Superconductors in Applications; Some Practical Aspects

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Abstract— **The first blush of success in the search for a new superconductor is usually a high transition temperature, T_c. However, all power applications of superconductors and most other applications requires good current carrying capacity, usually characterized by a critical current I_c, within substantial magnetic fields, usually characterized by a critical magnetic field H_c. Furthermore, a number of other characteristics must be satisfied before commercial success can be obtained, such as acceptable cost, mechanical strength, stabilizers, and appropriate insulation materials. I examine a number of superconductors, starting with the workhorse NbTi, and look at the hard road to success for the successful commercialization of a new superconductor. I also review the applications, potential and actual, in which superconductors might be used.**

***Index Terms*—superconducting materials, superconducting devices, high-temperature superconductors, reviews**

I. INTRODUCTION

SINCE the initial discovery of superconductivity in 1911 by Kamerlingh Onnes [1], steady advances have been made in both the understanding of the phenomenon and the materials which exhibit it. The greatest leap in understanding so far occurred with the BCS [2] microscopic theory of superconductivity, although there have been many other empirical and theoretical contributions to our knowledge. The materials which exhibit superconductivity have steadily grown in number and variety, but the number used in practical, commercial applications is still rather small, with NbTi still dominating all commercial power applications, even though it was first discovered in 1962.

This paper will briefly review the variety of materials that have presently been found to be superconducting and then will discuss why so few have become commercial. An overview of present and possible future applications will be given with comments on the difficulties of achieving commercialization and advances needed to do it.

II. SUPERCONDUCTING MATERIALS

It took quite a while after the discovery of superconductors to find a material which was suitable for power applications, i.e., which carried a high current in a high magnetic field. The notable events in this regard were the discovery of Nb_3Sn in 1954 and its wire development in 1961 [3]. There followed quickly the discovery of other A15 materials [4] and NbTi, the currently most-used material. These enabled the construction of electromagnets which can produce much higher magnetic fields than conventional copper-wire electromagnets. This is because the cooling of copper conductors becomes impractical after current densities exceed a value which is well below the current-carrying capacity of the high-field superconductors and because the field levels produced by superconductors can exceed the magnetic saturation of iron, which is usually used to boost and focus the fields of copper/iron electromagnets, thereby eliminating the necessity for iron-core electromagnets. These superconducting magnets saw their first uses in laboratories as an enabling device for experimentation.

In 1986, Bednorz and Muller [5] discovered superconductivity in a class of copper oxides, often called HTS (high temperature superconductors), which now have transition temperatures (T_c) up to 138 K (164 K under pressure). These materials produced a frenzied rush to develop applications at much higher operating temperatures, for example at the much easier to achieve boiling point of liquid nitrogen (77 K). Unfortunately, the HTS materials drove home the point that T_c is not the only important parameter for practical wires. The wires must carry large currents, usually characterized by a limiting critical current I_c or current density J_c, in significant magnetic fields, which also have an operating limit H_c, the critical magnetic field (see Fig. 1). The HTS materials are anisotropic (planar) and have short coherence lengths, all of which have meant that the materials must have their major (a-b) planes well aligned to give low-angle grain boundaries that allow good current transport from grain to grain. Achieving this condition in long wires is second in difficulty only to producing kilometer-long single crystals, and this has been the reason for the hard work since 1986 on wire production, which continues today.

The discovery of HTS was certainly not the only materials surprise. Other recent examples include the finding [6] that a well-known material, magnesium diboride (MgB_2), is a superconductor with a T_c of 39K, certainly the highest for materials that look like traditional BCS superconductors. Another example [7] is the fulleride compound, CsC_{60}, with a T_c of 38 K. While the nature of the CsC_{60} compound makes it seem an unlikely candidate for applications, MgB_2 may have a different fate. It appears to be more easily formed into wire-

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like shapes than the HTS, may carry significant currents in high magnetic fields, and has relatively low-cost constituents. Therefore, there is a strong effort to develop this material into wires for applications, perhaps as a replacement for the workhorse NbTi. Most recently, an iron-based series of compounds [8], $LaO_{1-x}F_xFeAs$, have been discovered whose T_c has already risen to 52 K. These materials have not yet been produced in single crystal form but appear to be somewhat analogous to the cuprate HTS materials and may also have magnetically mediated pairing [9]. Their discovery suggests that the family of HTS materials and superconducting materials in general may supply still more surprises and expand further in the future.

