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One hundred years of superconductivity: science, technology, products, profits and industry structure

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Abstract: Superconductivity was empirically discovered 100 years ago. While scientific efforts were rewarded by no fewer than seven Nobel Prizes, there has been only one major application: MRI. The unfulfilled potential of other electrical and electronic applications resulted in the acquisition of the MRI division of Oxford Instruments by Siemens in 2002 and of IGC by Philips in 2006. In this paper, we review the evolution of superconductivity during the past 100 years and conclude with a forecast of the industry's future. We offer policy recommendations for continuing research, development and engineering in this promising but, as of today, still unexploited field of applied science.

Keywords: superconductivity; cryogenics; oxford instruments; intermagnetics general; American superconductor; GE; general electric; Philips; Siemens; MRI; magnetic resonance imaging; electric power transmission.

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1 Introduction

Superconductivity – the absence of electrical resistance in certain materials at very low temperatures – has evolved from the empirical discovery of this behaviour in mercury to the first, and to date only, major commercial application of Magnetic Resonance Imaging (MRI) in the 1980s. Heike Kamerlingh Onnes, a Dutch physicist, having successfully liquefied helium in 1908, investigated the low-temperature resistivity of mercury in 1911. He found that the resistivity suddenly dropped to zero at 4.2 K, a phase transition to a zero-resistance state. This phenomenon was named superconductivity, and the temperature at which it occurred the critical temperature. However, the observation of this phenomenon, which was greeted with high hopes for groundbreaking applications in the electrical and electronic industries, was not followed by actual engineering breakthroughs. The story of this discovery and its disappointing aftermath offers insights into the complex links between science and technology, technology and entrepreneurship, products and profits, business strategy and industry structure.

The paper is organised as follows. First, we review the nature and limitations of superconductivity and the gradual increase in scientific understanding of this novel and unexplained phenomenon, the development of a theoretical model (the so-called BCS theory), the experimental proof of this theory and the subsequent extension of the theory by IBM researchers, leading to discovery of higher-temperature superconducting materials. Second, we review the evolution of the technology from the commercial production of superconducting materials to the design of the first commercial product – superconducting magnets – initially for the limited laboratory market and afterwards for the exploding medical diagnostics imaging market. Third, we analyse the evolution of the industry structure from entrepreneurial ventures started by researchers to independent but slowly growing public companies, and their relationships with clients, national research agencies and leading multinational corporations in the healthcare industry. Fourth, we discuss the strategies of the independent superconductivity companies and their multinational customers, which led to consolidation through acquisitions and to major changes in the structure of the industry. Fifth, on the basis of historical review and analysis, we attempt to explain the reasons for the extraordinary yet isolated success of superconductivity in the healthcare industry, and the failure, so far, to find commercial applications in industries like electric power, electronic computing, high-speed transportation, energy storage, etc. Finally, we attempt to forecast some practical applications beyond the healthcare industry, utilising the methodology of economic long waves. This forecast, admittedly speculative, leads to recommendations for continuing Research, Development and Engineering (R&D&E) activities in the promising but largely uncharted realm of applied science and engineering.

To clarify the key events and the strategic issues of this story, the 100-year history of superconductivity may be divided into six periods:

1. the era of science and discovery (1908–1961)
2. the era of technology and innovation (1962–1970)
3. the era of entrepreneurship (1971–1981)
4. the era of products and profits (1982–1990)
5. the era of new materials and applications (1991–2003)
6. the era of industry consolidation (2004–2007).

It is important to note that these eras overlap, and that each era builds on the preceding ones. For instance, era four (product and profits) was built on the achievements of era one (science), era two (technology and innovation) and era three (entrepreneurship).

The main actors in the field of superconductivity are university researchers, national labs, technological entrepreneurs, new ventures, multinational companies and government institutions that sponsor R&D. The key strategic issues faced by these actors during the six eras are discussed throughout this paper and summarised in the conclusions.

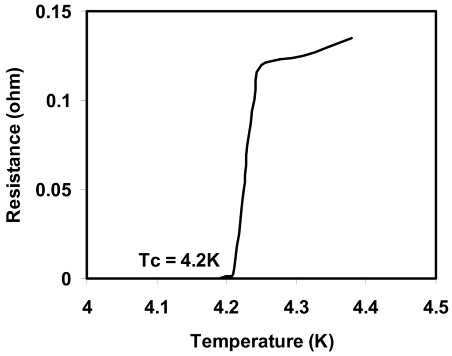
This historical review, encompassing 100 years, and the forecast that follows, should be of interest to engineering and management scholars, high-tech entrepreneurs and entrepreneurial managers in new ventures and mature multinational companies because it offers the following insights and lessons:

- although the links between science and technology are often weak and unclear, advances in both areas are required for breakthrough technological innovations
- technological entrepreneurs have a unique role in bringing high-risk innovative products to emerging markets that are of no interest to established companies
- established companies can profitably exploit a new technology by waiting for the window of opportunity (in terms of market size and growth rate) and by utilising the advantage of their existing complementary assets
- as the market for new breakthrough applications becomes established and the technology stabilises into a dominant design, large multinationals lead the industry and increase their profits through vertical integration by acquiring the pioneering entrepreneurial companies
- both science and technology develop in waves of enthusiasm and hype after major R&D&E accomplishments, but these waves cannot be sustained unless the industry is ready and able to accept and incorporate promising applications into the existing systems and their business and economic infrastructure.

2 The era of science and discovery (1908–1961)

Superconductivity is the natural phenomenon whereby certain materials display zero electrical resistance at very low temperatures. It was discovered in 1911 after helium was first liquefied by Heike Kamerlingh Onnes, professor of physics at the University of Leiden in the Netherlands (McKelvey, 1989). The objective of Onnes' scientific research was to study the behaviour of materials at very low temperatures, a few degrees above absolute zero (0 K = –273°C). To achieve these temperatures, Onnes liquefied helium and measured the resistance of solidified mercury as the temperature decreased. Above 4.3 K, the resistance decreased proportionally to the temperature as shown in Figure 1. However, unexpectedly, at 4.3 K resistance fell very rapidly and became zero below the 'critical' temperature (T_c) of 4.2 K.

Figure 1 Electrical resistance of mercury displaying superconductivity when cooled to low temperatures

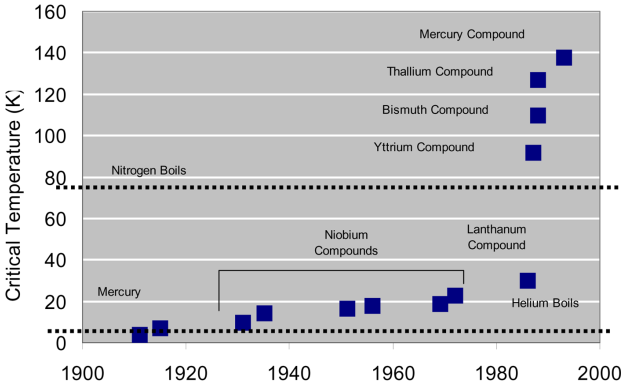


The next major discovery occurred in 1933. German researcher Walter Meissner discovered that a superconducting material repels a magnetic field. In a superconductor, the induced currents exactly mirror the field that would have otherwise penetrated the superconducting material, causing the magnetic field to be repulsed. This phenomenon is known as strong diamagnetism and is today often referred to as the Meissner effect. The Meissner effect is so strong that a magnet can actually be levitated over a superconductive material.

