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Abstract

A first assessment of the technical and economical consequences of liquid nitrogen cooling of new superconductors is given. For the investigation the applications of superconductivity are classified in two categories: First, systems where superconductors are practically indispensable for achieving the system's objectives; second, superconductor applications in competition with highly developed conventional technologies. Further development of those superconducting systems in the first category for which the cost of cryogenic equipment is a smaller fraction of the total system cost (e.g. fusion reactor or MHD generator) will hardly be affected. However, for systems like particle accelerators, research magnets, and NMR spectroscopy and imaging systems, the cryogenic equipment expenditures are significant and LN_2 cooling leads here to a reduction of investment and operating costs, to simplified handling and maintenance, to better reliability and availability, and will thereby improve the acceptance and further spread of these systems. In the second category each application of superconductivity has to be compared with its conventional counterpart, separately. Here, electronic components, power switches, resistive current limiters, and especially the power transmission cables are those applications which look most promising. For magnet applications the main advantageous arguments are less the cost saving aspect but more the higher reliability, simplicity, N_2-availability, and ease of handling.

Abschätzung der potentiellen Vorteile von Hoch-T_c-Supraleitern für technische Anwendungen der Supraleitung

Es wird eine erste Abschätzung der technischen und ökonomischen Konsequenzen der Stickstoff-Kühlung von neuen Supraleitern gegeben. Für die Untersuchung werden die Supraleitungsanwendungen in zwei Kategorien eingeteilt: Erstens, Systeme für die zum Erreichen der Ziele Supraleiter praktisch unabdingbar sind; zweitens, Supraleitungsanwendungen im Wettbewerb mit hochentwickelter konventioneller Technologie. Die weitere Entwicklung jener Systeme der ersten Kategorie, für die die Kosten der kryogenen Ausrüstung ein kleinerer Bruchteil der Gesamtkosten sind (z.B. Fusionsreaktor oder MHD-Generator), wird kaum beeinflußt. Für Systeme wie Teilchenbeschleuniger, Forschungsmagnete sowie Kernspin-Spektroskopie- und Kernspin-Tomografie-Systeme sind jedoch die Kosten der Kryo-Ausrüstung von Bedeutung, und LN_2-Kühlung führt hier zu einer Verringerung der Investitions- und Betriebskosten, zu vereinfachter Handhabung und Wartung, zu erhöhter Zuverlässigkeit und Verfügbarkeit und wird damit die Akzeptanz und weitere Verbreitung dieser Systeme fördern. In der zweiten Kategorie muß jede Anwendung der Supraleitung separat mit ihrem konventionellen Gegenstück verglichen werden. Vielversprechend erscheinen hier elektronische Komponenten, Leistungsschalter, resistive Strombegrenzer und vor allem elektrische Energieübertragung. Bei Magnetanwendungen liegen die Hauptvorteile weniger bei der Kostenersparnis als vielmehr bei höherer Zuverlässigkeit, Einfachheit, N_2-Verfügbarkeit und leichter Handhabung.

Contents

1. Introduction

The recently discovered high T_c-superconductors (htsc) with transition temperatures > 90 K raised enthusiastic expectations about future revolutionary changes in electrical engineering. The aim of this study is to make a first engineering assessment of the potential advantages of cooling superconductors with liquid nitrogen instead of liquid helium and to estimate the impact of htsc's on developments in fields both where He-cooled superconductors are either already well established and where superconductor applications have to compete with well developed conventional technology.

The study is made under the assumption that the new superconductors can be developed to such an advanced state that they will be available at prices and with characteristics comparable to those of present day superconductors like NbTi, Nb_3Sn and other advanced conductors in corresponding applications. The only difference should be that htsc's are cooled with LN_2 at 77 K rather than with He at around 4.2 K.

For the time being such a study can only be very preliminary and incomplete and can only lead to an orientation. However, there exists already the experience with the introduction of present-day superconductors to technical applications in competition with conventional technology. Transfer of this experience to the new superconductors gives confidence that the study's results represent a realistic picture of technical and economic prospects.

From our present knowledge we conclude that htsc's might first be suited for low field applications. For the production of high magnetic fields, the conductor technology would have to be developed much further. Another difficult task might be the development of htsc's for ac-applications at moderate or higher fields.

2. Advantages of cooling with LN_2

2.1 Cooling efficiency and physical characteristics of nitrogen

The data collected by Strobridge already in 1974 (s. Fig. 1, taken from ref. 1) are approximately still valid today. This means that in a closed cycle the cooling efficiency for refrigeration temperatures around 80 K as a percentage of the Carnot value varies from 2% at microminiature coolers (cooling power < 1 W at 80 K) up to 40% at intermediate and large refrigerators (> 1 kW). In this study which concerns larger units, one may assume an average efficiency of 28% of the Carnot COP ("coefficient of performance") corresponding to a required electric power of 10 W for removing 1 W at the LN_2 boiling temperature (77 K). In comparison to this, one needs about 400 to 500 W_{el} for a cooling power of 1 W at LHe-temperature.

