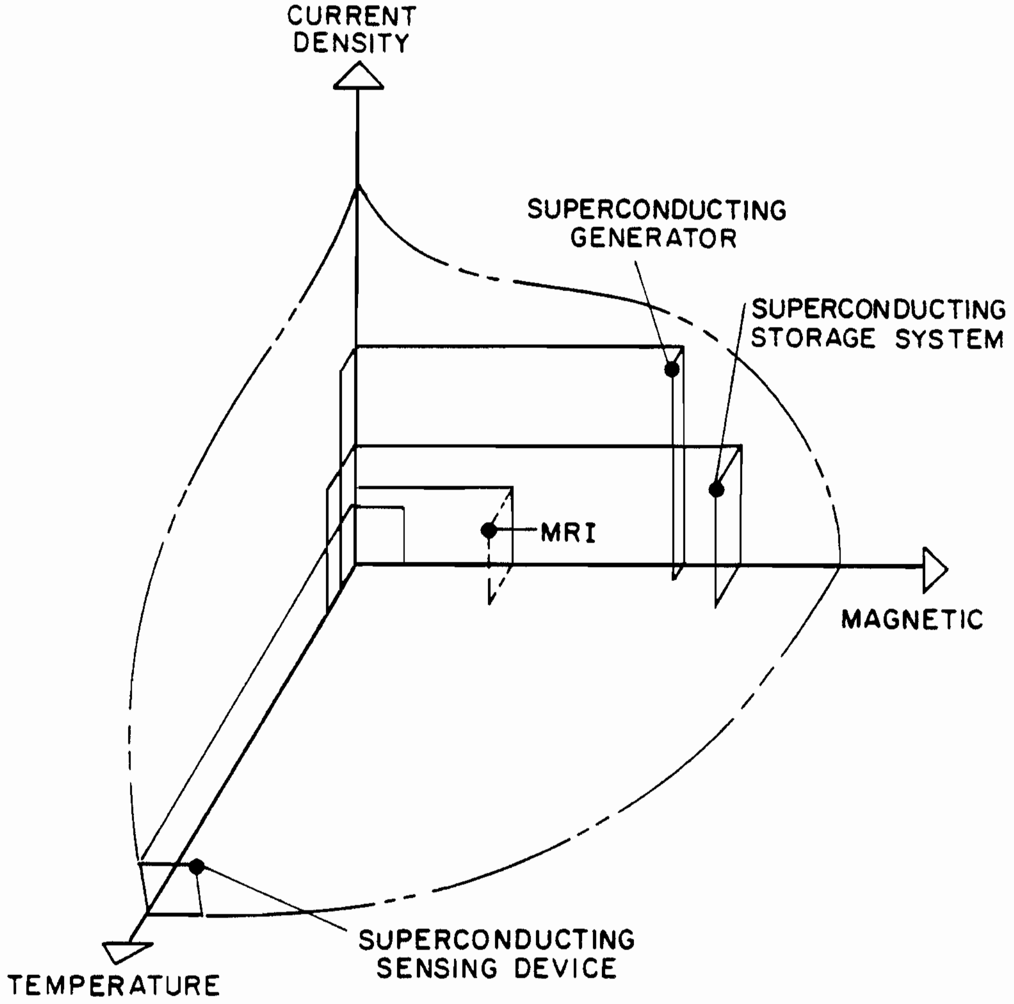
As the figure illustrates, this was a sequential process that involved four steps. First, the scenarios were defined, then each was compared with application-specific baseline performance. Those situations that were able to pass this screen were then compared with competitive technologies. As a final step, we identified the opportunities for applications that were able to pass the screening of competitive technologies. These scenarios were tested against application-specific baseline performances, involving, for example, a.c. generators, transmission lines, and Josephson junction logic circuits. We examined the performance of existing low-temperature superconductors and the perceived barriers to applying the technology and judged whether our hypothesized new high-temperature materials provide a competitive advantage over conventional technologies.

Depending on the application being considered, the optimum superconducting properties -- critical temperature, magnetic field density, and critical current density -- can be very different. Figure 3 depicts what Dr. Mehmet Rona calls the "Hershey Kiss" of superconductivity, a property envelope within which a specific material would be superconducting. It can be seen that for applications such as a superconducting generator or storage system where you may need relatively high current densities and have high magnetic fields in order to maximize both the current and field properties, it is necessary to operate at quite low temperatures. MRI applications actually have a much lower requirement for field and current properties than depicted in the figure and could be operated at a higher temperature, but are operated in the region shown because 4.2 K cryogenic technology is convenient and available. A superconducting sensor, on the other hand, can be operated very close to the critical temperature since current and field considerations are not important parameters.

There are a number of other parameters in addition to current density, magnetic field density, and critical temperature, which will influence our judgment of product viability in each of the three areas -- electric power, high-energy magnets, and electronics -- we have considered. For example, in electric power applications and high-energy magnet applications, a.c. losses and frequency effects are major areas of concern. The cost of refrigeration would be dictated by the operating temperature being considered in the application's design. In electronics, these are not the major problem areas. Instead, the barriers are not directly related to the superconductivity properties.

FIGURE 3

SUPERCONDUCTING PROPERTIES REQUIRED FOR MAJOR APPLICATIONS



Source: Electric Power Research Institute

These include compatibility of processing with semiconductors, problems of compatibility with existing electronic circuit architecture, and yields and reliability in the processing of superconductors. For all three broad areas there are different, competitive technologies to be considered.

SCENARIO DEVELOPMENT

Our baseline scenario involves existing commercially available superconducting materials -- niobium tin and niobium titanium -- fabricated in standard shapes (wire, cable, film) by current fabrication technology, and operating at liquid helium temperature, 4.2 K.

Our alternative scenarios are based on the present high-temperature superconductor, yttrium barium copper oxide (YBCO). This material is also called the 1-2-3 compound because of the ratio of Y, Ba, and Cu in the compound. The scenarios also take into consideration a composite of the best reported properties. We have extrapolated these properties to a hypothetical improved high-temperature material with a transition temperature substantially above room temperature and therefore capable of operating at room temperature. We also assume an ability to fabricate such materials into suitable shapes and forms; we do not, however, assume any new technology for cooling and cryogenics. Since the analysis described in this report, new high-temperature superconductors have been discovered (e.g., Tl-Ca-Ba-Cu-O and Bi-Ca-Sr-Cu-O). Although these materials have been observed to have improved critical function temperatures, these discoveries do not impact the analysis and conclusion of this report.

Table 2 lists values for parameters of the four scenarios used in our analysis. We considered three operating temperatures: 4.2 K (liquid helium), 77 K (liquid nitrogen), and 300 K (room temperature). We chose two critical temperatures of the new HTSC material: 90 K -- within current state of the art -- and a hypothetical 400 K transition temperature (to allow us to consider operating at room temperature). We also have two critical field values, 30 and 100 tesla, and two values of critical current, which differ by a factor of 10. The baseline scenario uses the properties of existing low-temperature commercially

TABLE 2

PROPERTIES OF BASELINE AND SCENARIO MATERIALS

			Scenario Parameters			
	Baseline		**S1**	**S2**	**S3**	**S4**
Operating Temperature, T_o (K)	4.2	4.2	4.2	77	77	300
Critical Temperature, T_c (K)	10	18	90	90	400	400
Critical Field, H_c (tesla)	10	20	100	30	100	30
Critical Current, J_c (amp/mm^2)	$5x10^3$	$10x10^3$	$30x10^3$	$3x10^3$	$30x10^3$	$3x10^3$
Material	NbTi	Nb_3Sn	YBCO	YBCO	New RTSC	New RTSC

Source: Arthur D. Little, Inc.

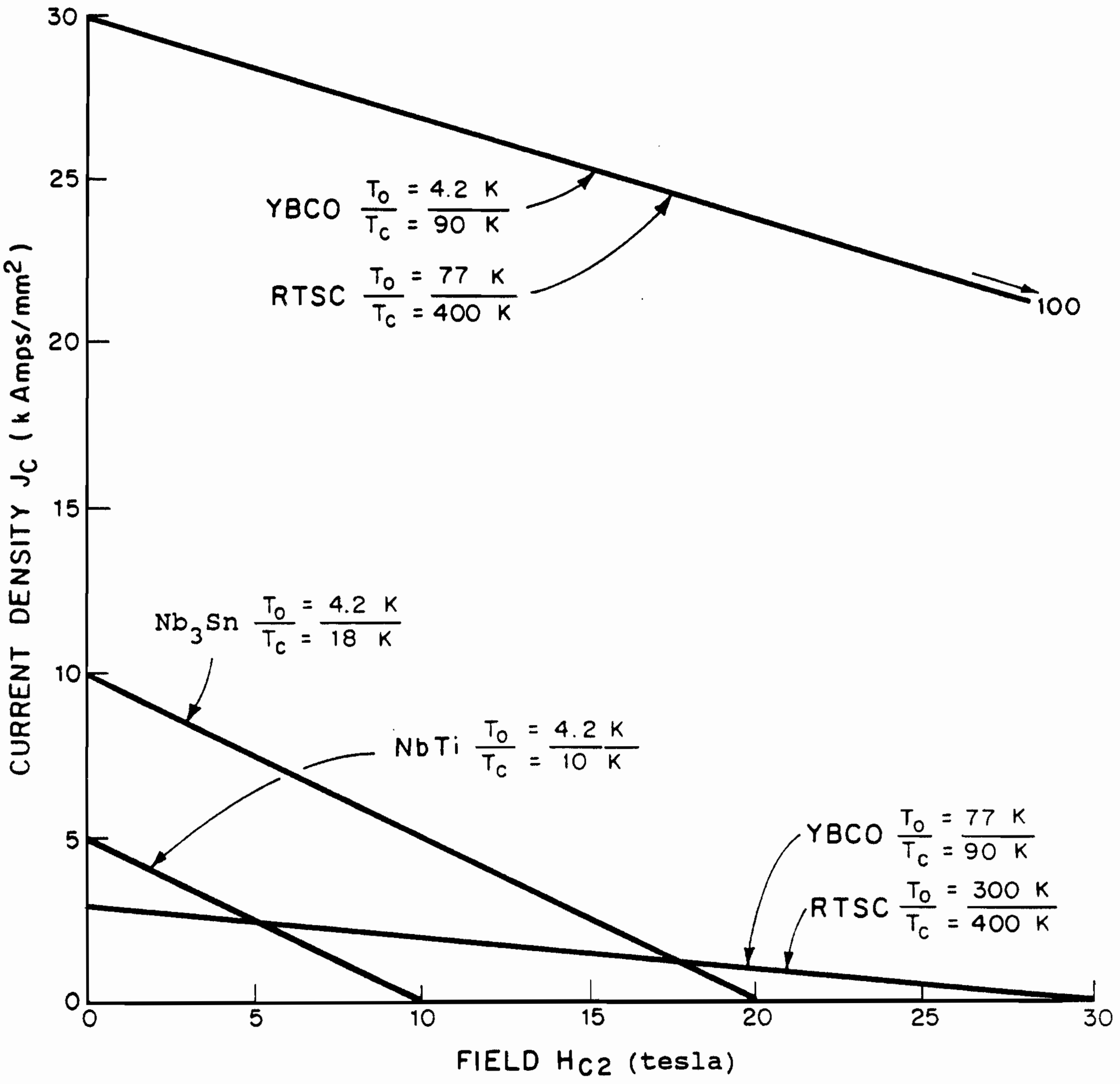
commercially available superconducting materials; scenarios 1 and 2 consider the 1-2-3 compound, YBCO; and scenarios 3 and 4 consider a yet-to-be-developed room temperature superconductor (RTSC).

There are four key considerations for our analysis: the cost of the superconducting materials, the cryogenic refrigeration cost, the critical field to critical current relationship, and the difference between the operating temperature and the critical temperature.

The straight lines in Figure 4 representing the critical field to critical current relationships are simplified representations of the actual relationship and are adequate for our purposes. Niobium tin and niobium titanium, the two standard materials, form the baseline for our comparison. YBCO and the hypothetical room temperature superconductor show two types of behavior, which depend not only upon the material's critical temperature but also upon its operating temperature. Thus, the behavior of YBCO and the new HTSC material when operated near their critical transition temperatures is represented by the lower curve. The field-current relationship represented by the upper curve depicts a high-performance relationship for these materials, which we project as their maximal properties when operated substantially below their critical temperatures: i.e., YBCO with transition temperature of 90 K operating at 4.2 K (liquid helium temperature), and the new room temperature material with 400 K transition temperature operating at 77 K (liquid nitrogen temperature).

FIGURE 4

CRITICAL FIELD - CRITICAL CURRENT RELATIONSHIP FOR BASELINE AND ALTERNATIVE SCENARIOS

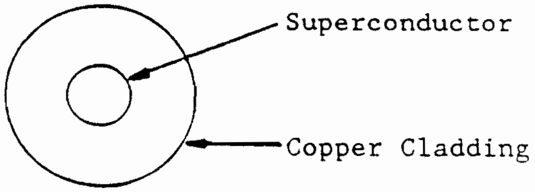


Source: Arthur D. Little, Inc., estimates.

Table 3 shows a breakdown of the costs for superconducting wire in dollars per meter. We considered three different overall diameters of a wire consisting of a superconducting filament clad in a copper sheath, with the cross-sectional area of the surrounding copper being twice that of the superconductor. The materials cost is based on today's prices for these metals and compounds. The fabrication costs are based not only on our understanding of the niobium titanium fabrication process, but also on our estimates of certain ceramic processes. Finally, we estimate a selling cost of \$8-27 per meter depending on the diameter of the material. Niobium-titanium wire at \$27 per meter is comparable to today's selling price.

TABLE 3

ESTIMATED SELLING PRICE PER METER OF SUPERCONDUCTING WIRE



Assumptions

Diameter total = 3-6 mm

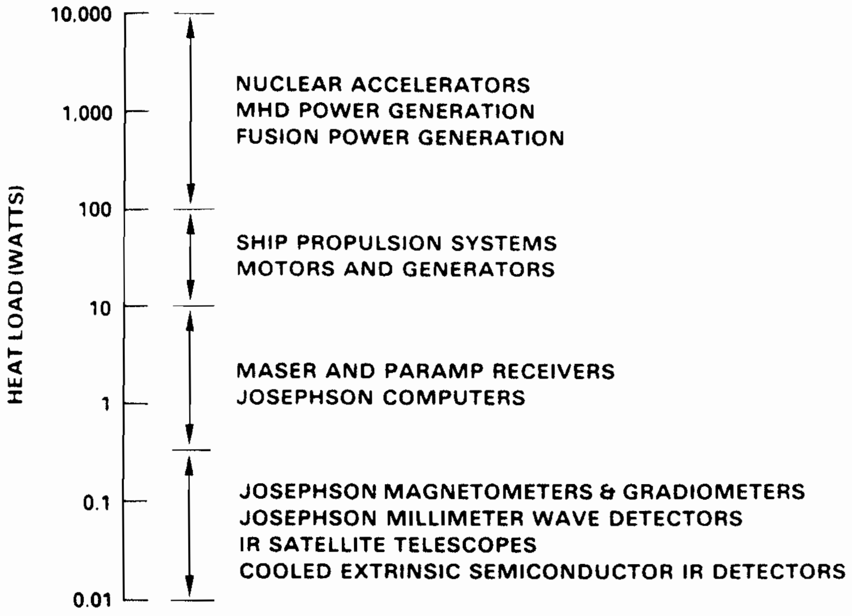
Area
Superconductor = 1/2 Area Cladding

Manufacturing Cost	($/meter)	
(estimated at 70% of Selling Price)	3mm Diameter Fiber	6mm Diameter Fiber
Material Cost (estimated at 12% of Mfg. Cost)		
Nb_3Sn	0.61	2.03
NbTi	0.68	2.28
YBCO	0.46	1.43
Fabricating Cost (estimated at 88% of Mfg. Cost) (NbTi basis)	5.00	17.00
Estimated Selling Price		
Nb_3Sn	8.00	27.00
NbTi	8.10	27.50
YBCO	8.00	27.00

Source: Arthur D. Little, Inc., estimates.

FIGURE 5

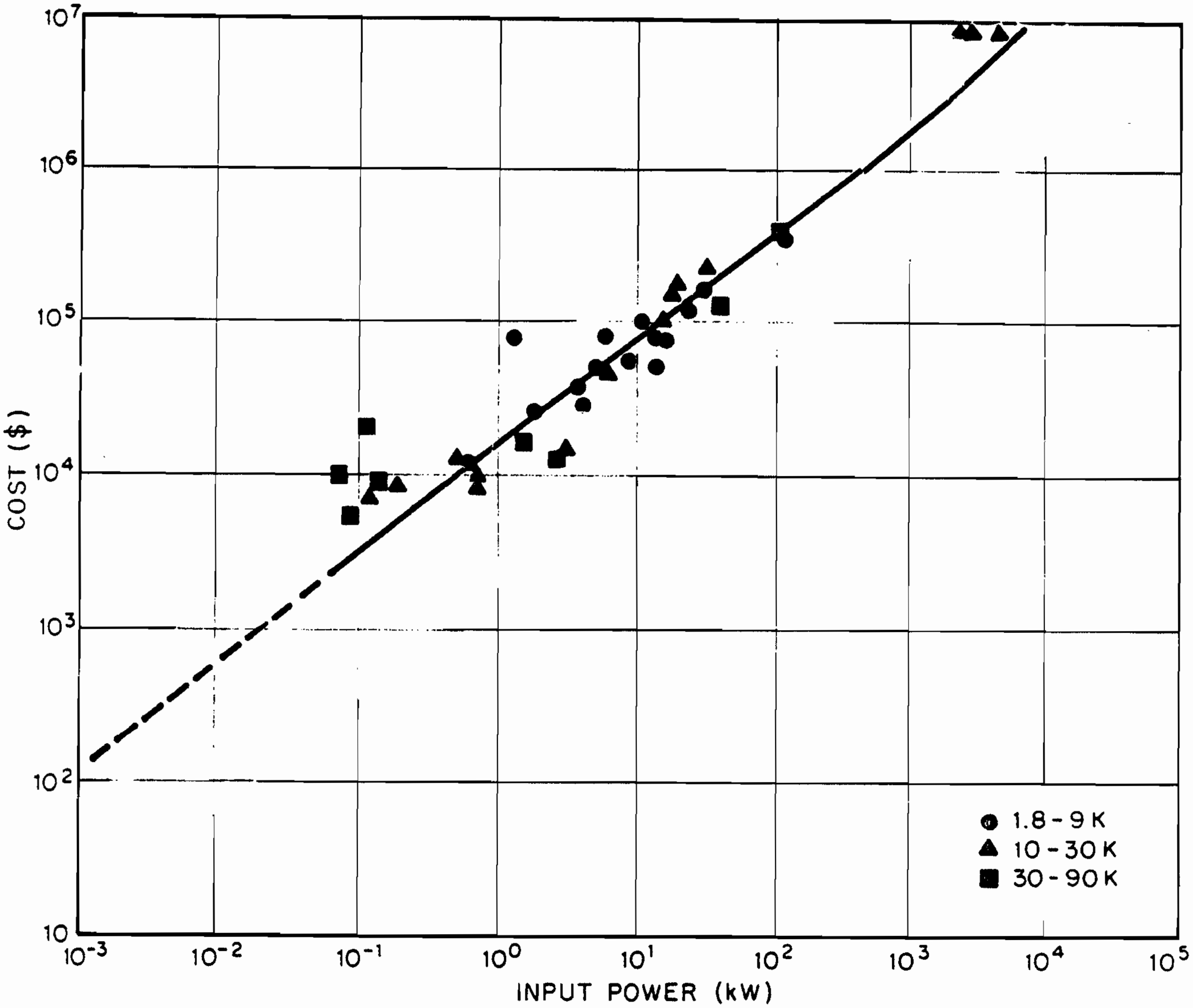
HEAT LOAD DISSIPATION IN VARIOUS APPLICATIONS



Source: G. Gamata, IEEE Transaction on Magnetics, January 1981, Vol. 17, #1 © 1987, IEEE.

FIGURE 7

COST OF CRYOGENIC EQUIPMENT, 1987



Sources: Arthur D. Little, Inc., estimates, based on T.R. Stobridge, IEEE Trans. on Nuclear Science, June 1969, © IEEE.

TIMELINES, OPPORTUNITIES, AND ORGANIZATIONS

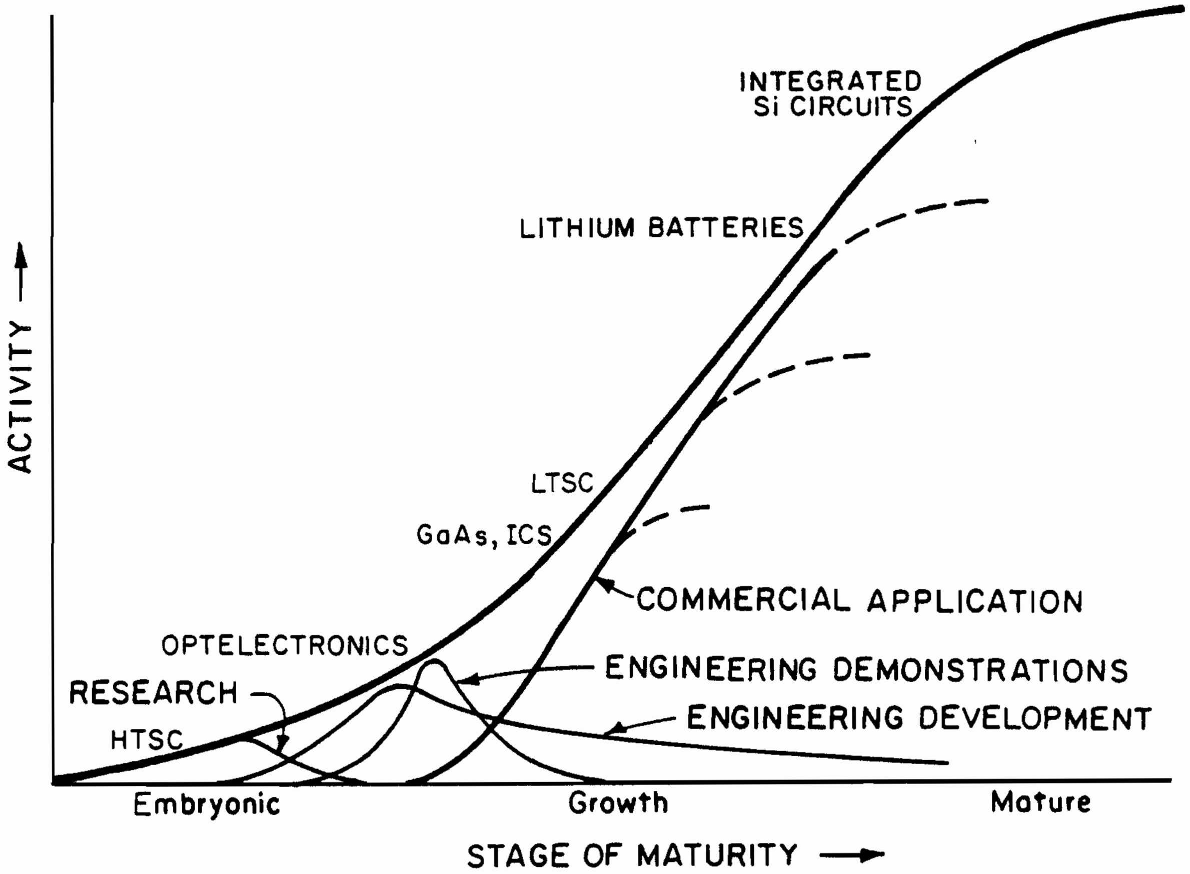
The steps in the development of a product from research to commercial production can be visualized as different stages in a technology's life cycle curve (Figure 8). At different stages of maturity certain activities grow and assume importance while others decline. For example, research activity is maximum in the embryonic stage and declines as the technology matures and activity becomes concentrated in engineering development. This is followed by overlapping activities in engineering demonstration and finally by commercial application and production. The summation of these separate but overlapping activities is the life cycle curve of that technology.

The top curve shows our perception of the stages of maturity of some technology products. Low-temperature superconductivity technology is judged to be in an early growth stage, while silicon-based integrated circuit technology is becoming mature. The present status of high-temperature superconductors is clearly that of an embryonic technology with activity focused entirely in research.

In each of the three application sectors analyzed, estimates of the time frame for the technology to proceed from research to commercial application are made based on a consideration of the technical and economic viability of the technology and its competitiveness. For example, the left side of Figure 9 shows that research on niobium titanium wire continued for about three to five years after 1960. Rather quickly, engineering development began and proceeded in parallel and has

FIGURE 8

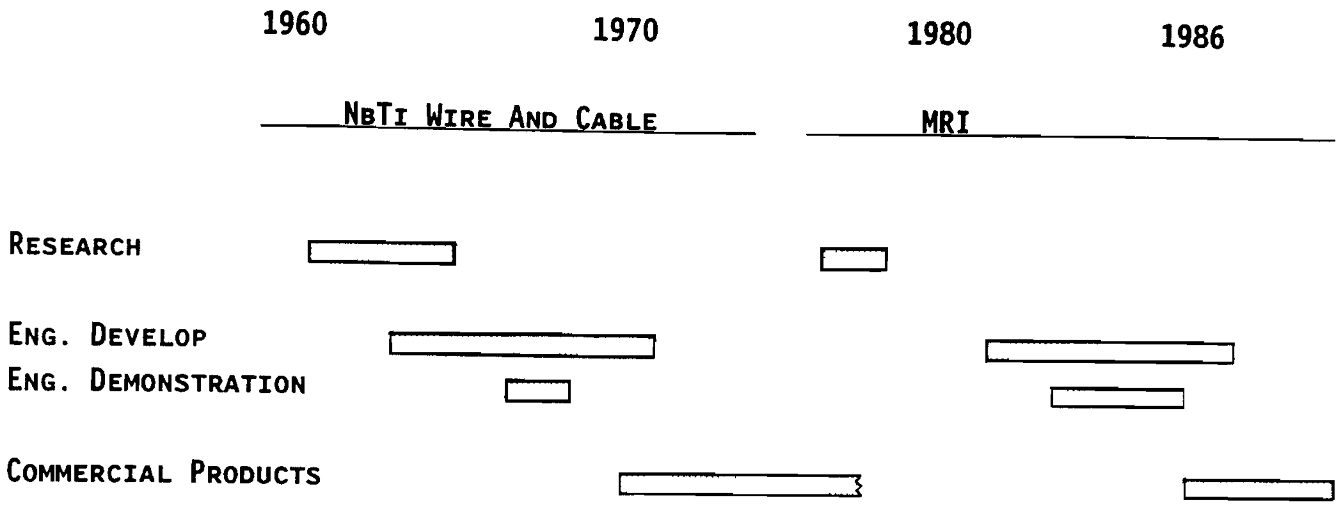
DEVELOPMENT PATH FROM RESEARCH TO COMMERCIALIZATION



Source: Arthur D. Little, Inc.

FIGURE 9

TIMELINES: NbTi SUPERCONDUCTOR WIRE AND MRI SYSTEMS



Source: Arthur D. Little, Inc.

continued as new applications such as the superconducting supercollider require improvements in the properties of NbTi wire. Engineering demonstrations in high energy magnets were made in the late sixties, and commercial products became available by 1970.

MRI (magnetic resonance imaging) timelines are depicted on the right side of Figure 9. MRI technology moved into commercial development very quickly. Computer tomography scanning technology had previously been introduced and had set the pace of research and opened the market. Thus MRI, with a market niche waiting for it, found few barriers to acceptance.

In Figure 10 the value-added chain for potential HTSC commercial products is shown schematically, together with an identification of possible opportunities in materials, components, and systems and examples of companies who might participate in the future. In a sense the schematic represents the structure of the industry for low-temperature superconductors today as far as it has developed, and it may be viewed as the potential structure of the future HTSC industry. Thus, there are raw materials suppliers; precursor chemical suppliers; materials fabricators (who today are primarily NbTi wire and cable producers); device, component, and subsystem manufacturers (magnets, Josephson junction devices, sensors, etc.); and finally systems manufacturers (e.g., computers, generators and motors, and imaging systems). In each of the sectors we identify areas of opportunity; however, we believe that value-added opportunities will generally be in the device subsystems and systems areas rather than in supplying raw materials.