This new phenomenon contradicted the then-dominant theory of electrical resistance that was attributed to the interaction between the flowing electrons and the stationary atoms of a conductor. This interaction causes a transfer of energy from the electrons to the atoms that can be observed macroscopically as the electrical resistance of the material causing energy loss and heating.

Onnes had discovered superconductivity but could not explain why electrons below the critical temperature were not interfering with the atoms of the mercury. He was awarded the Nobel Prize in 1913 for his empirical discovery and continued his research until 1924. In successive years, from 1928 to 1930, three important new superconductors were identified: tantalum (T_c of 4.4 K), thorium (T_c of 1.4 K) and niobium (T_c of 9.2 K). Onnes was aware that helium cryostats were cumbersome, unreliable and unavailable commercially. In addition, helium is present only in small quantities in the atmosphere and difficult and expensive to produce in large quantities. Therefore, scientific research was oriented towards the discovery of other superconducting materials (metals and intermetallic compounds) exhibiting higher critical temperatures, as shown in Figure 2. In subsequent decades, other superconducting metals, alloys and compounds were discovered. In 1941, niobium-nitride was found to be superconducting at 16 K. In 1953, vanadium-silicon displayed superconductive properties at 17.5 K.

Figure 2 Superconducting critical temperatures have increased with the discovery of new compounds (see online version for colours)



In 1953, research at Bell Laboratories raised the T_c of superconductors to 17.86 K with NbN-NbC. That discovery was followed the same year at the University of Chicago with another 17 K superconductor, V_3Si, but of a new crystal structure, A15, that would eventually supply a series of important superconductors. Another A15, Nb_3Sn, would be added the following year at Bell Labs, with a further increase in T_c at 18 K. The highest temperature reached in 1970 was 23.2 K for Nb_3Ge (Matthias et al., 1967). An alloy of niobium (Nb) with 47 weight percent, titanium, was also discovered. It is now by far the most important commercial superconductor, widely used in magnets for MRI systems in hospitals. In parallel, but at a much slower pace, the technology of cryostats improved.

The search for new high-temperature materials continued to be empirical and was greatly hampered by the lack of a scientific theory that explained why certain materials were superconducting and others were not. In 1957, John Bardeen, Leon Cooper and Robert Schrieffer published a theory (the BCS theory, from their last names) that explained superconductivity as a quantum mechanical effect of coupled electrons (Betz, 1993). They received the Nobel Prize in 1972. The mathematically complex BCS theory, which was the basis for the creation of new classes of superconducting materials, explained superconductivity at temperatures close to absolute zero for elements, metals and simple alloys. However, at higher temperatures and with different superconductor systems, the BCS theory has subsequently become inadequate to fully explain how superconductivity occurs.

Another significant discovery came in 1962 when Brian D. Josephson, a graduate student at Cambridge University, predicted that electrical current would flow between two superconducting materials – even when they are separated by a non-superconductor or insulator (Josephson, 1962). His prediction won him a share of the 1973 Nobel Prize in physics. Ivar Giaever, a GE researcher, independently demonstrated tunnelling in superconductors, which also won him the Nobel Prize in 1973 (Abetti, 2002). This tunnelling phenomenon, known today as the Josephson effect, has been applied to electronic devices such as the SQUID, an instrument capable of detecting even the weakest magnetic fields.

In summary, during the era of science and discovery, superconductivity was discovered experimentally, and successful theories were developed to explain that new, baffling phenomenon. However, no practical applications were implemented.

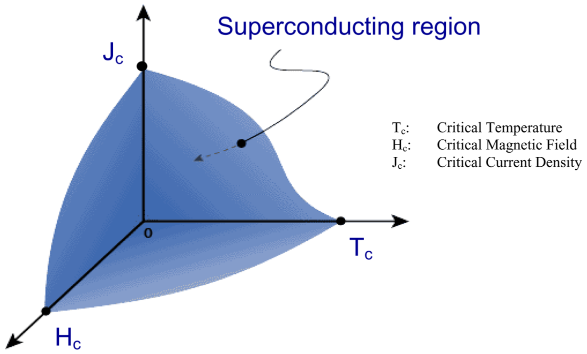
3 The era of technology and innovation (1962–1970)

Let us review briefly the engineering status of superconductivity in the early 1960s. Empirical research had shown that certain materials exhibit zero resistance in the three-dimensional domain shown in Figure 3. The three parameters describing superconductors are:

- critical temperature
- critical magnetic field
- critical current density.

If one or more of these critical parameters is exceeded, the material regresses from the superconducting to the normal state. For practical applications, superconducting materials should have relatively high critical parameters. As discussed, critical temperature is the most important. In addition, these materials must have certain mechanical properties: ductility for drawing the wires, strength for resisting mechanical forces caused by magnetic fields, and affordable cost of raw materials and manufacture.

Figure 3 Critical superconductor parameters of magnetic field, temperature, and current density (see online version for colours)



In 1962, scientists developed the first commercial superconducting wire, an alloy of Niobium and Titanium (NbTi). High-energy, particle-accelerator electromagnets made of copper-clad niobium-titanium were developed in the 1960s at the Rutherford-Appleton Laboratory in Britain, and were later employed in superconducting accelerators in the USA (Laverick, 1967). In the 1960s, the most promising engineering application appeared to be superconducting magnets that would achieve much higher magnetic fields than had conventional coils of copper wires. These copper coils were expensive, and they consumed high amounts of electricity that was converted into heat. Therefore, R&D labs of major electrical companies worked on the development and manufacture of superconducting wires and on the design of high-field superconducting magnets. From the late-1960s onward, the needs of the high-energy physics community propelled considerable advances in superconducting wire technology first for research and then primarily for accelerator magnets. Many advances in the 1960s and 1970s were in the area of increasing the critical current density in superconductors, thereby reducing costs since less of the superconductor was required, while operating magnets at higher magnetic fields.

General Electric (GE) succeeded in building the world's first 100,000 G (10 T) magnet in 1962. While this was a spectacular scientific and technical success, the commercial aspect was not satisfactory. The accumulated development costs were over $ 200,000, well above the fixed-price contract of $ 75,000 that Bell Labs had paid GE. The emerging market, mainly government and academic labs, was limited and was unserved by GE's traditional distribution channels. Many other potential applications were demonstrated with superconductors, such as superconducting generators, motors and transformers. However, this apparatus was technologically mature, had achieved high electrical efficiencies and was becoming almost a commodity, with cost, rather than performance, being the dominant procurement criterion for customers, essentially electric utilities and large industrial plants. Another potential application was superconducting cables for power transmission in areas where overhead power lines could not be used, for instance over large bodies of water and in highly populated areas. While the gains in efficiency were higher in this case, the need for expensive and unreliable cryostats greatly reduced the attractiveness of this potential market.