In case one wants to cool cryogenic equipments with LN_2 in the open cycle mode, the handling of LN_2 is much simpler and more economical than that of LHe. The latent heat of evaporation is much higher in the case of LN_2. Additionally, the enthalpy - content of vapor between the boiling and ambient temperatures of N_2 is smaller than the corresponding values of He. It is thus not so mandatory to use the vapor for precooling of thermal shields, spacers, current-feedthroughs, etc. as it is with LHe-cooling. The figures in Table 1 which are based on one liter liquid gas illustrate clearly these advantages of LN_2.

Table 1: Some relevant data for LHe and LN_2

	helium	nitrogen
Latent heat of evaporation (kJ/l)	2.6	161
Vapor enthalpy content of 1 l liquid (kJ)	193	187
Costs of larger liquid quantities (DM/l)	15	0.2 - 0.4

Apart from the above advantages of LN_2 as compared to liquid, superfluid or supercritical He there are several more following from other physical characteristics of LN_2. The 63-times higher latent heat of evaporation (s. Table 1) and 7.2 times better thermal conductivity (135 W/mK) as compared to LHe results also in a much better stability in the case of transient events in electrical systems. The peak nucleate boiling heat flux of LN_2 reaches up to 12 W/cm^2 as compared to 0.8 W/cm^2 of LHe[4,5]. Nitrogen gas is a 12-times better electric insulator than He at room temperature and atmospheric pressure, the dielectric strength of non-boiling LN_2 with respect to dc and ac voltages is better by around a factor 1.7 than the corresponding values of LHe or transformer oil[6]. The pulse voltage strength of LN_2 is somewhat better than of LHe and somewhat worse for N_2 vapor as compared to He vapor close to the respective boiling points[7].

Disadvantages in some cases as compared to LHe might be the higher specific weight (0.809 g/cm^3) or the higher dielectric losses of some insulator materials[7] at 77 K as compared to 4.2 K (e.g. polypropylene with $\tan\delta = 2x10^{-5}$ instead of $8x10^{-6}$.)

2.2 Cost of cooling system

Fig. 2 shows a comparison of data collected by Strobridge in 1974 (from ref. 1) with those average US-refrigerator system costs published by Parmer and Liggett[2] in 1985. In the figure included are also European prices of recently sold or at least offered systems based on 1986 German Marks[3]. One can see that the system costs (including installation, transfer, and storage costs) are almost exclusively functions of the input power and practically do not depend on the cryogen used. The average cooling system costs in Europe may be described by the simple function

$$\text{costs (DM)} = 7000 \times \text{input power (kW)}.$$

However, the cost range may extend from 1/2 to twice of this value.

From the above efficiencies and the cost studies follows immediately for He-cooled superconducting installations without intermediate temperature shields that for the same cooling power at operating temperature the LN_2 cooling equipment is on the order of 50 times cheaper than LHe systems.

2.3 Availability and reliability

The availability and reliability of LN_2-cooled equipment is better than that of LHe because of

- lower requirements on the thermal insulation,
- smaller consequences of insulation damages,
- lower costs of additional stand-by equipment,
- simpler and cheaper LN_2 storage systems,
- well established LN_2-infrastructure, at least in industrial countries,
- faster cooldown capabilities
- easier handling

2.4 Superconductor stability

The stability behaviour of superconductors is an important factor, especially with respect to their applicability in magnet technology. A first basic condition is stability by enthalpy only (adiabatic stability), resulting in a requirement for maximum allowable superconductor dimensions, which have to be reduced with decreasing specific heat of the superconductor and its neighbouring normal conducting matrix materials. Fortunately, not only is the specific heat of htsc's two orders

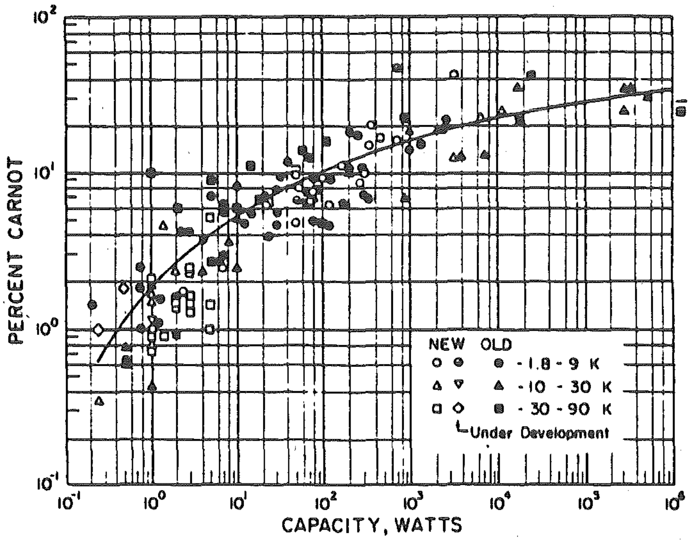

Fig. 1: Efficiency of cryogenic cooling systems
(after Strobridge, 1974)