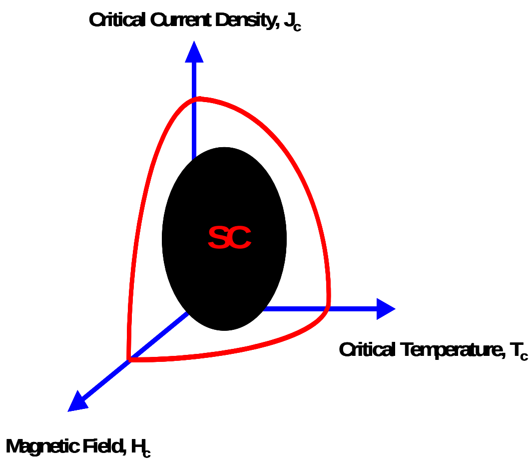

Fig. 1. Operating parameters of a superconductor. The outer lines represent the limits of superconducting operation, and the dark volume represents a zone of engineering design, with safety margins.

A selection of the wide variety of superconducting materials which have been discovered is shown in Table I. A striking fact apparent in the table is that NbTi has a much lower T_c than many other superconductors and yet it remains the most widely used one, despite the fact that it is now around 46 years old. The next section will delve into why this is so.

III. Materials Parameters Required for Commercialization

To understand better the difficulty of carrying forward superconducting materials to commercialization, we first examine the three critical parameters of Fig. 1 (I_c, T_c, H_c) further. All three parameters are functions of the other two parameters below their critical values. H_c does not often limit the use of superconductors in itself because, in power applications, the field is almost always being produced by the superconductor itself, and so the system design limitations come from T_c or, most often, I_c, and these are reduced by the value of the magnetic field H at the superconducting wire. The engineering limitations of working with superconductors are especially important. Safety margins must be established for machine reliability and life, and that means that the designer should only design to some fraction (e.g., half) of I_c and T_c, the theoretical capability or "entitlement" of the machine.

The value of I_c is of particular interest because it is a primary goal in power applications to conduct large currents, and I_c is not an intrinsic property of the superconductor, unlike T_c and H_c. There is a theoretical "depairing limit" for I_c which can be related to H_c [9], but it is much larger than the practical values encountered in practical superconductors, which are type II, and therefore have I_c dictated by the motion of flux lines penetrating the superconductor. Moving flux lines dissipate heat within the superconductor, destroying the prime desired property of zero resistance and energy dissipation. These flux lines can be pinned spatially by the judicious use of defects (e.g., grain boundaries, impurities, dislocations, second phases) within the superconductor during manufacturing, and the optimization of such pinning defects without reducing the desired superconducting properties of the bulk is a very difficult, time-consuming task requiring the efforts of many material scientists. It is worth noting that the HTS materials are thought to be d-wave superconductors with somewhat different flux line structures than the more traditional BCS materials (e.g., NbTi), and we do not know if this causes additional difficulty with the flux-line pinning task.