Nonetheless, the GE researchers involved with superconductivity continued to champion the commercialisation of superconducting wire for electrical applications but could not find a home for the new technology. According to its charter, the GE Research Laboratory was not permitted to start new business units but had to work exclusively through the operating departments. Since superconducting magnets are coils, GE's large transformer business appeared to be the natural home for producing and marketing these magnets. But a business study yielded negative results: the market was too small and uncertain, the payback time too long and the risk too high for superconducting magnets to pay off. Other electrical applications corresponded to potential large markets, but electric utilities, as controlled monopolies with guaranteed rates of return on investment, would be very reluctant to introduce high-risk radical innovations into their systems to achieve marginal savings. The forecasted adoption time would be decades. Therefore, GE decided not to commercialise this technology. Similar decisions were made by other major manufacturers in the USA, Europe and Japan.

In summary, the structure of the electrical industry during this era was unfavourable for superconducting applications. Electric utilities had low economic incentives to innovate, and manufacturers were risk-averse and reluctant to expand their market beyond the stated requirements of their traditional customers (Christensen, 1997).

4 The era of entrepreneurship (1971–1981)

Fortunately, small groups of researchers in the USA and Britain believed in the new technology and were much more optimistic about it than were the mature electrical manufacturers. By necessity, these researchers became technological entrepreneurs and created successful new ventures, Intermagnetics General Corporation (IGC) in the USA and Oxford Instruments in Britain that championed the commercialisation of superconductivity.

4.1 Intermagnetics General Corporation

In spite of GE's decision not to pursue commercial applications of superconductivity, the GE researchers wanted to continue to pursue the emerging markets. Fortunately, an entrepreneur, Carl Rosner, was able to create an independent spinoff, IGC, 40% owned by the researchers, 20% by Rosner and 40% by GE, which owned the intellectual property but did not contribute cash. GE granted a non-exclusive license to IGC, thereby retaining the right to reenter the business at a later time.

The new venture, focused on making laboratory-size magnets and receiving government R&D grants, became profitable within one year and continued on a modest but steady growth curve. The venture principals maintained a good relationship with the parent, and since IGC was located in the same metropolitan area as GE's R&D facilities, it used some of GE's technical resources on a favourable pay-as-used basis. The strong entrepreneurial team that headed the company was able to attract many good people from government labs and firms with related technology. The company grew in staff and technical capability, always focusing on superconductivity and closely related technologies. Although it became the leading firm in its field, its business growth rate was limited by the growth of the laboratory market and by its dependence on government funds for R&D and major scientific projects like supercolliders. Once interest re-emerged in large-scale applications of the technology, particularly energy, GE again became interested and a number of projects were undertaken on a joint venture or sub-contract basis. Since the venture had greatly extended the technology, a reverse technology transfer was needed to re-educate the parent company.

As discussed later, the incorporation of superconducting magnets in MRI systems greatly expanded the market, and IGC became a major supplier to GE and its competitors, including Technicare (Formerly known as Ohio Nuclear, Technicare made MRI scanners and other medical imaging equipment. Originally an independent company, it was purchased by Johnson and Johnson, where it did not do well. In 1986, it was sold to GE, a competitor). However, the contractual interactions between IGC and GE, still the major stockholder and customer, raised conflict-of-interest questions from other stockholders. As a result, IGC bought GE's shares, earning a tidy profit for GE. Further changes in equity led to IGC's going public in 1981 with good results for the entrepreneurs and original employees as well as for early investors.

At the same time, GE had to learn or duplicate many of the skills of the venture, which suggests that it should have kept the activity in-house. However, neither the technology nor the business could have developed within a large corporation in the same way they did externally. IGC took major risks – some winners, some losers – but the entrepreneurial spirit kept the firm going and growing in ways that would have been impossible under a corporate umbrella. Therefore, GE's decision to spin off the venture was correct. Other large firms such as Westinghouse kept their work on superconductivity in the laboratory, which led to its decline and demise owing to a lack of interest from operating units and a resulting absence of practical implementation.

IGC continued to prosper and achieved revenues of $30 million in 1990. However, profits were unstable because IGC depended heavily on government R&D contracts and major supply contracts from multinational corporations. The stock was a superperformer in those early years. IGC made superconducting wire, cryogenic systems and superconducting magnet systems used in MRI systems. Its principal customers were

Philips and GE, which still owned 20% of IGC's superconductor wire unit. Toshiba was another big customer. IGC's government business was expanding rapidly. The company had been chosen by the government's Superconducting Supercollider Laboratory (SSCL) as one of seven suppliers of superconducting wire cable in a $20 million contract. The SSCL was part of an ambitious $650 million project to recreate the origins of the universe. IGC continued to expand and diversify into other areas, including superconducting wire, high-field magnets, magnetic separation equipment, cryostats, cryogenic coolers, etc.

4.2 Oxford Instruments

Oxford Instruments was founded in 1959 by Martin Wood, senior research officer at the Clarendon Laboratory at Oxford University, and his wife, Audrey Wood. He held his tenured position at Oxford for ten years, work that often overlapped with his company activities. Martin Wood provided scientific input and engineering design, while his wife served as the day-to-day manager and also contributed an aptitude for finance, legal matters and administration (Wood, 2001).

In addition to design and consulting, the company developed and marketed magnets for university and government research. On 4 November 1961, the two founders attended a conference at MIT in Cambridge, Massachusetts, where they learned that high-field magnets could now be made with NbZr superconducting wire. They built the first high-field magnet outside the USA in March 1962, with a maximum intensity of 4 T. Housed first in a trailer and then in an old laundry, the new business took off. They received the Queen's award in 1967 for their 10 T magnet and a 'dilution refrigerator' that reached 0.03 K. The company obtained venture capital in 1967 and grew to 95 employees by 1970.

At that time, the world market for superconducting magnets was small and highly dependent on government funding for R&D. Therefore, Oxford Instruments acquired Newport Instruments to diversify into complementary magnets and instruments, specialised wound components, ambulatory monitoring and trailers, at the time their most profitable product line! In the 1970s, Oxford Instruments became a major supplier of magnets for Nuclear Magnetic Resonance[1] (NMR) spectrometers used in chemical R&D. When NMR was applied to medical diagnostics, Oxford Instruments designed and manufactured the first magnet with a 1 m inner diameter. Oxford Magnet Technology (OMT) was founded in 1982 by Oxford Instruments to commercialise its proprietary technology for magnets and accessories used in MRI body scanners.