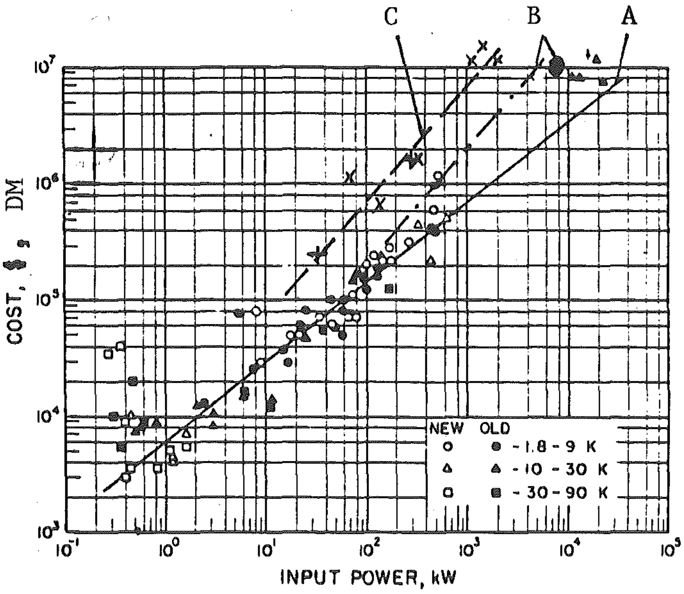

Fig. 2: Cost of cryogenic cooling system
A: Strobridge 1974, cost in \$
B: Parmer and Liggett 1985, cost in \$
(—·—· 4.5 K, ● 77 K)
C: KfK 1987 (x...LHe-refrigerators,
+ ..LN_2-refrigerators), cost in DM

of magnitude higher than that of conventional superconductors but the value for the stabilizing copper at 77 K is increased, too, by a factor of 2000 compared to that at 4.2 K. Therefore a high intrinsic stability of the htsc's and of htsc-copper compounds can be expected, allowing for up to a factor of 10 greater thickness of the superconductor or increased current densities, if achievable, or higher disturbance energies.

Looking for "cryogenic stabilization" of superconductors, the heat produced in a normal zone has to be balanced by cooling. The generated heat is proportional to the electrical resistivity of the copper matrix which is at 77 K still higher by a factor of 5, even if the magnetoresistance at 10 T is taken into account. However, the critical heat flux from the htsc to liquid nitrogen is as high as 1.2×10^5 W/m^2 at atmospheric pressure. This value is roughly 15 times higher than that of liquid helium, so that the higher heat generation can be more than compensated if the corresponding temperature difference of 11 K can be tolerated, e.g.by lowering the operating temperature.If full advantage is taken of the higher critical heat flux, the cross-section of the stabilizing copper could even be reduced by a factor of 2 to 3.

3. Cost of energy losses in electric power systems

The costs of such losses cannot be specified in a general manner. The assessment of the present worth of savings due to lower losses of htsc-equipment, when applied to power systems, depends strongly on the costs of power availability (= costs of making the power available), of energy, on capital costs, inflation, useful life time, rate of utilisation, the fractions of load and no-load losses, and other parameters. These parameters are rated very differently depending where the considered equipment should be installed. For example, taking only the Federal Republic of Germany, the different utility companies show variations of power availability costs from 200 DM/kW per year to 550 DM/kW per year, and of energy costs from 0.0625 to 0.11 DM/kWh. Out of these data the transformer industry calculates values of approximately DM 5000/kW for transformer load losses and DM 15000/kW for no-load losses[10]. These values are used also in this study to evaluate systems where losses play a decisive role, like generators, power cables and transformers. However, one has to realize that in special cases the costs of losses might be lower or higher and the attractiveness of a superconducting installation might change accordingly.

4. Systems with superconductors as indispensable components

The technology of He-cooled superconductors for all applications which are described in this section is already well developed and does not pose major problems any more. The development or utilization of such systems is thus not restrained by superconductor technology. The economical impact of superconductor and cryogenic equipment cost as well as of cooling cost at different temperatures depends on the special application as discussed below.

4.1. Systems where cryogenic installation costs are low compared to overall investment costs.

Fusion reactors and MHD generators belong to this category. In both cases, for the development and later use of these systems it does not matter significantly whether the magnets are cooled with helium in the superfluid, normal fluid, or supercritical state, or with liquid nitrogen at 77 K.

For instance, the costs of the He-cooled magnets of a 1.5 GWe fusion reactor are estimated to constitute around 20% of the construction costs[8]. The refrigerator system will amount to 0.7% of these costs. With htsc's one could only save some of the refrigerator, the cryostat, and the operating costs. This means that the economic future of fusion power will not be influenced significantly. Only if the new conductors should turn out to be much better radiation resistant as compared to present day superconductors, important positive effects might result on the layout and costs of a future fusion reactor. Due to less stringent shielding requirements the reactor could become more compact in such a case. Similar statements can be made with regard to MHD-generators. The costs of the whole magnet system including the cryogenic equipment are estimated to lie between 10% and 20% of the costs of the main system components (combustor, generator duct, air preheater, seed recovery, inverter, steam turbine-generator set, etc.)[9]. The cost savings due to LN_2-cooled superconductors might thus be not significant.

4.2 Systems where cryogenic installation and handling costs contribute significantly to the overall costs

Large particle accelerator and storage rings, research magnets, scientific instruments, or NMR spectroscopy and imaging systems belong to this category. The reduction of investment and operating costs, the simplification of handling and maintenance, and the better reliability and availability will certainly improve the acceptance and further spread of these systems.