FIGURE 10

POTENTIAL AREAS OF OPPORTUNITY FOR MANUFACTURERS

VALUE-ADDED CHAIN	PRODUCT LEVEL	COMMENTS/EXAMPLES
SUPPLIERS OF PRECURSOR CHEMICALS	. SPECIALTY CHEMICALS AND COMPOUNDS . FORMULATIONS	EXISTING TECHNOLOGY AND MANUFACTURERS (RHONE-POULENC, MOLYCORP)
↓		
MATERIALS FABRICATORS	. COMPOSITE WIRE, CABLES, TAPE	EXISTING LTSC PRODUCERS . SUPERCON . IMG . OXFORD . HITACHI START-UPS . AMERICAN SUPERCONDUCTORS OTHERS . DU PONT . CORNING . GTE
↓		
DEVICE/COMPONENT/ SUBSYSTEM MANUFACTURERS	. MAGNETS . JJ DEVICE/SENSORS	INTEGRATED MATERIAL FABRICATORS SEMICONDUCTOR PRODUCERS START-UPS
↓		
SYSTEM MANUFACTURERS	. GENERATORS, MOTORS . IMAGING SYSTEMS . INDUSTRIAL EQUIPMENT MFG	EXISTING SYSTEM MANUFACTURERS
↓		
MARKET		

Source: Arthur D. Little, Inc.

We estimate that 75-100 organizations in the United States are now actively involved or interested in the development of high-temperature superconductors. It is our understanding that over 200 companies in Japan have at least some interest and activity in this area. The perceived impact of HTSC technology has resulted in an increase of international competitiveness -- e.g., Presidential initiatives, special studies, reallocation of federal funds for research, and some Congressional proposals for substantially increased budgets in 1988 and beyond.

In the following chapters of this report the scenarios described in this chapter will be applied to the major applications perceived for HTSC in the future. The three big areas of applications are dealt with in separate chapters. In each instance the technology and economies of HTSCs are reviewed and compared with competing technologies. Timelines for materials, components, system development, and commercialization are estimated. A summary of the principal companies and institutions presently involved in HTSC R&D is provided in a separate chapter of the report.

We wish to emphasize that this report is not a market or technology forecast. Rather, this is an analysis of the viability of HTSC technology that assumes realistic properties and certain advancement in materials processing. We believe that the insight gained as a result of this analysis will provide a valuable contribution to the complex issue of potential opportunities for HTSC technology.

2. HIGH ENERGY MAGNET APPLICATIONS

by Edward J. Cook, Ph.D.

SUMMARY

The impact of high-temperature superconductivity will eventually be significant, but this impact will depend upon several intermediate developments. There are formidable technical obstacles. The 90 K superconductor material will be useful for high-energy magnets only if the HTSC current density can be increased and if the brittle wire problem is solved. If these conditions cannot be met, it will be impossible to fabricate practical HTSC high-energy magnets. Even if a high-temperature superconducting material is developed that is acceptable in terms of mechanical and magnetic properties, it is probable that cryogenics will still be used. In order to achieve the level of performance needed for some market-opening applications, HTSC will probably be operated far below its critical temperature.

The present high-temperature superconductor, $YBa_2Cu_3O_{7-x}$, can handle current densities suitable for high-energy magnets only in single-crystal form. In addition, the material is extremely brittle, a characteristic that has severely limited the application of Nb_3Sn, a low-temperature superconductor that is superior to the ductile NbTi in all other important measures of performance. Thus, it is not likely that $YBa_2Cu_3O_{7-x}$ will prove to be suitable for high-energy magnets, and a different class of high-temperature superconductor will probably be required to realize the scenarios presented.

At present, the high-energy magnet market is constrained by the cost and performance limitations of low-temperature superconductors to about $120 million annually, with the major application being magnetic resonance imaging (MRI) and an occasional large, high-energy physics system. Scenarios predicated upon the successful development of high-temperature superconducting wire suggest that the high-energy magnet market has the potential to increase to about $1.5 billion by the year 2000, with the largest growth occurring in magnetic separation, high-energy physics, and pulsed energy storage.

For MRI use, HTSC materials would rapidly replace the low-temperature superconductor wire in magnets with a field strength of more than 0.5 tesla. In magnets with a field strength of less than 0.5 tesla, the HTSC would probably lose out to permanent magnets. Overall, the impact on MRI market growth would be relatively small since there is insufficient overall system price impact.

There appears to be no real opportunity for HTSC to impact the Superconductive Supercollider unless construction is delayed for 5 or 10 years. There is good long-range potential in this area, however, because of the potential for high current density and critical field at 4.2 K.

The same factors of high current density and critical field at 4.2 K could lead HTSC to have a great impact on system design in the areas of fusion devices and pulsed energy. With their complex field shapes and high field cycle rates, however, these applications become extremely challenging.

The estimated impact of HTSC on various industries is discussed in this chapter. For most of the producers of raw materials, the impact should be negligible. There may be some increase in the demand for yttrium, though it now appears possible that advanced HTSC may not include yttrium or rare earth elements.

The companies currently fabricating low-temperature superconductivity wire are very specialized and have tremendous overcapacity. Some of them may be forced out of business by HTSC developments. Significant opportunities may develop for those companies that are more technologically oriented and diversified in their manufacture. Sophisticated new technology may be required for in-place deposition of HTSC magnet windings. The biggest beneficiaries, however, could well be companies that are systems-oriented, for HTSC may lead to the development of new and important markets involving large-scale systems and installations. Such applications could well develop in the power generating industry, the defense industry, and the minerals and chemical industries.

TABLE 5

SUPERCONDUCTING MAGNET APPLICATIONS

Application	Material	Status	Volume	Value (at Status Date)
Magnetic Resonance Imaging	NbTi	Commercial 1987	150 tons/year (magnets)	$75 million/year
Magnetic Separation	NbTi	Commercial 1987	2 tons/year	$1.0 million/year (magnets)
Accelerators				
Tevatron	NbTi	Completed 1983	100 tons	$15 million
Supercollider	NbTi	1990s construction	2000 tons	$1.1 billion
Fusion	NbTi, Nb_3Sn	Mid-1990s construction	600 tons/machine	$500 million/machine (magnets)

Source: Arthur D. Little, Inc.

High-Energy Physics

The high-energy physics market in general is geared toward accelerators and colliders. New machines of this sort are spaced in time by about a decade and create a temporary huge demand for new magnets. The Tevatron at the Fermi Laboratory near Chicago is the first of these machines to employ large numbers of superconducting magnets. It incorporates a total of approximately 1,000 magnets of both dipole and quadripole tied configuration. During the five-year Tevatron magnet construction period, a market base was established for niobium titanium superconducting alloy and magnet wire.

The superconducting supercollider, SSC, will probably also employ niobium titanium wire. This project should provide a market for the period of time during which the supercollider is under construction. At present, there are three SSC prototype magnets being developed by separate teams at the University of Texas, the Fermi Laboratory, and the Brookhaven and Lawrence Livermore National Laboratories. Each of the groups is using niobium titanium in its prototype. Construction of the SSC is expected to begin in the early 1990s and would require about 10,000 magnets.

Fusion

Fusion represents another very large potential market. At present, there are about half a dozen new fusion machines being considered in various parts of the world. Each of these would require about 600 tons of composite superconducting wire in its construction.

Pulsed Energy Storage

Pulsed energy storage has great importance in connection with some of the Strategic Defense Initiative (SDI) applications and other military and industrial systems and can be a potentially important and sizable market for future consideration. Although such applications are presently beyond the technical capability of low-temperature superconducting inductors (magnets), appropriate high-temperature superconductor developments would improve the prospects for this area of application.

CHARACTERISTICS OF HIGH-ENERGY MAGNETS

The characteristics of high-energy magnets are depicted in Table 6. As a consequence of the high field and the generally large volume over which the magnetic field is established, superconducting magnets contain large amounts of stored energy, usually in excess of 1 megajoule (MJ). MRI magnets store up to 7 MJ, the Tevatron magnets about 200 MJ, and 15-foot diameter bubble chamber magnets about 800 MJ.

Although high energy storage is usually incidental to the application requirements, it is always associated with very high fields and high working volumes. This fact has important implications in terms of the way in which superconducting magnets have to be designed in order to assure their safety in case of component failure. Many of the early magnets ended their lives in a cloud of vapor as all the stored energy was almost instantaneously distributed throughout the magnet as a result of an unplanned and uncontrolled conversion from the superconducting to the normal state.

TABLE 6

CHARACTERISTICS OF HIGH-ENERGY MAGNETS

- High Energy Storage

  1 to >100 Megajoules (MJ)

  as a result of

- High Magnetic Field

  >1 tesla (10,000 gauss)

  and/or

- High Working Volume

  >1 cubic meter

Source: Arthur D. Little, Inc.

TECHNOLOGIES

A number of different technologies that can be used to create high-energy magnets; these technologies compete with superconductivity. Table 7 illustrates the important characteristics of each technology.

Iron Core/Resistive Conductor

This is the oldest and most basic technology for magnet applications. In many instances, it is also the most efficient alternative. For applications where the field required is relatively low and the "air gap" or working volume small, this is the technololgy of choice.

TABLE 7

HIGH-ENERGY MAGNET TECHNOLOGIES

Technology	Max. Field Strength (tesla)	Typical Operating Field Strength (tesla)	Power Consumption (MW/MJ)*	Weight (tons/MJ)	Comments
Iron Core/Resistive Conductor	2	1-1.4	0.1	50	Baseline Technology
Air Core/Resistive Conductor	25	5-10	2	2	High Coolant Flow
Iron Core/Permanent Magnet	1	0.2-0.4	0	30	Nd-B-Fe
Air Core/LTSC	18	1.5-6	0	1	4.2 K
Air Core/HTSC	-	-	0	—	See Scenario discussion in text

* Conductor Dissipation/Stored Magnetic Energy

Source: Arthur D. Little, Inc.

The iron core resistive conductor consists of ordinary copper wire wound on an iron core. These magnets typically operate in the range of less than one tesla to as much as 1.4 tesla. The magnet is limited to a field of 2 tesla because of the saturation point of the iron. (A tesla is 10,000 gauss).

Iron core magnets are electrically efficient and require only about one-tenth of a megawatt per megajoule of stored energy. However, the weight per unit energy stored is quite high: i.e., about 50 tons per megajoule.

Air Core/Resistive Conductor

Air core, copper-wound magnets presently provide the highest magnet fields attainable but usually operate in the range of 5-10 tesla. Power consumption is extremely high, approximately two megawatts per megajoule of stored energy.

Air core magnet technology provides a distinct weight advantage over iron core design. However, the low efficiency of air core magnets leads to very high coolant flow requirements. It has been estimated that the very high field magnet at the Bitter National Laboratory at the Massachusetts Institute of Technology requires a coolant flow nearly equal to that of the nearby Charles River.

Iron Core/Permanent Magnet

The iron core permanent magnet provides a nice compromise between the advantages and disadvantages of the two alternative technologies already discussed. This approach has become even more competitive with the advent of the new neodymium-boron-iron permanent magnets. Moderate fields (0.2-0.4 tesla) can be provided at zero power consumption. Weight is estimated at about 30 tons per megajoule, somewhat less than iron core resistive wire magnets but well above air core designs.

Air Core/LTSC

Air core low-temperature superconducting magnets are able to produce magnetic fields as high as 18 tesla. However, this level of field strength is achieved only through the use of niobium tin, which is a notoriously brittle material. If niobium titanium is used in the magnet, the field strength is more typically limited to about 6 tesla at 4.2 K.

An advantage of superconducting magnets is that the power consumption is essentially zero. Some power is required, of course, to maintain the refrigeration system, but this generally amounts to only a few hundred watts. Weight is also low: i.e., on the order of one ton per megajoule.

Air Core/HTSC

The potential operating characteristics of high-temperature superconducting magnets is left for the scenario discussion below. No such magnets have been built to date.

MAGNET REQUIREMENTS vs. APPLICATIONS

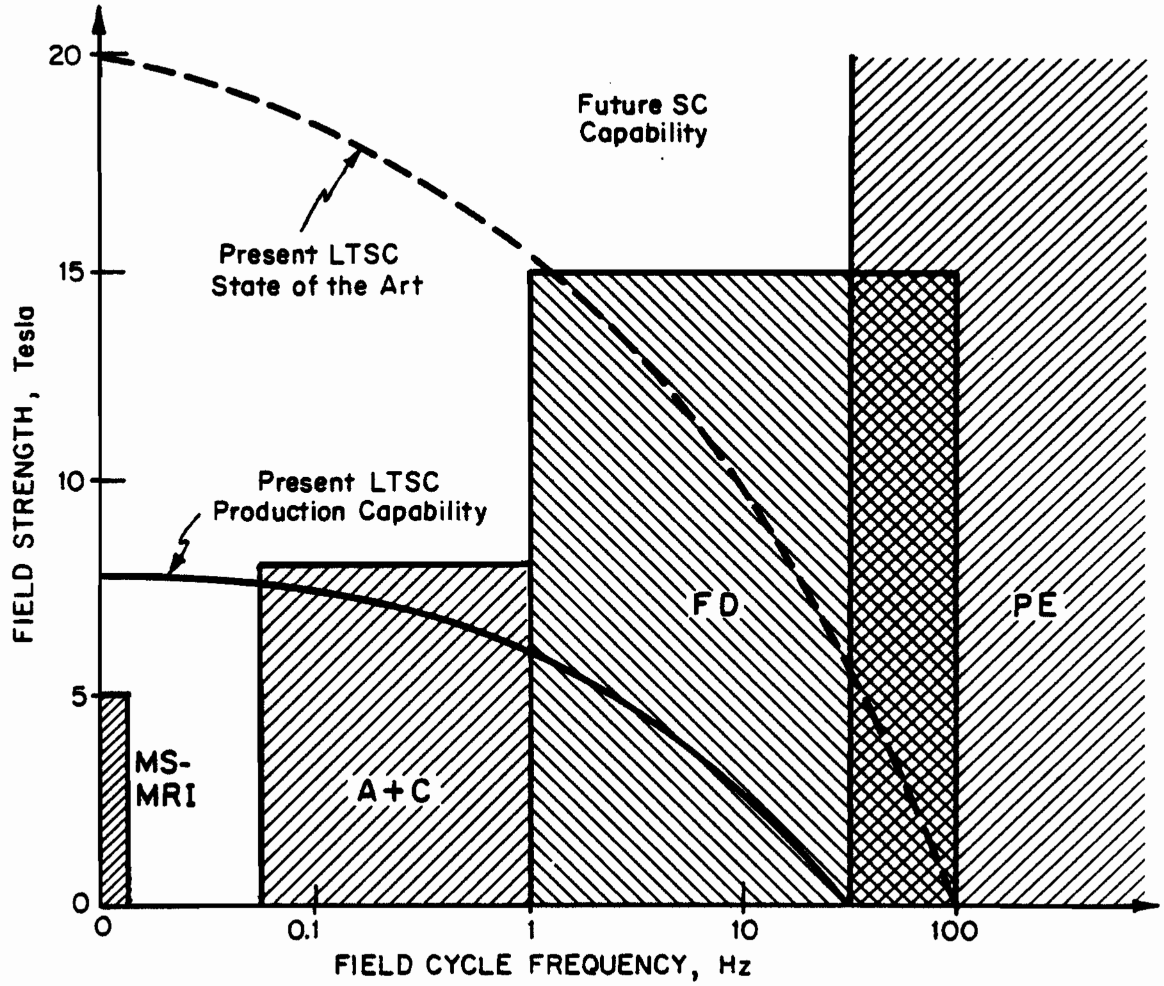
The applications for which superconducting magnets are appropriate is determined in part by the field strength and field cycle frequency requirements. A steady state magnetic field is ideal and makes the best use of the zero loss persistent current flow which is unique to the superconducting state. In many applications, however, it is necessary to change the field over time. This has very significant implications for the use of superconductivity.

Figure 11 illustrates the match between superconducting technology and the field strength and cycle requirements of different applications. Applications such as magnetic resonance imaging and magnetic separation are the least complicated because they require a steady state magnetic field of only moderate strength. (In the case of magnetic separation this is not strictly true because some variation accompanies the process material transport.) The field range needed for these applications is typically up to about 1.5 tesla for MRI and up to about 5 tesla for magnetic separation. The present low-temperature superconductivity technology is well able to meet these needs.

For other applications, however, the variability of the magnetic field poses some problems. In accelerators and colliders the magnetic field must be programmed to track the particle energy. In the Tevatron, for example, the field cycle period is on the order of a second. Fusion devices require even faster rates of change and much greater peak fields. Pulsed energy storage, particularly that for SDI applications, calls for

FIGURE 11

MAGNET REQUIREMENTS VS. APPLICATIONS



MS-MRI = Magnetic Storage - Magnetic Resonance Imaging

A + C = Accelerators and Colliders

FD = Fusion Devices

PE = Pulsed Energy

Source: Arthur D. Little, Inc.

storing extremely large amounts of energy and then dumping it very quickly. This sort of application is well beyond the capability of present superconductivity technology.

SUPERCONDUCTING WIRE DESIGN

The design of the wire used in superconductivity applications is critical. The combination of high field plus high rate of change places stringent requirements upon the wire. Table 8 summarizes the design aspects of superconducting wire for high-energy magnets.

TABLE 8

SUPERCONDUCTING (SC) WIRE DESIGN

- Absolute stability required
- Present technology: Composite construction using normal conductor (NC) -- copper or aluminum -- as stabilizer

  NC/SC (area ratio) 1:1 to 15:1
- NC/SC increases as the magnetic field (H) and the rate of change in H over time increase
- Large H requires multifilament SC (typically 8-10 microns diameter)
- Appreciable H requires resistive isolation between filaments, and wire twist
- High H requires more-extensive resistive isolation and increased twist

Source: Arthur D. Little, Inc.

The primary requirement for any wire used in a high-energy superconducting magnet is absolute stability. Absolute stability means that the magnet structure can withstand a change from the superconducting state to normal state without failure and can recover to the superconducting state. Because of the large amount of energy storage in these magnets, a transition from the superconducting to the normal state can result in a huge amount of dissipation. The system must be protected from this type of transition; it must have sufficient heat transfer and cooling capacity to return the wire to a superconducting state, even during a period of total dissipation of the input current. The magnet may look like a normal resistive magnet, but it must be able to cool down to a level at which the wire can become superconductive again.

In order to provide the necessary stability, present technology involves a composite construction in which a normal conductor acts as a stabilizer. In most instances, this conductor is copper, although aluminum can also be used. This conductor serves several functions. It allows for improved conduction of heat from the superconducting wire. It also acts as a shunt to carry the current when the superconducting material is in the normal state and more resistive than copper.

The ratio of normal conductor to superconductor in a composite wire ranges from about 1:1 to 15:1. In general, the greater the amount of copper in a system, the greater the stabilization effect. However, the addition of more copper means that the superconductivity is being diluted.. This results in a lower current carrying capacity for wire of a given size in the superconducting state.

The ratio of normal conductor to superconductor must increase as the magnetic field strength is increased. It also must increase as the time rate of change of the flux increases or as the time rate of change of the transport current increases.

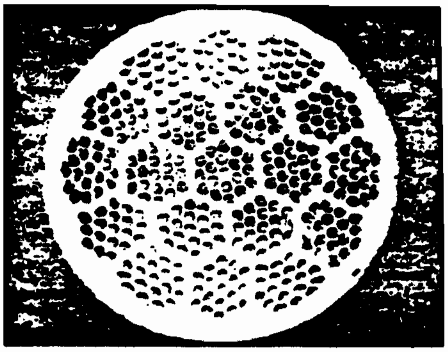
A very large magnetic field requires a multifilament superconductor. Typically, these filaments are on the order of 8-10 microns in diameter and there may be as few as four or five or as many as several hundred filaments in the wire. In order to prevent flux jumping from one strand to another, resistive isolation must be provided between the strands. In addition, the wires are twisted so that the strands have a helical pitch along the wire. Increased field and higher field cycle frequency require a greater degree of resistive isolation and greater twist. Obviously, the structural properties of the filaments in the wire must be compatible with whatever fabrication technology is used to produce the finished product.

Figure 12 illustrates the construction of a typical superconducting wire. In this illustration, the cable consists of bundles of superconducting filaments embedded in a copper matrix. There is relatively little in the way of resistive isolation between the wires. This sort of cable would be employed in an MRI magnet or in a low cycle frequency high-energy physics application.

Figure 13 illustrates a wire that is presently under development for high field, high cycle frequency use. Here, the superconducting filaments are subdivided into clusters and isolated from each other by a high-

FIGURE 12

TYPICAL COMPOSITE SUPERCONDUCTING CABLE

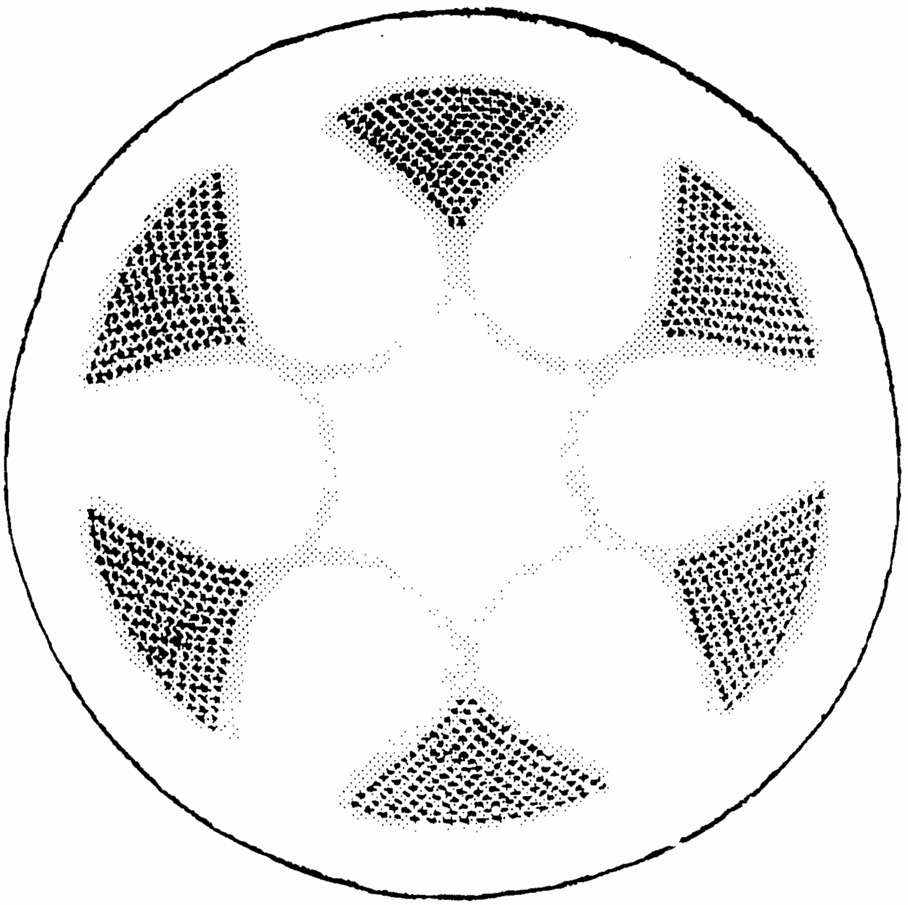


Note: 15-micron NbTi filaments embedded in copper matrix.

Source: Labalestier et al., "High Field Superconductivity," Physics Today, pp. 24-33, March 1986. Reprinted with permission.

FIGURE 13

HIGH-PERFORMANCE COMPOSITE SUPERCONDUCTOR OF "TULIP" DESIGN



Note: NbTi filaments and copper regions resistively isolated with cupro-nickel alloy.

Source: Labalestier et al., "High Field Superconductivity," Physics Today, pp. 24-33, March 1986, Reprinted with permission.

resistance copper nickel alloy. The very light areas, again isolated by copper nickel, contain the copper conductor that is used for stabilization. This construction provides a resistive isolation that subdivides the cable into independent areas and confines the transport current and the fluxoids to the individual bundles of superconducting wire.

DESIRED PROPERTIES OF SUPERCONDUCTING WIRE

The properties required in a superconducting wire for use in high energy magnet applications are:

a) High Critical Field

This allows the wire to remain superconducting at the high magnetic fields involved in these applications.

b) High Critical Current Density

The critical current density is directly related to the amount of superconducting wire needed to wind a magnet of given magnetic field strength and volume.

c) High Critical Temperature

Performance improves as the difference between the operating temperature and the critical temperature is increased.

d) High Thermal Conductivity

This improves the stability of the superconducting state.

e) High Specific Heat

Also important to stability.

f) High Ductility

This facilitates composite wire fabrication and increases the life and reliability of the finished magnet.

COMPARISON OF MATERIALS

Table 9 compares superconductor properties. Of particular interest is the comparison between niobium tin and niobium titanium, the most-studied low-temperature superconductors. Niobium tin is superior in all respects except in the areas of ductility and thermal conductivity. Ductility, however, has been so important to wire fabrication and magnet reliability that niobium titanium dominates all applications, even very high field ones where users would rather operate niobium titanium at 1.8 K than niobium tin at 4.2 K.

Table 9 also shows that the new 1-2-3 material ($YBa_2Cu_3O_{7-x}$) is superior in terms of critical field, critical temperature, and specific heat. However, it is very poor with respect to critical current density, thermal conductivity, and ductility.

TABLE 9

COMPARISON OF SUPERCONDUCTING MATERIALS
(1 = Best, 3 = Poorest)

Property	NbTi	Nb_3Sn	$YBa_2Cu_3O_{7-x}$
Critical Field (H_c)	3	2	1
Critical Current Density	2	1	3
Critical Temperature (T_c)	3	2	1
Thermal Conductivity	1	2	3
Specific Heat	3	2	1
Ductility	1	2	3

Note: The ductility of NbTi has led to its dominance of the LTSC market despite having lower H_c and T_c than Nb_3Sn.

Source: Arthur D. Little, Inc., estimates.

FACTORS DRIVING THE MARKET

There are identifiable forces driving the market for superconducting materials. In some areas, it is apparent that improved material properties would produce significant market opportunities. In other areas of application, new materials would have little impact. Table 10 summarizes the present market-limiting factors for each application.

For MRI, the magnetic field capability now available is adequate. There remains a disagreement as to the optimum field strength for these systems. Some experts advocate operating at about 1.5 tesla, while others insist that a few tenths of a tesla is preferable. There is no overall agreement that a higher field is needed. The major driving force for this application is cost containment. If MRI systems could be sold at a considerably lower cost, such as 50% less, then the market would be considerably expanded.

For magnetic separation, lower system cost is again relevant, but not dominant. Economic analyses have shown that the added cost of superconducting magnets for these systems is recovered rapidly, yet little displacement of resistive magnets has occurred. Even more important than cost for these applications is the compatibility with the industrial environments in which these magnets are used. These are often dirty environments, and the general feeling has been that helium cryogenic systems are not suitable for use in the mineral separation industry. If superconducting magnets can be developed that do not require liquid helium cooling, this market could be greatly expanded and resistive wire magnets would be replaced.

TABLE 10

MARKET FORCES IN MAGNET APPLICATIONS

MRI

- Lower magnet cost

Magnet Separation

- Lower magnet cost
- Industrial environment

Accelerators and Colliders

- Improved uniformity and reliability
- Radiation resistance
- Lower cost

Fusion Devices

- Higher magnetic field
- Radiation resistance
- Fast cycling

Pulsed Energy Devices

- Fast cycling
- High magnetic field
- High critical field

Source: Arthur D. Little, Inc.

For accelerators and colliders, the need is for uniformity and high reliability since so many magnets are used in a single machine. Cost is also a consideration, and higher field capability would aid in this respect by allowing a smaller diameter ring at a given energy level. The magnet materials must also be radiation-resistant.

In the case of fusion devices, the driving forces are clearly higher magnetic fields and the capability for fast cycling. Radiation resistance is also important. For use in these devices, cost is not viewed as a major consideration.

The application of superconductivity to pulsed energy devices is presently limited by the lack of superconducting materials and wire with sufficiently high critical field, critical current, and field cycling capability. Superconductive magnetic energy storage is desperately needed for the progress of many new systems, but the technical limitations of present superconductors are preventing its application.