TABLE I Superconducting Materials Examples

Metals	**Transition temperature(K)**
Nb	9.25
Tc	7.8
V	5.4
NbTi	9.8
Intermetallics	
Nb_3Ge	23.2
Nb_3Si	19
Nb_3Sn	18.1
Nb_3Al	18
V_3Si	17.1
Ta_3Pb	17
V_3Ga	16.8
Nb_3Ga	14.5
V_3In	13.9
Unusual	
Cs_3C_{60} (Highest-T_c Fulleride)	40
MgB_2 (Highest T_c binary compound)	39
$Ba_{0.6}K_{0.4}BiO_3$	30
$HoNi_2B_2C$ (Borocarbides)	7.5
Fe_3Re_2	6.55
$GdMo_6Se_8$ (Chevrel Phases)	5.6
$CoLa_3$	4.28
MnU_6 (Heavy Fermions)	2.32
$Sm(O_{1-x}F_x)$ FeAs (pnictides)	52
Cuprates	
$Yb_{0.9}Ca_{0.1}Ba_{1.8}Sr_{0.2}Cu_4O_8$	86
$YBa_2Cu_3O_{7-d}$	93
$Y_2Ba_4Cu_7O_{15}$	93
$Bi_{1.6}Pb_{0.6}Sr_2Ca_2Sb_{0.1}Cu_3O_x$	115
$Tl_{1.6}Hg_{0.4}Ba_2Ca_2Cu_3O_{10+d}$	130
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$ (record)	138

The three critical parameters mentioned so far are certainly not the only important ones for practical applications. Mechanical properties are also critical, since large magnetic fields and machine motions (e.g., centripetal forces) may produce substantial forces on the superconductor which must be well accounted for if damage is to be avoided. Cyclic forces may produce fatigue of the superconductor. Ductility, malleability, hardness, and strain tolerance affect the ease with which the wires may be manufactured and then wound into desired coil shapes. Asperities and sharp edges on superconducting wires must be considered for their potentially deleterious effects on insulation or other parts of the machine. The camber or straightness of the wire is important for successful wire handling, processing, and winding into coils. The ability to form joints between superconducting wire segments is always necessary, since it is unlikely that continuous wire lengths long enough to wind large coils can be produced. These joints have the additional difficult requirement of being superconducting themselves with properties comparable to the wire if the coils are expected to operate in persistent mode (i.e., able to maintain lossless currents when closed upon themselves).

For operation at low temperatures (e.g., in liquid helium at 4.2 K, as is most common), superconducting wires and other materials have very low heat capacity, making them subject to large temperature excursions from small, often unexpected energy inputs. This can lead to quenching (loss of superconductivity) of magnets and training of magnets (repeated quenching of a magnet during initial operation as the wires move into their lowest energy positions under magnetic forces and thermal-expansion-mismatch forces). Reduction of quenching and training requires strong and stiff mechanical support structures. During a quenching event, the superconductor must be protected from permanent damage, which may result from either thermal-expansion-mismatch forces or simply excessive temperature caused by the sudden ohmic losses in the now-normal superconducting wire. This is usually accomplished by surrounding the superconductors with stabilizers (e.g., copper), which provide a less resistive path for the current flowing in the quenched state and more heat capacity than the quenched superconductor, until the energy can be removed from the coil by an external “dump” circuit. These stabilizers must be in intimate contact with the superconductor and therefore be completely compatible with it. Fortunately, the HTS materials can operate at higher temperatures, where heat capacities are much larger and therefore quenches are less likely. However, unfortunately the hot zone from a local quench in a HTS magnet tends to propagate much less quickly within the magnet, and this concentrates the ohmic loss energy and increases temperature rapidly in that zone, threatening damage which is very difficult to avoid. This problem of quench protection of HTS coils in all circumstances is an important unsolved one.

The need to satisfy all of these performance parameters should indicate to the reader why it has been so difficult to displace NbTi from its leadership position in power applications, despite the fact that other materials (e.g., HTS) have been found with substantially higher T_c. If this is not enough, and sometimes most difficult of all, these solutions must be obtained within a process and with materials which allows costs of the system to be competitive with other means to accomplish the goal, or with the current cost of using NbTi, if the goal is to displace it.