For instance, the sophisticated cryostat of a scientific 8T- NMR spectrometer amounts to about 50% of the whole magnet system expenditures. The magnet system in turn constitutes about the half of the overall investment costs, the other half is electronic and diagnostic equipment[10]. One may thus save only between 10% to 15% of the installation costs by using LN_2 for cooling. As the heat load is kept extremely low in these systems, the operating costs are of minor significance and therefore application of LN_2 instead of LHe does not lead to a sizeable effect.

The situation is somewhat different for whole body imaging systems of e.g. the 0.5 T class where the cryogenic equipment again amounts to half of the overall installation costs. However, the extremely well insulated cryostat causes the major part of the costs of this one half[10]. With LN_2 cooling, the installation costs could thus be lowered significantly. The operating costs of imaging systems have to be considered also in view of extra personnel required in hospitals applying such a system. The manpower costs are about 80% and only the rest is cooling cost. Therefore the total operating costs can be reduced here only marginally by replacing LHe byLN_2.

5. Superconductor technology competing with conventional technology

In many cases potential superconductor applications have to compete with conventional, well developed technologies like electronics or electrical power engineering. The expected reduction of cryogenic installation and operating costs, as well as other characteristics of the new conductors and the cryogen may lead to increased efforts in current developments or even revivals of postponed ideas or projects.

5.1 Electronics

Electronic equipment or equipment parts, like computers, AD-converters, SQUIDS, etc., are promising candidates for first htsc applications. Thin films of htsc's can be produced already today, however, the required qualities still have to be verified. The resistivity of the htsc's in the normal conducting state[11] is on the order of 10^{-5} Ωm. Apart from Josephson elements, therefore, electronic switches might well be realized also as cryotrons. The general main advantages of superconducting switches are high speed, low power losses resulting in potential high packing densities, low switching voltages, and also low resistances of the current leads between the superconducting elements. In comparison to conventional apparatus with semiconductor elements, LN_2-cooling constitutes only small restraints or cost increases.

5.2 Electrical power installations and magnet applications

5.2.1 Power switches, ohmic current limiters

Htsc's might find relatively early applications in power switches or limiters for high dc or ac currents. At the time of this writing (June 1987), thin htsc layers with 1 µm can be produced already with current densities[12] of > 10^5 A/cm^2 in zero field at 80 K. Assuming an operating current density of 10^5 A/cm^2, one would need a layer width of 10 m for a 10 kA switch. For instance, this could be realized using 500 tapes, each 1 cm wide, with a htsc layer on both sides. For demonstration purposes we consider a 240 MVA, 20 kV three phase power switch (for rated voltage only). With a resistivity of 10^{-5} Ωm of the normal conducting (quenched) conductor layer, such tapes would have to be 12 m long for reducing the 7 kA ac current (10 kA amplitude) to 1 kA$_{rms}$. The ohmic heat generation would be 10 W per cm^2 which could be just cooled by LN$_2$ within the nucleate boiling region. 75 liter per second would be evaporated per phase in the off-state of the switch.

If a current density of 10^6 A/cm^2 could be achieved, such a switch might become already more attractive. A layer width of 1 m would be needed for the same switch. With a minimum length of 12 m corresponding to 10 W/cm^2 joule heating, the current would be reduced to 100 A$_{rms}$ with a LN$_2$ evaporation rate of 7.5 l/s and phase.

5.2.2 Superconducting power transmission lines

5.2.2.1 Three phase cables

The competitiveness of a future power transmission line employing htsc's may best be assessed by comparing it with outside water-cooled oil cable systems. Such oil cables in the 1 GVA, 380 kV-range have been in service for many years already [13,14]. The optimum voltage for superconducting cables would be lower. By comparing a 380 kV htsc-cable with a corresponding oil cable one has to keep in mind that there is still potential for further improving the economy of the superconducting cable by using lower voltages.

One phase of a 380 kV, 1 GVA oil cable including the outer jacket and without joints presently costs around 1 to 1.3 MDM/km based on a 10 km system length[10]. It is interesting to note that the copper material price constitutes only around 3% of this value (for 1200 mm^2 copper cross section). On the other hand, the high voltage insulation is relatively expensive. One important insulation cost factor is the vacuum impregnation of the insulation with oil.

Such oil cables have to be cross-bonded every 300 to 400 m in order to reduce the outer sheath losses. For this one needs complicated and expensive joints within large joint buildings (about 3x9x4 m^3 ore more)[14,15,16]. The joints without the buildings can be estimated to cost around 300 000 DM/km per phase[10]. The cooling pipes for indirect water cooling contribute another 3% of the system costs (without construction costs).

If the prices of future htsc's do not exceed those of present day superconducors by orders of magnitude, it can be assumed that the costs of the electrical part (= without cryogenic enclosure) of a superconducting power transmission line without joints is comparable to those of a corresponding oil cable including the outer sheathing. One sc-cable phase would possibly consist of an inner conductor made up from htsc-tapes wound onto a mechanical core, the high voltage insulation, and a coaxial outer htsc-conductor, probably again consisting of tapes. Outside of this, a relatively thin star point insulation and armor, as well as a gas tight sheath (corrugated tube) might be applied. The only fundamental additional component as compared to a corresponding oil cable would be the outer coaxial conductor. This would shield any magnetic field from penetrating to the outside. On the other hand, the insulation manufacturing process is probably cheaper since no vacuum impregnation is necessary. The high voltage insulation quality of cryo-cables does practically not depend on the content of humidity[17]. Three such cable phases would be arranged within one common cryogenic enclosure.