PRESENT APPLICATIONS OF SUPERCONDUCTIVITY

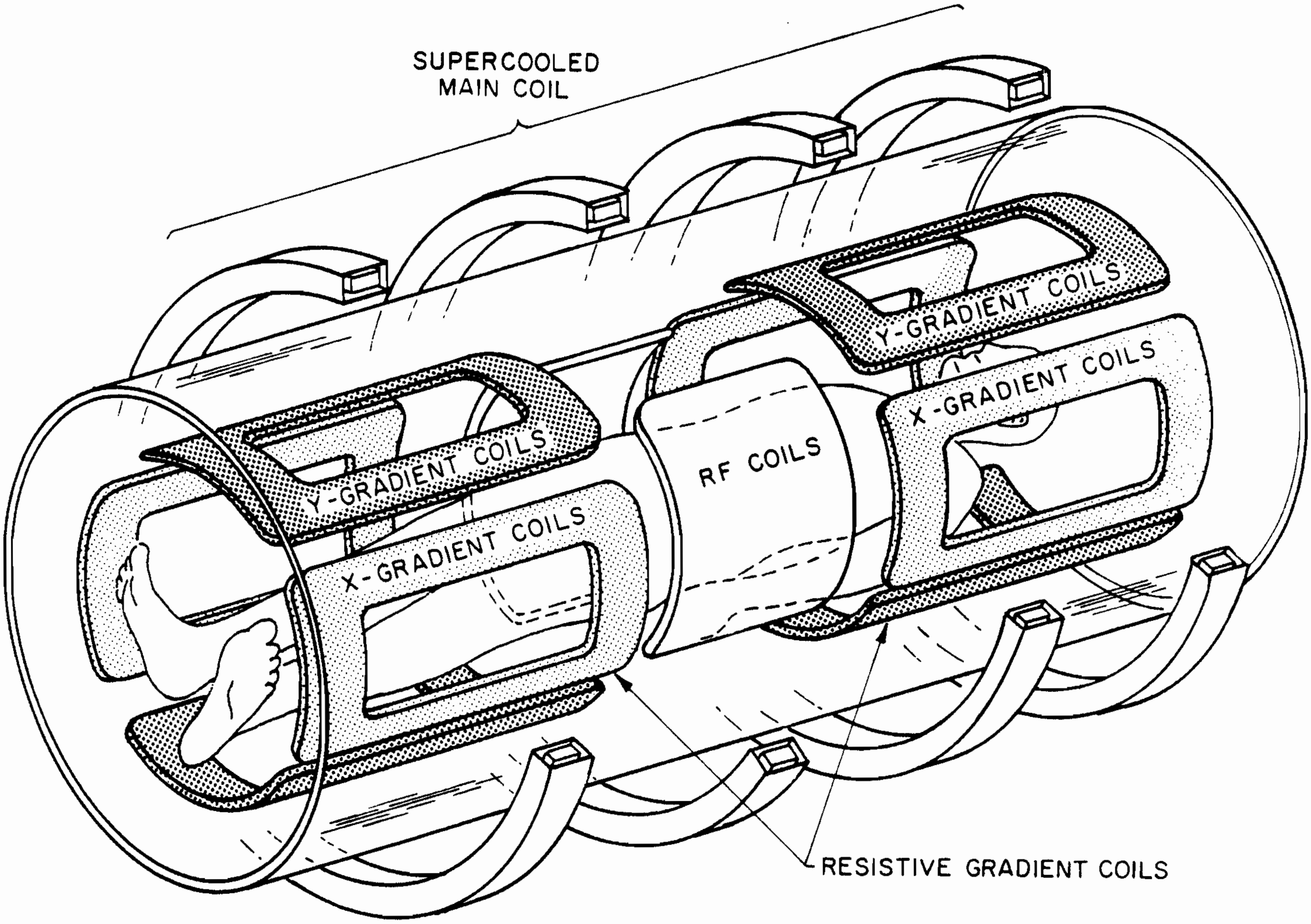
Magnetic Resonance Imaging

Figure 14 shows a typical magnetic resonance imaging system. The main coil is a superconducting solenoid that produces an axial magnetic field. That is the only part of the magnetic field structure that is supercooled. The gradient coils -- i.e., the ones that perturb the local field and provide the scanning that creates the image -- are wound with normal conductive wire. That is done for two reasons. First, these coils produce a time-varying field, and second, the magnetic field they create is relatively weak compared with the field produced by the main coil.

Although the field produced by the superconducting coil can be as high as 1.5 tesla and must be very uniform, the overall requirement is relatively easy to meet because the magnetic field is essentially static and has a simple shape.

FIGURE 14

TYPICAL MRI SUPERCONDUCTING MAGNET



Source: Arthur D. Little, Inc.

Cost Scenarios

The selection of a superconducting magnet for MRI will depend upon its cost, assuming that the field and reliability requirements are satisfied. Table 11 reviews the scenario parameters for the MRI application. Table 12 lists the elements of cost, exclusive of the composite superconducting wire, to be used for the scenario calculations. Figure 15 provides the magnetic characteristics for each scenario.

TABLE 11

HTSC SCENARIO PARAMETERS

Scenario	T_c	T_o
S-1	90 K	4.2 K
S-2	90 K	77 K
S-3	400 K	77 K
S-4	400 K	300 K

Baseline Comparison

NbTi $T_o = 4.2$ K

Source: Arthur D. Little, Inc.

TABLE 12

ANALYSIS OF COST ELEMENTS FOR MRI MAGNET

Data Component	Operating Temperature (K)	Cost (MM$)
Coil & Support	All	50
Cryostat	4.2	100
Cryostat	77	50
Cryostat	300	0
Refrigerator	4.2	50
	77	6
	300	0

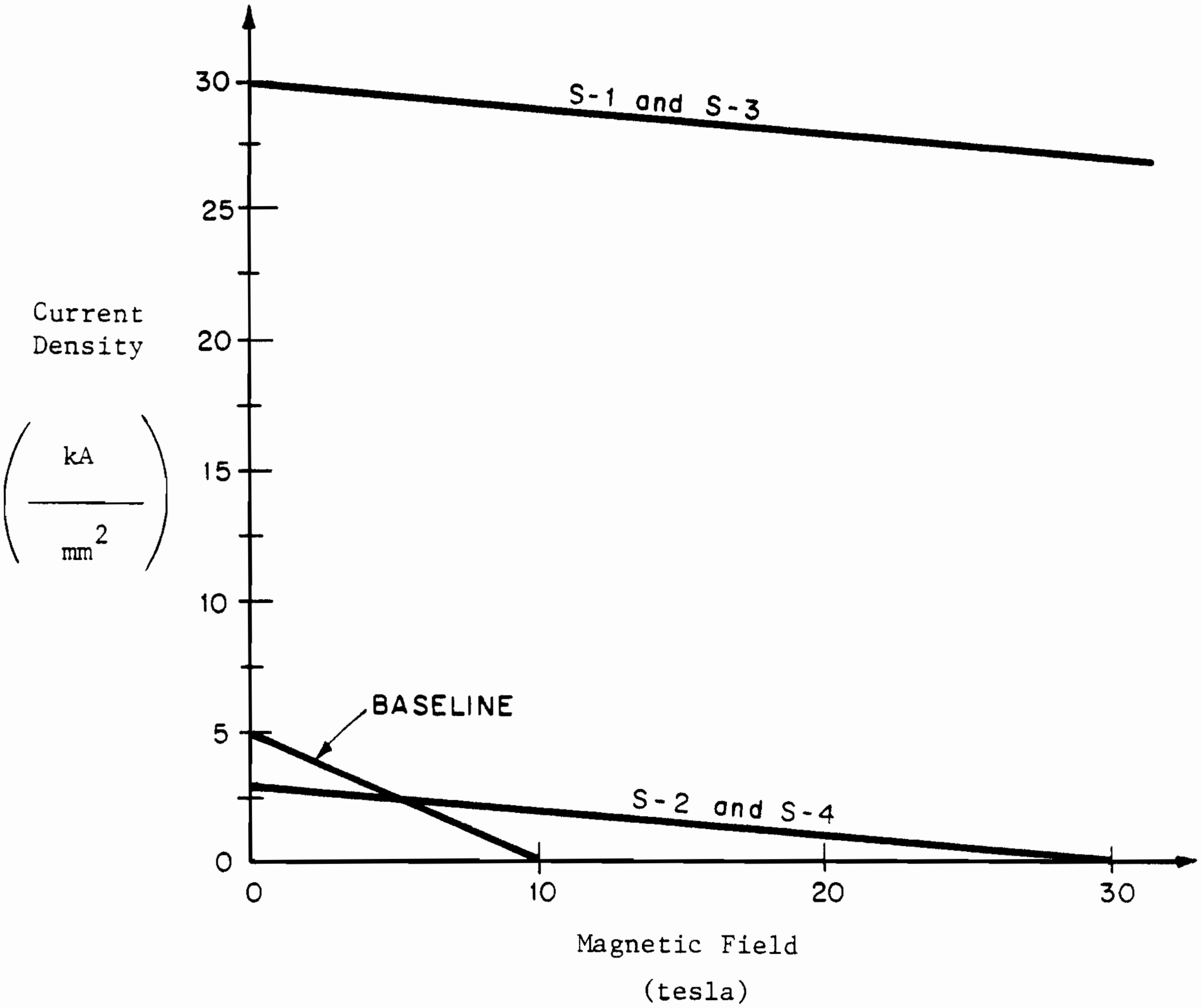
Material	(Cost $/cm^3$)
NbTi	0.24
HTSC	0.15

For comparison, the Cu/NbTi wire price for a 1.5-tesla magnet is approximately $100,000.

Source: Arthur D. Little, Inc., estimates.

FIGURE 15

MAXIMUM CURRENT DENSITY VS. MAGNETIC FIELD



Note: See Table 11 for scenario parameters.

Source: Arthur D. Little, Inc.

In estimating the wire cost, we have made the simplifying assumption that cost is proportional to the required magnetic field divided by the maximum current density that can be supported. This figure is then multiplied by the unit material cost. This relationship can be represented thus:

$$\text{Wire cost} = \frac{\text{H (magnetic field)}}{\text{J (current density)}} \times \text{Unit material cost.}$$

And it assumes:

- o $J = J_c \left(1 - \frac{H}{H_{c2}}\right)$
- o All costs other than wire are essentially independent of H.
- o Magnet dimensions remain constant.

The scenarios of Table 12 further assume that all costs other than the wire are independent of the magnetic field. The cost of such components as support structure, cryostat, and cooling are therefore assumed to be independent of the magnetic field. This assumption is not entirely correct; these costs will vary slightly because as the magnetic field increases, the mechanical forces will also increase and slightly stronger structures will be required. There may also be slightly increased heat leakage, so cooling costs may increase a little. For all practical purposes, however, these costs are essentially constant and the analyses are based upon this assumption. Also assumed constant are the dimensions of the magnet.

Table 13 estimates the cost of the MRI magnet, comparing the various scenarios that have been described versus the magnetic field that is required. At very low fields, all the high-temperature superconductor scenarios give significantly lower costs than the baseline. However, at low field, there is strong price competition from the new permanent magnet systems. Therefore, high-temperature superconductors are not expected to impact the low-field MRI applications.

At a field strength of 1.5 tesla, the S-3 scenario has a dramatic advantage. However, the S-1 scenario, which is the 90 K superconductor operating at 4.2 K, and the S-2 scenario, the 90 K superconductor operating at 77 K, are quite comparable. The same conclusions apply at a field strength of 5 tesla.

TABLE 13

ESTIMATED PRICE OF MRI MAGNET
(thousands of dollars)

Scenario	0.25 T	1.5 T	5.0 T
Baseline	287	300	370
S-1	109	209	209
S-2	195	196	212
S-3	105	105	105
S-4	139	140	156

Source: Arthur D. Little, Inc., estimates.

advantages and disadvantages of the two alternative technologies already discussed. This approach has become even more competitive with the advent of the new neodymium-boron-iron permanent magnets. Moderate fields (0.2-0.4 tesla) can be provided at zero power consumption. Weight is estimated at about 30 tons per megajoule, somewhat less than iron core resistive wire magnets but well above air core designs.

Air Core/LTSC

Air core low-temperature superconducting magnets are able to produce magnetic fields as high as 18 tesla. However, this level of field strength is achieved only through the use of niobium tin, which is a notoriously brittle material. If niobium titanium is used in the magnet, the field strength is more typically limited to about 6 tesla at 4.2 K.

An advantage of superconducting magnets is that the power consumption is essentially zero. Some power is required, of course, to maintain the refrigeration system, but this generally amounts to only a few hundred watts. Weight is also low: i.e., on the order of one ton per megajoule.

Air Core/HTSC

The potential operating characteristics of high-temperature superconducting magnets is left for the scenario discussion below. No such magnets have been built to date.

MAGNET REQUIREMENTS vs. APPLICATIONS

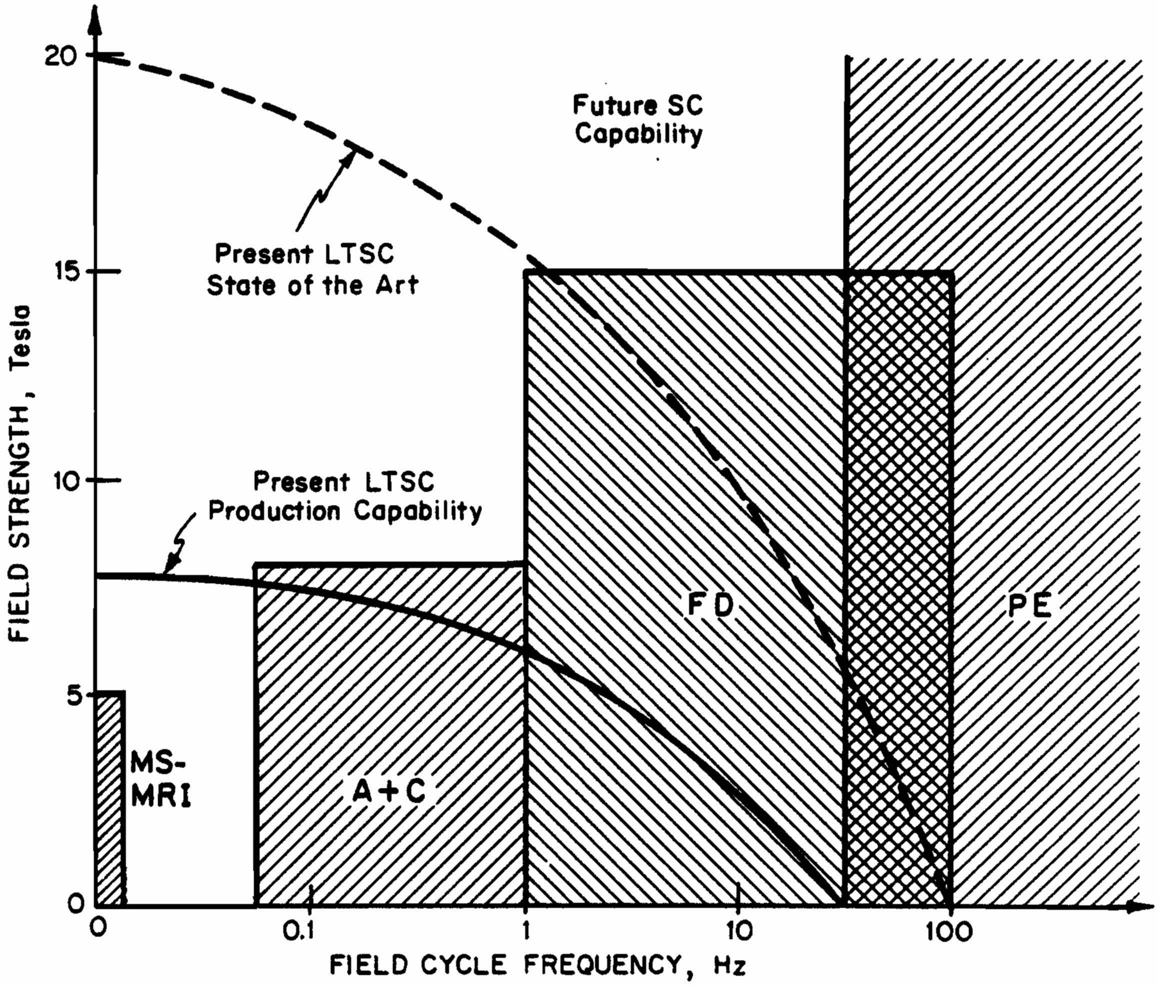
The applications for which superconducting magnets are appropriate is determined in part by the field strength and field cycle frequency requirements. A steady state magnetic field is ideal and makes the best use of the zero loss persistent current flow which is unique to the superconducting state. In many applications, however, it is necessary to change the field over time. This has very significant implications for the use of superconductivity.

Figure 11 illustrates the match between superconducting technology and the field strength and cycle requirements of different applications. Applications such as magnetic resonance imaging and magnetic separation are the least complicated because they require a steady state magnetic field of only moderate strength. (In the case of magnetic separation this is not strictly true because some variation accompanies the process material transport.) The field range needed for these applications is typically up to about 1.5 tesla for MRI and up to about 5 tesla for magnetic separation. The present low-temperature superconductivity technology is well able to meet these needs.

For other applications, however, the variability of the magnetic field poses some problems. In accelerators and colliders the magnetic field must be programmed to track the particle energy. In the Tevatron, for example, the field cycle period is on the order of a second. Fusion devices require even faster rates of change and much greater peak fields. Pulsed energy storage, particularly that for SDI applications, calls for

FIGURE 11

MAGNET REQUIREMENTS VS. APPLICATIONS



MS-MRI = Magnetic Storage - Magnetic Resonance Imaging

A + C = Accelerators and Colliders

FD = Fusion Devices

PE = Pulsed Energy

Source: Arthur D. Little, Inc.

storing extremely large amounts of energy and then dumping it very quickly. This sort of application is well beyond the capability of present superconductivity technology.

SUPERCONDUCTING WIRE DESIGN

The design of the wire used in superconductivity applications is critical. The combination of high field plus high rate of change places stringent requirements upon the wire. Table 8 summarizes the design aspects of superconducting wire for high-energy magnets.

TABLE 8

SUPERCONDUCTING (SC) WIRE DESIGN

- Absolute stability required
- Present technology: Composite construction using normal conductor (NC) -- copper or aluminum -- as stabilizer

    NC/SC (area ratio) 1:1 to 15:1

- NC/SC increases as the magnetic field (H) and the rate of change in H over time increase
- Large H requires multifilament SC (typically 8-10 microns diameter)
- Appreciable H requires resistive isolation between filaments, and wire twist
- High H requires more-extensive resistive isolation and increased twist

Source: Arthur D. Little, Inc.

The primary requirement for any wire used in a high-energy superconducting magnet is absolute stability. Absolute stability means that the magnet structure can withstand a change from the superconducting state to normal state without failure and can recover to the superconducting state. Because of the large amount of energy storage in these magnets, a transition from the superconducting to the normal state can result in a huge amount of dissipation. The system must be protected from this type of transition; it must have sufficient heat transfer and cooling capacity to return the wire to a superconducting state, even during a period of total dissipation of the input current. The magnet may look like a normal resistive magnet, but it must be able to cool down to a level at which the wire can become superconductive again.

In order to provide the necessary stability, present technology involves a composite construction in which a normal conductor acts as a stabilizer. In most instances, this conductor is copper, although aluminum can also be used. This conductor serves several functions. It allows for improved conduction of heat from the superconducting wire. It also acts as a shunt to carry the current when the superconducting material is in the normal state and more resistive than copper.

The ratio of normal conductor to superconductor in a composite wire ranges from about 1:1 to 15:1. In general, the greater the amount of copper in a system, the greater the stabilization effect. However, the addition of more copper means that the superconductivity is being diluted.. This results in a lower current carrying capacity for wire of a given size in the superconducting state.

The ratio of normal conductor to superconductor must increase as the magnetic field strength is increased. It also must increase as the time rate of change of the flux increases or as the time rate of change of the transport current increases.

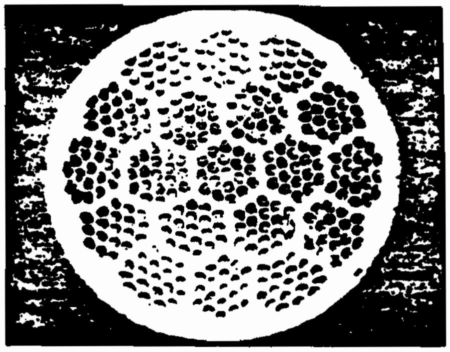
A very large magnetic field requires a multifilament superconductor. Typically, these filaments are on the order of 8-10 microns in diameter and there may be as few as four or five or as many as several hundred filaments in the wire. In order to prevent flux jumping from one strand to another, resistive isolation must be provided between the strands. In addition, the wires are twisted so that the strands have a helical pitch along the wire. Increased field and higher field cycle frequency require a greater degree of resistive isolation and greater twist. Obviously, the structural properties of the filaments in the wire must be compatible with whatever fabrication technology is used to produce the finished product.

Figure 12 illustrates the construction of a typical superconducting wire. In this illustration, the cable consists of bundles of superconducting filaments embedded in a copper matrix. There is relatively little in the way of resistive isolation between the wires. This sort of cable would be employed in an MRI magnet or in a low cycle frequency high-energy physics application.

Figure 13 illustrates a wire that is presently under development for high field, high cycle frequency use. Here, the superconducting filaments are subdivided into clusters and isolated from each other by a high-

FIGURE 12

TYPICAL COMPOSITE SUPERCONDUCTING CABLE

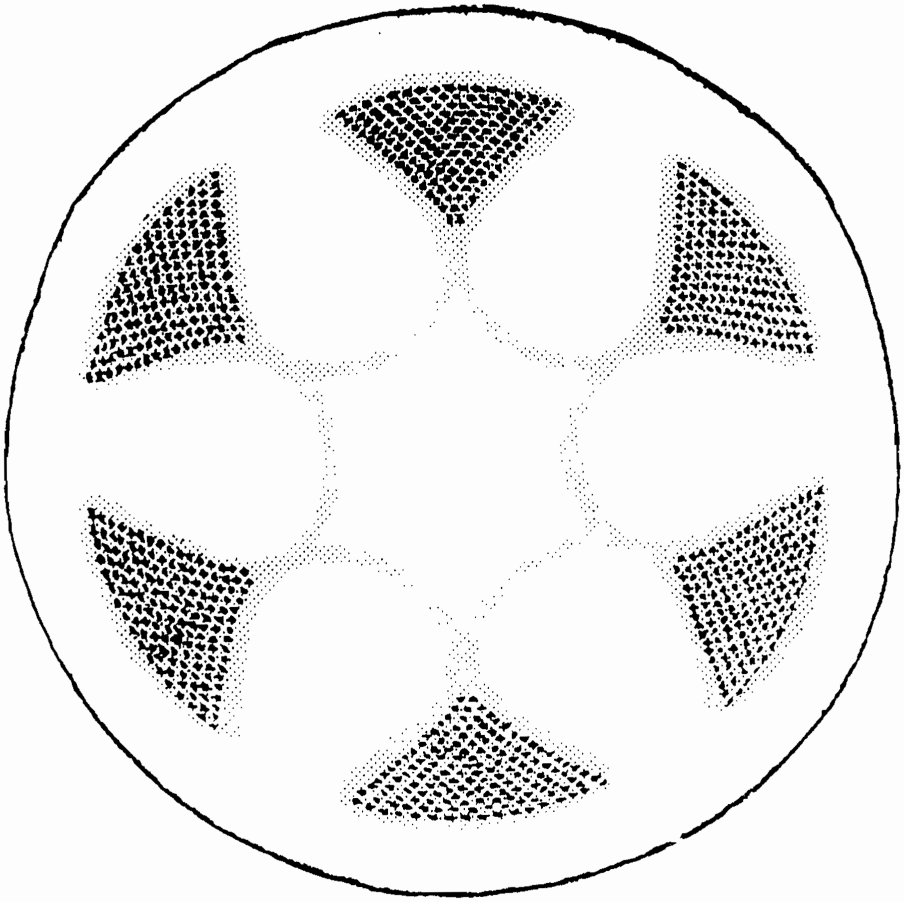


Note: 15-micron NbTi filaments embedded in copper matrix.

Source: Labalestier et al., "High Field Superconductivity," Physics Today, pp. 24-33, March 1986. Reprinted with permission.

FIGURE 13

HIGH-PERFORMANCE COMPOSITE SUPERCONDUCTOR OF "TULIP" DESIGN



Note: NbTi filaments and copper regions resistively isolated with cupro-nickel alloy.

Source: Labalestier et al., "High Field Superconductivity," Physics Today, pp. 24-33, March 1986, Reprinted with permission.

resistance copper nickel alloy. The very light areas, again isolated by copper nickel, contain the copper conductor that is used for stabilization. This construction provides a resistive isolation that subdivides the cable into independent areas and confines the transport current and the fluxoids to the individual bundles of superconducting wire.

DESIRED PROPERTIES OF SUPERCONDUCTING WIRE

The properties required in a superconducting wire for use in high energy magnet applications are:

a) High Critical Field

This allows the wire to remain superconducting at the high magnetic fields involved in these applications.

b) High Critical Current Density

The critical current density is directly related to the amount of superconducting wire needed to wind a magnet of given magnetic field strength and volume.

c) High Critical Temperature

Performance improves as the difference between the operating temperature and the critical temperature is increased.

d) High Thermal Conductivity

This improves the stability of the superconducting state.

e) High Specific Heat

Also important to stability.

f) High Ductility

This facilitates composite wire fabrication and increases the life and reliability of the finished magnet.

COMPARISON OF MATERIALS

Table 9 compares superconductor properties. Of particular interest is the comparison between niobium tin and niobium titanium, the most-studied low-temperature superconductors. Niobium tin is superior in all respects except in the areas of ductility and thermal conductivity. Ductility, however, has been so important to wire fabrication and magnet reliability that niobium titanium dominates all applications, even very high field ones where users would rather operate niobium titanium at 1.8 K than niobium tin at 4.2 K.

Table 9 also shows that the new 1-2-3 material ($YBa_2Cu_3O_{7-x}$) is superior in terms of critical field, critical temperature, and specific heat. However, it is very poor with respect to critical current density, thermal conductivity, and ductility.

TABLE 9

COMPARISON OF SUPERCONDUCTING MATERIALS
(1 = Best, 3 = Poorest)

Property	NbTi	Nb_3Sn	$YBa_2Cu_3O_{7-x}$
Critical Field (H_c)	3	2	1
Critical Current Density	2	1	3
Critical Temperature (T_c)	3	2	1
Thermal Conductivity	1	2	3
Specific Heat	3	2	1
Ductility	1	2	3

Note: The ductility of NbTi has led to its dominance of the LTSC market despite having lower H_c and T_c than Nb_3Sn.

Source: Arthur D. Little, Inc., estimates.

FACTORS DRIVING THE MARKET

There are identifiable forces driving the market for superconducting materials. In some areas, it is apparent that improved material properties would produce significant market opportunities. In other areas of application, new materials would have little impact. Table 10 summarizes the present market-limiting factors for each application.

For MRI, the magnetic field capability now available is adequate. There remains a disagreement as to the optimum field strength for these systems. Some experts advocate operating at about 1.5 tesla, while others insist that a few tenths of a tesla is preferable. There is no overall agreement that a higher field is needed. The major driving force for this application is cost containment. If MRI systems could be sold at a considerably lower cost, such as 50% less, then the market would be considerably expanded.

For magnetic separation, lower system cost is again relevant, but not dominant. Economic analyses have shown that the added cost of superconducting magnets for these systems is recovered rapidly, yet little displacement of resistive magnets has occurred. Even more important than cost for these applications is the compatibility with the industrial environments in which these magnets are used. These are often dirty environments, and the general feeling has been that helium cryogenic systems are not suitable for use in the mineral separation industry. If superconducting magnets can be developed that do not require liquid helium cooling, this market could be greatly expanded and resistive wire magnets would be replaced.

TABLE 10

MARKET FORCES IN MAGNET APPLICATIONS

MRI

- Lower magnet cost

Magnet Separation

- Lower magnet cost
- Industrial environment

Accelerators and Colliders

- Improved uniformity and reliability
- Radiation resistance
- Lower cost

Fusion Devices

- Higher magnetic field
- Radiation resistance
- Fast cycling

Pulsed Energy Devices

- Fast cycling
- High magnetic field
- High critical field

Source: Arthur D. Little, Inc.

For accelerators and colliders, the need is for uniformity and high reliability since so many magnets are used in a single machine. Cost is also a consideration, and higher field capability would aid in this respect by allowing a smaller diameter ring at a given energy level. The magnet materials must also be radiation-resistant.

In the case of fusion devices, the driving forces are clearly higher magnetic fields and the capability for fast cycling. Radiation resistance is also important. For use in these devices, cost is not viewed as a major consideration.

The application of superconductivity to pulsed energy devices is presently limited by the lack of superconducting materials and wire with sufficiently high critical field, critical current, and field cycling capability. Superconductive magnetic energy storage is desperately needed for the progress of many new systems, but the technical limitations of present superconductors are preventing its application.