4.3 Summary

The era of entrepreneurship was characterised by the emergence of new technical ventures in the USA and Britain, while established companies decided not to commercialise applications of superconductivity. IGC was created as a spinoff by researchers at the GE Research Laboratory, while Oxford Instruments was a spinoff of the Clarendon Laboratory at Oxford. Both ventures maintained close ties with their parents, who assisted them with technology, equipment and business contracts. Both companies tried to diversify beyond the limited magnet markets into cryogenics, still an imperfect and costly technology. Both companies grew, but their profitability was low and unstable because of the small size of the market and funding uncertainties. Nonetheless, both companies were well positioned to be first movers as soon as a new opportunity arose.

The case histories of IGC and Oxford Instruments (and later of American Superconductor Corporation) show that technological entrepreneurs are able and willing to assume risks that appear too high to conservative corporations. At first, it appears that the risk of entering a radically new business is higher for a small entrepreneurial company that has limited financial, human and technological resources than it is for a large corporation with plenty of cash and an extensive professional staff of R&D, marketing, production, legal and financial experts. The objective risk did not change by transferring the potential business from the parent to the new venture. On the other hand, risk is evaluated subjectively, and the new-venture entrepreneurs were willing to assume it. In fact, they believed that a small company with lower overhead and greater flexibility was better suited to establish itself in the targeted market niche.

The strategic attractiveness of superconductivity changed drastically when a major new application with a very large market appeared: MRI.

5 The era of products and profits (1982–1990)

5.1 The emergence and rise of MRI

In the 1970s, two companies had become leaders in the medical diagnostic market with the new Computerised Axial Tomography (CAT) system that replaced conventional X-rays. The pioneer was EMI, which started the new business in Britain but expanded rapidly to the much larger, more advanced US market. However, EMI encountered major technical and managerial problems and major losses (Bartlett, 1983). In the meantime, GE Medical Systems adopted the “fast follower … and over taker strategy” (Abetti, 1989), developed a superior system and became the world leader, later acquiring EMI’s medical business.

Both companies realised that the new modality (MRI) would yield diagnostic information complementary to, and more valuable than, CAT. To experiment, both companies needed large-bore superconducting magnets. EMI naturally turned to Oxford Instruments, and so did GE initially, because IGC was not yet in production. Therefore, we will discuss Oxford Instruments first.

5.2 The evolution of Oxford Instruments

In the late-1970s, there was worldwide interest and rising expectations in the MRI diagnostic modality, but at Oxford Instruments there was anxiety. One memorandum read

> “There is race between the major companies for a supposed three billion dollar market of which Oxford Instruments produces an essential element. We are likely to become essential suppliers of a vital part to several larger companies who may want to buy us or kill us.” (Wood, 2001)

The first two commercial whole-body magnets were delivered to EMI and to the University of California, San Francisco, in 1980. A third magnet was shipped to GE.

The market exploded and magnet orders increased from £1 million in 1981 to £25 million in 1982, when Oxford Instruments commanded some 90% of the available market. There was doubt whether the company would have enough capacity in the future, with its only production facilities in England. Therefore, they licensed the technology to Siemens AG, which would continue to buy magnets from the company but would also manufacture some in house, according to Oxford Instruments designs. The majority of the orders came from the USA, and in 1982 Oxford created a partnership in Carteret, NJ, with Airco Inc., the US subsidiary of Air Products, and with Chemicals Inc. (which had acquired the chemicals and plastics business of Airco in the 1970s), to manufacture and service the systems. To finance, the explosive growth in the MRI market, the Oxford imaging operation became a separate group subsidiary, Oxford Magnetic Technology. In October 1983, Oxford Instruments had their initial public offering on the London Stock Exchange, which was oversubscribed seven times.

The euphoria did not last long. One month later, GE launched its first MRI product with a 1.5 T Oxford magnet. While this represented a surge in orders, Oxford Instruments managers were worried by GE's announcement that it was planning to manufacture its own magnets by 1985, much earlier than expected. It was feared that the MRI boom would subside in 1986 and 1987, and that Oxford Instrument's share would fall from 90% to 30%. To maintain a good growth rate and keep 'the City' (London Stock Exchange) satisfied, further profits would have to come from major acquisitions that could be quite risky. Instead Oxford Instruments, to lighten the management load, divested many non-essential subsidiaries. In 1989, OMT became a joint venture between Siemens (51%) and Oxford Instruments (49%). Customers included Siemens and third-party customers.

5.3 GE re-enters the business

GE realised that manufacturing superconducting magnets was the key to achieving performance, reliability and added value in MRI medical diagnostic systems, and decided in 1983 to further develop the technology and build their own plant. This decision appears to be justified in terms of market size and corresponding technical, functional and market risks (Abetti, 1999).

The situation had changed drastically since 1971. GE was supplying MRI systems to its traditional customers (hospitals and clinics) through well-established channels of its Medical Systems division. MRI was considered a major extension of CAT systems, of which GE was the leading supplier. The technical risk for making magnets was low since comparable superconducting magnets had been produced successfully by Oxford Instruments and IGC. Thus, three major factors justified GE's decision to reenter the superconducting magnet business:

- the potential market had increased from tens of millions to billions of dollars
- the overall risk had decreased significantly
- GE now had a more entrepreneurial climate that encouraged risk taking by operating units.

Why did GE redevelop its core competencies in-house instead of buying out IGC, whose excellent research, engineering and production facilities would have saved time and possibly money? Several reasons can be advanced to explain this decision:

- The 'Not Invented Here' syndrome that existed at GE's R&D Center. The researchers there believed they could design better superconducting magnets than could a small company.
- Fear of antitrust action by the US government. As the largest electrical company in the world, GE was carefully watched by the Justice Department. Buying IGC was a strategic acquisition for the vertical integration of the Medical Systems business, but it could also be interpreted as buying out a potential competitor.
- Fear that the principals of IGC would not remain at GE after the acquisition. They had enjoyed the freedom and excitement of running their own company and might not relish dealing with the corporate bureaucracy. Furthermore, the principals would receive substantial capital gains by selling their shares, which they might invest in new ventures related to superconductivity, possibly in competition with GE.

5.4 The evolution of GE medical systems business (1984–1990)

The history of GE Medical Systems has been related in detail by Morone (1993). We will discuss here the evolution of the MRI product line only. GE concluded that the design and manufacture of superconducting magnets would be a 'core competence' that must be jealously guarded and continuously developed in-house, in parallel with the imaging hardware and software that yielded customer value. GE's first MRI system, under the trademark Signa, was rolled out in fall 1984 with 1.0 software. Significantly improved versions followed every six months. By mid-1990, GE was offering upgrade 4.5 with greatly enhanced images and many new features, and there was an installed base of over a 1000 systems.

