INTRODUCTION TO PROGRESS AND PROMISE OF SUPERCONDUCTIVITY FOR ENERGY STORAGE IN THE ELECTRIC POWER SECTOR

prepared by

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On behalf of the Executive Committee of the IEA Implementing Agreement for a Co-Operative Programme for Assessing the Impacts Of High-Temperature Superconductivity on the Electric Power Sector

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INTRODUCTION TO PROGRESS AND PROMISE OF SUPERCONDUCTIVITY FOR ENERGY STORAGE IN THE ELECTRIC POWER SECTOR

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ABSTRACT

Around the world, many groups conduct research, development and demonstration (RD&D) to make storage an economic option for the electric power sector. The progress and prospects for the application of superconductivity, with emphasis on high-temperature superconductivity, to the electric power sector has been the topic of an IEA Implementing Agreement, begun in 1990. The present Task Members are Canada, Denmark, Finland, Germany, Israel, Italy, Japan, Korea, the Netherlands, Norway, Sweden, Switzerland, Turkey, the United Kingdom and the United States. As a result of the Implementing Agreement, work has been done by the Operating Agent with the full participation of all the member countries. This work has facilitated the exchange of information among experts in all countries and has documented relevant assessments. Further, this work has reviewed the status of SMES and is now updating same, as well as investigating the progress on and prospects for flywheels with superconducting bearings. The Operating Agent and Task Members find a substantially different set of opportunities for and alternatives to storage than was the case before the 1987 discovery of high-temperature superconductivity. Beside the need to level generation, there is also the need to level the load on transmission lines, increase transmission stability, and increase power quality. These needs could be addressed by high power storage that could be brought in and out of the grid in fractions of a second. Superconducting Magnetic Energy Storage and flywheels with superconducting bearings are devices that deserve continued RD&D because they promise to be the needed storage devices.

I. INTRODUCTION

Great progress toward the future practical application of ceramic superconductors has been made since the discovery in 1987 of YBa$_2$Cu$_3$O$_{7-x}$, a ceramic composed of yttrium, barium, copper and oxygen.

As was widely reported then, this ceramic was observed to become superconducting at 92 K, a far higher temperature than had been obtained with any other material. A material in the superconducting state can transport a direct electrical current without resistance (i.e., energy loss). The discovery of high-temperature superconductors, as they are called, raised the hope that further research, development and demonstration (RD&D) would yield materials that would offer economic advantages over those now employed by the electric power sector. The basis for this hope rested on (a) the belief by scientists that the hardest part of the problem had been solved (and so subsequent challenges would be overcome) and (b) the fact that today's refrigeration technology is able to maintain even lower temperatures than 77 K without great expense or inconvenience, when compared with the very low temperatures (i.e., 1.8-4.2 K) that had previously been required for superconductivity. Technically experienced persons understood that great difficulties
remained and that the commercial fruit of the scientific discovery was uncertain, at best. This uncertainty stimulated many to want to better understand the situation as it would continue to develop. An international collaboration was formed to meet that need.

This paper draws upon the work, now under way as well as already accomplished by that international collaboration, now constituted as the International Energy Agency Implementing Agreement for a Co-Operative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector. This IEA Implementing Agreement (IA) concerns itself with future applications of ceramic superconductors in the electric power sector. The IA is described, its efforts are sketched, and its observations are summarized.

II. IEA IMPLEMENTING AGREEMENT

The discovery of YBa2Cu3O7-x was hardly an isolated event. It was stimulated by the 1986 discovery in Switzerland of La1.85Sr0.15CuO4, a ceramic material that becomes superconducting at 38 K. That discovery was completely unexpected by the scientific community. Indeed, a Nobel Prize was soon awarded. Nor did investigation of related materials stop with YBa2Cu3O7-x. Investigators in Japan and the US soon identified Bi2Sr2CaCu2Ox and Bi2Sr2Ca2Cu3Ox as ceramics that become superconducting at higher temperatures; soon thereafter, TlBa2Ca2Cu3Ox was found to have a higher transition temperature. Important and startling scientific progress was made almost simultaneously in Europe, North America and Asia.

All observers understood that no one had a monopoly on progress and that there were many groups of investigators, geographically dispersed, from whom to learn. Energy policy makers and funding agencies were aware of the enthusiasm of scientists and began to consider the potential importance of technical success. In 1988, the International Energy Agency (IEA) organized a meeting of experts hosted by the Ministry of International Trade and Industry of Japan in Tokyo in September. The twenty-five participants, drawn from ten countries, represented electric utilities, industry, public and government-supported R&D organizations, and government agencies. The participants found that they had much the same goal — to assess the likelihood and potential impacts of scientific and/or technical progress, while bearing in mind that the electric power sector requires long-term planning based on the best available information.