PRESENT APPLICATIONS OF SUPERCONDUCTIVITY

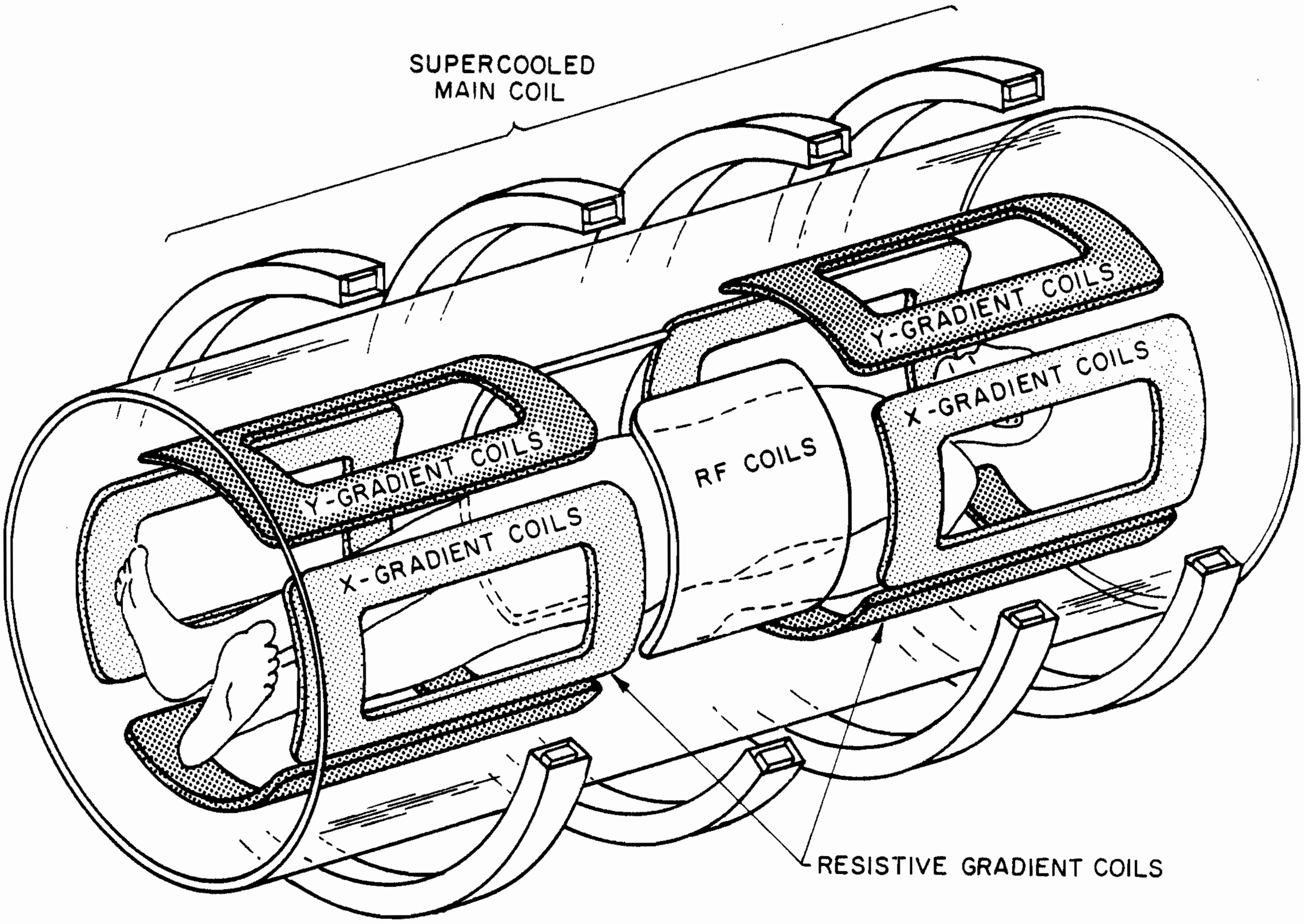
Magnetic Resonance Imaging

Figure 14 shows a typical magnetic resonance imaging system. The main coil is a superconducting solenoid that produces an axial magnetic field. That is the only part of the magnetic field structure that is supercooled. The gradient coils -- i.e., the ones that perturb the local field and provide the scanning that creates the image -- are wound with normal conductive wire. That is done for two reasons. First, these coils produce a time-varying field, and second, the magnetic field they create is relatively weak compared with the field produced by the main coil.

Although the field produced by the superconducting coil can be as high as 1.5 tesla and must be very uniform, the overall requirement is relatively easy to meet because the magnetic field is essentially static and has a simple shape.

FIGURE 14

TYPICAL MRI SUPERCONDUCTING MAGNET



Source: Arthur D. Little, Inc.

Cost Scenarios

The selection of a superconducting magnet for MRI will depend upon its cost, assuming that the field and reliability requirements are satisfied. Table 11 reviews the scenario parameters for the MRI application. Table 12 lists the elements of cost, exclusive of the composite superconducting wire, to be used for the scenario calculations. Figure 15 provides the magnetic characteristics for each scenario.

TABLE 11

HTSC SCENARIO PARAMETERS

Scenario	T_c	T_o
S-1	90 K	4.2 K
S-2	90 K	77 K
S-3	400 K	77 K
S-4	400 K	300 K

Baseline Comparison

NbTi $T_o = 4.2$ K

Source: Arthur D. Little, Inc.

TABLE 12

ANALYSIS OF COST ELEMENTS FOR MRI MAGNET

Data Component	Operating Temperature (K)	Cost (MM$)
Coil & Support	All	50
Cryostat	4.2	100
Cryostat	77	50
Cryostat	300	0
Refrigerator	4.2	50
	77	6
	300	0

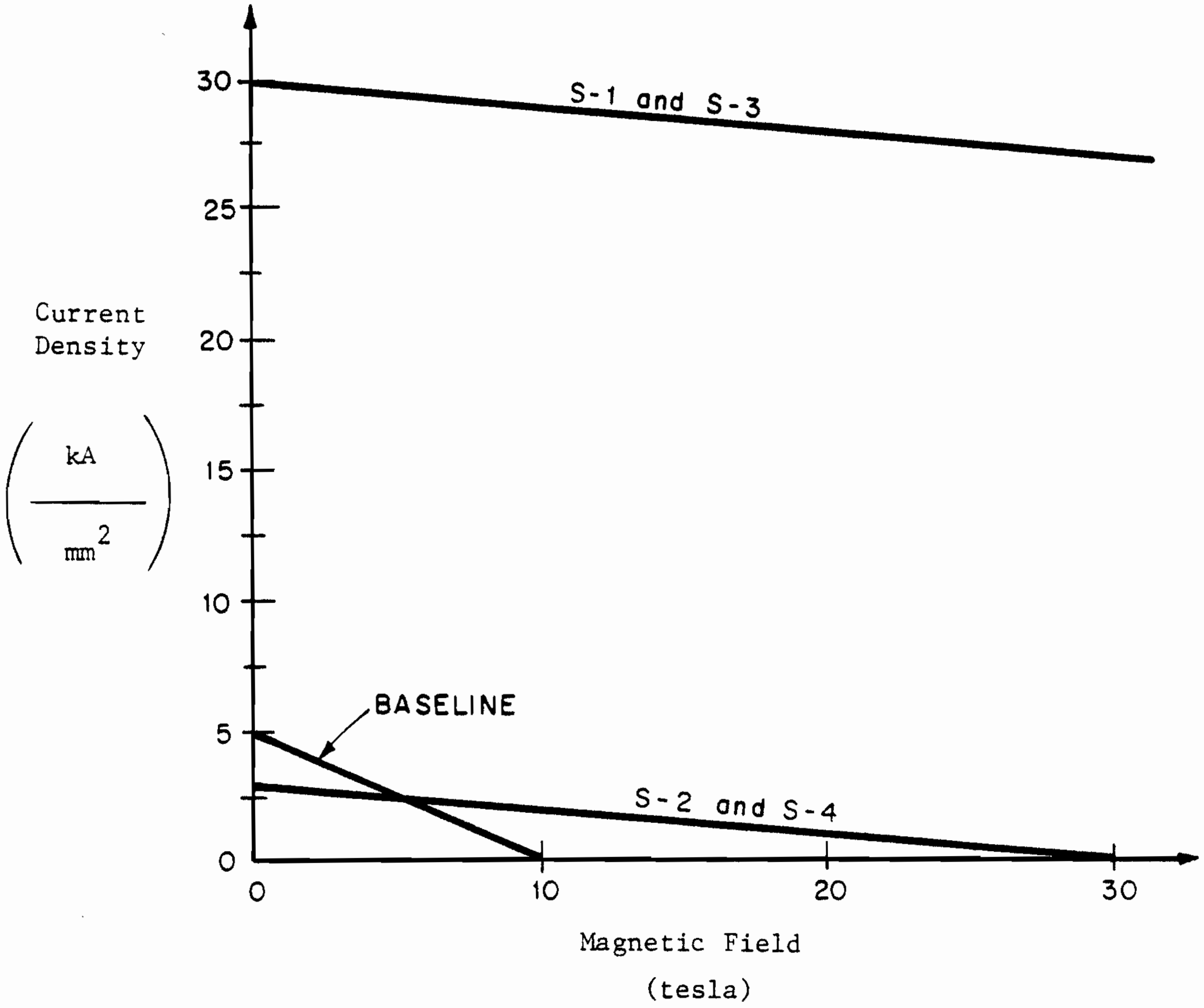
Material	(Cost $\$/cm^3$)
NbTi	0.24
HTSC	0.15

For comparison, the Cu/NbTi wire price for a 1.5-tesla magnet is approximately $100,000.

Source: Arthur D. Little, Inc., estimates.

FIGURE 15

MAXIMUM CURRENT DENSITY VS. MAGNETIC FIELD



Note: See Table 11 for scenario parameters.

Source: Arthur D. Little, Inc.

In estimating the wire cost, we have made the simplifying assumption that cost is proportional to the required magnetic field divided by the maximum current density that can be supported. This figure is then multiplied by the unit material cost. This relationship can be represented thus:

$$\text{Wire cost} = \frac{\text{H (magnetic field)}}{\text{J (current density)}} \times \text{Unit material cost.}$$

And it assumes:

- o $J = J_c\left(1 - \frac{H}{H_{c2}}\right)$
- o All costs other than wire are essentially independent of H.
- o Magnet dimensions remain constant.

The scenarios of Table 12 further assume that all costs other than the wire are independent of the magnetic field. The cost of such components as support structure, cryostat, and cooling are therefore assumed to be independent of the magnetic field. This assumption is not entirely correct; these costs will vary slightly because as the magnetic field increases, the mechanical forces will also increase and slightly stronger structures will be required. There may also be slightly increased heat leakage, so cooling costs may increase a little. For all practical purposes, however, these costs are essentially constant and the analyses are based upon this assumption. Also assumed constant are the dimensions of the magnet.

Table 13 estimates the cost of the MRI magnet, comparing the various scenarios that have been described versus the magnetic field that is required. At very low fields, all the high-temperature superconductor scenarios give significantly lower costs than the baseline. However, at low field, there is strong price competition from the new permanent magnet systems. Therefore, high-temperature superconductors are not expected to impact the low-field MRI applications.

At a field strength of 1.5 tesla, the S-3 scenario has a dramatic advantage. However, the S-1 scenario, which is the 90 K superconductor operating at 4.2 K, and the S-2 scenario, the 90 K superconductor operating at 77 K, are quite comparable. The same conclusions apply at a field strength of 5 tesla.

TABLE 13

ESTIMATED PRICE OF MRI MAGNET
(thousands of dollars)

Scenario	0.25 T	1.5 T	5.0 T
Baseline	287	300	370
S-1	109	209	209
S-2	195	196	212
S-3	105	105	105
S-4	139	140	156

Source: Arthur D. Little, Inc., estimates.

From an economic standpoint, the new material can be used in either of two ways. It can be operated at the temperature of liquid nitrogen or at 4.2 K. The magnet cost is about the same in each instance, about two thirds that of a niobium titanium magnet. This represents a potential saving of $100,000-200,000, which is about 10-15% of the cost of the entire system. This cost advantage may not, therefore, have a very significant impact on the MRI market overall. Although high-temperature superconductors might quickly replace the low-temperature superconductors, their use would probably result in little MRI market expansion.

In summary:

- All HTSC scenarios result in lower-priced MRI magnets than the baseline design.
- Lowest overall price is for HTSC with T_c = 400 K operated at 77 K.
- HTSC with T_c = 90 K will reduce magnet price by about 30-40% for operation at either 77 K or 4.2 K.
- HTSC will probably not contribute significantly to overall MRI market growth.

Magnetic Separation

There are two approaches to magnetic separation. One is High-Gradient Magnetic Separation, HGMS, in which a matrix of magnetic material is immersed in a uniform magnetic field. This creates an intense local perturbation of the magnetic field, which attracts paramagnetic materials to the matrix. This approach is shown in Figure 16. The other approach called Open-Gradient Magnetic Separation, OGMS, utilizes the magnetic field gradient produced by the magnetic structure itself. A typical system is shown in Figure 17. Here the magnetic forces extend over larger distances and a continuous separation takes place according to the magnetic susceptibility of the material. In HGMS the particles being separated from the slurry collect on the matrix and are then flushed off. In OGMS the separation system is continuous and there is no flushing cycle.

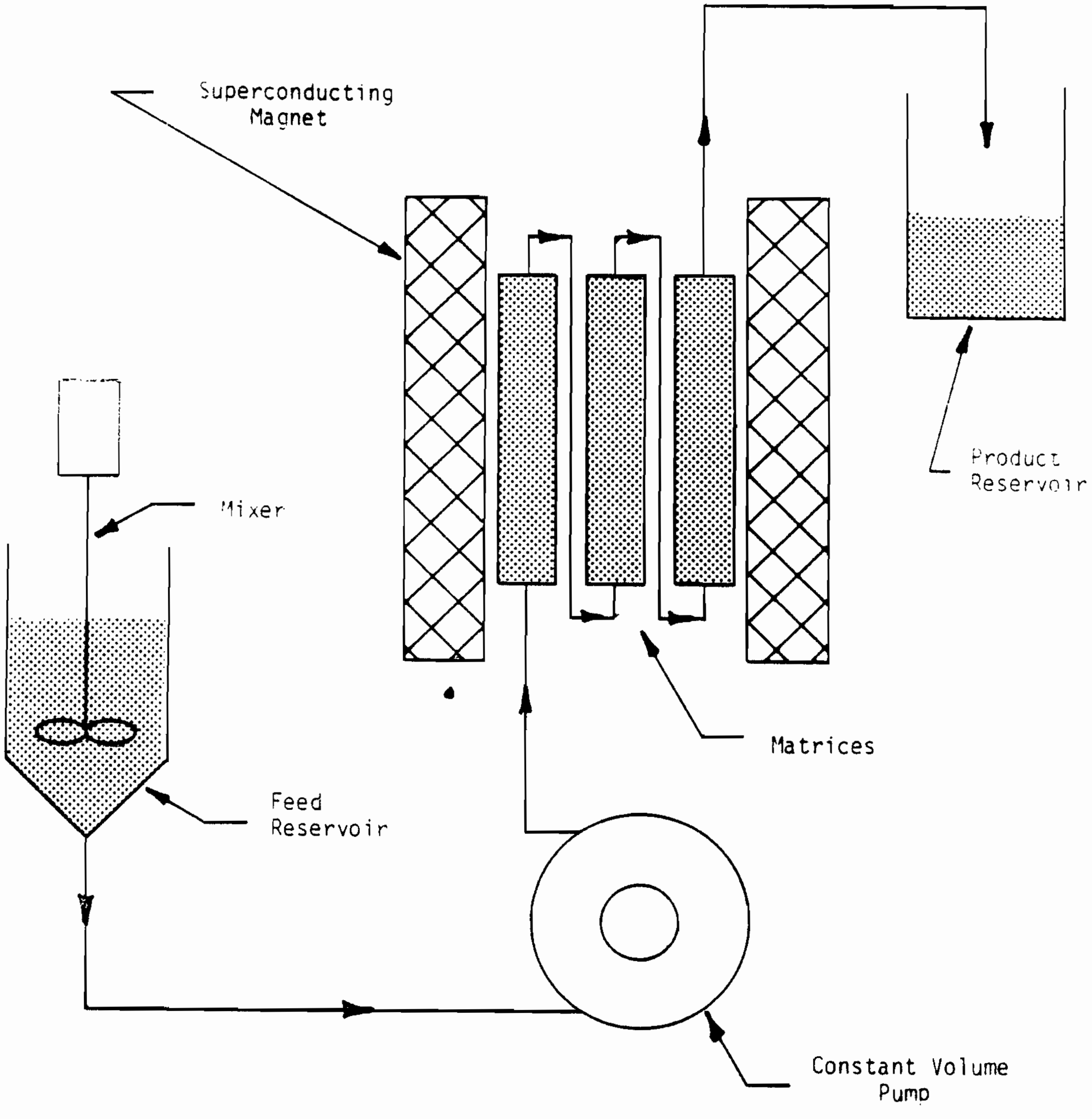
For magnetic separation, the magnetic field uniformity does not have to be as good as for an MRI system, but the field strength may be higher and the field shape can be somewhat more complex. In addition there may be a greater perturbation of the field as a result of the process material transport. Overall, the degree of technical difficulty for the magnet may range from slightly less difficult to slightly more difficult than in the MRI case.

A more significant difference between the two applications, however, lies in the local environment. The MRI setting is clean and benign whereas the magnetic separators are located in extremely dirty and harsh industrial surroundings.

Using the same scenarios as for the MRI analysis, we find that all the high-temperature superconductivity scenarios result in a lower-priced

FIGURE 16

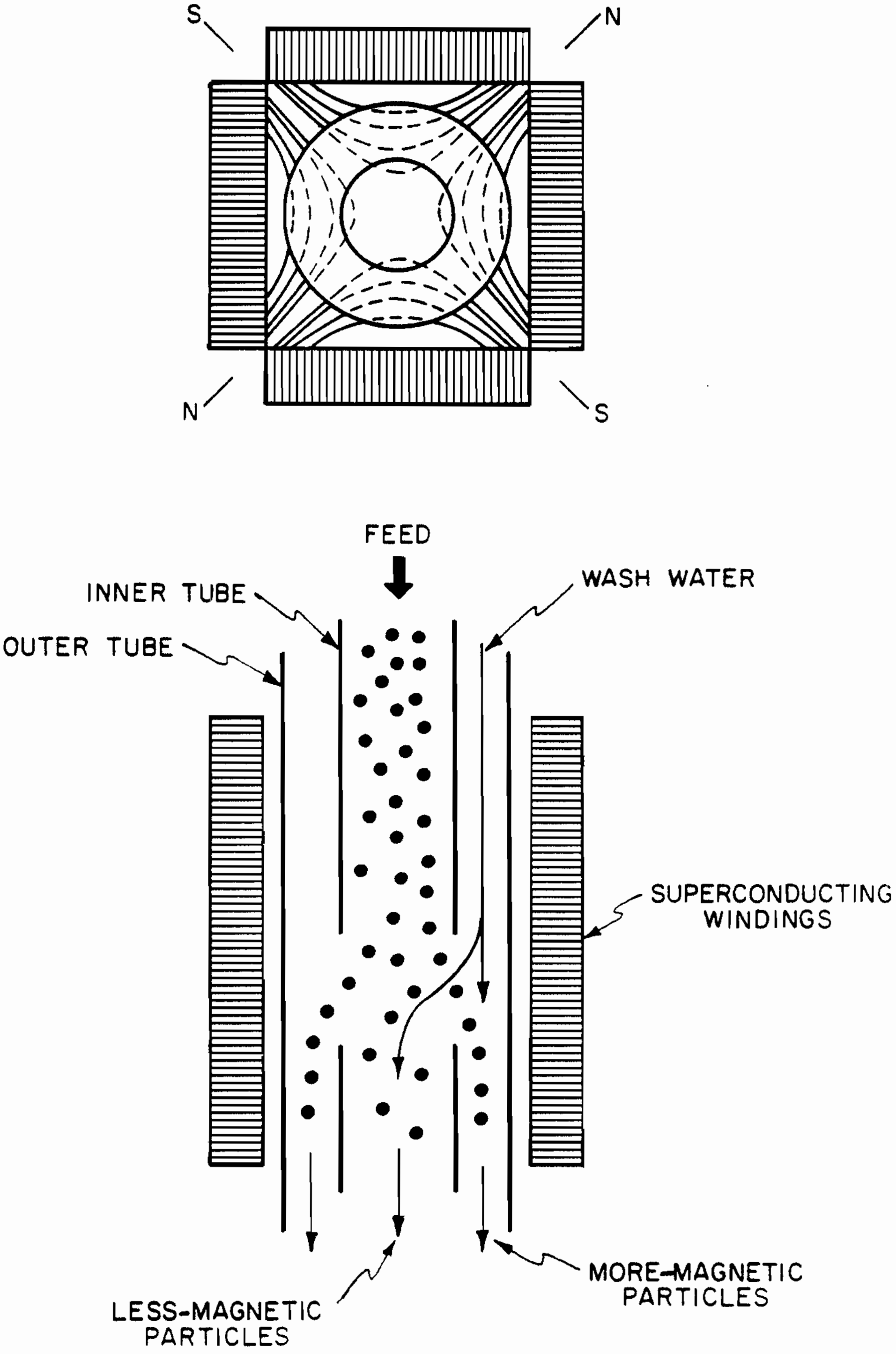
HIGH-GRADIENT MAGNETIC SEPARATOR



Source: Z.J.J. Stekly et el., "Coal Preparation Using Magnetic Separation," EPRI Report CS-1517, Vol. 2 (July 1980).

FIGURE 17

OPEN-GRADIENT QUADRUPLE MAGNETIC SEPARATOR



Source: Arthur D. Little, Inc.

magnet. In summary:

- The impact of HTSC will be greater than the cost benefit alone because the option to eliminate the helium cooling system will be perceived as assuring compatibility with the industrial process environment.
- All HTSC scenarios result in lower-cost magnets than the baseline design.
- The lowest overall cost is for HTSC with T_c = 400 K operated at 77 K.
- HTSC with T_c = 90 K will reduce magnet price by about 30-40% for operation at either 77 K or 4.2 K.

Accelerators and Colliders

Magnets for accelerators and colliders provide either beam bending or beam focusing functions. A uniform transverse field is required for the former purpose and alternating quadripolar fields for the latter. These magnets operate in a clean, laboratory-like environment but must be able to withstand exposure to radiation and must be designed to accommodate the field cycling required for stabilizing the particle orbit diameter. In addition, they must be extremely reliable because there are so many used in each machine.

When the various scenarios are applied to magnets for accelerators and colliders, the conclusions are:

- S-1 and S-3 show both performance and cost advantages over the baseline design.
- S-2 and S-4 yield poorer results than the baseline design.
- The S-1 and S-3 scenarios are really the only viable scenarios because of the high magnetic field and high current density required. The HTSC will not be suitable if operated near its critical temperature.
- HTSC development time will rule out use in superconducting supercolliders unless the program is delayed 5-10 years.

Fusion

Fusion applications represent a further escalation of the technical difficulty of magnetic field design. The magnetic field strengths and field cycle rates are increased as are the radiation levels. The field configuration and winding geometries can also be extremely complex.

The analysis of the performance under scenarios S-1 to S-4 shows that:

- S-1 and S-3 show both performance and cost advantages over baseline.
- S-2 and S-4 are not acceptable.
- HTSC may allow development of devices not possible using baseline material.

The conclusions are very similar to those for the accelerator/collider. The high-temperature-difference scenarios for HTSC show the prospects for improved magnet performance. The capability for fusion systems could be enormously increased if a material was available that would operate according to the S-1 and S-3 scenarios.

Pulsed Energy Storage

Pulsed energy storage provides yet another level of technical difficulty in which very high fields, current densities and cycle ratios are required. In addition, the winding shapes are complicated by the requirement for low external fields. The application environment may also be harsh, but more generally would be of the laboratory type.

Application of the scenarios shows that

- S-1 and S-3 show both performance and cost advantages over baseline.
- S-2 and S-4 are not acceptable.
- HTSC may allow development of devices not possible using baseline material.

The magnet requirements for pulsed energy storage are beyond present superconductor capabilities. A new material is needed. If HTSC can be developed to perform as in S-1 and S-3, a great impetus will be given to pulsed energy storage and a large market opportunity created.

DEVELOPMENT OF MARKETS

Figure 18 provides some time frame estimates for the development of the market areas discussed in this report. It must be emphasized that these time frames depend upon the development of HTSC meeting the scenario guidelines in the period 1990-1995. The probability of that development is open to conjecture, and it could be a very long time before such wire is available. Significant breakthroughs are required in terms of HTSC materials and composite wire design.

Table 14 projects the potential impact on overall world markets of scenario realization. The impact is not particularly great in the case of MRI, but is considerable in areas of magnetic separation and pulsed energy storage. Ultimately, the effects will be considerable in areas involving fusion. Overall, there is the potential for a large expansion of the superconductive, high-energy magnet market.

TABLE 14

ESTIMATED WORLDWIDE MARKETS FOR HIGH-ENERGY MAGNETS, 1987 and 2000 (millions of 1987 dollars)

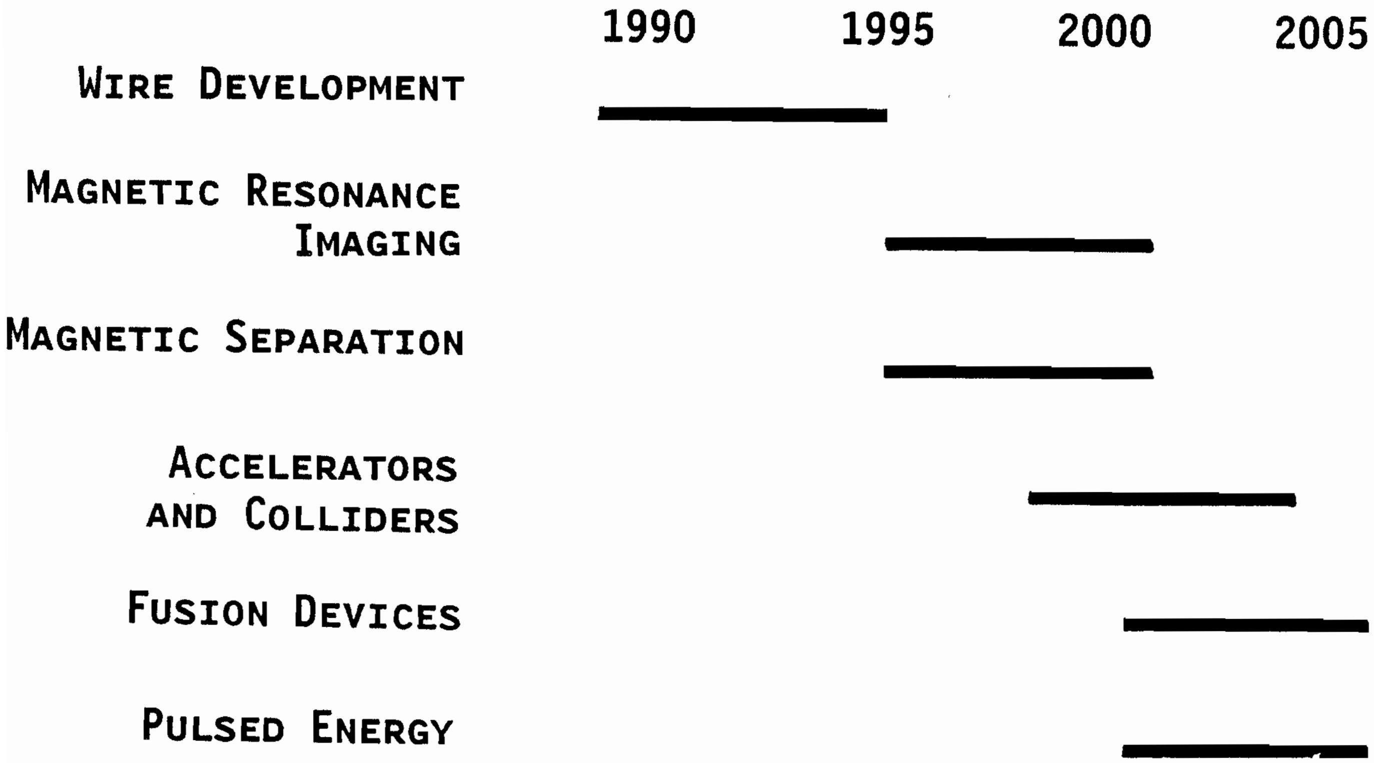
	1987 (NbTi)		2000 (HTSC)	
	Wire	Magnets	Wire	Magnets
MRI	40	150	100	200
High-Energy Physics	8	20	400(1)	1,200(1)
Magnetic Separators	2	2	75	150
Pulsed Energy Storage	0	0	30(2)	100(2)

1. Assumes SSC + Fusion.
2. Assumes 10 GJ Pulsed Energy Storage.

Source: Arthur D. Little, Inc., estimates.

FIGURE 18

TIMELINES FOR MAGNETIC APPLICATIONS



Source: Arthur D. Little, Inc., estimates.

3. ELECTRIC POWER APPLICATIONS OF SUPERCONDUCTIVITY

by Lawrence J. Stratton, M.S.