5.5 The evolution of IGC (1984–1990)

IGC expanded the wire division and acquired APD Cryogenics from Air Products to establish an integrated capability for superconducting magnet manufacturing. It continued to supply GE with superconducting wire and GE's competitors with superconducting magnets. IGC also considered vertically integrating and building its own MRI systems. Since it lacked competencies in electronics, high-frequency electromagnetic fields and displays, its R&D unit was located in the new-business incubator at Rensselaer Polytechnic Institute. A part-time staff of MS and PhD students was hired. Within two years, with a budget of only $5 million (believed to be one-tenth of GE's expense), IGC succeeded in building prototypes of MRI systems that were functionally equivalent to those marketed by GE and its competitors. Unfortunately, IGC lacked complementary assets (Teece, 1986) such as reputation with leading research hospitals and a sales and service infrastructure, and thus was unable to attract additional capital to expand the MRI systems business. IGC, therefore, concentrated on manufacturing superconducting MRI magnets, which were sold to Philips only. It also focused on the market niche of high-field superconducting magnets for a variety of research applications, including high-field (up to 20 T) NMR magnets. One potential application was magnetic separation for separating low-grade ores, which is traditionally done in leaching fields with disastrous environmental consequences. However, mining companies were uninterested owing to their dire financial straits and distrust of radical innovation.

Intermagnetics went public in 1981. As the company evolved, Intermagnetics was organised under two major segments to design, develop, manufacture and sell its products: Magnetic Products and Refrigeration Products. Magnetic Products consisted primarily of low-temperature superconducting magnets, wires and cable. The main customer for Intermagnetics superconducting MRI magnets remained Philips, who was rapidly expanding in the medical diagnostic area. The MRI magnets were IGC's major source of revenue. These were developed and sold through its Magnet Business unit while the wires were sold through the Advanced Superconductors division. As a part of its Magnetic Products segment, Intermagnetics also developed and unsuccessfully attempted to sell permanent magnet-based MRI systems through its Field Effects division. The refrigeration products segment was expanded to consist of low- and extremely low-temperature refrigerants and refrigeration equipment, which was designed, developed, manufactured and sold through the wholly owned subsidiary, APD Cryogenics Inc. (Intermagnetics General Corporation, 1997).

5.6 Summary

During the era of products and profits, superconductivity was utilised for MRI, a fast-growing and profitable application. However, the largest share of profits accrued to the system integrators, the multinationals leaders in healthcare systems. The advantages of the multinationals (GE, Siemens, Hitachi, Toshiba and Philips) over the magnet suppliers (Oxford Instruments and IGC) were due to the nature of the market and the structure of the industry.

The MRI market was a world market because it could assist in the diagnosis of diseases that occurred worldwide. New modalities were first adopted in the USA, then in Europe, later in Japan and the Pacific Rim, and finally in developing countries. To compete successfully, the multinationals had to serve the world market, with economies of size and of scope. The nature of the healthcare industry, whether government or privately financed, is such that customers (hospitals and clinics) demand complete packages for new high-tech products: equipment (hardware and software), training, maintenance and prompt service. The multinationals already had the complementary assets, the infrastructure and the customer relations to provide the entire package and be handsomely compensated. Because of their size, procurement practices and threat of vertical integration into magnets, their negotiating power was much stronger than the power of the two magnet suppliers.

In economic terms, the multinationals profited from the oligopolistic MRI market, while the suppliers suffered from the oligopsonic magnet market. Given this industry structure, the strategy of the multinationals was to increase the dependency of their suppliers and then integrate vertically through in-house development (GE) or acquisition (Siemens, Philips).

The strategy of the suppliers was to diversify beyond MRI magnets, either through businesses unrelated to superconductivity such as x-ray lithography (Oxford Instruments) or to seek new potential large markets for superconductivity (IGC). Both companies made slow progress in their diversification until a new scientific breakthrough – High-Temperature Superconductors (HTS) – revived their hope for a brighter future.

6 The era of new materials and applications (1991–2003)

In 1986, a truly breakthrough discovery was made in the field of superconductivity. Alex Müller and Georg Bednorz, researchers at the IBM Research Laboratory in Zurich, Switzerland, developed a ceramic–barium–lanthanum–copper oxide crystal ($Ba_xLa_xCuO_4$) – that displayed superconductivity at 30 K (Bednorz and Müller, 1988), work for which they received the Nobel Prize in 1987. What made this discovery so remarkable was that ceramics are normally insulators and do not conduct electricity. Therefore, researchers had not considered them as possible high-temperature superconductor candidates.

This discovery triggered a flurry of activity in the field of superconductivity. Researchers around the world began researching ceramics in a quest for higher and higher T_c's. In January 1987, a research team at the University of Alabama in Huntsville and the University at Houston substituted yttrium for lanthanum in the compound and achieved a transition temperature of 92 K. For the first time, a material (today referred to as YBCO) had been found that was superconducting at temperatures warmer than liquid nitrogen, a commonly available coolant. Additional discoveries have since been made by substituting bismuth, lead, thallium, mercury and strontium in the base perovskite ceramic that was discovered by Müller and Bednorz. The world-record T_c of 132 K is now held by a mercuric-cuprate composed of mercury, barium, calcium, copper and oxygen (Schilling et al., 1993).

Tremendous hype and publicity followed the discovery, crowned by Nobel prizes, of higher-temperature superconductors. A New York Times headline called it "The Biggest Jolt to Power since Franklin Flew His Kite" and the cover of Time magazine showed a futuristic automobile controlled by superconducting circuits. Business Week's headline was "Superconductors! More important than the light bulb and the transistor". International meetings, attended by thousands of scientists and engineers, followed. The US government funded research in order not to be left behind in this scientific and technological revolution. However, in spite of generous R&D funding, the revolution has still not occurred for a variety of reasons that will be discussed below. The first problem was that technological development lagged behind scientific achievements. A 50-year gap between scientific discovery and the first practical application of superconductivity is not uncommon in the history of science (Von Hippel, 1981).

6.1 American Superconductor Corporation

The discovery in 1987 by Swiss IBM researchers of new superconductors with a critical temperature of 92 K (above the boiling point of nitrogen, 77 K) was followed by hype and excessive optimism. Owing to the brittle nature of the materials, the development of reliable and economical products was very slow. The first HTS film was developed in 1988, the first wire in 1989, the first coils in 1990.

As had happened 20 years earlier, the multinational manufacturers were not interested. Instead, in April 1987, an entrepreneurial company, American Superconductor Corporation (ASC) was spun off from MIT by Greg Yurek and others. The company was able to attract venture capital for R&D, and in 1991, Home Depot co-founder Kenneth Langone took ASC public. By 2007, the company had raised over $450 million of capital in several public offerings. However, its revenue was slightly over $50 million, with significant accumulated losses of $385 million to date. It has generated operating losses every year since its inception in 1987 (over $34 million in 2006) and expects to continue incurring losses through 2009. The company expects to raise additional capital before it turns profitable (American Superconductor Corporation, 2007).

