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To cite this version:
W. Heinz. LARGE-SCALE APPLICATION OF SUPERCONDUCTING MATERIAL. Journal de Physique Colloques, 1978, 39 (C6), pp.C6-1618-C6-1628. <10.1051/jphyscol:19786609>. <jpa-00218104>

HAL Id: jpa-00218104
https://hal.archives-ouvertes.fr/jpa-00218104
Submitted on 1 Jan 1978

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LARGE-SCALE APPLICATION OF SUPERCONDUCTING MATERIAL

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Résumé.— On passe en revue l'application à grande échelle de la supraconductivité dans le régime des hauts courants et des hauts champs magnétiques. On discute les propriétés des supraconducteurs techniques. Des aimants supraconducteurs sont déjà utilisés dans une large mesure dans la recherche actuelle des particules élémentaires et des solides. L'application de la supraconductivité dans l'industrie est prévue pour les machines électriques, la levitation magnétique pour le transport à grande vitesse et pour la séparation magnétique des minerais. Des aimants supraconducteurs sont considérés comme indispensables dans les futurs réacteurs MHD et de fusion.

Abstract.— A review of large scale applications of high current and high field superconductivity is given. Requirements to and properties of technically used superconductors are discussed. Superconducting magnets as research tools are widely used in elementary particle and solid state research. Applications of superconductivity for industrial purposes seem to be promising for electrical machinery, magnetic levitation for high-speed ground transportation or magnetic ore separation. Superconducting magnets are considered to be indispensable components for future MHD and fusion power plants.

1. INTRODUCTION.— The last decade has been a period of rapid growth and significant progress of applied superconductivity. Since its discovery by Kamerlingh Onnes in 1911, the potential of important technical applications of superconductivity has been realized. However, it was only in 1961 that the successful operation of the first superconducting solenoid has been announced. From this time on, superconducting was no longer a scientific curiosity. At the present time, development of very large magnets for high energy and controlled fusion research, huge generators, and levitated trains demonstrate the technical importance of superconducting devices.

The benefits and difficulties are due to the unusual properties of the superconductors: They carry current without resistance as long as they remain below their critical parameters: transition temperature, critical field and current. The current density can be several orders of magnitudes higher than in normal conducting metals. Most of large scale applications of superconductivity rely on that property which promises an improved performance and economy compared to conventional devices.

Superconductors show a perfect diamagnetism, magnetic flux is fully excluded below a critical field $B_c$ (Meissner State). Flux exclusion has seldom been used /1/. If a free space is surrounded by a superconductor either being in its Meissner or mixed state external flux is shielded from the interior. This shielding has been utilized in several experiments /2/.

Finally there are the quantum phenomena which characterize the superconducting state. They may be used directly in superconducting electronic devices, but will not be considered in this paper.

Most of the difficulties of superconducting technology arise from the extreme sensitivity of superconductors to small heat inputs. That is due to its transition behaviour and the fact that all materials have a very low heat capacity at low temperature. Thus a rather weak disturbance generating a small heat input may drive the superconductor normal. The skill of the engineer lies in avoiding uncontrolled heat and flux release and providing sufficient cooling to allow the superconductor to recover from disturbances before going normal.

Even if these technical problems can be solved satisfactorily the expectations and achievements may diverge for economical reasons. Superconductors need a cryogenic environment at 1 He temperature. This adds a basic load to all superconducting devices which will usually make only large scale applications economically attractive.

2. WHERE MAY WE BENEFIT FROM SUPERCONDUCTORS ?— One may use a new technology, such as superconductivity for one of two reasons; either:

- to achieve a performance which otherwise is technically impossible irrespective of cost, or

- to improve the performance in relation to cost, weight, or space required compared to alternative
technologies.
Both happen with superconducting devices: superconducting quantum devices using flux quantisation properties (e.g. s.c. magnetometers) and Josephson effects (e.g. SQUIDS) or large s.c. magnets for economic production of high fields in big volumes (e.g. bubble chamber magnets). Mostly large scale applications are of the second type.