SUMMARY

Superconductivity offers potential for more-efficient, smaller, lighter, and less costly generators. The technical problems associated with a moving cryogenic rotor are essentially unchanged for operation at liquid nitrogen temperatures compared to liquid helium, but the economics are improved, provided the superconductor has reasonable current density in high magnetic fields. A superconductor able to operate at room temperature would obviate most of the technical problems and reliability would become less troublesome; such technology would have significant commercial applications. If the a.c. losses of room-temperature superconductors were low enough to permit their use in stators, their impact on electric machinery would be revolutionary, affecting not only generators but also electric motors.

The technology of superconducting a.c. underground power transmission cables using niobium tin (Nb_3Sn) and liquid helium has been demonstrated, but their long-term reliability has not. Furthermore, extremely large amounts of power must be transmitted to make this technology economical. If an yttrium barium copper oxide (YBCO) superconducting cable operating at liquid nitrogen temperature could achieve low a.c. loss at reasonable current density, then underground a.c. power transmission cables would become more economical at lower power and their reliability would not be so critical. A room temperature superconducting cable with low a.c. loss

and reasonable current density could possibly be economically configured for overhead a.c. power transmission, thereby reducing transmission losses and/or permitting power transmission over greater distances.

A recent study has shown that superconducting magnetic energy storage (SMES) using niobium titanium (NbTi) and liquid helium could be an economical alternative for supplying large amounts (5000 MWh) of electric energy during peak periods. The use of YBCO carrying current densities similar to those of NbTi but operating in liquid nitrogen should make such an installation more economical. This could lead to a multiplicity of smaller SMES devices having fewer technical problems. If high-temperature superconductors are developed with low a.c. losses, a multitude of room temperature superconducting coils carrying reasonable current densities could provide a viable means for load-leveling and maintaining network stability during transient conditions.

Superconductivity in ship propulsion has been demonstrated successfully in the forms of electrically driven propellers using homopolar motors and generators, and electromagnetic thrust acting directly on the sea water. Superconductors capable of large d.c. fields and operating at 77 K, or more significantly, at room temperature, would make electric drive with superconducting machinery technically and economically attractive. Even electromagnetic thrust could be attractive for some ship propulsion needs.

Superconductivity in high-speed land transportation is used for experimental tests of vehicular magnetic levitation (MAGLEV) and linear synchronous motor (LSM) propulsion. Availability of 77 K superconductors should slightly improve the economics and reduce the technical problems (but not materially change the status) of high-speed land transportation. Although availability of room temperature superconductors could have a great impact, other factors, such as right-of-way availability or politics, could be more significant.

LARGE POWER GENERATORS

The basis for the opportunity to improve electric power generators is shown in a very fundamental relationship for electric machines (Table 15). The power is a function of the diameter of the rotor squared, the length of the rotor, the flux density in the air gap, the current in the stator windings, and the speed. The rotor diameter squared times its length is proportional to the volume of the rotating member; this can be considered a measure of the size of the machine. The potential of superconducting lies in increasing the flux density in the air gap (B). This is normally 0.7 tesla, about the best that can be accomplished in machines utilizing magnetic steel. Increasing B would increase power production in direct proportion, or alternatively decrease size and weight in inverse proportion. Only the rotor winding, which carries direct current, is superconducting; the stator winding has copper conductors since it must carry alternating current.

These considerations point to a number of potential advantages of this technology. Currently, high-power synchronous generators operate at efficiencies of 98%. Superconducting generators might operate at efficiencies of 98.5% to 99%. If efficiency is improved from 98% to

TABLE 15

COMPONENTS OF POWER IN A SUPERCONDUCTING ELECTRIC MACHINE

$$P = K D^2 L B \Delta N$$

Where:

P = Power
K = Constant, depending on units, type of machine, etc.
D = Diameter of rotor
L = Length of rotor
B = Magnetic flux density in working air gap
Δ = Stator ampere conductors per unit length of rotor periphery
N = Speed of rotation

Note: B = 0.7 tesla in a conventional machine.

Source: Arthur D. Little, Inc.

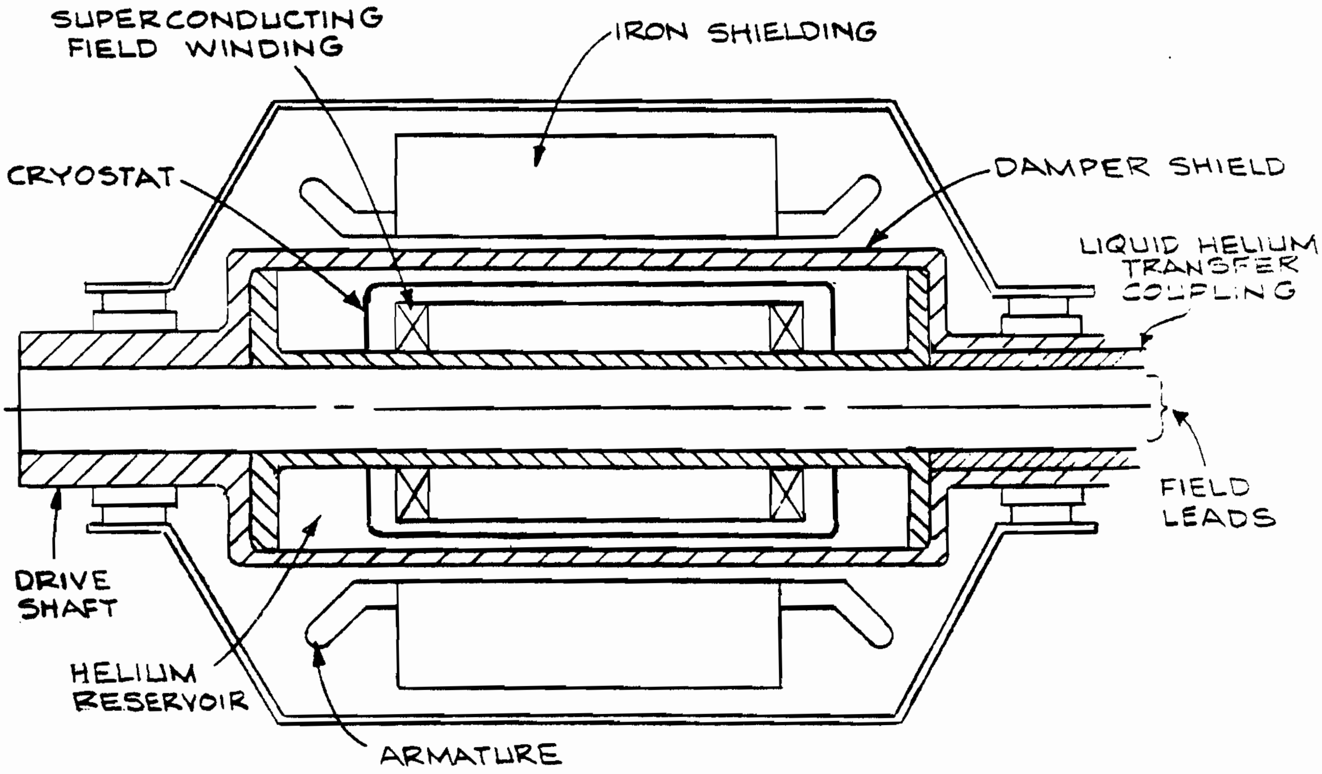
99%, the power loss is decreased from 2% to 1%; this represents an improvement of 50%. When machines of the order of 1000 megawatts are considered, this reduction in power losses would reduce the fuel used and pay for the generator over its lifetime. Doubling the flux density would result in a 50% decrease in weight and size of a superconducting generator compared with a conventional generator. A further advantage is improvement in system performance. Once a flux density of 1.5-2 tesla can be obtained, there is no longer a need for steel in the machine. Without steel, some of the reactances of the machine would be lowered, giving faster response to changes and resulting in improved performance. Also, without steel near the stator windings, there is the possibility of a higher output voltage, which could eliminate the need for a transformer between the generator and the transmission network. Lastly, larger power ratings are possible.

The above-mentioned possibilities are not easily achieved, especially considering the high reliability necessary to encourage the first innovative commercial investments. In a schematic typical of a research superconducting generator (Figure 19), we see that the superconducting technology is manifested mainly in the rotor circuit, which consists of a superconducting field winding, niobium titanium in this case, immersed in a liquid helium cooling reservoir -- a rotating cryostat. Technologies difficult to incorporate in a rotating machine include rotating liquid helium transfer couplings, a torque tube to prevent heat leakage into the rotating member, thermal radiation shields, extra conducting shields and damper shields, and vacuum containment. The difficulties would remain, although the economics would improve, if liquid nitrogen and a higher-temperature superconductor were used.

A number of manufacturers have recognized the possibility of superconducting generators. Table 16 lists experimental generators utilizing niobium titanium and liquid helium. Smaller generators had been built prior to 1980. In the 10-50 MVA range, the USSR and Japan produced 20, 30, and 50 MVA machines during 1981-1984; in the United States, General Electric produced with its own funding a 20 MVA rotor and the Department of Energy supported work at MIT on a 10 MVA machine. One larger machine has been produced by the USSR (a 300 MVA generator scheduled for testing during 1987), and Japan has completed initial design of a 200 MVA machine. Westinghouse and the Electric Power Research Institute (EPRI) began collaboration on a 300 MVA generator in 1980, doing much work on damper windings, transfer couplings, and radiation shields. However, that project terminated in 1986 when EPRI

FIGURE 19

SCHEMATIC OF A SUPERCONDUCTING GENERATOR



Source: Arthur D. Little, Inc.

TABLE 16

EXPERIMENTAL GENERATORS WITH A CAPABILITY OF 10 MVA OR GREATER

Manufacturer	Country	Rating or Rotor Diameter	Status	Tests
All-Union Institute	USSR	20 MVA	Rotor test 1980-81	Generator 1981
General Electric	USA	20 MVA	Rotor test 1981	Generator 1982
Fuji/Mitsubishi	Japan	30 MVA	Rotor finished 1981	Generator 1982-83
Hitachi	Japan	50 MVA	Rotor finished 1981	Generator 1982-84
MIT	USA	10 MVA	Rotor finished 1984	Generator 1984-88
Electrosila	USSR	300 MVA	Under construction	Generator 1987
Westinghouse/EPRI	USA	300 MVA	Terminated 1986	
Kansai	Japan	200 MVA	Initial design 1987	
		Test Rotors With Large Diameter		
Alsthom	France	1060 mm	Rotor finished 1980	from 1980
KWU	West Germany	1170 mm	Under construction	1986-87
Toshiba	Japan	1000 mm	Under construction	1985-86
Ansaldo	Italy	1200 mm	Under construction	1984-85
		Conceptual Designs		
IR&D	England	1300 MVA		
Brown Boveri	Switzerland	Various ratings		

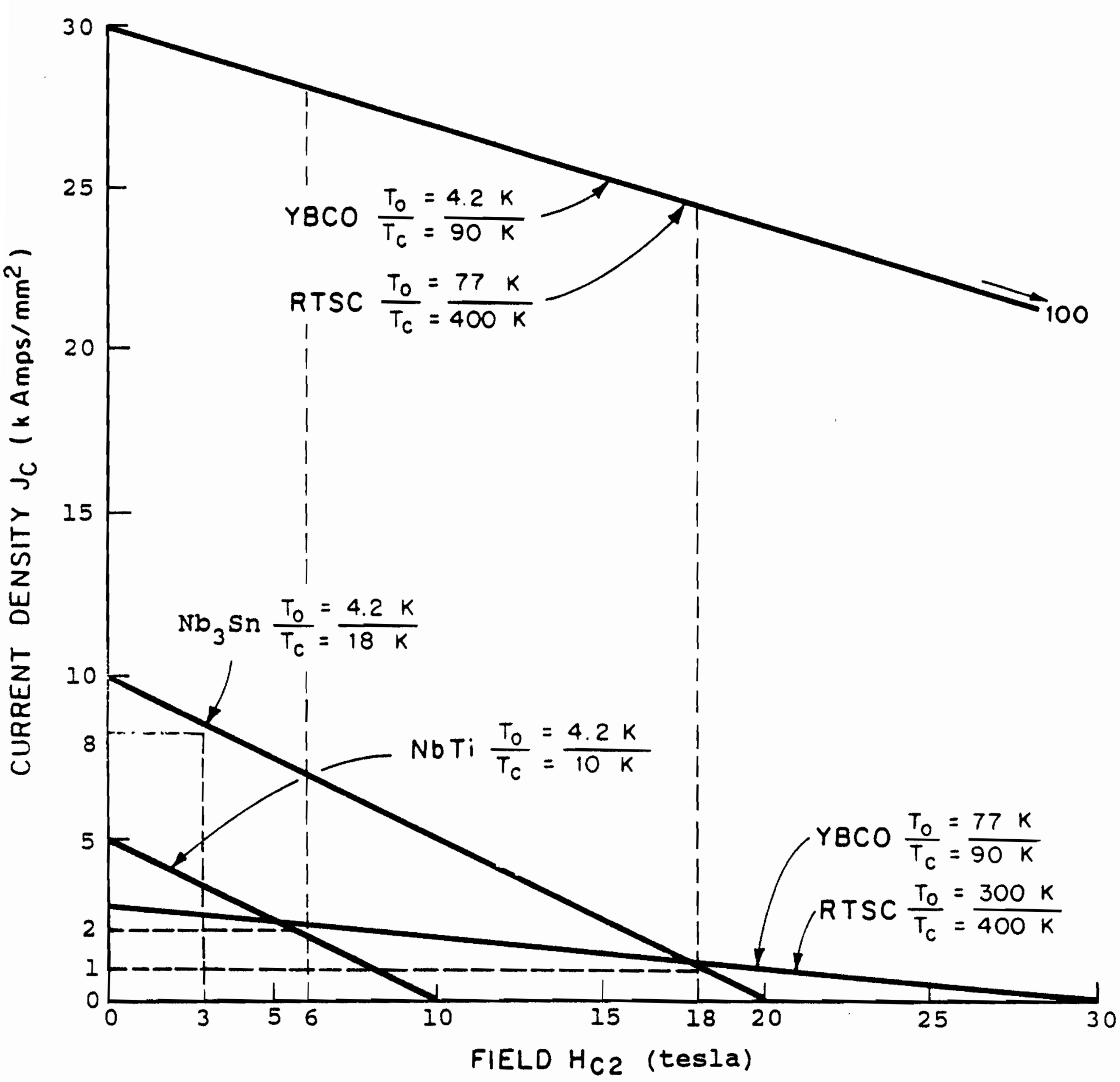
Sources: "Superconducting Turbogenerators," IEEE Trans. on Magnetics, 1984.
"Main Stages of Manfacturing a 300 MW Superconducting Generator," Cryogenics, 1987.
Arthur D. Little, Inc., estimates.

reallocated its funding for other investigations. Companies throughout the world are working on large-diameter rotors, demonstrating wide acceptance of the challenge to solve the rotor design problems.

Figure 20 graphs the relationship of critical current to critical field strength for various materials at various operating temperatures and critical temperatures. For example, in typical designs mentioned above, a niobium titanium winding operating at 4.2 K with a critical temperature of around 10 K can produce a peak field of about 6 tesla with a current density in the d.c. field winding of around 2 kiloamps per square millimeter. We have selected for one scenario YBCO operating at 77 K; the line depicted is a projection of what some of the best measurements have been. We hypothesize that a room temperature semiconductor would follow a similar curve. Similarly, we have conjectured another line at the top of the graph, with a very high critical current density of 30 kAmps/mm^2 projected out to a field density of 100 tesla. This line represents the possible performance of YBCO operating at 4.2 K or an RTSC operating at 77 K. For this discussion, we will consider field strengths of 6 tesla and 18 tesla, with corresponding current densities of 2kAmps/mm^2 and 1kAmp/mm^2, respectively, as shown on Figure 20.

FIGURE 20

CRITICAL FIELD - CRITICAL CURRENT RELATIONSHIP IN VARIOUS SCENARIOS



Source: Arthur D. Little, Inc., estimates.

Table 17 shows a comparison of costs of a conventional 1200 MVA generator with three kinds of projected superconducting generators (all assuming mature technology). The first column, for the conventional generator, shows the breakdown of costs for its parts, totaling about $19 million. The second column shows the breakdown for a niobium titanium machine operating with liquid helium at 4.2 K; note the air gap flux density has been doubled and that even on this machine there is a reduction in cost, to some $15 million. Next, a YBCO machine operating at 77 K has a higher cost for the rotor wire since a lower current density for YBCO must be used compared to NbTi, but the rotating cryostat is less expensive and the cost of refrigeration is much less. Because we can triple the maximum flux density, the corresponding cost for a smaller stator goes down by a factor of three, resulting in a machine of about half the cost of a conventional generator. Continuing this scenario concept to a room temperature superconducting machine, with lower rotor mechanical costs and no cryostat or refrigeration cost, results in still greater savings.

Although the economics for superconducting generators seem favorable, a number of other considerations are less so. The present U.S. market for a.c. generators is very small -- approximately $150 million/year -- with a growth rate of only about 1%/year. Thus, there is little driving force for manufacturers to invest their own money in research and development and there are limited government funds. (A possible exception would be Space Defense Initiative (SDI) applications, where there is a perceived need for high-power, lightweight generators in space.) There is the need for high reliability and much testing before a superconducting generator can be put on line. Certainly a room temperature superconductor having a reasonable magnetic field and current density, eliminating the need for

TABLE 17

COST OF GENERATORS WITH SUPERCONDUCTING D.C. FIELDS
(Millions of 1987 dollars and % of total price)

Cost Elements	Conventional		Superconducting					
	1200 MVA B = 0.7		NbTi (4.2 K) B = 1.4 (6) J_c = 2		YBCO (77 K) B = 4.2 (18) J_c = 1		RTSC (300 K) B = 4.2 (18) J_c = 1	
	MM$	%	MM$	%	MM$	%	MM$	%
Rotor Wire	0.1	0.3	1.0	6.4	1.2	11.6	1.2	14.8
Rotor Winding	1.7	8.9	1.4	9.0	2.8	27.2	2.8	34.5
Rotor Mechanical	3.1	16.5	2.0	12.8	1.5	14.6	0.5	6.2
Rotating Cryostat	-	-	2.6	16.7	1.0	9.7	-	
Refrigeration	-	-	1.0	6.4	0.2	1.9	-	
Stator	10.3	53.5	6.2	39.7	2.2	21.4	2.2	27.2
Auxiliaries	4.0	20.8	1.4	9.0	1.4	13.6	1.4	17.3
Total	19.2	100.0	15.6	100.0	10.3	100.0	8.1	100.0

Notes: B = Air gap flux density in tesla (field strength in tesla).

J_c = superconductor current density in kA/mm^2.

Source: Arthur D. Little, Inc., estimates.

refrigeration and its associated problems, would quickly demonstrate reliability and might lead to older generators being replaced at lower cost, thereby broadening the market.

European and Japanese firms are continuing to work on machines using NbTi and liquid helium and are continuing to solve those mechanical problems that exist. If and when a practical high-temperature (77 K) superconductor becomes available, these firms would be in the best position to substitute it and proceed with the development of a superconducting generator.

Finally, we consider the prospects for a generator with not only a superconducting field but also a superconducting a.c. stator. The fact that a.c. losses in superconductors are high requires that the field involved must be incredibly small. These losses depend not only on the material but on the construction of the superconducting wire or cable. Even with highly engineered cables, components of power are lost to hysteresis in the superconducting filament and also to eddy currents in the copper portion of the cable. These losses are a strong function of magnetic field density, current density, temperature, and frequency. If YBCO or another superconductor, at 77 K or at room temperature, could be made to operate with low a.c. losses and at reasonable field strengths -- on the order of 7 tesla -- and with reasonable current densities, then stators of a.c. generators could also be superconducting. This achievement could result in 99.5%-efficient, low-cost machines possibly one-tenth the size of conventional generators. Such revolutionary machines are not anticipated in the foreseeable future.

ELECTRIC POWER TRANSMISSION CABLES

At present, the transmission of electric power by utilities has the following characteristics:

- Ninety-nine percent of power transmitted is a.c. A drawback to transmitting power by d.c. is the cost of converter stations necessary at each end of the line. Among circumstances which do justify such costs for d.c. transmission are when the lines are very long, when tying together systems with different frequencies, or when they are necessary to stabilize electric networks.
- Over 90% of power transmitted is by overhead cable. Underground cables, necessary for superconducting transmission, are ten times as expensive as overhead cables.
- Approximately 5% of power generated is lost in transmission. This is the driving force for thinking about superconducting a.c. power transmission.
- The rate of growth in new transmission is only 1-2%/year.

Thus, a superconducting power transmission cable must be designed to carry a.c. power to avoid the cost of converter stations and to reach the largest market. Any such technology relying upon liquid helium or nitrogen would have to be underground, a much more expensive technique.

Studies and experiments have used niobium tin -- which is brittle and difficult to use in fabricating cables, as opposed to niobium titanium --

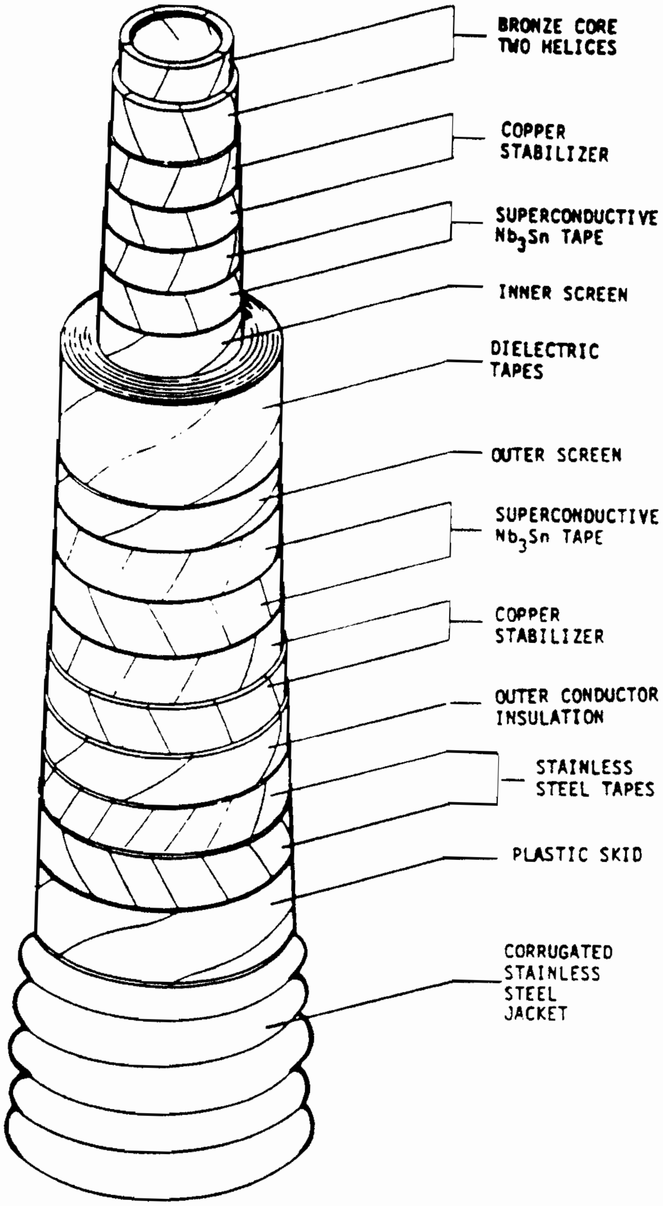
in order to make cables having low a.c. losses. A general assembly diagram of a flexible superconducting cable is shown in Figure 21.

One experiment operated a test cable with a very low field permitting a high current density of 8 kAmps/mm^2 at a temperature of 4.2 K. Figure 20 shows that a field of 3 tesla could be tolerated by niobium tin at this current density. A conclusion of these studies was that the a.c. power carried has to be very large for an economic break-even. In these experiments, superconducting tapes were made by a chemical vapor deposition technique using niobium tin or niobium germanium. In tests on a pair of 100-meter cables, a.c. losses were 50-100 times greater than had been measured in short sample lengths. There were problems with the solid cable insulation (a cross-linked polyethylene) at cryogenic temperatures, heat leakage, refrigeration reliability, and mechanical integrity. In this full-scale test, carrying power on the order of 1000 MVA and operating at a temperature of 7.5 K (Table 18), there were current-dependent losses (0.8 watt/meter), voltage-dependent losses (0.15 watt/meter in the dielectric), and heat leakage (0.45 watt/meter).

Table 19 illustrates relative cost factors under the scenarios we consider, comparing niobium tin with YBCO and with room temperature superconductors operating at two different temperatures. The superconductor cost is directly related to the amount of power handled times the cable length. Note the significant decrease in refrigeration and capitalized cable and heat leak loss, by a factor of 30, between niobium tin at 7 K and YBCO at 77 K. The lower current density capability of YBCO requires higher superconducting cable and cryostat costs. In

FIGURE 21

GENERAL ASSEMBLY DIAGRAM OF FLEXIBLE SUPERCONDUCTING TRANSMISSION CABLE DESIGN



Source: "Performance Summary of the Brookhaven Superconducting Power Transmission System," by E.B. Forsyth & R.A. Thomas, Cryogenics, 1986, pp. 599-614. Reprinted with permission of the publishers, Butterworth & Co. (Publishers), Ltd. ©

TABLE 18

CHARACTERISTICS OF 1000-MVA TEST SYSTEM

Number of cables	2
Length of each cable (meters)	115
Cable outer diameter (over armor) (cm)	5.84
Inner conductor diameter (cm)	2.95
Enclosure outer diameter (cm)	40
Maximum operating temperature (K)	9
Operating pressure (MPa)	1.55
Cooldown time (hours)	100
Rated voltage (3-phase) (kV)	138
Rated impulse withstandability (kV)	650
Maximum impulse sustained to date (kV)	488
Maximum steady state power rating (MVA)	980
Emergency power level (MVA) (for 1 hour)	1430
Surge impedance load (MVA)	872
Surge impedance (ohms)	25
Current-dependent loss at rated power, 3-phase (7.5 K) (watts/meter)	0.8
Voltage-dependent loss at rated power, 3-phase (7.5 K) (watts/meter)	0.15
Enclosure heat in-leak, 3-phase (7.5 K) (watts/meter)	0.45

Source: "Performance Summary of the Brookhaven Superconducting Power Transmission System," by E.B. Forsyth & R.A. Thomas, Cryogenics, 1986, pp. 599-614. Reprinted with permission of the publishers, Buttersworth & Co. (Publishers), Ltd. ©

TABLE 19

FACTORS DETERMINING COST OF SUPERCONDUCTING UNDERGROUND A.C. POWER TRANSMISSION

	Nb_3Sn	YBCO	RTSC	RTSC
	7 K	77 K	300 K	77 K
	$J_c = 9$	$J_c = 3$	$J_c = 3$	$J_c = 30$
Superconductor Cable Cost	MVA-mile	x 1.8	x 1.8	x 0.2
Cryostat, Dielectric, & Structural Costs	MVA-mile	x 2	x 2	x 0.5
Refrigerator Costs	refrig. pwr.	x 1/30	-	x 1/30
Capitalized Cable Loss	MVA-mile	x 1/30	low	x 1/30
Capitalized Dielectric Loss	kV-mile	same	lower	same
Capitalized Heat Leak Loss	MVA-mile	x 1/30	-	x 1/30

Note: J_c is superconductor critical current density in kA/mm^2 for low fields.

Source: Arthur D. Little, Inc., estimates.

the room temperature superconductor (RTSC) at 300 K, these two costs are the same since the current density is the same, while refrigeration cost disappears since it is unnecessary; capitalized cable costs are lower, and costs for dielectric loss are much lower since more-conventional dielectrics could be used. Further, in the RTSC at 77 K with very high current density, cable costs drop significantly, as do cryostat and refrigeration costs.

The underlying hypothetical assumption is that a.c. losses in YBCO can be made to be at least as low as those in niobium tin. The reduced cryostat and refrigeration costs for YBCO would justify its lower current density capability. And if a room temperature superconductor is developed with similar low a.c. power loss, the prospect of superconducting overhead transmission becomes more plausible; this would have a significant market impact.