6.2 The continuing evolution of Oxford Instruments

The evaluation by Oxford Instruments of the prospects of the new HTS ceramics materials was rather pessimistic, because

> "ceramics do not lend themselves to being drawn into wire conductors and although the critical magnetic fields were high as well as the critical temperatures, the currents these materials could carry were very low. Clearly there was no imminent threat to the technology Oxford Instruments had been developing for over 25 years." (Wood, 2001)

Nonetheless, funds were allocated to finance R&D work in this area at Oxford Superconducting Technology (the R&D subsidiary of Oxford Instruments). According to their 20-plus years of experience, superconductivity had found its best markets in situations where it was the only way to get the job done, or it allowed the job to be done in a much easier, more practical and economical way: magnets for high-field research, high-resolution NMR spectroscopy and, finally, MRI.

Therefore, Oxford Instruments concentrated on improving its manufacturing capabilities for higher quality and lower costs, with incremental product improvements such as shielded MRI magnets. In 1989 they persuaded Siemens to abandon their in-house production of superconducting magnets, which was unprofitable, and enter into a joint venture by acquiring 51% of Oxford Magnet Technology, the magnet company of Oxford Instruments. The entire group was reorganised in 1999 under new management, and all magnet businesses except MRI were merged into Oxford Instruments Superconductivity. The wire operation in New Jersey remained separate, and the MRI joint venture with Siemens was unaffected.

6.3 The continuing evolution of IGC

IGC recognised the importance of HTS and formed the HTS group fully dedicated to R&D in this new field. They developed a 1-MVA HTS transformer in 1998 with first-generation bismuth-based superconducting wire they had produced. In 2000, they purchased the HTS patent portfolio from Lucent Technologies, which had lost interest in HTS. In the same year, IGC established the subsidiary SuperPower LLC to develop and market electrical applications of HTS. They built a pilot facility for producing HTS second-generation wire.

SuperPower investigated several applications of HTS for the electric power industry, such as current limiters, energy storage, motors and generators. To date, the only application in operation is a 20 m HTS cable connected to the power grid, which is working satisfactorily. In spite of the many potential benefits with respect to copper and aluminium wire (three to five times more capacity in existing cable size, smaller size and weight of apparatus, reduced power losses by half, no toxic or flammable materials like SF6 or oils), not a single HTS application has been adopted by the electrical power industry.

The main reason has been the split of the previously vertically integrated industry into fragmented, competitive businesses of generation, transmission and distribution. This fragmentation has caused severe operating problems, including blackouts, high cost of power, loss of profitability and an almost total freeze on new investments in plant and equipment, with little inclination to assume the risks inherent in radical technological innovations (Abetti, 2000). As was indicated earlier for low temperature superconductors, many potential applications were demonstrated, including generators, motors and transformers. However, unless cost and reliability are substantially superior to the incumbent power devices, it is unlikely that HTS materials will ever displace them in the market place. Another potential application is superconducting magnetically levitated trains, but here again the public transportation industry is highly fragmented and subject to unstable political influences and funding.

6.4 Summary

In this era of new materials and applications, the major electrical manufacturers were not interested in HTS, and the three entrepreneurial companies – IGC, Oxford Instruments and ASC – continued to struggle to develop new applications. The main obstacles to commercialisation were:

- high cost of HTS wire, \$150 per kilo amp-meter (kA-m), compared with \$20 for copper
- operating temperatures still limited to 35–70 K, lower than the boiling point of nitrogen
- cryogenic systems that do not operate reliably and efficiently in a high voltage environment.

While progress is slowly being achieved in the above technical and economic areas, the fragmented state of the electrical power industry is not conducive to rapid improvements and radical changes in structure. Thus, the longer-range market prospects of the entrepreneurial companies were not brilliant, since future funding for commercial applications (in contrast to R&D) is uncertain. Consequently, the two major independent champions of superconductivity, although financially solid, became willing potential targets for acquisitions by multinationals.

7 The era of industry consolidation (2004–2007)

7.1 The status of superconductivity in 2004

By 2004, the status of superconductivity could be summarised as follows:

- There is one, and only one, major commercial application – MRI – in a highly profitable and growing oligopsonic market.
- There are relatively uncertain and remote prospects of applications in other industries, due to the unavailability of commercial HTS products and the fragmented structure of the targeted industries. Consequently, Oxford Instruments and IGC realised that it would be difficult to survive, let along grow independently, and developed the exit strategy of takeover by multinational leaders in medical diagnostic systems.

7.2 Siemens acquires Oxford Instruments' stake in the joint MRI venture

Siemens had developed its own high-field (2T) MRI system, 'Helicon', launched in 1987, while continuing to procure low-field low-value systems from Oxford Magnetic Technology, the MRI subsidiary of Oxford Instruments. The Helicon system weighed 30 tons, while Oxford Instrument's 'active shield' magnet was much lighter and less expensive to manufacture. Therefore, Oxford Instruments persuaded Siemens to discontinue its own design and enter into a joint venture, in which Siemens would acquire a 51% stake in OMT. All production would be in England because manufacturing costs were lower there than in Germany. To avoid antitrust problems, OMT would continue to supply its other customers as well as Siemens. The joint venture was launched successfully in May 1989.

In November 2003, Siemens acquired the remaining 49% of OMT from Oxford Instruments for £9.1 million. Thus, the market value of OMT was £18.6 million ($26 million). The balance sheet value of Oxford Instruments's 49% share of OMT was £1.8 million, which means the 'goodwill' payment was £7.3 million, including ongoing use of intellectual property. The joint news release stated that OMT employed 700 people in its factory near Oxford and exported 97% of its systems. They had shipped over 7000 magnets to more than 100 countries, corresponding to one-third of all magnets installed in world hospitals (PR Newswire Europe, 2003).

After the divestiture, Oxford Instruments operated in three areas: medical systems (for monitoring patients), instrumentation (for manufacturing processes) and superconductivity, limited to supplying magnets, wire and components to research laboratories. We will not discuss Oxford Instruments after their exit from MRI, but it is worth mentioning that its profits have fallen from £10.0 million in 2004 to a loss of £(3.4) million in 2006. This shows that it is hard to survive without MRI. This lesson was useful for developing IGC's strategy for divesture.

7.3 The acquisition of IGC by Philips (2006)

Carl Rosner recruited Glenn Epstein, who had worked for Oxford Instruments in 1986, as president and COO in 1997. Epstein succeeded Rosner in 2002 as CEO. Since IGC had only one major customer (Philips), it was under pressure to expand to grow its revenue base. Instead Epstein's new strategy was to concentrate on MRI and divest the businesses IGC had developed or acquired for the purpose of diversification. He then 'dressed the bride' for an acquisition by a major multinational, following the example of Oxford Instruments.

Epstein implemented the new strategy in several steps:

- *2001*: Divested the low temperature superconducting wire division, IGC Advanced Superconductors to a Finnish company, Outokumpu for $32 million
- *2002*: Sold the helium refrigeration business, IGC-APD Cryogenics, to Sumitomo Heavy Industries for $10 million
- *2005*: Sold the cryogenic vacuum pumps business, Polycold subsidiary, for $49 million, to Helix Corporation
- *2006*: Announced that the HTS division, SuperPower LLC, would be spun off.