Superconducting magnets are able to produce intense fields over large volumes with negligible power e.g. for charged particle beam handling. Very high continuous fields can be obtained. They allow a high power density, which is used in superconducting machinery, and they enable the generation of stronger magnetic forces than with normal conducting magnets which may be used in separating magnetic from nonmagnetic material.

Low losses and high quality factors are essential features of superconducting r.f. devices. Large scale application benefit from the reduction in r.f. power losses which may be more than a factor 10^7 in a cavity with a niobium surface compared to room-temperature copper cavities.

The high current carrying capacity of superconductors can be used in superconducting transmission lines.

Because I am most familiar with the magnet work I will mainly restrict myself to large scale applications of superconducting magnets and give a survey of the state of the art and an impression of size and performance of existing facilities.

3. TECHNICAL SUPERCONDUCTORS.

3.1. Present Superconducting Materials.- For high current applications of superconductivity high current densities and for magnet technology in addition high critical fields are desirable. Thus technical superconductors have to be hard superconductors. The operation temperature commonly used is 1 He-temperature (4.2 K), therefore the transition temperature of technical superconductors should be well above 4.2 K. Because tons of superconducting material are needed in large scale applications, the production process should be simple and cheap. Notwithstanding the variety of superconductors known only very few have been proved to be technically feasible: niobium, an alloy of niobium and titanium (NbTi) and an intermetallic compound of niobium and tin (Nb3Sn) (figure 1). To a limited extent V3Ga with its good high field properties is used especially in hybrid solenoids above a field level of about 13 T for the innermost insert.

Nb has a low upper critical field but also low a.c. losses and has therefore been used for a.c. power cables and superconducting r.f. cavities.

NbTi has a high upper critical field (12 T at 4.2 K), is ductile, and relatively simple to manufacture. Therefore NbTi-based superconductors are almost exclusively used in current magnet applications. Titanium contents of 40 to 50 % by weight are employed. Thin superconducting filaments (5 to 50 µm in size) are embedded in a normal conducting and ductile matrix of high purity copper or sometimes aluminium. The production process starts with thick NbTi rods in a copper (aluminium) boc which is worked down by extrusion (cold working with suitable heat treatments) to the final dimensions of the superconducting wire. Multifilamentary wires with hundreds to many thousands (10^7) of thin filaments may be produced /3/. During this process active pinning centres like dislocation walls and α-Ti-precipitates are introduced. These act as barriers for flux line motion and a high current carrying capacity is generated (table I).

<table>
<thead>
<tr>
<th>Tc[K]</th>
<th>Bc2[T] (at 4.2 K)</th>
<th>Jc[10^5A/cm²] (at 2 T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>9.5</td>
<td>0.16</td>
</tr>
<tr>
<td>NbTi</td>
<td>9.3</td>
<td>12</td>
</tr>
<tr>
<td>NbSiC</td>
<td>9.5</td>
<td>12</td>
</tr>
<tr>
<td>Nb3Sn</td>
<td>18.1</td>
<td>22</td>
</tr>
<tr>
<td>Nb3Ge</td>
<td>-23.0</td>
<td>37</td>
</tr>
<tr>
<td>PbMoS</td>
<td>-14.5</td>
<td>~ 55</td>
</tr>
</tbody>
</table>