It appeared that substantial cost savings might be realized by proceeding cooperatively. Further, the reliability of results from cooperative work could be checked by international peer review. Italy's Ente Nazionale per l'Energia Elettrica (ENEL) offered to host a follow-up meeting of experts for the EA in May 1989. The consensus of that meeting was that, although it would be many years before superconducting technology found routine commercial application in the power sector, progress was such that attention must be paid to both liquid nitrogen and liquid helium superconductors. The participants agreed to continue their hitherto informal cooperation within the framework of an IEA Implementing Agreement.

By the summer of 1990, the IEA Implementing Agreement for a Co-Operative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector was signed by interested parties from Canada, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Norway, Sweden, Switzerland, Turkey, the United Kingdom and the United States. Subsequently, Israel joined the Implementing Agreement. (Also, Belgium paid dues for years two and three, entitling Belgium to
receive the reports from the first three years.) During the past year, Korea also joined the IA.

The Implementing Agreement calls for Argonne National Laboratory (ANL) to be the Agreement's Operating Agent and for work to commence on 1 October 1990. According to the IA, ANL performs three subtasks with the participation of the member countries. Subtask I was to create and subsequently keep current a directory of all the relevant activity in each member's country. This directory keeps members informed about the technical topics (with level of activity) being investigated and it facilitates international communication. Subtask II was to summarize and synthesize assessments already performed within member countries. The resulting report enables each member to access the work of others and judge its relevance to the member's particular situation. Subtask III calls for brief reports, each describing a topic of common interest. These topics have included: IIIa) High Amperage Conductors, IIIb) HTS Use in Generators and Motors, IIIc) Refrigeration for HTS, IId) Progress toward Superconducting Energy Storage, IIIe) Modeling Behavior of Power Systems Using Superconducting Devices, IIIf) Cables and IIIg) Fault Current Limiters. Now, a report on flywheels, using superconducting bearings is under way. The purpose of these reports is to catalyze further consideration of these issues. In all cases, input from the participating countries has been important to the success of the Task.

Further contributions to this Task have been made by several members. Japan's Central Research Institute for the Electric Power Industry (CRIEPI) performed a first computer simulation of the result of a fault on a hypothetical superconducting transmission line with current limiter. Germany's Research Centre Karlsruhe (FZK) hosted an international meeting on Superconducting Energy Storage in October 1994. In April 1995, Israel's Ministry of Energy and Infrastructure hosted an International Workshop on Fault Current Limiters. And in April 1997, Italy's ENEL hosted an International Workshop on HTS Cables. The Task also stays in contact with CIGRE Working Group 11.05 by formal and informal liaison. The work of the Implementing Agreement is documented in a series of reports to the participants and related reports with wider distribution. They are listed, with a more extensive description of this Implementing Agreement, on the World Wide Web at the URL, http://www.iea.org/impagr/imporg/effene/a31htsup.htm. These papers should be consulted for further discussion of some topics mentioned here.

III. THE RECENT HISTORY OF SUPERCONDUCTING STORAGE AND ITS ALTERNATIVES

At this time, the present and projected needs of the electric power sector differ from what they were in the early 1980s. Further, the technical resources with which to respond to these needs are richer than they were in the past.

In the early 1980s, memory of the oil price rise of 1979, as well as the earlier one of 1973, was still fresh. The response had been the construction of nuclear electric generating stations. Their high capital cost and low operating cost made it desirable to baseload these plants. Thus, attention had been given to the possibility of diurnal storage, examples of which were (and remain) Pumped Hydro and Superconducting Magnetic Energy Storage (SMES). The economic attraction of Pumped Hydro depends strongly on geography and cost of transmission. The economic attractiveness of diurnal SMES was tempered with risk aversion because only large-scale SMES appeared economic and this would require substantial investment in an unproven technology. Despite interest by some governments, the required private capital was never forthcoming.
The discovery of ceramic superconductors raised the question of the possibility of substantial cost savings. As the result of subsequent analysis, it was realized that savings from reduced refrigeration costs would not be sufficient to make large-scale SMES economic, even if conductor made from ceramic superconductor were the same price as NbTi, a goal that has not yet been achieved.

In recent years, the perceived need to build new nuclear electric generating stations has abated because natural gas prices have declined, high performance natural-gas-fired turbines are reaching the market, and further advances are promised. These turbines have much lower capital cost than nuclear plants. Further, these turbines are so appealing in some parts of the world that they compete with nuclear power plants that must be relicensed. For example, such turbines may replace some nuclear stations in North America during the next twenty years. Thus, the competition is between adding diurnal storage and adding a gas-fired turbine.

IV. THE NEAR-TERM NEEDS

The need for storage has not vanished, rather it has changed. Smaller units with higher specific power are desired.