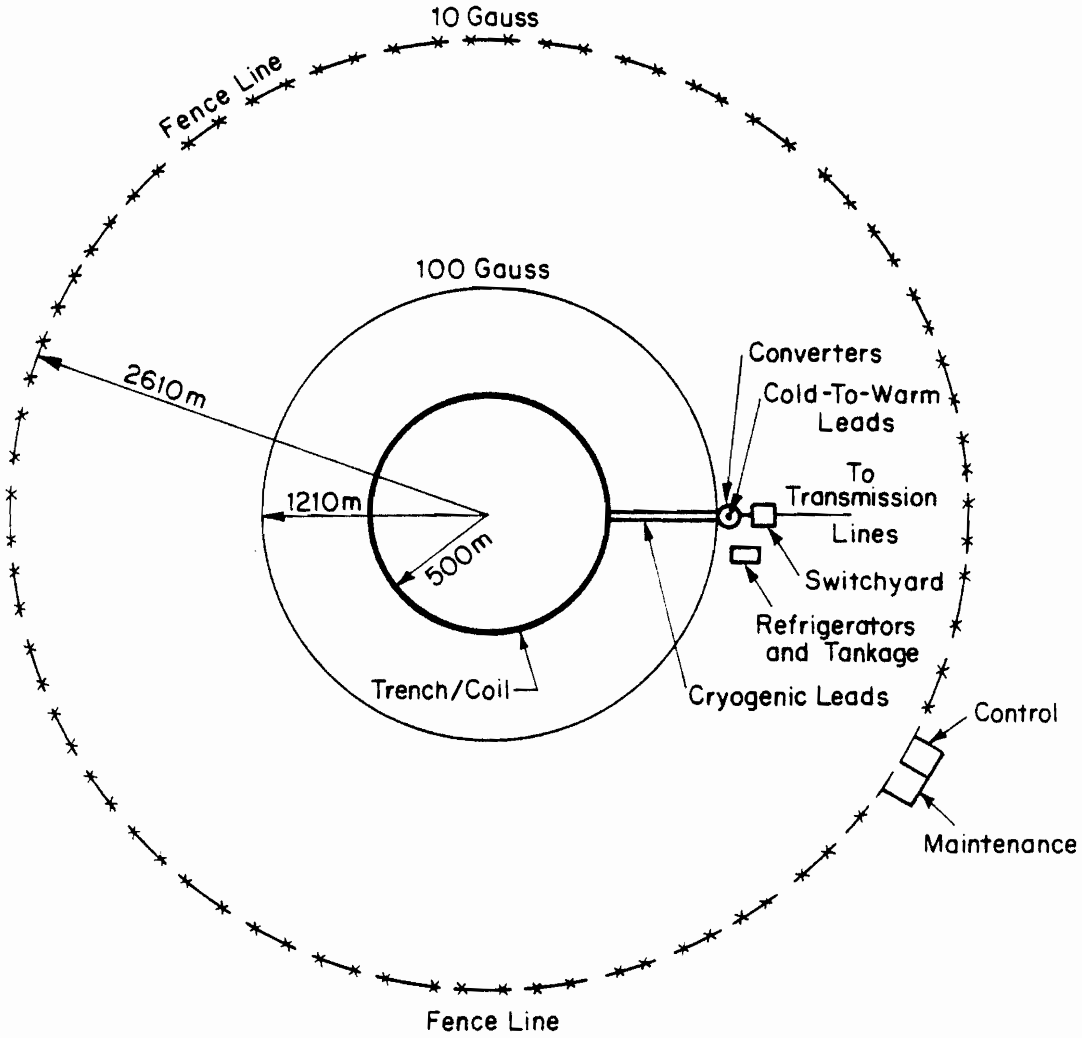
ELECTRIC UTILITY MAGNETIC ENERGY STORAGE

Superconducting magnetic energy storage (SMES) can provide utilities a means for supplying electric power during peak demand periods and for stabilizing the network during transient conditions. It would be an alternative to conventional techniques such as storage by pumped hydro, compressed gas, or batteries.

One study in 1987, sponsored by the Electric Power Research Institute (EPRI), envisioned a 5000-megawatt-hour SMES device with a superconducting coil of some 500 meters radius (Figure 22). It would be

FIGURE 22

PLAN VIEW OF THE 5000 MWh SMES PLANT



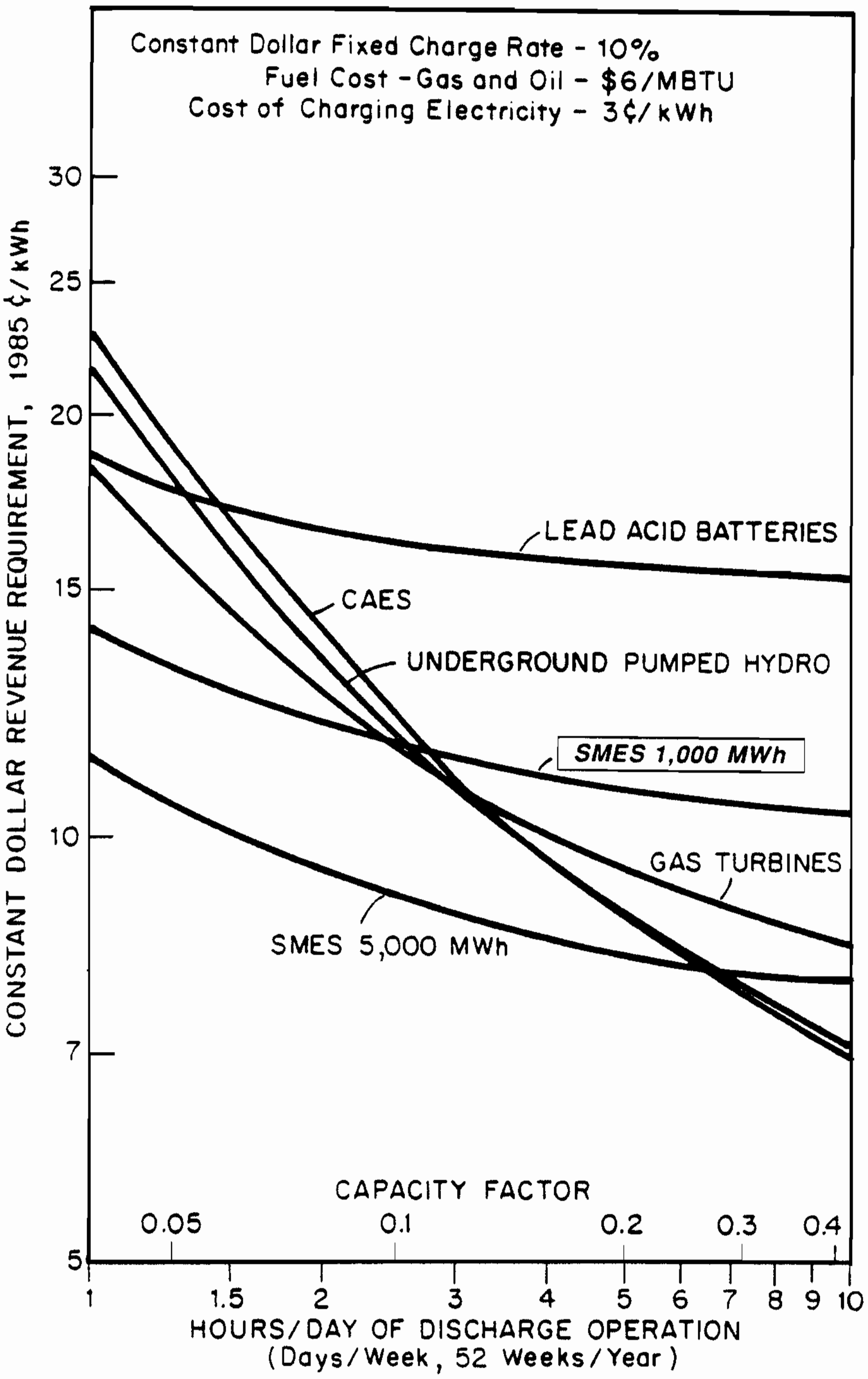
Source: Design Advances in Superconducting Magnetic Energy Storage for Electric Utility Load Leveling, IEEE, Trans. on Magnetics, 1987. Reprinted with permission. © IEEE capable of storing some 18 million megajoules of energy. Technically, there would be problems of very high stresses in such a device, requiring that it be supported by an underground rock formation. In addition, appreciable magnetic fields would exist out to a distance of 2600 meters from its center and several hundred meters above it, thus requiring precautions in locating the device.

Figures 23 and 24 compare the costs for various energy storage technologies and show SMES to be generally the lowest-cost approach. Table 20 breaks down the costs for a 5000 MWh device -- totalling $980 million in 1985 dollars. High-temperature superconductors in this case would help only marginally in improving the practicality of these devices, since the problem of mechanical stress in the structure remains the same as with low-temperature superconductors. Using YBCO and liquid nitrogen or a room temperature superconductor would improve the economics (by reducing or eliminating refrigeration costs) so that smaller installations could be economic alternatives.

If the a.c. losses in the high-temperature superconductors are small resulting in an improved economy, thereby enabling rapid charge and discharge, SMES could fill the market niche for an economical network-stabilizing device. Hence, many small devices (hundreds of megajoules) are likely to be built for this purpose. For peak-demand applications, however, the very large installations would be required. This sort of installation has not yet demonstrated the ability to provide high reliability.

FIGURE 23

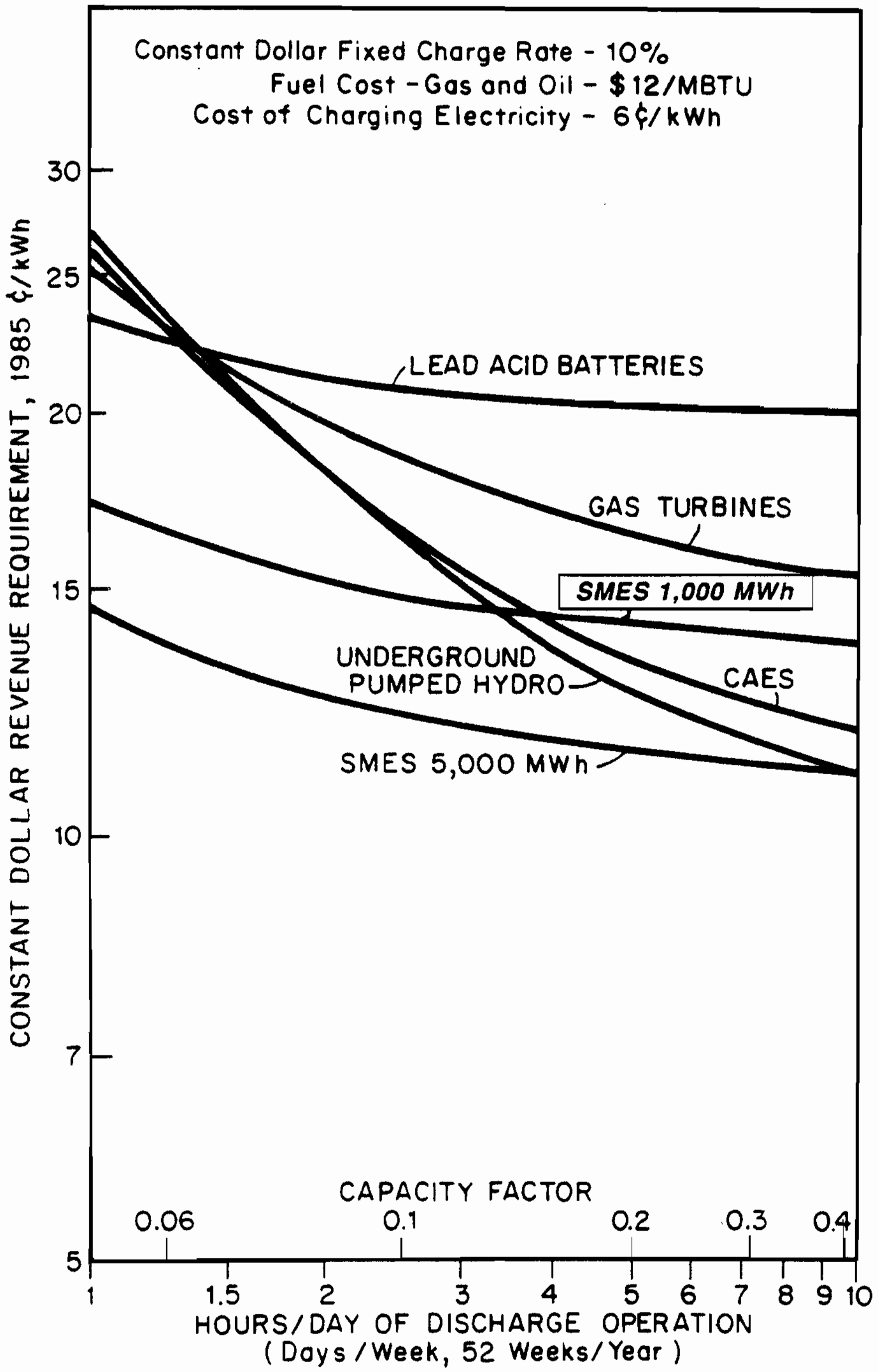
REVENUE REQUIREMENT FOR VARIOUS ENERGY STORAGE TECHNOLOGIES AND GAS TURBINES



Source: "Design Advances in Superconducting Magnetic Storage for Electric Utility Load Leveling," IEEE, Trans. on Magnetics, 1987. ©IEEE

FIGURE 24

REVENUE REQUIREMENT FOR VARIOUS ENERGY STORAGE TECHNOLOGIES AND GAS TURBINES -- BASED ON INCREASED COSTS FOR FUEL AND ELECTRICITY



Source: "Design Advances in Superconducting Magnetic Energy Storage for Electric Utility Load Leveling," IEEE, <u>Trans. on Magnetics</u>, 1987. © IEEE

TABLE 20

TOTAL ESTIMATED CAPITAL REQUIREMENT FOR SMES PLANT
(millions of 1985 dollars)

Cost Item	Storage-Related Costs	Power-Related Costs	Totals
Direct Process Capital:			
Materials and Offsite Fabrication	430	81	511
Construction	94	24	118
Total Direct Process Capital	524	105	629
General Facilities	31	8	39
Total Process Capital	555	113	668
Engineering	28	6	34
Geotechnical	2	-	2
Licensing	2	-	2
	587	119	706
Contingency	147	18	165
Total Plant Investment	734	137	871
Allowance for Funds Used During Construction	79	7	86
Total Plant Investment at Start-up	813	144	957
Preproduction	9	1	10
Inventory and Refrigerants	5	-	5
Land	8	-	8
Total Capital Requirement	835	145	980

Note: Assumes 5,000 MWh.

Source: "Design Advances in Superconducting Magnetic Energy Storage for Electric Utility Load Leveling," IEEE, Trans. on Magnetics, 1987. Reprinted with permission. © IEE

ELECTRIC PROPULSION FOR SHIPS

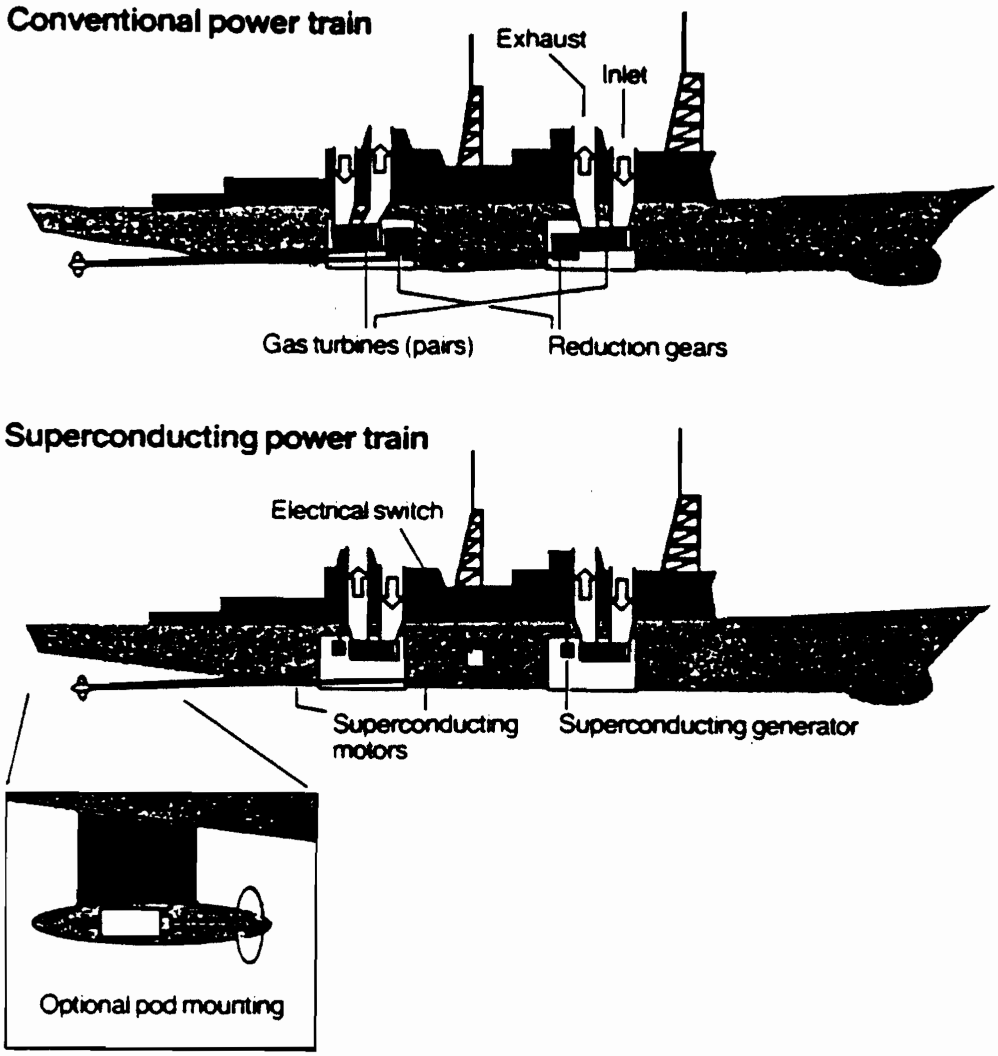
The applications of superconductivity to ship propulsion would be both in generating electricity and in superconducting motors. Some advantages would be:

- More freedom in arranging the ship propulsion power train (propellers could even be pod mounted) than with conventional power trains (Figure 25).
- Flexibility in operating capability -- ease of reversing direction, for example.
- Reduced drive train size and weight, and improved efficiency.
- The possibility of silent, high-speed underwater propulsion via electromagnetic thrust on the seawater itself.

The U.S. Navy R&D center has developed and successfully tested superconducting homopolar motors of 400 HP and 4,000 HP based on principles shown in Figure 26. These are powerful d.c. motors (so a.c. losses need not be considered here) of low voltage and very high amperage, for example, 10 volts d.c. and 400,000 amperes. The technology involved is very challenging, using liquid metal (sodium-potassium eutectic) brushes. In order to be useful, motors of some 40,000 HP would be necessary, an order of magnitude more powerful than the ones mentioned. Although development stopped several years ago, the advent of new superconductors will renew these efforts. In the near term, the U.S. Navy is meeting its needs, at least in terms of smaller sizes, with conventional electric drive.

FIGURE 25

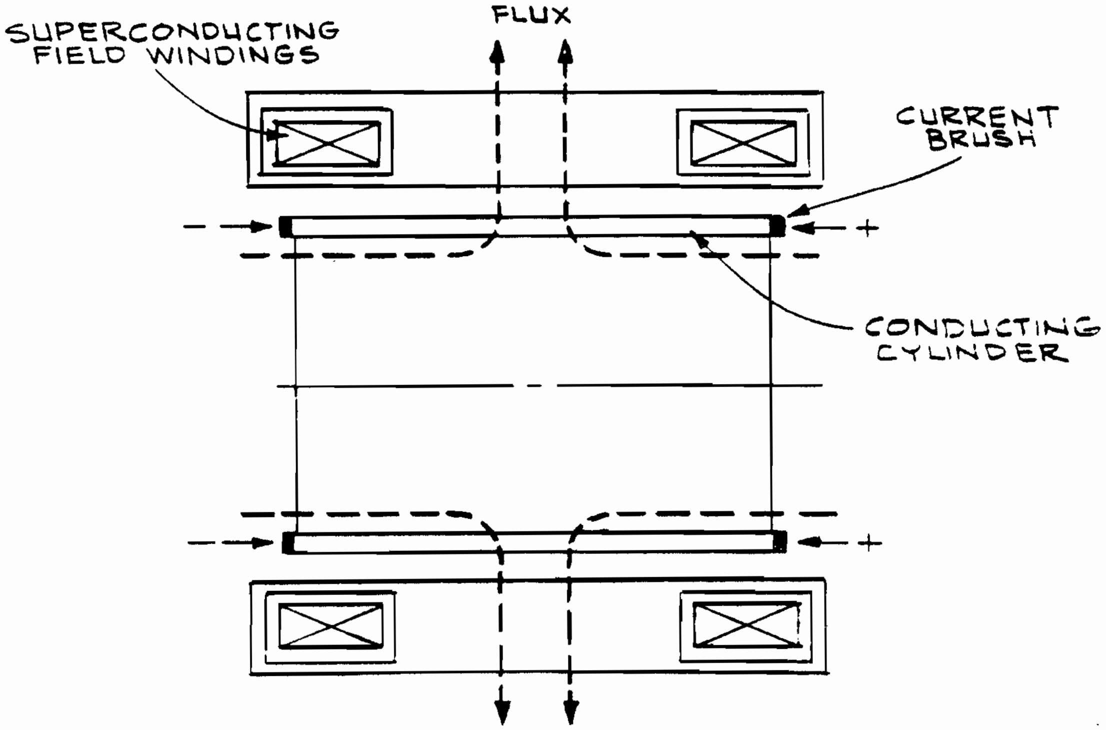
SHIP PROPULSION WITH CONVENTIONAL AND SUPERCONDUCTING POWER TRAINS



Source: <u>High Technology</u>, Vol. 2, No. 5, Sept/Oct 1982

FIGURE 26

PRINCIPLE OF SUPERCONDUCTING HOMOPOLAR MACHINES



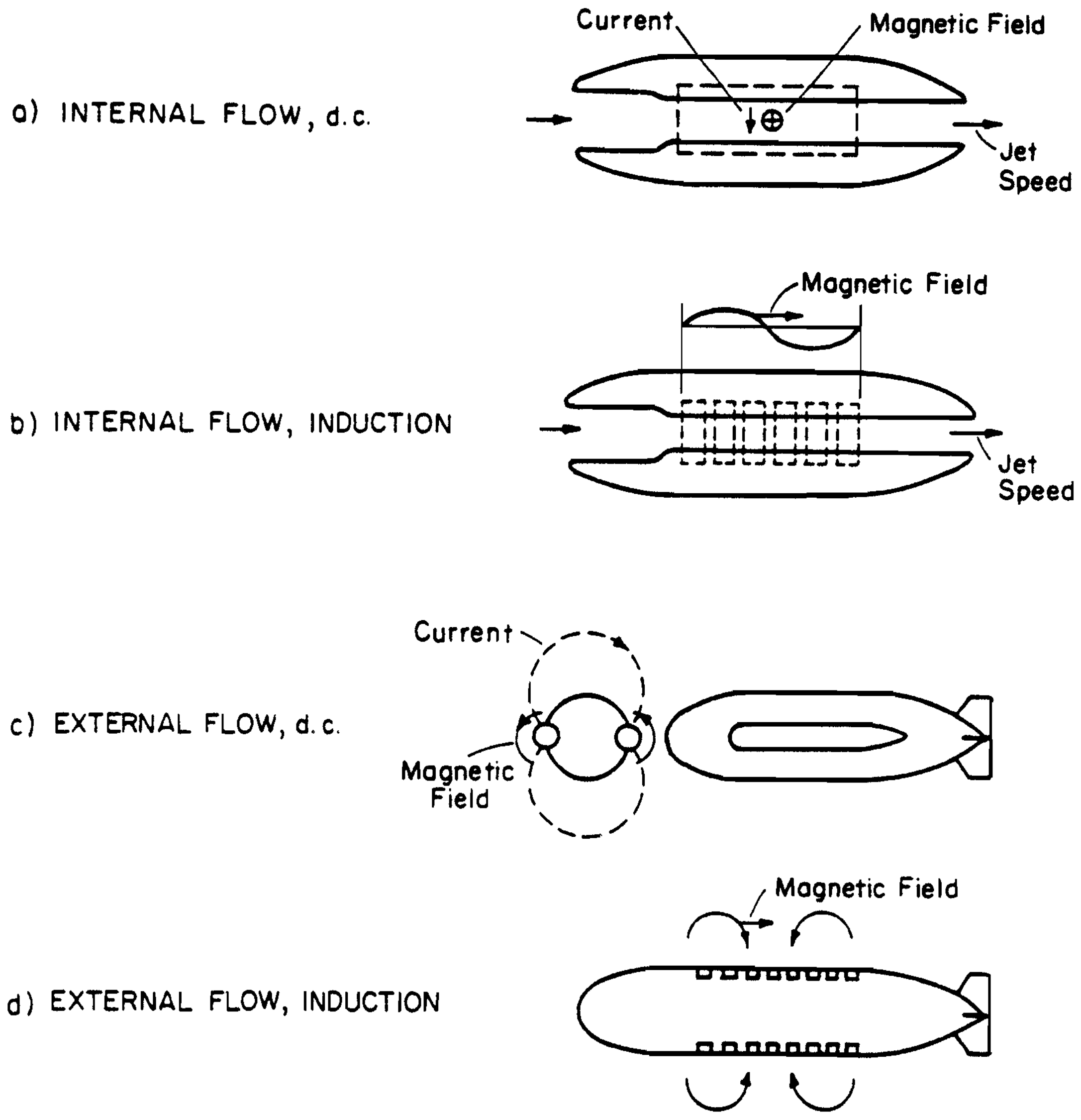
Source: Arthur D. Little, Inc.

A researcher at Westinghouse in 1968 described four different arrangements for ship propulsion using electromagnetic thrust directly on the seawater (Figure 27). Although surface vessels are limited by drag to some 22 knots, submerged vessels could develop much faster speeds (Figure 28).

Major problems are encountered in mechanically supporting (without large heat leaks), the huge cryostat containing the superconducting coil. A room temperature superconductor would greatly minimize the mechanical problems and make superconducting electromagnetic propulsion more feasible. And, of course, potential environmental effects would make high-magnetic-field containment necessary, so significant development would still be required.

FIGURE 27

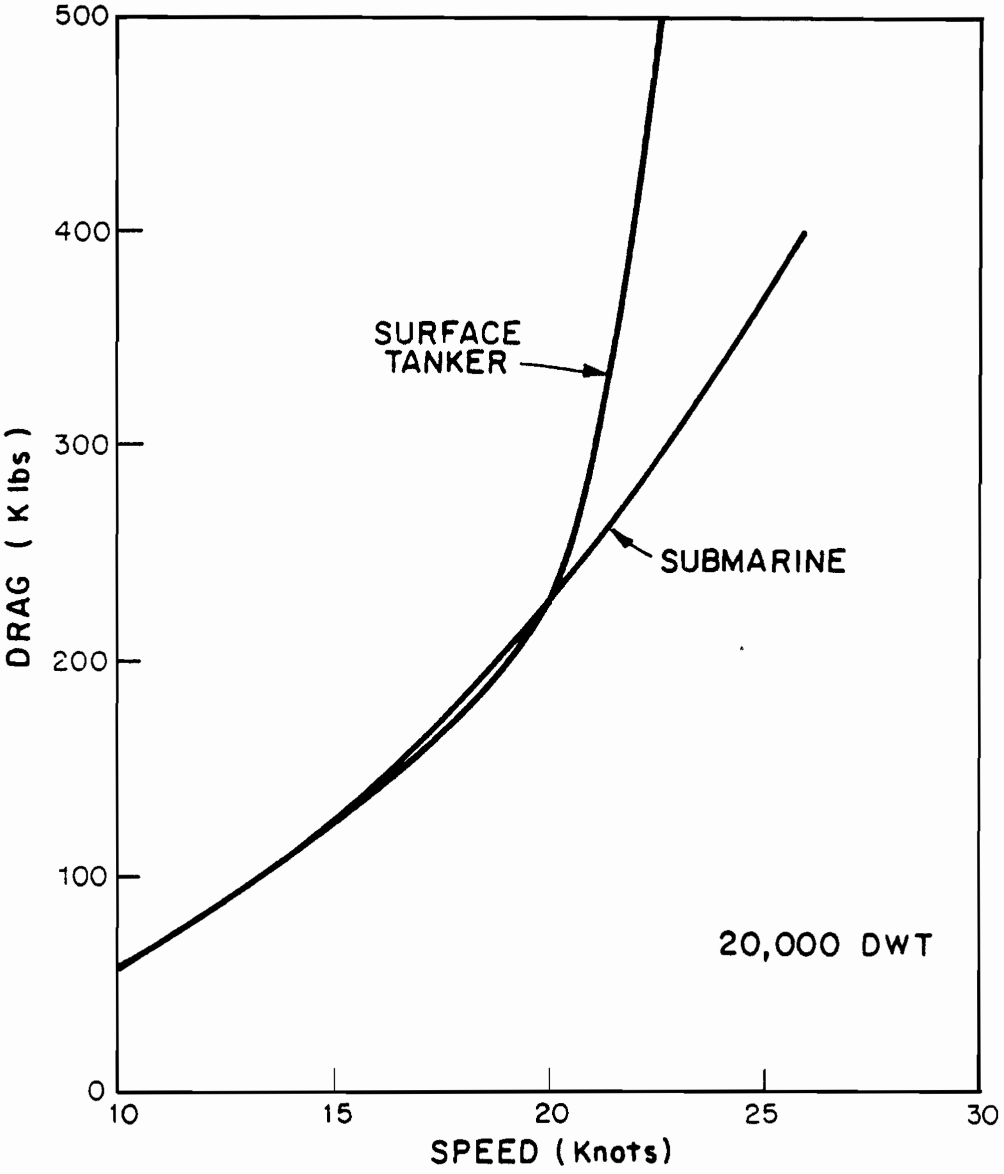
METHODS FOR ELECTROMAGNETIC PROPULSION



Source: "Electromatic Propulsion for Cargo Submarines," Journal of Hydronautics, 1968. Reprinted with permission of the American Institute of Aeronautics and Astronautics.