In parallel, Epstein's strategy was to grow medical devices, the newly focused 'core business' of IGC, with the following steps:

- *2003*: Signed an agreement to exclusively supply superconducting magnets to Philips Medical Systems, with potential annual sales of $20 million
- *2003*: Acquired Invivo Corporation, with product lines complementary to the MRI business, for $150 million
- *2004*: Acquired MRI Devices Corporation for $100 million.

After these strategic moves, IGC had become the leading developer, manufacturer and marketer of cutting-edge technology for advancing a complete range of MRI imaging and patient-care products. IGC supplied the five largest MRI systems companies: Philips (exclusively), GE, Siemens, Toshiba and Hitachi. IGC also served end-users directly and indirectly – regional hospitals, emergency departments, intensive care, cardiac rehabilitation and imaging centres – with RF coils, patient monitors, etc. through the Invivo brand.

Because of the acquisitions and divestitures, the financial performance of IGC from 2002 to 2006 showed impressive sales growth with somewhat unstable profits and stock prices. Nonetheless, by the end of fiscal year 2006, IGC was well positioned with sales of $313 million, net income of $25 million (return on sales = 8.0%), a market capitalisation of more than $1 billion and over 1100 employees. The bride was now well dressed and ready for marriage with an older, experienced suitor whom she had known intimately for several years – Philips of the Netherlands.While GE is the world leader in MRI systems and is vertically integrated in MRI magnets, Philips is the world-leading manufacturer of MRI components and accessories. Thus, Philips was a better match than GE for the IGC bride. In addition, antitrust considerations in the USA and Europe favoured Philips. In contrast to GE, the growth of Philips over the last 25 years had been unstable, profitability unsatisfactory, and the company has suffered several crises (Bartlett, 2006). Philips is the world leader in lighting with 40,000 employees. Medical Systems has over 30,000 employees and is third in market share. Consumer Electronics, Domestic Appliances and Personal Care employ 25,000, but have problems competing with their more agile Asian competitors. Therefore, the IGC acquisition would strategically assist Philips in moving from commodities towards high-value-added, faster-growing and profitable markets.

The acquisition was approved by IGC shareholders in September 2006, effective 1st January 2007 with the following provisions:

- Philips would pay €1 billion ($1.3 billion)
- Intermagnetics would become the global headquarters of Philips' enlarged MRI business
- Glenn Epstein would join Philips to lead the MRI business and the integration process.

After her mother Intermagnetic's marriage, SuperPower became a de facto orphan. Her future will depend on the future of superconductivity outside MRI, which we will now attempt to forecast.

7.4 Summary

It is interesting to compare the last years of the two leading MRI multinationals and of the two major independent superconductivity companies.

- GE spun off IGC in 1971, retaining 40% equity, which it sold back to IGC for antitrust reasons. GE procured magnets from Oxford Instruments and IGC, integrated vertically in 1982 and is now world leader in MRI systems.
- Siemens procured magnets from Oxford Instruments and then developed its own complete systems. Siemens abandoned these in 1993 and entered into a joint venture with Oxford Instruments, acquiring 51% of OMT. Siemens acquired the remaining equity in 2003 and is now the second in the world in MRI.
- Oxford Instruments had 700 employees in 2003 and was worth approximately $23 million.
- IGC, including SuperPower, had 1100 employees in 2006, when it was acquired by Philips for $1.3 billion. Philips is now third in the worldwide MRI business.

We can conclude that IGC did a much better job in 'dressing the bride' and finding a rich suitor. Oxford Instruments has financial problems and IGC's SuperPower became an orphan.

8 A look at the future of superconductivity

Before attempting to forecast the future of superconductivity, let us look back at its 100-year history and draw some tentative conclusions that might give insight into the future, according to the Latin quote: *Historia magistra vitae*! (History is the teacher of life!)

A review of the information presented in this paper leads to the following conclusions:

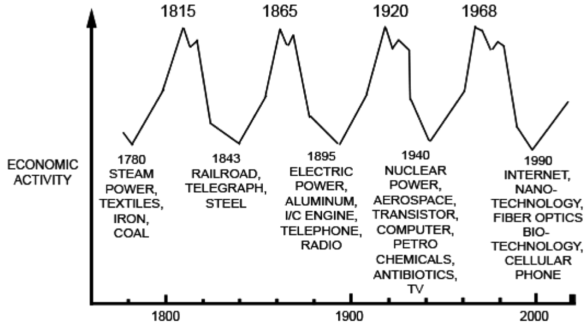
- There has been and still is a major time lag between scientific discoveries, the development of the technology and profitable commercial applications.
- MRI is the only significant profitable application to date. The reasons are that MRI offers unique medical diagnostic information unavailable through competing modalities (CAT, ultrasound, PET, etc.), the worldwide industry is oligopsonic and highly profitable, and MRI magnets and cryostats operate in the controlled environment of hospitals.
- New technologies require applications with substantial benefits and value propositions that cannot be achieved by conventional means. More importantly, the success of technology is clearly in its ability to innovate new applications and uses that did not exist previously.
- Other applications have not materialised to date because they do not offer sufficient economic incentives over traditional electric power and transportation systems.
- The fragmented and politicised structure of the power and transportation industries is change-averse and risk-averse and lacks the financial resources to adopt radical innovations.
- The industry structure has evolved into multinationals that are not interested in developing applications beyond MRI, and government-financed R&D, which is subject to political influences.
- Entrepreneurial ventures have been absorbed by multinationals, and the few remaining have an uncertain future. New ventures will be heavily dependent on venture capital that has become scarcer after the collapse of the 'internet bubble'.

In light of these conclusions, it appears that the future industrial development of superconductivity will depend on new breakthrough applications (like MRI in 1982) that offer unique performance that cannot be achieved with existing technologies. Such breakthroughs are hard to predict (Florida and Kenney, 1991). Nonetheless, it is possible to forecast possible future developments, utilising the theory of economic long waves and the analogy between nanotechnology and semiconductor technology.

The Soviet economist N.D. Kondratiev measured the long-term economic activity of England and discovered that it followed a pattern of long waves (Figure 4). He also found a correlation between times of basic innovation and times of economic expansion (Kondratiev, 1984). His work was revived by Mensch in Germany (Mensch, 1975) and by Ayers in the USA (Ayers, 1990). Their analyses, shown in Figure 4, yield the following observations:

- the length of the waves is 50–55 years
- technological innovations appear at the bottom of the wave
- innovations are successfully implemented at the top of the wave (25–30 years later)
- The new technologies last for two waves (100–110 years). Industries based on these technologies decline after that period, unless they adopt new higher-performance technologies.