Since no cross-bonding is necessary, the joints of a superconducting cable would be much simpler. However, the cryogenic envelope is a significant cost factor, too. Concluding from experience with prototype enclosures[10,18] one can assume material costs of 150 000 DM/km and construction costs of 100 000 DM/km. Considering evacuation and leak testing, an upper cost limit of 500 000 DM/km (or 170 000 DM/km per phase) may be assumed.

Table 2 shows a very rough cost comparison between a water-cooled oil cable system[15,16] and a htsc-cable. The comparison is based on a cable length of 10 km, joints and enclosure[18] are included. The costs of underground structures are not taken into account. For separately laid cable phases, these latter expenditures may amount to 1/2 or more of the cable costs in urban areas[10].

Depending on the loss evaluation, htsc-cables might have a 15-30% economical lead even at the 380 kV level as compared to oil cables. Even with relatively higher superconductor costs or losses, or heat leaks of the thermal enclosure, such a cable could remain competitive. Large costs could be saved due to the small line width and joint buildings. Other advantages are less ageing of the insulation, complete thermal, electrical, and magnetical shielding, the potential of running the cable with natural power, and practically no upper power limit. As already mentioned, the economy of a htsc-cable employing a lower line voltage would be even better.

The current amplitude of such a 1 GVA, 380 kV cable would be 2.15 kA. With a conductor diameter similar to that of a corresponding oil cable (46.5 mm) and a htsc layer thickness of 1 µm, the required current density would be 1.5×10^6 A/cm^2. This is not too far away from already achieved values.

Table 2: Cost comparison of 1 GVA, 380 kV three phase cables

	Oil cable	Htsc-cable
Investment costs without underground structure (MDM/km)	4.5	4.5
Conductor losses (kW/km)	125	10*
Dielectric losses (kW/km)	34	10**
Additional losses, heat leaks (kW/km)	14	15
Overall losses	173	35
Cost of losses (MDM/km)	0.9-2.6	0.18-0.53
Cooling system costs (MDM/km)	0.34	0.25
Total costs (MDM/km)	5.7-7.4	4.9-5.3

* Refrigerator efficiency 10 W/W, the losses correspond to an existing He-cooled 1 GVA, 138 kV superconducting cable prototype[19]

** Plastic-paper or plastic insulation[7,17], $\varepsilon \tan\delta = 3 \times 10^{-4}$.

5.2.2.2 DC-cables

The specific costs of dc-cables are much lower than those of three-phase cables of the same transmission power. This statement is valid both for conventional cables as well as for superconducting ones. The electrical part of a two-pole coaxial superconducting dc-cable could be as small or even smaller than one phase of a corresponding ac-cable. The current of such a dc-cable would not be limited by ac-losses but by the critical current only. The current carrying capacity of dc-conductors is thus much higher than that of ac-cables. Additionally, a dc-cable would not have to be designed for high overcurrents because of the current limiting effect of the converters.

The cable current can thus be adapted easily for optimal converter configuration. For instance, two 4 kA-thyristor sets could be connected in parallel for a 1 GW, 8 kA, 125 kV superconducting dc-cable. In a two-pole cable, the 125 kV-insulation would be arranged between two coaxial conductors, with an additional thin insulation layer on top of the outer conductor.

Apart from the installation costs, the costs of losses of a superconducting dc-cable with LN_2-cooling would be much lower as compared to an ac-cable. There are neither conductor nor dielectric losses to be expected, the thermal leak would be smaller because of the smaller enclosure diameter, too.

Because of the relatively high costs of the converter stations at both ends, a dc-cable has to be very long to be competitive with ac-cables. The break-even length lies between 40 km and 150 km for normal conducting cables[20]. About the same value is to be expected for htsc-cables. For instance, if one considers a two-pole 1 GW cable, the specific costs of the electrical part are assumed to be about the same as those of one phase of an ac-cable. From Tab. 2 and considering the cryogenic envelope, specific costs on the order of about 1.7 MDM/km can be assumed and cost savings on the order of 3 MDM/km cable may thus be expected. With a 125 kV, 8 kA-cable, the specific overall costs of the converter can be estimated to be 150 DM/kW, and the converter efficiency[10] to be 98%. Depending on the converter loss evaluation, the break-even length of the dc-cable would be between 80 km and 150 km. However, additional savings as compared to a three-phase cable might be caused by a smaller outside diameter of the enclosure, and the obsoleteness of reactive power compensators or short circuit limiting devices.