FIGURE 28

RESISTANCE OF SURFACE AND SUBMARINE TANKERS



Source: "Electromagnetic Propulsion for Cargo Submarines," Journal of Hydronautics, 1968. Reprinted with permission of the American Institute of Aeronautics and Astronautics.

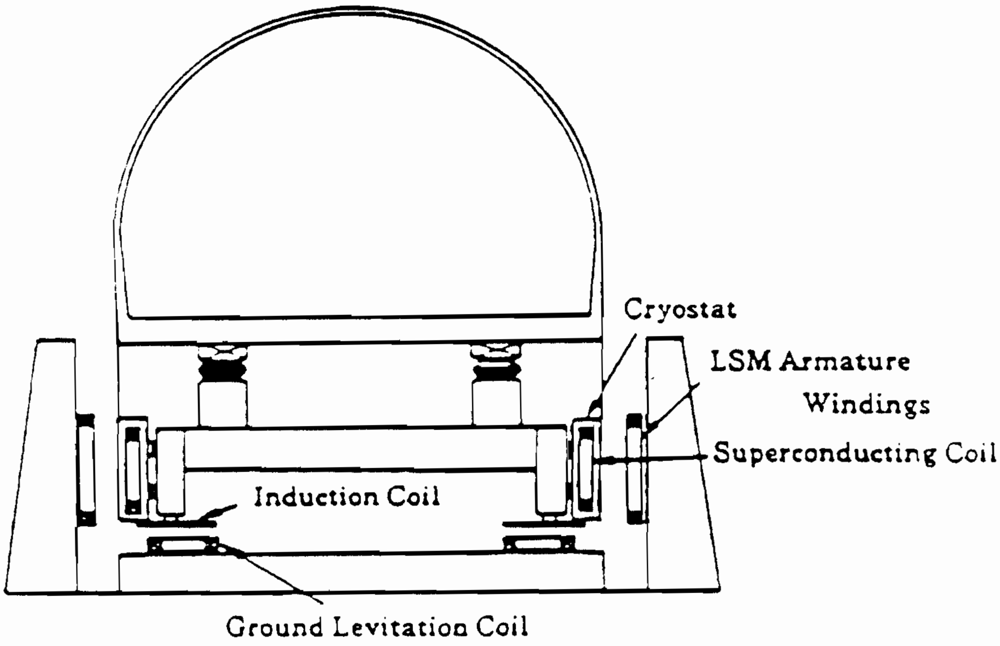
The possible future for superconductivity in land transportation is influenced in part by the forces shaping land transportation design. These include:

- The building and opening to service of the first "super railway" in Japan -- the Tokaido line between Tokyo and Osaka -- in 1964.
- The competitive threat to the conventional passenger railway presented by short-haul jet air travel, wide automobile ownership, and massive investment in urban and rural roads.
- Forecasts of excessive travel demand and congestion in both urban areas and major intercity corridors, leading to significant constraints on economic growth and worsening quality of life.
- The emergence of several new technologies that offer the promise of quantum improvements over conventional railway technology. These include magnetic levitation (MAGLEV, Figure 29), air cushion vehicles, linear motors, and evacuated tube transport systems.

Only the MAGLEV and the linear motors could benefit from high-temperature superconductivity. Japan and Germany, among other countries, have persisted in MAGLEV development and will be in the best position to employ high-temperature superconductors. Availability of room temperature superconductors will eliminate the problems associated with the cryostat and will make the economics of these designs more attractive. However, the prospects for using superconductivity in land

FIGURE 29

MAGLEV



Source: "Three-Dimensional Eddy Current Analysis of Cryostat Outer-Vessel in Superconductive Magnetically Levitated Vehicle," IEEE Conference, 1987.

transportation in the United States are poor because of lack of availability of right-of-way and other nontechnical concerns.

TIME FRAMES

Approximate timelines for electric power application development are displayed in Figure 30. A suitable superconducting wire must become available for generator development to proceed, possibly by the year 2000. Reliability would be an overriding consideration before full-scale tests of generators could begin.

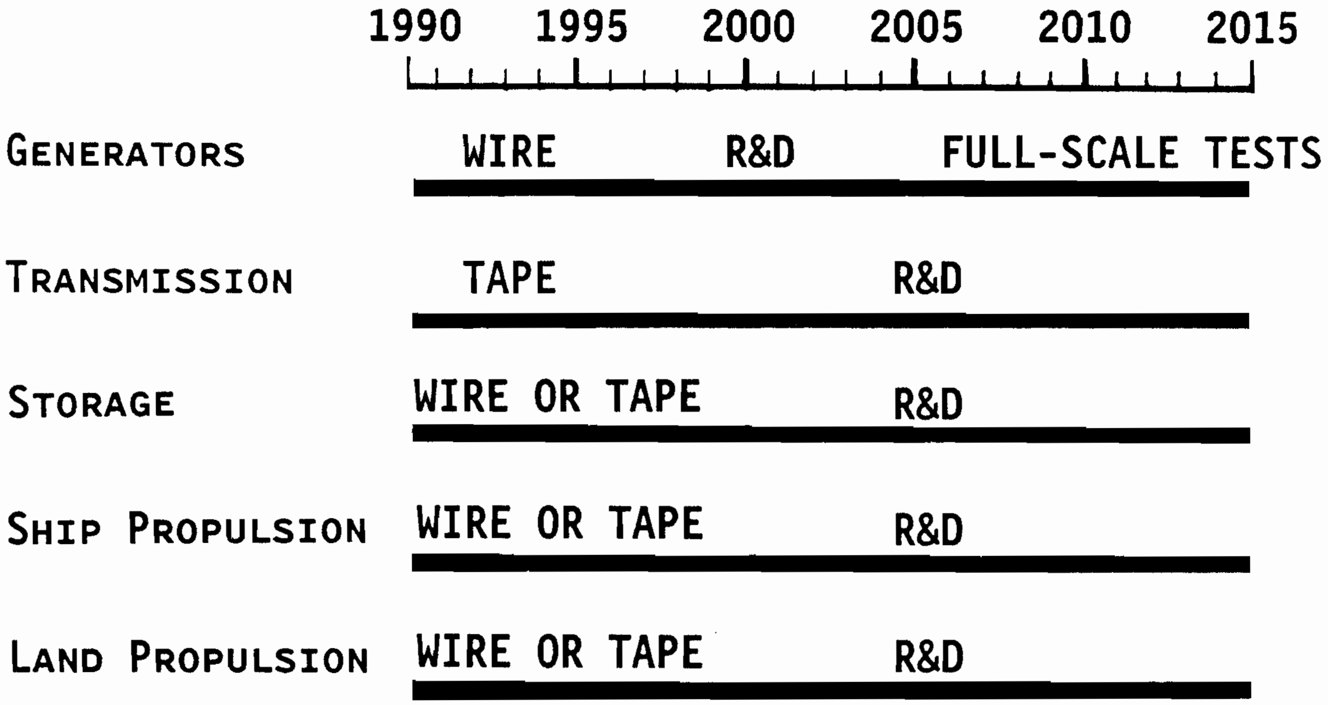
Transmission applications will require the development of special tapes in order to keep a.c. losses low. This requirement represents a difficult task, so near-term application is doubtful.

In energy storage, we foresee a large number of smaller SMES devices used more for stabilizing the network than for meeting peak demands, which would require very large devices. However, the requirement to rapidly charge and discharge the energy storage will delay application.

There are no strong driving forces for applying superconductivity to ship and land propulsion, so these applications will remain in the R&D stage for the foreseeable future.

FIGURE 30

ELECTRIC POWER APPLICATION TIMELINES



Source: Arthur D. Little, Inc.

4. ELECTRONICS APPLICATIONS

by Mehmet Rona, Ph.D.

SUMMARY

It is commonly assumed that superconductivity (SC) will one day become important in dense and fast electronics, e.g., in supercomputers. We question this assumption. We consider it significant that as long ago as 1983, IBM dropped its superconducting logic program because the time required to improve the yield of production of SC devices permitted semiconductor (SMC) logic technology to erode the performance margin SC held over SMC logic.

The advent of high-temperature superconductivity (HTSC) in the last 18 months has again raised expectations. However, we conclude that unless a three-terminal nonlatching logic device is developed, HTSC may not much improve the chances for application of SC in logic circuits. In sensor/analog application areas where SC has already made some inroads, the advent of HTSC may even actually prove undesirable in some cases because of increased thermal noise when higher operating temperatures are employed.

Nonetheless, if a deposition process compatible with silicon and gallium-arsenide device fabrication technologies becomes possible, HTSC sensors, transmission lines, and interconnects may be feasible. The latter, at 77 K, may provide only a marginal advantage over copper at the same temperature. A room temperature superconductor would find an excellent application in shielding.

We do not anticipate that the very exciting developments in HTSC will make any significant impact on fast and dense electronics in the near term. Meanwhile, optoelectronics, a competing technology, is making steady progress toward entry. Therefore, in the area of fast and dense logic circuits, superconductivity has a narrow window of opportunity over the next 3-5 years. During this time we anticipate tremendous activity in materials and new device ideas, which may put superconductivity back into competition for applications in high-performance electronics.

THE ELECTRONICS INDUSTRY

The electronics industry differs in a number of significant ways from the other industries in which superconductivity may play a role. First, it represents a commodity market, generating billions of dollars in revenues every year, while production volumes are small enough almost to be quantified in bushels. Worldwide sales of semiconductor devices were in excess of $30 billion in 1987. As a commodity market, it is extremely cost-sensitive; new devices that are far more expensive than existing devices are unlikely to sell well, even though they are much faster.

Second, the electronics industry is both influenced by technology and driven by applications. An example of the influence of a new technology is the establishment of the market for electronic wrist watches as a result of the low battery drain of complementary MOS technology. The application-driven aspect of the industry is seen in a number of products that have come into being as a result of the burgeoning personal computer market.

In addition, because there is such a wide installed base, new technological ideas must be implemented in such a way that they permit simple substitution -- i.e., an old device can be removed and replaced by the new device. This need for substitutability constitutes a major barrier for superconducting electronics.

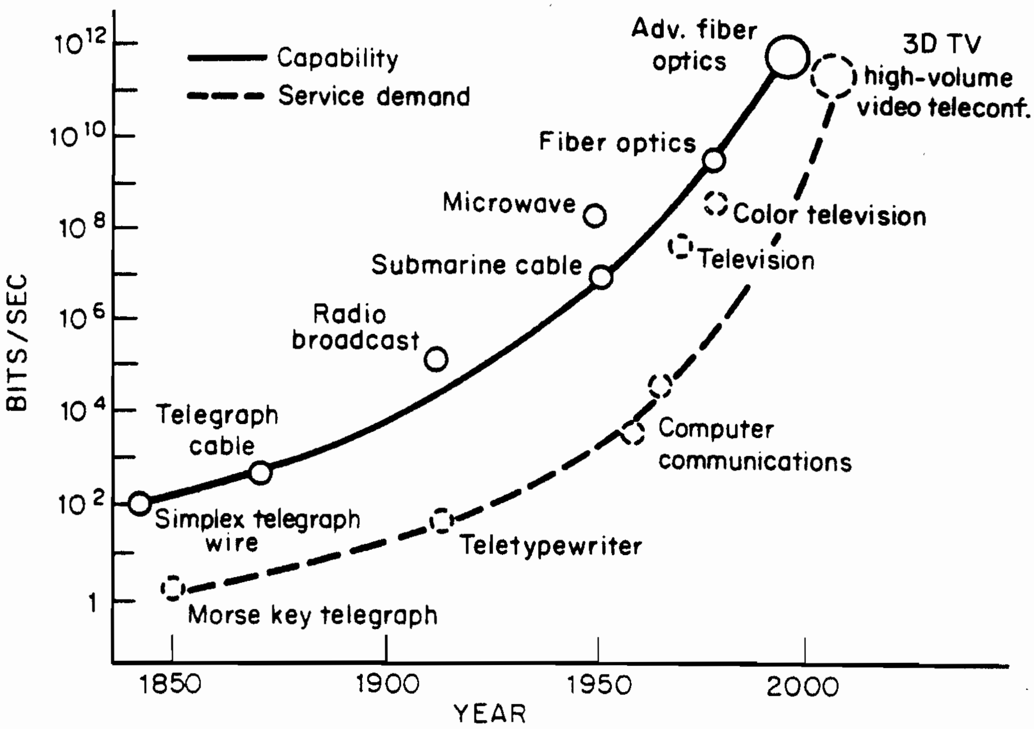
Another barrier to large-scale implementation of superconductivity in electronic applications is the fact that the industry is shifting from analog to digital electronics. The present penetration of SC into electronics, on the other hand, is confined mostly to analog electronics.

Despite these caveats, the electronics industry is large and contains many niches. If a new device can perform a significant function that cannot be performed any other way, the industry is willing to pay a considerable premium for it. For example, superconductivity has elbowed its way into the electronics industry in one such commercial application: the Hypres digital scope.

The major driving forces in electronics are the need for increased throughput (in terms of speed and system complexity) for both transmission and processing and the desire for decreased cost. Since 1850, the data transmission speed in existence has tended to exceed requirements by a factor of 100 (Figure 31). In other words, there has always been some excess capability available in the electronics industry. New technology designed to improve performance must therefore compete with the potential capabilities of existing devices and concurrently satisfy the industry's requirements for substitutability, manufacturability, and cost/benefit.

FIGURE 31

DATA TRANSMISSION SPEED, 1850-2000



Source: P.W. Smith, <u>IEEE Circuits and Devices</u>, 9-14, May 1987.
© IEEE

In order to increase throughput, an electronics designer is compelled to consider an increased level of integration and fabrication of faster transistors. Since an increased level of integration is achieved by packing more components on a chip, an adequate rate of heat removal from a chip needs to be implemented. Therefore, an increased throughput requires fabrication of transistors that switch faster with less power dissipation.

The product of the gate delay and power dissipation per switching event can be used as a figure of merit for a switching device. For a given transistor, the power dissipation is the energy dissipated per unit of time, and the gate delay is the time it takes for the signal to traverse the transistor. The product of the two quantities is the total amount of energy dissipated each time the transistor is turned on and off. Even superconducting devices, when applied to information processing, will have to go between a superconducting state and a normal state and thus experience energy dissipation.

In order to appreciate what is involved in this process, imagine a transistor as a garden hose, through which the flow of water is regulated by a valve. As was stated above, there is tremendous market demand to make this hose work faster. One approach would be to halve the length of the hose, so that the water has to traverse only half the distance: this is the major driving force behind miniaturization. Another approach might be to increase the rate of the water flow, i.e., to open the valve further so that the water flows faster. This turns out to be not such a good idea because as the velocity increases, power dissipation also increases. In the corresponding situation in electronics, the increased power dissipation can be dealt with by cooling the chips. However, such an increase is undesirable because it limits the areal density of devices on a chip. This is the approach used in the emitter coupled logic (ECL) family used in fast digital applications at present.

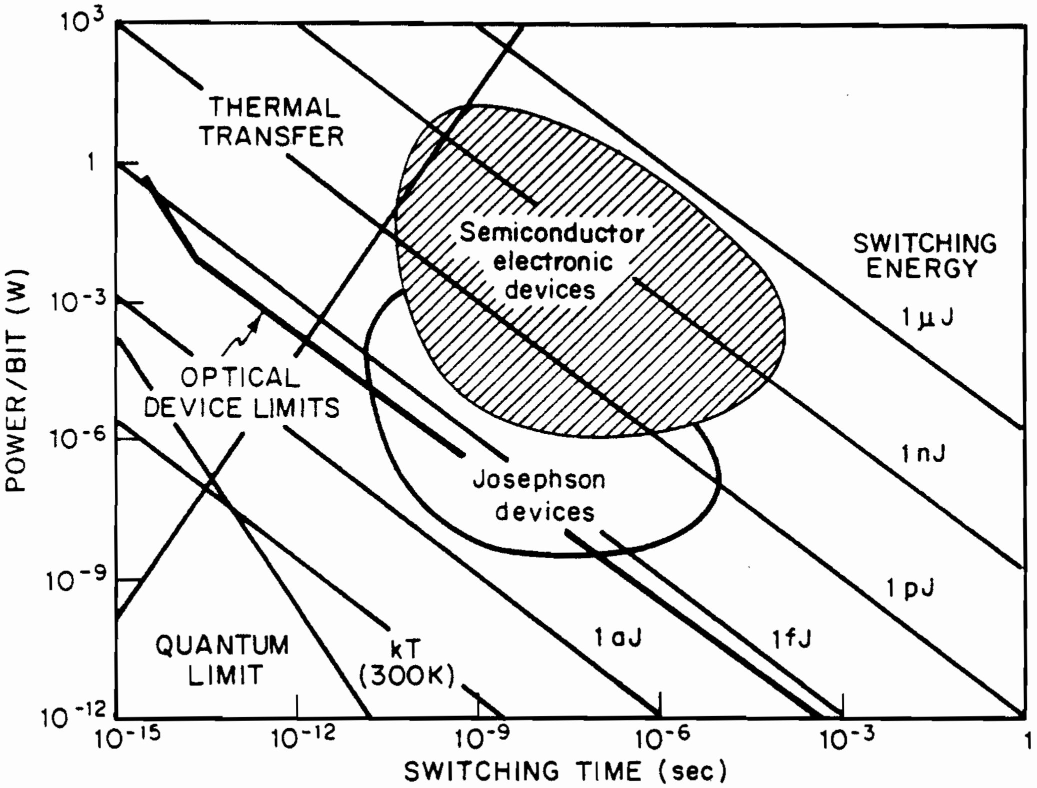
In Figure 32, the power dissipated per bit versus gate delay (switching time) is displayed for a variety of electronic components. The lines representing a constant product of the two appear as downward sloping straight lines in a log-log plot. In comparing the operating ranges of Josephson-junction-type devices, semiconductor-type devices, and opto-electronics, we see that there is a ratio of about a 1,000 in the switching energy between the best semiconductor devices and the best of the Josephson-junction (JJ) devices, and the best JJ devices exceed the limits of optical devices. This is the fundamental motivation to use JJ devices.

About 25-40% of the processing time of a calculating engine is devoted to the passage of the signals through the interconnects. If the chips are scaled down in order to decrease this overhead, then the number of devices per unit area of the chip increases and dissipation per unit area increases. Since JJ-based devices dissipate a thousand times less energy than transitors and are twice as fast, they appear to alleviate some of the problems associated with downscaling.

Even though this argument is often given to justify the inevitable significance of the implementation of JJ logic, it suffers from a flaw:

FIGURE 32

COMPARISON OF OPERATING RANGES OF SWITCHING TECHNOLOGIES



Source: P.W. Smith, Bell System Technical Journal, v. 61, pp. 1975-93 (1982). Reprinted with permission from the Bell System Technical Journal, ©, 1982, AT&T.

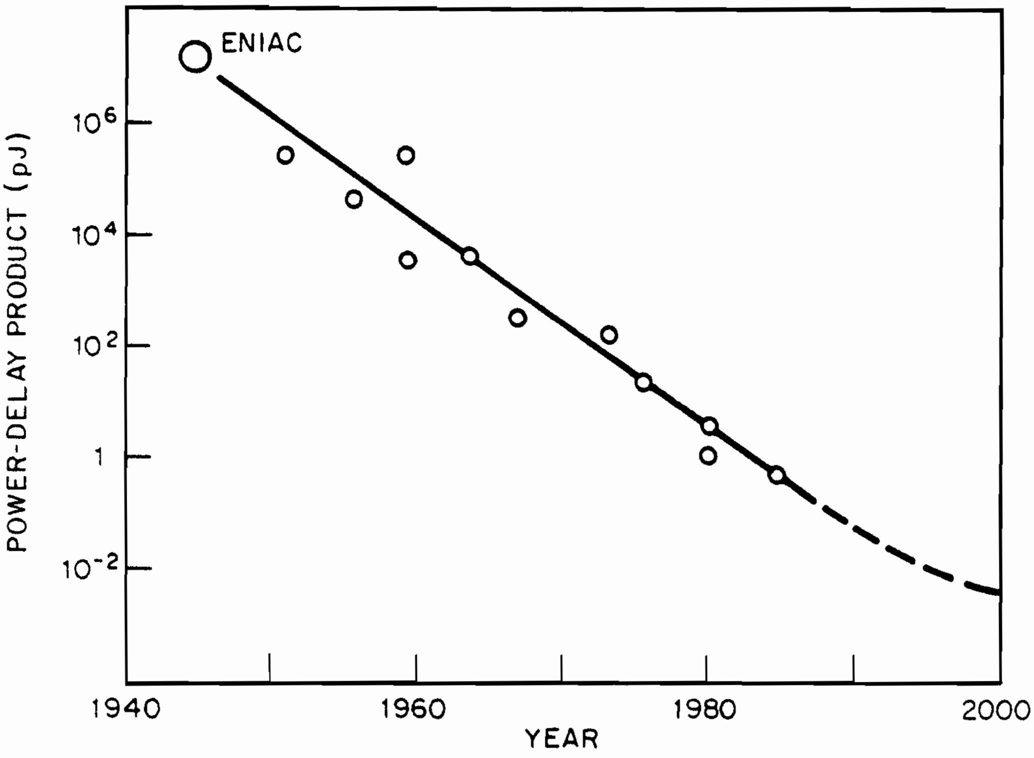
it assumes that while the chips are being scaled down in size, the transistors will remain fixed in size. However, in semiconductor device technology, scaling down the size of the chip often means scaling down the transistors as well, and scaling down a transistor by a factor of S means that the power dissipation decreases by a factor of S^3. Since device density increases by S^2, the net effect of scaling is to decrease power dissipated per unit area by S.

Hence, before we address the question of whether SC is the way to go for fast and dense electronics, we must evaluate where we are in terms of device scaling. Have we come to the limits of transistor downscaling, so that we need to achieve that extra factor of two in some other way? It is not possible to give an affirmative answer to this question at present.

Since the 1940s, the power-delay products of electronic devices have decreased some six orders of magnitude, or roughly two orders of magnitude per decade (Figure 33). Between semiconductor devices and JJ devices there are about ten to fifteen years of difference in terms of their switching energy. In other words, if the two orders of magnitude in improvement offered by JJ devices could be immediately put to use today, this advance would satisfy the requirements of the industry for about ten years. But ten years from today other technologies are likely to provide the same two orders of magnitude improvement some other way.

FIGURE 33

PROGRESS IN POWER-DELAY PRODUCTS, 1940-2000



Source: P.W. Smith, <u>Bell System Technical Journal</u>, v. 61, pp. 1975-93 (1982). Reprinted with permission from the Bell System Technical Journal. © 1982, AT&T.

POTENTIAL APPLICATIONS FOR SC IN ELECTRONICS

The principal applications of superconductivity to electronics are in Josephson-junction-based logic devices; in analog devices, including highly sensitive sensors; in transmission lines and interconnects; and in shielding. For each application area it is useful to address three questions: What key advantage may be achieved by superconductor substitution? What are the areas of potential substitution? And what are the problems?

Before we address these, we would like to dispel some common misconceptions we have encountered in connection with SC electronics.

One advantage people often claim for superconductivity is that it will permit a faster rate of data transmission. This is based on a basic misunderstanding of fundamental laws of physics. In fact, the rate of data transmission is governed by the speed of light, and nothing can be done to exceed that limit, as we know from the theory of relativity.

Similarly, a second claim is that superconductivity will allow electronic systems with no power dissipation. This claim ignores the second law of thermodynamics, which sets fundamental dissipation limits for information processing. Electronics applications of superconductivity differ significantly from the applications discussed earlier, such as magnetic applications, which directly utilize fundamental properties of the SC state, such as zero resistance and persistent currents. In contrast, electronics applications involve information processing, which in turn entails increase of entropy. In other words, information processing has to obey the second law of thermodynamics: no matter how careful we are, when a bit is turned on and off, some amount of energy will be dissipated and cannot be reclaimed through clever engineering.

Josephson Junctions

The main advantage of using JJs as the fundamental building blocks of logic circuits is that they dissipate about a thousand times less power than do transistors. This means that JJs can be packed much more densely than transistors. The main disadvantage associated with trying to improve the power-delay product using Josephson junction logic is that while transistors are three-terminal devices, JJs are two-terminal devices. A logic circuit based on two-terminal devices is designed with an entirely different architecture than a circuit based on three-terminal devices. As a result, there can be no simple drop-in substitution of three-terminal devices for two-terminal devices. JJ logic can be used practically only where it occupies an entire unit in which all the architectural changes are confined and where communication occurs throughout the system through some kind of a standard interface. At present, the only commercial application of superconductivity to electronics is the Hypres digital scope, which contains input units to which all superconducting components are confined.

As a present component market segment, emitter coupled logic gives an indication of the present demand for fast components. We estimate that worldwide sales of all types of ECL will approach $1.5 billion by 1992.

Clearly, if some technology provided equally fast (or faster) components with less power dissipation, this market segment would expand.

Let us now consider what technical achievements are required before this market share becomes available to SC electronics. For example, in Josephson junction logic, there is an insulating layer between the two superconducting conductors that is a few tens of angstroms thick. This insulating layer causes immense difficulties in both device fabrication yield and implementation. An even more daunting problem is the fact that two-terminal devices are latching devices: after they switch from zero to one, in order to return to zero it is necessary not only to remove the signal that turned them on, but also to shut the main power supply off briefly and then turn it back on. Although Josephson junctions switch twice as fast as gallium arsenide based devices (i.e., at present in 4 picoseconds, whereas gallium arsenide requires 9-10 picoseconds), they must then have their power turned off in order to come back down. According to recent estimates, the minimum time needed to turn off the power is 600 picoseconds. This is a fundamental problem.

Analog Devices

In terms of applications to analog devices, including sensors, the key advantage superconductivity offers is sensitivity and low noise. Superconductors are electrically extremely quiet for two reasons: superconduction is a highly condensed state, so that there are not too many fluctuations, and, until recently, superconducting devices have been operated at 4.2 K and thermal noise is proportional to the square root of temperature. Increasing the temperature of superconduction by a factor of 100 also increases the noise voltage by a factor of 10. In the superconducting sensors currently being applied to radioastronomy and infrared detection, all the geometrical factors have been engineered to produce minimum noise. Thus, the ultimate limit to this engineering process is the thermal noise. The question becomes whether each individual application can tolerate the increase in noise that accompanies a higher operating temperature. Of course, this issue can be avoided by operating high-temperature superconducting devices at low temperatures, but this resolution obviates the operational advantages of high-temperature superconductors.

Superconductivity makes possible a number of unique and very elegant solutions to some hard problems, such as detecting very faint magnetic fields, very small magnetic gradients, very faint voltages, and millimeter waves. In these areas, superconducting devices have been used successfully to achieve results that cannot be achieved by any other technology currently available. However, in terms of commercial opportunity, these applications -- e.g., radio telescope components, very sensitive magnetometers, and voltage standards -- represent a very limited market.

The only commercial product that has proven really successful to date is the Hypres sampling scope input unit, which has a helium-cooled transversal filter and sampler. Simply stated, this device is a transmission line to which an analog signal is applied, and then voltages are measured concurrently at various points, converted from a.c. to d.c. and summed. The device allows the user to multiply these tap voltages with specific weight numbers and then sum them in a given sequence, permitting a rather elegant means of signal processing, such as determining auto-correlations and cross-correlations. The Hypres system, which has a 4-picosecond sampling time, costs about $150,000. However, the input unit, where the superconductors are, costs only about $25,000 per type of input head. Clearly, in order to implement superconductivity in a niche application such as this one, it would be a mistake to build just the input head and sell it to a systems manufacturer, because the value added by incorporating the superconducting component into a much larger system is so much greater.