Figure 4 Major new technologies as related to Kondratiev waves (1780–2007)



Consider the automotive and telephone industries. Both technologies were first implemented at the bottom of Kondratiev's third wave (1895) and reached their peak 20–25 years later (1920). The depression followed and Kondratiev's fourth wave started after World War II (1950), peaking in 1974, just before the first energy crisis. The next bottom was in 2000 with the energy crisis, pollution, globalisation and the decline of the US automobile industry, which is still totally dependent on petroleum. The telephone industry (AT&T) also collapsed about the same time, but has now found its renaissance in wireless telephony and fibre optics, which are replacing traditional systems with copper wires.

Now, let us look again at superconductivity. The technology was developed at the bottom of the wave (1960) and peaked in 1985. Improvements in technology and applications should start again 25 years later (2010) with a new peak in 2035. In our opinion, the renaissance of superconductivity could appear in the next 10–15 years (2018–2023) and will be based not on incremental progress in the existing technologies (MRI, HTS), but rather on a radical breakthrough in a different highly attractive and rapidly growing industry, possibly nanotechnology, computer, communications, IT, entertainment, clean energy and transportation. The new industry structure could arise from a synergistic cooperation of established multinationals, entrepreneurial new ventures, universities and economic development agencies, and have significant effects on regional economic development. It is unlikely that new innovative applications of superconductivity will emerge from replacing products in the existing industries such as electric power delivery.

A major challenge that is currently facing the superconducting MRI industry is that of helium shortage that is beginning to develop worldwide. One-fifth of the world's supply of the super-cooled gas is used to cool the superconducting magnets in MRI scanning equipment. Helium prices have doubled in the past five years. The sale of MRI machines has grown tremendously, driving the demand for helium up by 25% since 2003. In contrast, helium production has increased by only about half as much. It is predicted that the helium resources, 70% of which came from the USA, will disappear by 2035 or earlier. Although it has not yet had an impact on patient care, it could serve as an emerging opportunity for high temperature superconductors that operate using liquid nitrogen instead of helium.

During the last 50 years, as we have seen, the scientific, technical and industrial development of superconductivity flourished in two geographically distant intellectual centres: Oxford in Great Britain and the Capital Region of New York State

(Albany, Schenectady and Troy) in the USA. This is no coincidence. Both areas are centred around leading universities and laboratories: Oxford University and the Clarendon Laboratory in Britain; The University at Albany (State University of New York), Rensselaer Polytechnic Institute, and GE's Global Research (formerly R&D) Center, all in the Capital Region in Upstate New York. As soon as the technology showed commercial potential, entrepreneurial companies were started by the researchers.

Both regions gradually became seedbeds for new technological ventures, backed by private and public funds. Both Oxford and the Capital Region have become technopolies, following the pattern of Cambridge in Britain and Route 128 around Boston, Massachusetts (Smilor et al., 1988). In Upstate New York State, the technopoly is becoming a world centre of excellence in semiconductors and nanotechnology. Four key drivers were instrumental in its strategy: selecting an overarching discipline (nanotechnology), investing in state-of-the-art infrastructure, focusing on world-class, hands-on education and training incorporating the whole supply chain, and leveraging public–private partnerships. This began in 2001 with the establishment of the Center of Excellence in Nanotechnology at the University at Albany with $150 million in funding from IBM and another $50 million from New York State. Today, the College of Nanoscale Science and Engineering of the University at Albany has established itself as the first college in the world dedicated to research, development, education, and deployment in the emerging disciplines of nanoscience, nanoengineering, nanobioscience, and nanoeconomics. CNSE's Albany NanoTech complex – a $4.2 billion megaplex has attracted over 250 global corporate partners – and is considered the most advanced research complex at any university in the world. This has had enormous economic impact in the Albany–Schenectady–Troy capital region of New York, estimated at over $1 billion. Employment has grown significantly through local hiring and the attraction of global companies. Firms that supply goods and services to the nanotechnology companies have realised the benefits of increased opportunities and the spin-off effects have positively impacted a variety of sectors, from software to service. The region's shift to a nanotechnology strategy has started to pay dividends. The investments in semiconductors and nanotechnology have attracted corporate partners that include IBM, TEL, Applied Materials, ASML, SEMATECH, Vistec, Infineon, Micron, Sony, Toshiba, etc., as well as other 'next generation' nanotechnology research organisations. The facilities established were also set up to provide technology acceleration and business incubation support that is expected to yield start-up and entrepreneurial companies similar to IGC, SuperPower, Cardiomag and others that were established several decades ago.

Therefore, if and when the next breakthrough of superconductivity is realised, the climate and infrastructure for rapid commercial implementation will be much more favourable than 50 years ago. New entrepreneurial ventures will compete and cooperate with established companies to exploit the full potential across a broad spectrum of products, services and industries.

9 Conclusions and policy recommendations

In this paper, we have followed the development of superconductivity through the past century, from science to technology, to products and profits. We have also discussed the evolution of the industry structure, from major research laboratories to entrepreneurial companies, to the adoption of a single major application (MRI) by multinationals and their acquisition of independent companies. We have also explained why MRI is the only breakthrough application of superconductivity to date and why other promising applications, principally in electric power and transportation, have not yet materialised.

It is hard to predict if and when the second breakthrough application of superconductivity will occur. As mentioned above, nanotechnology is one promising area. From a scientific, technological and industrial viewpoint, nanotechnology and semiconductors are being developed according to the concept of the 'triple helix', (Etkowitz, 2003) the close cooperation among academia, industry and government, sustained by the entrepreneurial spirit of the new ventures flourishing in the New York State Capital Region.

As it happened in the development of MRI, discussed above, and as is happening in the nanotechnology and biotechnology industry, new entrepreneurial ventures and established multinationals will become partners, the former in discovering and demonstrating feasibility, the latter in manufacturing and marketing worldwide, to achieve economies of scale and scope.

From this scenario, admittedly speculative, we can deduce some policy recommendations for the future development and applications of superconductive materials.

- research should continue at a cautious level on the development of HTS materials with critical temperatures above 77.36 K (the boiling point of nitrogen) that can be drawn into wire with mass productions costs on the order of $50 per kA-m
- applications should target radical innovations with high benefit-to-cost ratio (Leifer et al., 2000)
- applications should target industries that are growing rapidly with potential high profit, and that are not subject to excessive regulation
- the new technology should be made available, with reasonable financial conditions, to both established and entrepreneurial companies, which should be encouraged to cooperate
- the marketplace should experiment and decide which applications will eventually succeed, rather than allowing government organisations to preselect them or offer 'strategic' subsidies
- private and public grants should be given to all qualified applicants, independently of company size, nationality, affiliation and political connections
- international cooperation and exchange of information, researchers and practitioners need to be encouraged
- after scientific and technological breakthroughs, hype and unreliable predictions should be avoided.

In conclusion, persistence in rigorous R&D work during the next decade, coupled with patience in the industrial and financial communities, will be the driving factors that will enable superconductivity to make a second major contribution to the progress and welfare of mankind.

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Note

[1] This name was changed to magnetic resonance imaging to eliminate confusion with nuclear weapons.