The possibility of building new gas-fired stations to compete with existing generating stations has led some to wish for unregulated markets. Other reasons have prompted others to seek the deregulation of electric utilities. This trend toward deregulation differs in force and pace as one goes around the world. However, wherever patterns of generation are changing, new demands will be placed on the existing transmission system. Bottlenecks will show up where none existed before, because of changed power flows. In this situation, distributed storage can ease the peak load for transmission, as well as easing the peak load on the system's generation capacity. Further, transmission stability could be increased by adding variable reactance, such as provided by high power storage that could be brought in and out of the grid in fractions of a second.

On the other side of the meter, business customers wish for more high-quality power, so as to avoid disrupting the increasing amount of computer-controlled machinery on which they depend.

V. A POTENTIAL LONG-TERM NEED

Concern over environmental damage (e.g., global climate change) may prompt future demand for generation by wind and solar. Since these sources are weather dependent, their large scale use would require some form of energy storage so as to synchronize effective generation with effective demand. Of course, nuclear power also avoids the production of carbon dioxide, and the use of nuclear power may increase in some parts of the world (e.g., Asia), bringing with it the desirability of diurnal storage, as noted above.

VI. THE POTENTIAL COMMERCIAL ROLE OF SUPERCONDUCTIVITY

Power quality and transmission line stability might each be improved by developing and deploying Superconducting Magnetic Energy Storage in conjunction with requisite power electronics. The combination of SMES and power electronics appears best suited to demands for very rapidly changing power flows. In the near-term, coils made from NbTi or Nb3Sn will be most economic because of today's high cost of conductor made from ceramic superconductors. However, the cost of operating such coils can be substantially
reduced by using current leads made from ceramic superconductor. These leads can reduce the heat leak significantly and thus lower the refrigeration cost, a cost that is significant for small systems. Further, research on promising ways to lower the cost of ceramic superconductor is required. If successful, this research will further lower the operating cost of SMES.

Distributed energy storage and rapidly changing power flows might also be provided by flywheels. Here, ceramic superconductors offer the promise of magnetic bearings with very low loss. This is most important for energy storage, where energy leakage must be avoided for many hours. Ceramic superconductors are uniquely suited to this application, because the cost of maintaining the bearing at liquid-nitrogen temperatures will not be prohibitive.

VII. TECHNICAL ISSUES

As noted above, research to lower the cost of wire or tape made from ceramic superconductor is required before the full promise of SMES can be achieved. Successful research to increase the capacity of ceramic superconductors to carry current in high magnetic fields would contribute to making more compact devices, something of enduring importance.

Today, it is possible to make very-low-loss magnetic bearings from ceramic superconductors. However, research to determine the behavior of bearing materials over long times and repeated cycling between different conditions is very desirable. The result might be much-lower-cost distributed energy storage than was hitherto possible. Such storage could also provide rapidly changing power levels when coupled to the grid with suitable power electronics.

VIII. AVAILABILITY OF DEVICES AND RESEARCH UNDER WAY

Today, two firms, InterMagnetics General and American Superconductor (via its acquisition of Superconductivity, Inc.), each offer to sell SMES for power quality. Such units store 3-6 MWsec and supply 2-3 MW of power. Today's capital cost is in the range $500-750 K. It is likely that other firms in Europe and Japan could offer similar products, if motivated to do so. While devices are now offered for sale, significant improvements in both capital cost and operating cost are expected during the next few years. Further improvements are likely to require the research, development and demonstration mentioned above. A demonstration, in the US, of a SMES for stabilizing transmission lines is now being discussed. The proposed unit would store approximately 100 MWsec and provide 100 MW of power. Its capital cost would be approximately $30 million. Beside those mentioned, approximately 12 other groups are experimenting with SMES, most focusing on potential future application to improving power quality.

At this time, no flywheels with superconducting bearings are offered for sale. However, important research is under way by at least seven groups in Germany, Italy, Japan, the UK, and the US. Some groups hint at the possibility of a commercial device within the next three years. Such a device might consist of many small flywheels (e.g., 10 kWh, 3kW), sharing power electronics and overall containment. Today, Urenco at Capenhurst, the English arm of a tri-national firm (German, Dutch and English), is choosing partners in order to develop its flywheel, with conventional magnetic bearings; the immediate goal is power quality. Urenco is installing a power quality system using their own 'Pirouette' flywheel which supplies 100 kW of power and stores 2kWh of recoverable energy. The Urenco flywheel project was inherited from IES (England), who offered a flywheel that
stored 3.2 kWh of energy and supplied 5 kW of power. A bundle of ten such units might cost approximately 500 K £ or $800 K.

IX. CONCLUSION

Increased ability to store energy and discharge it over various time scales will be more important to the electric power sector in the near future than it is today. Superconductivity with power electronics offers the means to store energy with little loss and to effect rapid and very rapid changes in power. Further RD&D toward this end appears to be both warranted and promising.