Another material issue which deserves mention is insulation. All wires for all applications need it. It is sometimes not readily focused upon, since superconductors have zero resistance and current will flow in the easiest path. However, superconductors have zero resistance only for dc, and when they are ramped or subjected to ac, they will generate some internal voltage which must be shielded from causing current flows in undesired directions. Further, when wound into coils, the coil inductance may generate considerable voltages when the current changes. Coils also have internal capacitances and inductances that may lead to electrical resonances, which may enhance voltage problems in certain circumstances. Insulation tends to be considered a routine engineering request, but cryogenic temperatures or special superconductor handling and protection requirements may make this untrue and unwise.

Table II summarizes materials properties that must be considered when attempting to commercialize a superconductor, especially as a wire.

TABLE II SUPERCONDUCTING MATERIALS PROPERTIES IMPORTANT FOR COMMERCIALIZATION

T_c, H_c (margin, factor ~2)
J_c (better, J_e, the engineering current density, including, insulation, stabilizer, etc.) (margin, factor ~2)
Insulation (what is the maximum voltage at quench, fault, resonance?)
ac loss
Ease of manufacturing; yield
Stability/stabilizers (different for HTS vs LTS); protection against quench
Cost (NbTi ~ $1/kA-m)
Asperities, sharp edges
Wire camber/straightness
Mechanical handling/strength (cycling, bending, tensioning)
Ability to join (superconducting for persistent applications; otherwise, upper limit of resistance)
Long-term life
Quality (uniformity; standard deviations)
Availability in needed forms (e.g.: length; multifilaments: transposed, twisted; cross-section)
Compatibility with the other materials/processes of the system
EHS (salvage)

There are applications that do not require superconducting materials in long wire forms. These are chiefly in the electronics area, where the device size often calls for a small thin film. This greatly relieves the difficulty of supplying materials from the difficult-to-process HTS and so has speeded these applications, as described in the next section.

IV. The Applications

Applications of superconductors have arisen in areas other than electromagnets, more specifically in electronics and sensors, wherein the materials required are often small thin films which are much easier to produce in highly perfect forms, especially from HTS. In electronics, the Josephson effect [11] has enabled devices such as SQUIDs (superconducting quantum interference devices) for the most accurate measurement of magnetic fields [12], voltage [13], and related electromagnetic quantities. The Josephson effect refers to the interesting ac and dc properties of current transfer between two superconductors which have a weak connection between them. It has led to a class of devices which are today used mostly in the laboratory for experimentation and standards [14]. Researchers have also experimented with superconducting digital circuits [15], A/D converters [16], and transistors [17]. In superconducting bolometers, the sharp electrical transition to zero resistance as a function of temperature enables very sensitive thermometers, which have been used in wide-band astrophysics measurements [18], inter alia. The largest commercial use at present of superconducting electronic devices is as filters in cell phone base stations [19], where the low microwave resistivity and noise of HTS enables greater signal range and fewer dropped calls with cooling to 77 K (liquid nitrogen). Superconductors are also used for the highest Q resonant cavities [20], particularly in high-energy particle accelerators.

Another extraordinary property of superconductors is the Meissner effect [21], which is the tendency of superconductors to exclude magnetic flux. In low fields and type 1 superconductors, this exclusion is complete, leading to perfect diamagnetism. This effect has to date not led to major commercial applications but has been used in various laboratory and prototype applications to levitate magnets or superconductors and provide magnetic shielding. An equally important property of superconductors is their ability to trap penetrating flux through internally circulating supercurrents, and this has been used to provide stable, strong magnetic bearings [22] and "permanent" magnets which are much stronger than the conventional variety. The material requirements for such applications are clearly different from those for wires, since the superconductor is often in a block, bulk form. However, most of the mechanical and electrical considerations already discussed still apply.

Although not an application in the large-scale commercial sense, I mention the use of superconductors in scientific experimentation. Superconducting electromagnets have long been used to produce continuous magnetic fields up to the highest realized on earth for experimentation. Since superconductors are a rare example of exhibition of quantum mechanics on a large scale, they have often been used to study quantum phenomena and for teaching. A recent example of this is their use to study the fundamental unsolved question of how decoherence takes us from the quantum to the classical world [23]. A variety of other laboratory apparatus have included superconductors.