We do not think that superconducting dc-cables, even if they could be cooled with LN_2, will become very important in the foreseeable future. For large distance power transmission, the much cheaper overhead lines will be used as today. For smaller distances within urban or suburban areas ac-cables might be employed. However, dc-cables could be interesting in cases where power supply networks have to be decoupled anyway, or possibly for sea-cables. For the latter ones, fully flexible cryogenic enclosures would have to be used. At this point of time it is not clear yet whether a long length of such an enclosure could be evacuated economically, or whether one could use another thermal insulation of lower qualitiy. Another conceivable future application of htsc dc-cables is the transport of currents at low voltages from large photovoltaic power generator stations.

5.2.3. Inductive current limiters

Inductive, non-linear ac-current limiters consist of two iron cores per phase which are interlinked with a copper ac-coil each and a common dc superconducting coil[21]. The magnetic field of one of the series connected copper coils is in the same direction while that of the other coil is in opposite direction of the dc-field. In the normal operating condition the iron cores are saturated by the superconducting dc-coil, the reactances of the copper coils are low. In case of an overcurrent the field of the copper coil opposing the dc-field is strong enough to desaturate the iron so as to increase the reactance of the device. The copper coils change their roles after each half wave.

Such devices are anticipated to become important within future power supply interconnections to limit fault currents. Presently, the interest in such equipment is rather low. Short circuit currents are limited by using very high voltage lines, by dc-links, or other measures like sequential network tripping, splitting the grid, etc.[20,21]. If technical htsc's were available, the acceptance of such inductive current limiting devices might increase because of better reliability and ease of handling. Additional interest will eventually arise when htsc-cables become available. With such a current limiter lower voltage ac-cables with htsc's might be employed very economically.

5.2.4 Generators

Synchronous alternators with LHe-cooled superconducting field coils are already in a very advanced state of development. The advantages of such machines as compared to conventional generators are lower size and weight by up to 50 %, increased efficiency by 0.5 to 1 %, potential of generating higher voltages, and better stability[22-24].

The costs of a conventional generator including installation work[10] can be assumed very roughly to be around 30 DM/kVA to 35 DM/kVA. A 1 GVA generator may thus cost about 30 MDM or more. The costs of a superconducting alternator will probably not differ much from this value. However, the improvement of efficiency only by 0.5 % results in present worth cost savings of 25 MDM to 75 MDM, depending on the loss evaluation. These savings are thus of the same order of magnitude as the generator costs themselves.

The cooling losses of a LHe-cooled 1 GVA-generator[24] are of the order of 300 kW (refrigerator input power). The use of LN_2 as a htsc-refrigerant would thus increase the generator efficiency by only 0.03 %. The costs of the refrigerator would decrease from around 2 MDM to 50.000 DM. The new htsc's would thus somewhat increase the economy of such a generator. For a He-cooled superconducting rotor the cooling circuit is very complicated. To keep the temperature low enough at the cirumference and to remove ac losses from the windings, a complex system is required using self pumping and thermosyphon effects. However, much simplification of cooling could be achieved by applicability of LN_2. This would become the main advantage of a htsc generator resulting in better reliability, availability and maintenance.

Similar considerations may be true for "fully superconducting" generators with superconducting field and armature windings[25]. Such designs became feasible with the recent development of ultrafine NbTi multifilament conductors (He-cooled). In comparison to conventional generators, savings of weight and losses of 2/3 and 3/4, respectively, are claimed for such generators already with present day superconductor technology.

5.2.5 DC-motors

The development of homopolar motors for ship propulsion, especially for icebreakers, might get new impulses if htsc with desired qualities will eventually become available. Presently, the interest in such machines seems to be limited. One problematic key feature of such a motor is the current collection system. However, suitable sliprings and liquid metal brushes are already well developed[26-28]. The prospect of simplicity and reliability by cooling the superconductors with LN_2 might thus be a considerable incentive for further works on such motors.

5.2.6 Magnetic separation

Magnetic separation in this context means separating weakly magnetic ores or minerals from materials with even lower susceptibility. The acting magnetic force is given by the product of magnetic field and field gradient. Magnetic separation with superconducting magnets follows two lines[29]: Firstly,HGMS (high gradient magnetic separation) and secondly, OGMS (open gradient magnetic separation). A HGMS system consists typically of a solenoid magnet producing a constant background field, and of an insert made from fibrous magnetizable material, the dimensions of which determing the field gradient. The main application for this system up to now is cleaning of kaolin or China clay to improve the whiteness. The OGMS systems produce both the fields and field gradients by positions and shapes of the superconducting windings themselves. The conductor, therefore, plays a significant role in such a system. A selection of the different conceivable concepts of winding configurations has been tested so far.

While conventional magnetic separation is an accepted industrial process, the higher field magnetic separation with superconducting magnets has not yet found that broad industrial application which would be expected with regard to the clean process without any danger for nature. Several reasons can be seen: First of all, the new systems still need to prove their reliability and availability in the rough mining surroundings. Secondly, the price of the material to be treated must allow for the higher costs of the superconductor separator. Third, the number of separation processes requiring the higher fields of superconducting separators is still rather small, and thorough investigations of conceivable processes are needed. More recently, the number of superconducting systems is increasing, and the acceptance of these high technology separators by mining industry is steadily improving.