Transmission Lines and Interconnects

Transmission lines and interconnects are two possible areas of application of SC to electronics that have received much attention. Transmission lines are generally used in analog circuits. They are essentially designed either as a means to couple devices with a specific impedance and/or delay or, as mentioned above, as a transversal filter for signal processing. In monolithic microwave integrated circuits (MMIC) or hybrid, microwave integrated circuits (MIC), transmission lines are used for their more orthodox function.

In the hybrid variety, components are fabricated and bonded on a ceramic substrate upon which connecting lines (interconnects) and transmission lines are deposited by a suitable technique. The replacement of these by the new HTSC is likely to pose a minimal difficulty since ceramic substrates can withstand a range of production parameters without being degraded.

The situation with MMICs is less promising. MMICs are fabricated on gallium arsinide (GaAs) substrates, where the devices and the interconnects coexist. GaAsis a rather difficult material to work with; it is fragile and cannot withstand high temperature without being very significantly degraded. At present, very high performance circuits cannot be implemented as MMICs since MICs allow hand picking the best devices before the final integration. In MMIC fabrication, tradeoffs have to be made. The optimization of all devices on one monolithic drop is not always possible. Hence the difficulty in implementing HTSC in MMICs is not of great commercial importance.

In the case of digital ICs, interconnects provide the path for the input/output signal transmission between passive and active components. In digital circuitry silicon is the uncontested material. In order for HTSC materials to be able to be of use, they must be process-compatible with silicon fabrication.

Silicon as well as GaAs transistors can be operated at 77 K. As a matter of fact, C-MOS devices designed for room temperature run two or three times faster at 77 K. If the HTSC is process-compatible with silicon, the obvious question is how advantageous HTSC interconnects would be in comparison with the conventional ones. As it happens, copper has a low enough resistance at 77 K that it does not contribute much to the rise time of the circuit because the resistance of the transistor itself establishes a rise time that copper does not appreciably add to. Therefore, in silicon digital ICs, the advantages of present HTSC in interconnects look severely limited.

Shielding

Superconductors do not permit magnetic fields below a critical value to penetrate into their bulk. This permits a SC box to establish a magnetic-field-free volume.

Superconductors will also not allow low-frequency electromagnetic waves to penetrate their bulk. In general, there is some relationship between the critical value for the frequency of the wave below which electromagnetic shielding can occur and the transition temperature. The usual SC in general could shield frequencies below microwave frequencies, whereas HTSCs may perform this function for somewhat higher frequencies.

Since shielding in general requires a complete containment inside a closed surface, cooling a shielding enclosure may almost necessitate cooling everything contained inside the volume. Here the advantage of a room temperature SC is clearly visible. It would allow a simple box construction with no concern for perturbation of the normal operation of the system inside the enclosure.

MARKET POTENTIAL

Before commenting on the market potential for HTSC in electronics, we first consider the technical feasibility of their implementation. Our approach to the assessment of the feasibility is outlined in Table 21. In the first column, we list the devices and/or the application areas. In the second column we consider an insertion scheme that involves integration with semiconductor technology. Since it is essentially impossible to operate the present transistors at 4.2 K without major changes in the existing semiconductor technology, we judge that integration of SC and semiconductor devices is not feasible at this temperature. For HTSC at or above 77 K, the integration is feasible since semiconductor devices can easily be operated at this temperature range with little or no modifications. The desirability of such an integration is another question. The difficulties associated with such an insertion were discussed above. As the transition temperature is increased, the superiority of SCs over copper becomes more noticeable. Therefore, we mark the interconnects and shielding applications as being progressively more feasible with increased transition temperature.

In column three, we consider a scenario in which a nonlatching three-terminal switch having speed and dissipation characteristics of a JJ device is invented. This breakthrough would alleviate the difficulties associated with the present JJ switches. Assuming that this might not necessarily be a linear device, such an invention may not be applicable to the analog and sensor applications. Since such a device could function with any superconductor, the fabrication of interconnects out

TABLE 21

TECHNICAL FEASIBILITY OF SUPERCONDUCTIVITY UNDER SCENARIOS

Device/ Application Area	Insertion by Integration with Semiconductor (1)		Invention of SC 3-Terminal Nonlatching Device (2)		Status Quo With Changing Operating Temperature		
Operating T(K)	4.2	77	4.2	77	4.2	77	300
JJ Logic	nf	f	f	f	nf	nf	nf
Analog	nf	f	na	na	f	?	nf
Sensors	nf	f	na	na	f	?	nf
Interconnects	nf	f+	f	f+	nf	f	f
Shielding (dc)	nf	f+	nf	f+	nf	?	f
(ac)	nf	f+	nf	f+	nf	?	f

Key: f = feasible; nf = not feasible; f+ = increasingly feasible at higher temperatures

(1) Predicated on the establishment of a deposition process compatible with Si and GaAs processing.

(2) Predicated on a breakthrough in device research.

Source: Arthur D. Little, Inc.

of SC material would be feasible. For shielding applications this invention would not make an impact. Therefore, their feasibility rating does not change.

If we consider the present SC devices and architectures, the JJ logic is not feasible at any temperature. At low temperature, sensors and analog devices would be feasible because of the low noise. At room temperature, the noise would be too high for many present applications. Somewhere in between, there may be some HTSC for which these applications may be feasible. With low-temperature SCs, the feasibility of interconnects and shielding is so limited that for all practical purposes it is negligible. Room temperature SCs would be useful in any of these applications.

As was indicated above, the potential market for applications of superconductivity to electronics with known devices and implementation techniques is severely limited. In digital electronics, the segment of the present electronics market susceptible to penetration by SC is emitter-coupled logic. In analog electronics, only a part of the present sensors market is available for superconductivity. Technological breakthroughs may, of course, create new markets as well as address present market segments. However, past experience with superconductivity in digital electronics shows the importance of achieving technical targets within narrow windows of opportunity. Although our present knowledge does not allow us to make predictions with high confidence levels, we can sketch a likely flow of events, as follows:

- Material processing improvements (1988-1989);
- New device identification (1988-?);
- Optimization of new materials with old devices (1988-1990); and
- If no device breakthroughs, limited commercial availability for special applications (after 1990).

5. HIGH-TEMPERATURE SUPERCONDUCTIVITY PARTICIPANTS

by Edward T. Peters, Sc.D.

SUMMARY

We anticipate continued R&D and product development based on HTSC materials to proceed for at least the next decade. During this time, issues concerning the fabrication of wires, tapes, and cables as well as suitable thin-film structures will be addressed. It is likely that some new products that take advantage of improved properties relative to currently available superconducting materials will emerge at this time.

Table 22 summarizes the opportunities that we perceive in the various product categories associated with superconductivity. Although we cannot yet identify those companies that will emerge as the major manufacturers of components, devices, and systems, we have indicated those that are currently associated with various product categories.

TABLE 22

PRODUCT OPPORTUNITIES AND COMPANIES POISED FOR DEVELOPMENT IN SUPERCONDUCTIVITY

Business Segment	Product	Opportunity/Barriers	Representative Companies/Organizations
Chemical Suppliers	Oxides, rare earth compounds	o Mature industry o Current suppliers of specialty chemicals have large advantage	Rhone-Poulenc, Du Pont, W.R. Grace
Fabricators and Producers of Materials	Composite wire, fibers, films, sheets	o New technologies required o Existing manufacturers of wire/sheet are not well positioned o Opportunity for capital venture start-ups o Many niche applications	Current LTSC fabricators university research, national laboratories, capital venture start-ups
Manufacturers of Subsystems	Integrated devices, magnets, cables, etc.	o Unique opportunity for new technology o Large manufacturers of electronic components may back-integrate	Westinghouse, General Electric, Intermagnetics General
Manufacturers of Systems			
Electronics	Computers, instruments, equipment	o Innovative technological developments needed	Hypres, capital venture groups
Electric Power	Motors, generators	o Long-term developments o Large investments required	GE, Union Carbide, Westinghouse, GA Technologies
High-Energy Magnet	Particle Separation	o Large market expansion following HTSC wire development	Eriez Magnetics
	MRI, accelerators, and colliders	o Could replace existing technology o Modest market expansion	General Dynamics, General Electric, IBM, Westinghouse

SOURCE: Arthur D. Little, Inc.

INTRODUCTION

A few organizations have produced the bulk of published information on the development of high-temperature superconductivity technology. These participants have been the most innovative in advancing an empirical understanding of the physical and chemical properties of the new materials. Included in this group are IBM, AT&T, Du Pont, the University of Houston, and Argonne National Laboratory.

It is impossible to construct a complete list of current participants because new announcements are made daily. Therefore, the ensuing discussion of participants is meant to be representative of the kinds of participants according to the following categories:

- Government laboratories
- Universities and consortia
- Private Companies
    - R&D
    - Materials and component suppliers
    - Capital venture start-ups

Support companies (those involved in chemical supply, sensing and measurement, cryogenics, etc.) are generally widely diversified in their business interests and are not discussed here.

GOVERNMENT LABORATORIES

Government laboratories known to be participating in HTSC research and development are listed in Table 23.

As part of a Government Initiative, President Reagan has designated Argonne National Laboratory as the major laboratory for superconductivity applications, with the aim of catalyzing the transfer of commercial uses of superconductivity from the public sector to business. The laboratory has been doing research on superconductivity and on ceramic materials for more than 20 years. The other laboratories named as key centers of research include Ames Laboratory, for developing information in the basic sciences, Lawrence Berkeley Laboratory, to pursue thin film applications, and the National Bureau of Standards in Boulder, Colorado, for developing electronic applications and measurements.

TABLE 23

GOVERNMENT LABORATORIES PARTICIPATING IN HTSC RESEARCH

1. <u>Centers Designated by President Reagan (July 1987)</u>

    Argonne National Laboratory - lead laboratory on superconductivity
    Ames Laboratory - basic science information
    Lawrence Berkeley Laboratory - thin film applications
    National Bureau of Standards/Boulder - electronic applications

2. <u>Other Government Laboratories</u>

    Brookhaven National Laboratory
    Lincoln Laboratory (M.I.T.)
    Los Alamos National Laboratory
    National Aeronautics and Space Administration/Lewis
    National Magnet Laboratory
    Naval Research Laboratory
    Oak Ridge National Laboratory

Oak Ridge National Laboratory has established a Superconductivity Information System (SIS), principally as a means of communication. SIS is described as an interactive tool whereby researchers can "express their opinions, exchange information with peers, and report research progress." It includes references to published literature, notification of prepublication-information and conference papers, selected news articles, and information about future meetings. Information can be obtained from Arlene Corona, Department of Energy, Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, Tennessee 37831.

NASA Lewis is pursuing HTSC research since the space environment is very different from that on earth. Although the temperature of space is about 50 K, permitting the operation of an HTSC without cooling, there are other drawbacks to operating in space, such as near-zero gravity, a good vacuum, and space radiation. The opportunity for energy production from superconducting magnets that weigh much less than conventional magnets and the development of energy storage systems with low energy losses are of particular interest to NASA. Systems of greatest interest to NASA include space power and propulsion, communications, data systems, and aeronautics systems.

Some of the universities that have indicated active programs in HTSC are listed in Table 24. It is beyond the scope of this review to attempt a detailed review of individual programs. Brief descriptions of research directions and names of key researchers are given in the table.

A number of consortia have been established within the last year between schools, state governments, private businesses. The aim of these groups is to develop broad expertise in a specific area of HTSC, frequently emphasizing economic development on a regional basis. Some of these are described below:

TABLE 24

UNIVERSITIES PARTICIPATING IN HTSC (Partial Listing)

School	Area	Researcher
Colorado State U.	RTSC	Walajabad Sampath
Cornell U.	Thin films	Robert Buhrman
Drexel U.		
Georgia Inst. of Technology	RTSC	Admet Erbil
Johns Hopkins U.	Laser deposition of thin films	
Massachusetts Inst. of Technology	Numerous	David Litster
North Carolina State U.	RTSC	Jagdish Narayan
Northwestern U.		
Notre Dame U.		
Rutgers U.	Laser deposition of thin films	Arum Inam
Stanford U.	Numerous electronic	
SUNY Buffalo		
U. of Arkansas	RTSC	Allen M. Herman Zhengzhi Sheng
U. of California (Berkeley)	Electronics	John Clarke
U. of Delaware	RTSC	
U. of Houston	Numerous	Paul Chu
U. of Rochester	Electronic transmission speed	Gerard Mourou
U. of Wisconsin	Educational use	Arthur Ellis
Wayne State U.	RTSC	

Texas Center for Superconductivity (TCS)

Location: University of Houston
Director: Paul Chu
Funding: Initial - State of Texas $1.5 MM
- University of Houston 1.0 MM
- Private 1.0 MM
Annual goal - $9-10 MM

Staffing: 40 scientists (University of Houston, Rice, Texas A&M)
200 research personnel

Research: Seven individual laboratories are planned specializing in:

- Materials research - pursue higher-temperature superconducting materials
- Theoretical HTSC research - structure of compounds, theory of HTSC
- Magnet design and applications -
- Devices
- Chemical engineering pilot plant to process HTSC materials
- Metal-matrix manufacturing technology
- Thin-film microelectronics

Consortium for Superconducting Materials and Instrumentation (CSMI)

Location: University of Alabama/Huntsville
Funding: $200,000 or 1 man-year of research by each member

Membership (1987):

Universities

University of North Carolina
Georgia Institute of Technology
City University of New York

University of Texas
University of Kentucky
Auburn University
Massachusetts Inst. of Technology
Louisiana State University
The University of Alabama/Huntsville

National Laboratories

U.S. Army at Fort Monmouth
NASA Marshall Space Center
Jet Propulsion Laboratory
Naval Research Laboratory

Companies

Aerojet
American Superconductor Corp.
ATM (Advanced Technology Materials)
Boeing
Hughes Aerospace
Hypres
IIT Research Institute
Ionic Atlanta
Kaman Sciences
Lambertville Ceramics
Lockheed
Nichols
Perkin-Elmer
Raytheon
SAIC
Sprague Electronics
TRW
United Technologies

Research: R&D applications oriented to:

- Synthesis methods
- Characterization of materials
- Theoretical understanding
- New materials
- Device requirements
- Exchange of information between government, universities, and industry

Argonne National Laboratory - University of Chicago Development Corp. (ARCH)

Location: Chicago
Director: Steven Lazarus
Funding: $380 MM, nonprofit
Members: Argonne National Laboratory, Northwestern U., U. of Chicago, U. of Illinois, Fermilab, and industry

Background: ARCH was set up in 1986 to "facilitate commercial development of scientific and technical intellectual property originating at Argonne and the University of Chicago." A Superconductivity Affiliates Program was established in 1987. For a fee of $15,000- 25,000/year (depending on company size) corporations receive access to specialized facilities, equipment, and personnel.

Superconductivity Research: The objective is to "develop commercial applications as rapidly as possible" and to license inventions to interested corporations.

Institute for Research on Superconductivity

Location: SUNY/Buffalo
Director: David Shaw
Funding: Initial - $5 MM from N.Y. State Energy R&D Authority
Objective: $25 MM
Staffing: 27 faculty, 100 researchers

Objectives: "(1) demonstrate the technical feasibility of processing high-T_c materials into useful forms (films, flexible cables and tapes, fibers, devise monoliths, composites, etc.), (2) contribute to understanding the basic chemistry and physics of the new high-T_c materials in bulk and thin film, (3) develop design and manufacturing technology to support the fabrication of prototype applications, and (4) contribute to the development and growth of a viable industrial base for superconductivity."

Research: Fundamental properties and characterization
Fabrication and processing
Sensors, detectors, and devices
High-field magnets

Other Consortia (formed or in planning)

- Lehigh - industry. Eleven companies at $25,000/year
- M.I.T. Regional Center (under development)
- UCLA - focus on electronics
- Stanford affiliates
- Rutgers

COMMERCIAL COMPANIES

Numerous companies are pursuing research, development, fabrication and application of high temperature superconducting materials. They derive from two bases:

- Companies involved in R&D and commercial products of conventional (Low temperature) superconductivity.
- Companies pursuing R&D and/or supplying powders and thin films of HTSC materials.

Companies in the first category are listed in Table 25, which includes areas of participation. Most companies have active R&D programs concerning HTSC, but details of these programs are proprietary.

Companies that participate in superconductivity as a core business are briefly profiled below.

American Magnetics, Inc. (privately owned)
P.O. Box 2509
112 Flint Road
Oak Ridge, TN 37831-2509
(615-482-1056)

President - Dr. Ken Efferson
VP, Marketing and Sales - E.T. Henson

Manufacture of superconducting magnets and cryogenic accessories. Founded in 1968. Acquired by Diasonics Inc. in 1983 to build magnetic resonance imaging magnets. Purchased by principals end of 1986.

AMI specializes in the design, fabrication, and testing of magnets and magnet systems for experimental research and medical systems.

TABLE 25

COMPANIES WITH SUPERCONDUCTING EXPERIENCE PURSUING HTSC RESEARCH AND DEVELOPMENT

Areas of Participation

	LTSC									HTSC			
Companies	Principal Business	R&D	Materials	-Suppliers	-Fabricators	Magnets	-Components	-Systems	Electronics	R&D	Powders	Thin Films	Fabrication
American Magnetics	x						x		x				
AT&T Bell Labs		x								x			x
Biomagnetic Technologies	x							x	x				
Du Pont		x	x							x	x		
Energy Conversion Devices		x								x			
Eriez	x						x						
GA Technologies	x						x			x			
General Dynamics		x				x	x						
General Electric		x				x	x						
Hughes		x							x				
Hypres		x			x				x	x		x	x
Intermagnetic General	x				x	x		x	x	x			
IBM		x								x		x	x
Oxford Superconducting	x				x	x		x		x	x		
Supercon	x				x					x	x		x
TRW		x							x				
Unocal (Molycorp)		x	x										
Wah Chang Teledyne		x	x										
Westinghouse		x				x		x	x	x			

Source: Arthur D. Little, Inc.

Biomagnetic Technologies Inc. (privately owned)
4174 Sorrento Valley Blvd.
San Diego, CA 92121
(619) 453-6300

President, CEO - Stephen O. James
Founder and Senior VP - Bill Black

Formed as a start-up company in 1970, BTI has developed expertise in superconducting quantum interference devices (SQUIDS), in particular as applied to magnetoencephalography (MEG), a means of mapping the very weak electromagnetic emissions of the brain. MEG is complementary to magnetic resonance imaging (MRI), but works by measuring the natural magnetic fields created by the brain; in contrast, MRI imposes a magnetic field which, because of differences in chemistry and density of regions of the head, provides pictorial contrast. MRI is in itself complementary to computerized axial tomography, which is based upon X rays. The major advantage of MEG is that doctors can image the location in the brain corresponding to natural functions by external stimulation. Current annual sales of about $6 million are presently to researchers. BTI has no competition at present.

Eriez Magnetics
Asbury Road at Airport
Erie, PA 16514
(814) 833-9881

President - Chester Giermark
Principal Consultant - Jerry Selvagi, PE

Eriez Magnetics, founded in 1942, manufactures several types of magnetic and vibrator separators including one based upon a high-gradient, low-temperature superconducting magnet. The first commercial application for the $2 million LTSC separator system (84-in. diameter coil) was for removing magnetic and paramagnetic impurities from clay at considerable energy savings. A second LTSC separator system has been sold (120-inch diameter coil) for installation in a clay application in early February 1989.

Although particle separation economies are demonstrated for the LTSC system, it is too early to determine the practical utility of the HTSC materials.

GA Technologies Inc.
P.O. Box 85608
San Diego, CA 92138
(619) 455-3000

Chairman and CEO - Jay Neal Blue

GA Technologies has had a core business in gas cooled reactors and fusion research for some 25 years. It formed a Superconducting Magnet Group in 1975 which has carried out projects for the Bonneville Power Administration and for the National Bureau of Standards. The Applied Superconetics Division has built magnets for MRI, high energy physics, energy storage and ore separation (e.g., it built the LTSC magnet for impurities separation from clay for Eriez Magnetics - see above).

GA has made a major commitment to exploiting HTSC based on its experience with fabricating wires of brittle materials and on its ceramic coating capabilities.

Hypres
500 Executive Blvd.
Elmsford, NY 10523
(914) 592-1190

Chairman - Dr. Sadeg M. Faris
President & CEO - Charles C. Francisco

Manufactures a commercial LTSC Josephson junction microchip for use in high-performance test and measurement equipment, including voltmeters and oscilloscopes. Similar devices have potential application for a superconducting computer. Holding a license for some IBM patents, Hypres was formed in 1983 through capital venture funding. It has several government contracts to develop superconducting circuitry and interconnection technology.

Intermagnetics General
Charles Industrial Park
Box 566
Guilderland, NY 12084
(518) 456-5456

Chairman, President - Carl Rosner

IGC is the leading U.S. supplier of LTSC wire, cable, braid, and tapes and is a leading manufacturer of LTSC magnets for stationary and mobile MRI systems and high-energy magnetic applications. IGC fell victim to a restructuring of the diagnostic imaging industry, with Johnson & Johnson (a major customer of IGC) exiting the business and other companies consolidating through acquisition and joint venture. IGC also supplies cryogenetic refrigeration equipment through a subsidiary, ADP Cryogenics Inc.

Oxford Superconducting Technology
600 Melek Street
Carteret, NJ 07008
(201) 541-1300

Subsidiary of
Oxford Instruments Group
Eynsham
Oxford OX8 ITL England
(0865) 881-437

Oxford has a product line similar to that of IMG (see above), which is its major competitor. On a worldwide basis, Oxford supplies about half the LTSC magnets for MRI. It also makes LTSC wire and cable, competing with IMG and Supercon Inc.

Supercon Inc.
830 Boston Turnpike
Shrewsbury, MA 01545
(617) 842-0174

President - Dr. James Wong
VP, General Manager - Dr. Erik Gregory

Supercon Inc. is an LTSC materials supplier of wire, braid, cable and composite conductors for superconducting magnets. It competes in this market with IMG and Oxford (see above). Supercon performs considerable research with support from the Department of Energy and other national laboratories and agencies.

RECENT ENTRANTS

Newly formed companies or new business units of existing companies specifically pursuing applications for HTSC materials are listed in Table 26. Most of the activities within these companies centers around novel fabrication approaches or niche applications. Most of the companies listed in the table are briefly described below.

American Superconductor Corp.
21 Erie Street
Cambridge, MA 02139
(617) 499-2600

President - George McKinney

Based on an exclusive license from M.I.T. and capital venture funding from American Research and Development, Venrock, Kleiner Perkins, Bessemer, Berregan, ARETE, and Rothschild Ventures, the company develops and will manufacture alloy wires of the 123 composition produced from oxidation of the metallic precursor.

Applitech of Indiana
8150 Zionsville Road
Indianapolis, IN 46268

President, Nathaniel Quick

Making HTSC substrates by laser processing and other proprietary approaches to make a "seeded substrate." Funded by the Indiana Corporation for Science and Technology.

Ceramic Process Systems
840 Memorial Drive
Cambridge, MA 02139
(617) 354-2020

Chairman - H. Kent Bowen

Developing metal-ceramic superconducting advanced integrated circuit packages based on developed fine ceramic powder microengineering technologies. Received approximately $6 million program from DARPA to pursue HTSC wire making, based on a 3-month demonstration program funded by the same agency.

TABLE 26

NEW COMPANIES PARTICIPATING IN HTSC RESEARCH AND DEVELOPMENT

Areas of Participation

Companies	R&D	Supplier	-Chemicals	-Powders	-Thin Films	Fabrication	-Wire	-Thin Films	-Devices	Potential Field	-Magnets	-Electronics	Basis	-New Activity	-Start-up	-Capital Venture
American Superconductor	x						x				x					x
Applitech of Indiana	x				x			x							x	
Ceramic Process Systems	x						x				x				x	
Conductor Technologies	x											x				x
Conductus	x						x	x	x		x	x				x
Corning Glass Works	x				x									x		
Electroscience Lab	x				x							x		x		
W.R. Grace			x											x		
Gurnsey Coating Lab					x									x(1)		
Hydrostatics	x						x							x		
Lambertville Ceramic			x											x		
Monolithic Superconductors	x										x					x
National Superconductor	x								x			x			x	
Quantum Design									x		x				x	
Rhone-Poulenc		x	x													
Superconducting Components			x												x	
Superconductivity Inc.	x															x
Superconductor Technologies	x															x

(1) Also seeking capital venture support.

Source: Arthur D. Little, Inc.

Conductor Technologies
1001 Connecticut Avenue NW
Washington, DC 20036
(202)-452-0900

President - Stephen Lawrence

Start-up to pursue undisclosed HTSC research at university level to gain licensing patents.

Conductus
2275 Bayshore Road
Palo Alto, CA 94303
(415) 494-7836

President, CEO - John Shock

Capital venture start-up with about $6 million in funding to pursue HTSC electronics based on thin film techniques. Applications include very high speed digital devices, SQUIDS, detectors and sensors and high-speed interconnections.

Electroscience Laboratories Inc.
416 E. Church Road
King of Prussia, PA 19406
(215) 272-8000

A producer of thick-film parts, Electroscience is using powder processing technology to produce thick HTSC films for application to microwave transmission lines.

Hydrostatics Inc.
2005 Industrial Drive
Bethlehem, PA 18017
(215) 694-0212

President - Louise Percivall

Hydrostatics is a producer of very fine wire. It believes its process, which involves liquid pressure to squeeze material through a die, will allow it to sheath HTSC powder with a ductile metal and draw down to 40 mils diameter.

Monolithic Superconductors

Box 1654
Lake Oswego, OR 97035
(503) 684-2974

Owners and founders - Lawrence E. Murr and Alan Hare

Formed a company in March 1987 to produce high-density composite structures by explosive forming. Seeking venture capital and cooperative research.

Superconductivity Inc.

c/o Robert W. Shaw
Arete Ventures Inc.
Suite 1040
6110 Executive Boulevard
Rockville, MD 20852
(301) 881-2555

Set up to pursue HTSC technology on behalf of Utech Venture Capital Fund, financed by utilities interested in energy storage and transmission. The company is looking to support novel applications.

Superconductor Technologies Inc.

2200 Sand Hill Road, Suite 250
Menlo Park, CA 94025

CEO - Glenn Penisten

STI, founded by Continental Capital and Crocker Capital and seed funded by Alpha Partners in mid-1987, has completed its laboratory facilities at Santa Barbara. The company has raised over $6 million from venture capitalists and from three industrial affiliates: Lockheed Corp., Optical Coating Labs, and BE/Electronics. The company is aiming at early commercialization of electronic devices from both bulk and thin-film materials.

Related Publications from Arthur D. Little Decision Resources

---

Outlook for Advanced Composites

Advanced composites are certain to achieve high penetration of the aerospace market and show great potential growth in the ordnance and automotive markets. To help you evaluate the marketplace for advanced composites, Arthur D. Little Decision Resources has published Outlook for Advanced Composites. This comprehensive research letter gives you insight and information on such major topics as world and U.S. market size and growth; major user and industry markets; and key strategies over the next five years for suppliers, producers of intermediate products, and fabricators of final parts. A special section of this valuable reference focuses on advanced thermoplastic composites, the fastest-growing type of advanced composite.

October 1987 .... $975

Opportunities in Flat-Panel Displays

Demand for large-area flat-panel displays (FPDs) will expand rapidly over the next five years. To help you identify the opportunities accompanying this dynamic market growth, Arthur D. Little Decision Resources has published Opportunities in Flat-Panel Displays. This outstanding two-volume report provides you with valuable data on the technology and market potential for three major types of large-area FPDs: liquid crystal displays, electroluminescent displays, and plasma displays. Included are assessments of market size and growth, manufacturing costs, competitive outlook, technology overview, and business opportunities. Whether current participant or potential player, you'll benefit from the authoritative forecasts and perspectives contained in Opportunities in Flat-Panel Displays.

December 1987 .... $1850

Integrated Information Systems: User Needs and Vendor Opportunities

Integrated Information Systems: User Needs and Vendor Opportunities analyzes industry use of and progress towards integrated information systems (IISs). Based primarily on a third annual survey of over 140 individuals who set the directions of and commit resources to IIS plans, the report offers valuable insights on such key issues as how users define IIS, what they have installed and plan to buy, justification factors, and major obstacles to IIS implementation. Among the forecasts in this comprehensive study are growth and revenue to 1991 for integrated office information systems, nonintegrated office automation systems, and the rest of the information systems market, as well as U.S. corporations' spending on all office systems to 1991. A significant part of the report focuses on departmental systems including most-needed functions and capabilities, how users rate the departmental systems of 24 vendors, evaluations of 5 vendors that have the most potential to affect the marketplace (Data General, Digital Equipment, Hewlett-Packard, IBM, and Wang), keys to vendor success, and what you can expect from IISs in 1991.

December 1987 .... $1800

For further information, please contact **Jean Carbone**, Manager of Marketing, Arthur D. Little Decision Resources, 17 Acorn Park, Cambridge, MA 02140, 617-864-5770, extension 4425.