There is only one very large commercial power application of superconductors at present: magnetic resonance imaging (MRI [24]) (see Fig. 2). With thousands of units in hospitals world wide and global sales of several billion US dollars per year, this is truly a major product. The superconducting portion consists of a "basic" solenoid, which creates the background magnetic field required for nuclear magnetic resonance (NMR) of nuclei (almost always protons) in biological systems (chiefly humans). The superconductor employed is almost always NbTi. Fig. 3 gives some typical specifications that may be required for NbTi used for MRI.

Fig. 2: A typical MRI magnet, in this case a GE 3 Tesla MR750^{TM}.

- Material: NbTi / Cu
- Insulated Dimensions: 1.20 +/- 0.015 mm x 1.80 +/- 0.020 mm
- Bare dimensions: 1.13 mm x 1.72 mm
- Insulation: Formvar
- Insulation thickness: 0.025 +/- 0.013 mm
- Corner radius: 0.20 – 0.40 mm
- Cu/Sc Ratio: 1.65 +/- 0.20
- Filament Diameter: 93 micrometers
- Filament Number: 102
- Filament Twist Pitch: 75 $\pm$ 13 mm
- Guaranteed Current at 4.2K: 1500A at 5T; 1200 A @ 6 T
- Expected Ic: ~25% higher
- Residual Resistivity Ratio: ~80 expected

Fig. 3. Some typical specifications of NbTi superconducting wire for MRI. These are simplified, since the detailed specifications are generally proprietary.

Note the level of detail, which is actually simplified, since the detailed specifications are proprietary to the manufacturers. The "simplicity" of the magnet is belied by the requirement for very high field homogeneity within the imaging volume (< 30 ppm variation required) and the necessity to allow for the large hoop forces generated by the large fields (3 Tesla common now) in volumes which accommodate humans. It is an important point that superconductors are not inherently necessary for MRI, only a means to reliably create a large (in volume and magnitude) magnetic field. It is possible to do so with conventional electromagnets, but the cooling of the copper wires is prohibitive. Permanent magnets can also be used, but their field magnitude is quite limited (less than around 0.5 T) compared to superconducting magnets, and so they are used for lower priced MRI or in locations where liquid helium cannot be easily obtained. Signal-to-noise ratio in MRI depends on the magnetic field magnitude linearly with H, and so the desire for short imaging times or more image detail drives us toward higher-field superconducting magnets. There is a limit to this, however, since the temporal field gradients necessary for imaging cannot penetrate the entire human body well at too high frequencies, which increase as H increases, and so 3 T is the most popular compromise at present.

MRI provides amazingly detailed views of the interior of the body. Its potential continues to be explored and to increase, since MRI is characterized by more parameters than more familiar diagnostic methods such as x-ray. For proton imaging, the proton density and the relaxation times of the proton's polarized spins (commonly called T_1 and T_2) all may be manipulated to reveal different features of the image, whereas x-ray fundamentally probes only electron density. Furthermore, there are other nuclei in the body (e.g., C^{13}, P^{31}, and F^{19}) that can produce NMR signals, and these can also produce diagnostic images, albeit with lower resolution due to their lower density in the body. Since these nuclei may be involved in various metabolic processes in the body, during which they change their chemical environment and thus the detailed nature of their NMR signal, these processes may be monitored with MRI, giving rise to the field of functional MRI (fMRI). Since NMR signals are highly dependent on the local magnetic field, an entire field of contrast agents is developing, in which small magnetic particles are targeted to specific sites in the body to reveal specific details of their form or function. Experimentally, researchers are developing non-metallic surgical tools to perform difficult operations under the guidance of MRI, which is safer than working in an ionizing radiation field such as x-ray. There is no doubt that MRI will continue to increase in importance as a diagnostic tool in the future.