Table I: Critical data of some superconductors.
Superconductors with the highest known transition temperatures are intermetallic compounds with A15-structure, but all are extremely brittle. Ribbons with a thin layer of Nb₃Sn are used for a long time. They suffer from lack of stability against field components perpendicular to the tape. Recently, multifilamentary Nb₃Sn-superconductors became available which will enable a wide spread use of Nb₃Sn in magnets. The manufacturing utilizes a solid-state diffusion process. On the bronze route for example, niobium rods are embedded into a tin-bronze. The composite is worked down to its final size and then thermally treated. During this period diffusion of tin and a reaction to form a Nb₃Sn layer takes place. The filamentary size has to be very small (less than 5 μm) because of the brittleness of the reacted layer. In Nb₃Sn grain boundary pinning is the dominating process for fluxoid stabilization. The size and distribution of the grains are optimized by suitable reaction conditions and heat treatments. The critical current densities obtained are considerably higher than with NbTi (table I). V₃Ga is produced by a similar technique. Both Nb₃Sn and V₃Ga are very sensitive to mechanical stresses, but a Nb₃Sn multifilament wire may withstand a strain of about 0.5 % without appreciable current degradation. Because of the stronger contraction of the bronze the Nb₃Sn layer is prestressed during cool-down. Therefore its initial current density slightly improves when an external stress is applied /4/. This effect peaks at about 0.3 % of strain and decreases for higher values up to the point of no recovery at about 0.9 % /5/.

3.2. New Superconducting Materials.- There are at least three goals for improvements of superconducting materials:

1. increased critical parameters, especially transition temperature. This would permit the use of liquid hydrogen for cooling,
2. improved mechanical behaviour and irradiation resistance,
3. processing economy.

A promising candidate for the first objective is Nb₃Ge, which has a Tc of 23 K /6/. The critical current density Jc of Nb₃Ge at 15 K is similar to that of NbTi at 4.2 K (figure 1).

Good mechanical behaviour and improved irradiation resistance may be expected from materials with a less complex crystal structure compared to the A15's. Especially promising candidates in this respect are amorphous materials like metallic glasses in case they are superconducting and have sufficiently high Jc-values. At present transition temperature observed are low and critical current behaviour is unknown.

Carbon fibres are known for their excellent mechanical stress behaviour. Multifilamentary niobium carbonitride wires may offer a near-term solution to the second goal. Carbon fibres with niobium carbonitrides deposited on their surface have shown similar values of Tc and Jc to those of Nb₃Sn in small samples /7,8/.

Highest critical fields have been observed in ternary molybdenum chalcogenides /9/. High Tc- and Jc-values together with the possibility of producing them in multifilamentary form make them good candidates for use in very high field technology.

3.3. Stabilization.- Superconductors may become locally unstable when heat is generated in some region at a faster rate than it can be stored or taken away by the cooling system. As the temperature rises, one of the three critical parameters will be exceeded.

A superconducting magnet is fully or cryostatically stable when a normal conducting bypass of sufficient dimensions is provided. This bypass can carry the full current without heating up beyond the transition temperature of the superconductor. After the disturbance has died away the superconductor may recover and take over the full current again. Copper to superconductor ratios of 10 to 25 are employed.

A superconductor is adiabatically stable if the dissipated energy is kept small enough to be stored as a local temperature rise without causing problems and dynamically stable if the heat is removed more rapidly than produced. Both can be achieved by subdivision of the superconductor, usually in the form of thin filaments embedded in a normal conducting matrix. The ratio of copper of superconductor can be as low as 1:1.

3.4. Mechanical Behaviour.- The major cause of current degradation in magnets is mechanical. This is not very well understood at present. In addition A15-conductors suffer from their extreme brittle-
ness. In bulk form Nb$_3$Sn breaks at a tensile strain of about 0.2%. It is certainly better with materials in multifilamentary form. But the usually accepted strain limit in magnets is 0.1 to 0.2%, the lower limit resulting in greater mechanical stability.

Another phenomenon which has been observed is a quench-dependent current degradation in magnets or short samples of superconductors. The degradation reduces with the number of quenches. Magnet training is observed. A few to several hundred training steps are necessary to reach full current. Magnet training is due to several reasons: conductor movements, impregnation cracking, slippages of parts of the magnet, and stress induced material changes which all may lead to a heat release driving the magnet normal. Short sample training of NbTi seems to be stress induced only. It occurs above a certain low strain and starts again in subsequent steps only after exceeding the previous strain level which has led to a quench /10,11/. The process of energy release is revealed to be strongly dependent on the metallurgical history of the NbTi-alloy. Dislocation interaction with point defects and shape memory effects due to stress induced (martensitic) phase transformations may explain this phenomenon /12/.