Advanced demonstration plants nowadays have an integrated, automatic helium cooling circuit which does not need highly qualified operators during normal operation. Nevertheless, if helium could be replaced by nitrogen, the much higher availability of N_2 anywhere in the world and its easy handling certainly would increase the acceptance of superconducting separators. Furthermore, as in a number of OGMS systems, the highest force region is occupied by thermal insulation of the cryostat. A reduction of this space and accepting higher losses at liquid nitrogen temperature level would improve the efficiencies of these systems considerably. The reduction of the costs, however, would be only marginal and is estimated to be on the order of 20 % for both the capital and operation costs[10]. This amount is certainly not of decisive magnitude, however, it will give significant incentives for further developments.

5.2.7 Magnetic levitation

Three different main versions of magnetic levitations were investigated in the Federal Republic of Germany[30]:

- Permanent magnetic systems (repulsive)
- Electrodynamic systems (repulsive)
- Electromagnetic systems (attractive).

The first two of these three levitation systems were given up as not economical. The electromagnetic systems is further investigated in the "Transrapid" prototype levitated train.

Superconducting coils were considered as having economical potential for the repulsive electrodynamic system only. Such a system was developed to a very advanced prototype stage by the Japanese National Railways[31]. In Germany, these developments were terminated after very successful operation of a prototype system for the following reasons: High energy consumption due to breaking losses, little flexibility with regard to operating speed, the need of a second driving gear and active dampers. As further disadvantages were considered the complicated handling of the cryogenic equipment including re-energization of the magnets, and high complexity due to the cryotechnique.

Htsc's would allow simpler on-board euqipment, higher reliability and easier handling. However, the main reasons for stopping the electrodynamic system development program were not the relatively small drawbacks of the "conventional" superconductor technology. Therefore, one cannot expect that possible new superconductors with LN_2-cooling will revive superconducting magnetic levitation developments, at least not in Europe.

5.2.8 Superconducting magnetic energy storage

According to American and Japanese studies based on present day technology[32,33], superconducting magnetic energy storage (SMES) systems with storage capacities of a few GWh might become interesting in future for diurnal load levelling. For instance, the refrigeration system costs of a 5 GWh, He-cooled SMES[32] unit would amount to around 5 %, those of the thermal shielding to 2 %, of the cold-to-warm struts to 14 % and the superconductor costs to 33 % of the direct investment costs. These investment costs make up only about 50 % to 60 % of the total capital cost requirements. Potential savings by using LN_2-cooled superconductors could only be on the order of 10 % at most. Only if the costs of the new superconductors would be dramatically lower than those of present day superconductors, additional significant savings might be achievable. The He-cooled system under consideration is assumed to have a thermal shield at 80 K. The reduction of cryogenic losses by using LN_2 instead of LHe would thus be on the order of 15 % only, compared to LHe-cooling.

Concluding from this, one cannot expect significantly increased interest in SMES systems if suitable htsc should become available.

5.2.9 Reactive power control and system stabilization

Reactive power control and transient system stabilization can be achieved, for instance, with reactors, capacitors, synchronous condensors, transformers, switches, and combinations thereof ("static VAR-compensators"). Such VAR-compensators are very often thyristor-controlled for high flexibility with respect to varying power system requirements[34,35].

A special static VAR compensation circuit comprises fixed capacitors, a full-wave, three phase thyristor bridge, and a superconducting coil carrying a nearly constant coil current[35]. The new htsc's are not expected to increase significantly the competitiveness of such a system as compared to a He-cooled one. For instance, the whole magnet system including the refrigerator and cryostat of a 40 MVAR-unit makes up only about 14 % of the initial costs of the system and only 5 % of the overall losses. Presently, the main hindrance for a wider introduction of such a system is caused by the high costs and the losses of the thyristors.

Small SMES units might have better chances for superconducting power system stabilisation. As compared to VAR-compensators, the advantage of such a system is the ability not only to store and release reactive but also active power[36]. Small SMES units will probably also be suitable to stabilize future fully superconducting synchronous generators[37].

As a result from experiments with a He-cooled, 30 MJ (8.3 kWh) prototype[38] it can be assumed that the efficiency of such small SMES-units might be increased from 90 % of He-cooled systems by a few percent points with LN_2-cooling. The maximum converter rating, the storage capacity of the SMES, and the maximum field change dB/dt are closely interrelated for a certain stabilization capability within a power system[36]. If the magnet could be cooled with LN_2 and thus the cost of cryogenic losses be reduced significantly, the tradeoff between these parameters and thus the optimization of the system might be influenced. For the time being, the impact of LN_2 - cooling on the overall economy of such a unit is not clear yet.

5.2.10 Transformers

The application of superconductors to transformers was studied already in the early sixties. However, all concepts which were considered until recently turned out to be not economical because of excessive losses. Only with the advent of the ultrafine filament superconductors (filament diameter < 1 µm) in the last years, superconducting transformers seem to become attractive alternatives.

With existing He-cooled ultra-fine filament superconductors, loss savings by a factor of up to three, and even higher weight savings can be expected[39,40]. However, it is not feasible to use sufficiently large conductor cross sections in order to avoid quenches in the case of faults. Even with the most modern present superconductors the operating losses for those large cross sections would become excessive. The windings of such a transformer thus have to be dimensioned for overcurrents (= critical currents) on the order of maximum twice the operating current only. As opposed to conventional transformers, fault currents would be dramatically reduced by the quenched windings. This is considered to be an advantage since neither the transformer itself nor other equipment of the same circuit needed to be designed for high short circuit currents and forces. However, a fast switch would be required in series to such a transformer in order to avoid excessive heating of the windings after a quench.