V. Future Applications

The last ~30 years have seen the development of a number of prototypes of new superconducting power equipment. None other than those mentioned above have been successfully commercialized. The problem has usually been the cost of the superconducting version versus other non-superconducting solutions [25]. Superconducting motors and generators [26] are one strong example; a number of prototypes have been successfully built and tested to full function [27], but the economics have not allowed commercialization. Other examples in the power area are fault current limiters [28], underground power cables [29], transformers [30], levitated trains, magnetic bearings, magnetic separators [31], power leads for cryogenic equipment [32], and superconducting magnetic energy storage (SMES) [33].

A particular example application, superconducting generators, is instructive of the hurdles that must be surmounted for a future application. Superconducting coils can produce much larger magnetic fields within the generator than can be achieved with the usual cooled copper windings of similar size. However, only the field winding in the generator is close to dc in frequency, and so superconductivity can be applied well only to this rather than to the ac armature windings, unless a very ac-capable form of the superconducting wire is available and the ac losses can be accommodated economically by the cryorefrigeration. There are presently no ac-capable commercial forms of HTS, and the refrigeration costs of ac operation at 4 K are prohibitive. Hence, only the field is superconducting in most machines, and HTS are preferred to reduce refrigeration cost by operating at ~30 K or higher rather than 4 K. This still allows high fields, which can be used to reduce machine size/weight or to improve machine efficiency by removing ohmic losses from the field. Focusing to utility-scale generators, size/weight reduction is not of much value, and so efficiency increase is the target. The conventional versions of these machines are already very efficient (~98%), and improvement of this by ~0.5-1 % may be possible in a superconducting version. This improvement, while small, can offer significant additional revenue over the life of the machine. However, many hurdles must be overcome. The mechanical stresses due to rotor rotation (usually 3000 or 3600 rpm) are large and difficult to sustain for most HTS materials. Presently well-established generator rotors must be redesigned to accommodate HTS, vacuum insulation, and cryogenics. The new equipment for the cryogenics adds cost, complexity, maintenance, and reliability issues. Last but not least, utilities by their nature are risk averse to new technology that does not have a strong reliability record, requiring prototyping and long test periods to gather appropriate reliability data. All of these factors mean that when a company looks at the cost of commercialization (R&D costs, retooling costs, testing costs, added production costs), superconducting utility generators no longer look economically attractive compared to other potential uses of R&D funds for utility projects.

A closely related application is large motors. Table III gives reasonably representative customer specifications/criteria for large motors in two areas, commercial and military, and they are listed roughly in customer priority order. These criteria may change, of course, for any specific application, but the table is illustrative. Criteria in italics or bold are disadvantages or advantages for the superconducting version, respectively. We notice in the table that there is no customer criterion for superconductivity or cryogenics; these are invisible to him. The military criteria are somewhat more likely to benefit from superconductivity and so may offer the best first entry point. Notice that most of the disadvantages (e.g., "proven technology") can only be removed by building and operating a number of machines over a significant time period.

TABLE III Potential customer criteria (2 types) for large motors in approximate priority order. Italics and bold denote problems and advantages for superconducting versions, respectively; a question mark could go either way.

Commercial customer:	**Military customer:**
First cost	**Noise (EM)**
On-time delivery	**Size/weight**
Custom design to application	Custom design to application
Quality/reliability	*Ruggedness/reliability*
Proven technology	**Efficiency**
Serviceability	Fail safe mode
Noise (audible)	Serviceability
Vibration	Noise (audible; structure-borne)
Life cycle cost ?	Vibration
Efficiency	Life cycle cost ?
20-50 year life	*On-time delivery*
	Commercial availability

Other applications do not involve high power levels or magnetic fields. These are mostly in the electronics field and have been mentioned above. It is certain that such work will continue, and the material issues should be less daunting since smaller amounts of material are needed, usually in thin film form. However, success in commercializing further such devices will depend on the same criteria of cost and performance versus other available means to address the objective at hand. New application ideas will surface. For example, superconductors have been suggested as the most likely implementation technology for yet-to-be-realized quantum computers [34] because of their low-noise cryogenic environment, low dissipation, and ability to manipulate single flux quanta.