If one could use suitable LN_2-cooled htsc's, the attractiveness of such a transformer could become much higher than with present day ultrafine superconductors. Tab. 3 shows a comparison of a htsc, 1000 MVA, three phase trans former with a typical conventional[10] one. The data of the superconducting transformer are based on the concept of a bank of three single phase coaxial turn transformers[40,41]. The order of magnitude of these data is considered to be representative also for other transformer concepts, e.g. for superconducting three phase core transformers. Htsc characteristics like ac-losses and critical current densities are assumed to be the same as presently achievable with ultrafine multi-filament wires[37,42]. Superconducting as well as conventional transformer production costs are presumed to be comparable.

The conductor losses of such a htsc-transformer become practically negligible. Therefore, one could also consider increasing the conductor cross section in order to avoid quenches in the case of fault currents. On the premises of sufficient low conductor prices, such transformers with electrical characteristics similar to those of conventional ones might be interesting for utility companies, too. The weight and losses, and possibly the costs of such a transformer might be still much lower than those of conventional ones.

Table 3: Comparison of 1000 MVA three phase transformers

	conventional	htsc-transformer
Investment cost (MDM)	15	15
Iron losses (kW)	400	200
Current lead no-load losses (kW)	-	4.7*
Heat leak, dielectric losses (kW)	-	1*
Overall no-load losses (kW)	400	206
Cost of no-load losses** (MDM)	6	3.1
Conductor losses (kW)	1600	6*
Current lead load losses (kW)	-	2.3*
Cost of load losses *** (MDM)	8	0.04
Refrigerator cost (MDM)	-	0.1
Fast power switch (MDM)	-	1
Total cost (MDM)	29	19.3
Conductor weight (t)	150	80×10^{-3}
Total weight (t)	600	110

* Refrigerator efficiency 10 W/W included

** Present worth 15.000 DM/kW

*** Present worth 5.000 DM/kW

6. Other applications

Apart from the described systems, in the past many other superconductor applications were conceived or already investigated comprehensively. Some examples are rf-cavities, magnetic screening of scientific or medical instruments, electromagnetic thruster ship propulsion systems, or magnetic refrigerators. Some ideas seem to be realizable in a more distant future only, others are for rather limited applications. The influence of htsc's on these developments, again, depends on the special case.

7. Summary

A first attempt has been made to assess the technical and economical consequences of future practical superconductors which might be cooled with liquid nitrogen. The investigation is based on the premise that the availability, feasibility, electrical properties, and cost of such high T_c-superconductors (htsc's) are comparable to those of present day superconductors in corresponding applications. The only differences considered are that the operating temperature is 77 K and that the superconductor has a high resistivity ($\rho \approx 10^{-5}\,\Omega m$) in the normal conducting state.

The main advantages of cooling with LN_2 as compared to He-cooling are:

- High efficiency; we assume 10 W input power per 1 W cooling power for cooling capacities of more than several hundred watts;
- Low refrigerator system cost; a simple approximation is valid for He and LN_2 cooling:
  average cost (DM) $\approx$ 7000 x input power at room temperature (kW);
- Low liquid gas cost;
- High reliability and availability because of lower requirements on the thermal insulation, lower cost of stand-by equipment and LN_2 storage systems, well established LN_2-infrastructure, and easier handling;
- Large latent heat of evaporation per liquid volume, high thermal conductivity and peak nucleate boiling heat flux, high specific heat of involved materials at 77K;
- Very good electrical insulation capabilities.

For the evaluation of superconducting equipment where energy losses play a significant role a present worth cost bandwidth extending from 5 000 DM/kW to 15 000 DM/kW is taken.

Two main categories of superconductor applications are discerned: In the first category systems are counted where superconductors are practically indispensable for achieving the system objectives; the second category contains potential superconductor applications which have to compete with highly developed conventional technologies. The following table gives an overview of the expected impact of htsc's on the various applications:

Table 4: Expected impact of htsc's on future development of various superconductor applications

		Impact	
	negligible	improvements with increasing marketing effects	significant
1. Systems where SC are indispensable			
1.1 Cryogenic cost low compared to overall costs:			
Fusion reactors	x		
MHD-generators	x		
1.2 Cryogenic installations contribute significantly to overall costs:			
e.g. particle accelerators, NMR		x	
2. Systems where SC have to compete with conventional technology			
2.1 SC electronics			x
2.2 Power switches			x
2.3 Power transmission cables		x	
2.4 Current limiters		x	
2.5 Magnetic separators			x
2.6 Levitated trains	x		
2.7 Transformers			x
2.8 SC generators		x	

In conclusion one could say that practical high-T_c superconductors might have significant technical and economical impact mainly in fields where superconductor application is already in progress or the cost of losses plays a major role. However, in potential applications where the key problems are others than those in connection with superconductor technology, the impact of htsc's will be small or even negligible.

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