VI. Cryorefrigeration

Any paper about superconducting applications should not neglect to mention its necessary ally, cryogenics. All superconductors (at least, unless near room-temperature superconductors are achieved) require cryogenic technology for any application. Description of this engineering field, in which most applications are not motivated by superconductors, is outside the scope of this paper, but the reader should be aware that future successes in this field in reducing the cost, size, weight, unreliability, etc. of cryogenic equipment will have a direct and strong bearing on how quickly various applications mentioned here can be commercialized [35]. Indeed, without the cost of cryorefrigeration, many of these applications would probably have already been commercialized. Because of the cryogenic burden, new superconducting applications are most likely to achieve early, widespread success in situations where there is no satisfactory conventional solution to the problem.

Cryogenics carries notable burdens for superconducting machine. First is the cost of the cryogenic subsystem. It is not unusual for the cryogenics to constitute half or more of the cost of using superconductors. Second is the added maintenance cost. The refrigerators require significant electrical power during operation and periodic replacement of various parts and filters, and the required vacuum insulation system can produce troublesome leaks if not manufactured and maintained well. Finally, the cryogenic system constitutes a new addition to the potential unreliability of the overall system, and this must be countered with appropriate redundancy and other potentially expensive engineering measures.

New superconductors which can operate at higher temperatures can do much to help ameliorate the burden and cost of the cryogenics. Fig. 4 illustrates that fact that the input power to the cryorefrigerator is reduced markedly as the operating temperature increases. The capital cost of refrigerators also decreases as the operating temperature increases. Furthermore, as the temperature of operation gets to around liquid nitrogen (77 K), many other commercial applications, such as some in food processing, biology and healthcare, come into play to help reduce refrigeration costs and increase research on new systems. However, the reader should remember that superconductors, especially HTS, must operate well below T_c to have sufficient performance, i.e. current carrying capacity in high fields.

OPERATING TEMPERATURE	CARNOT COP (Watt Input per Watt Lifted)	"TYPICAL" COP FOR >100 WATT HEAT LOADS (Watt Input at 300 K per Watt Lifted at T_{op})
[illegible] K	0.11	~ 0.4
[illegible] K	[illegible]	~ 2
[illegible] K	1.01	~ 4
[illegible] K	[illegible]	~ [illegible]
77 K	[illegible]	~ [illegible]
[illegible] K	[illegible]	~ [illegible]
40 K	[illegible]	~ [illegible]
30 K	[illegible]	~ [illegible]

T_{reject} = 300 K

Fig. 4. This illustrates the amount of power (Watts) input to a typical cryorefrigerator for the number of Watts actually available for cooling. COP is coefficient of performance. T_{reject} is the temperature at which the heat is rejected from the refrigerator. T_{op} is the operating temperature. The Carnot COP is the theoretical lower limit of this parameter. [36]

VII. Conclusion

Given that prediction of the future is always uncertain, it can be safely stated that superconductivity will continue to supply science with a magnificent platform and incentive for new discoveries and theories in condensed matter physics. It is clear that we do not yet know all the ways that the Cooper pairing phenomenon or zero-resistance coherent states can arise in condensed matter or the detailed properties of these states. Recent material discoveries mentioned here provide ample proof that materials research will continue to synthesize new materials that may reveal these new phases in an experimental sense or improve on those already known. The more applied work of converting these new materials into commercializable forms, from which application benefits may be derived, may generate the most future effort of all, if the HTS story is an indication.

It should also be clear that advances other than in superconducting materials themselves - e.g. manufacturing processes, insulation, cryogenics, cryorefrigeration, and cost reductions - are also helpful and necessary for continued success in superconducting applications. Unless there is no other way to solve a problem, a superconducting design will always be in competition with other solution methods, which may be more cost effective or reliable. Superconducting materials may contribute to the effort most readily by increasing the available system operating temperature, but the other properties discussed above are also critical.

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