3.5 Composite Conductors.—Big magnets call for high currents to reduce inductance in order to avoid untolerable high voltages during a quench. The conductor has to be reinforced to withstand the huge magnetic forces and also to be provided with enough cooling to allow cryo statically stable operation. Besides the stability of the superconductor itself, thermal conduction along and transverse to the composite, heat transfer to the helium, helium flow through the cooling passages, the state of the helium, and a.c. or eddy current losses in the superconductor and the reinforcing material must be taken into account.

A.C. losses of single strands and composite conductors can be reduced by transposing and twisting the conducting filaments or by including high resistive barriers between filaments and strands to decouple them. The conductor is thus "laminated". The conductor may be provided with bath or forced flow cooling. For very big magnets the latter one seems to be preferable.

Depending on the magnet system the conductor has to carry currents of several kA (up to 20), to operate in a magnetic field of about 8 T (NbTi) or 12 T (Nb$_3$Sn), and to withstand tensile and compressive stresses near the yield stress of hard copper (100 Min/m$^2$).

There are three main concepts which have been used or are under development:

- Cabled conductor, where single wires are cabled to a flat or circular conductor. The advantage is a large cooling surface. Reinforcing copper or steel must be included. The conductor may be encapsulated (figure 2) /13/.

![Fig. 2: Forced cooled cabled conductor for high currents (11 kA/8 T) and stresses.](image)

- Monolithic conductor, in which the conductor consists of one block or strip of superconductor, stabilizing and reinforcing material /14,15/. This construction will mainly be used together with bath cooling.

- Hollow conductor, which might be monolithic or a tube enclosed cable. Cooling ducts are integral part of the conductor. This allows a simple cryostat construction, but overall current density is low /16/.

4. LARGE SCALE APPLICATIONS OF SUPERCONDUCTING MAGNETS.—By far the most important large scale applications of superconductivity involve magnets. Somewhat arbitrarily I will divide this chapter into (1) s.c. magnets as research tools, (2) s.c. magnets in electrical power systems, (3) s.c. magnets for other industrial applications and (4) s.c. magnets for future power stations.

4.1 Superconductivity Magnets as Research Tools.—4.1.1. High energy research. High energy research has initiated a lot of developments in superconductivity. Higher particle energies call for larger accelerators, bigger detectors and longer beam li-
nes. The use of superconducting magnets will lead to considerable savings in electrical energy and space.

Beam lines can be shortened by using higher bending and focusing forces which is both economical and desirable when experiments with short-lived particles are performed. For example, a set of superconducting quadrupoles /17/ in a hyperon beam line at CERN has allowed an increase in the intensity of the famous $\Sigma^-$ to such an extent that counter experiments can be performed. The magnets have effective length of 1.1 and 1.4 m respectively and field gradients of 156 T/m. They are remotely and automatically operated, because they are sitting in an inaccessible concrete shielded part of the beam. A high reliability of the whole system, magnets and cryogenics, has to be provided and was demonstrated.

High precision superconducting dipoles for a beam line in the experimental area of CERN have been built and tested by Saclay (figure 3). The integrated field accuracy is as good as $\pm 2 \times 10^{-6}$, the bending force $9 \text{Tm} /18/$. A Nb$_3$Sn sextupole magnet as a focusing element in a neutron beam line is under development at Rutherford Laboratory. A sextupole field of 4.5 T at 25 mm radius will be produced. A great variety of similar magnets have been built and are in use in all big accelerator laboratories. Their performance is good and the technique of superconducting beam line magnets is well established.

Proton synchrotrons or storage rings have huge diameters. It will further grow with increasing particle energies. For economic and dimensional reasons all plans for new accelerators or the exploitation of existing ones involve superconducting magnets. In accelerators these must be pulsed with rise times of several seconds to several minutes. The development of such magnets has proved to be feasible. A.C. losses can be kept low.

Two major projects are seriously being considered in the U.S.: "The Energy Saver" at Fermilab and the Intersecting Storage Accelerator "Isabelle" at BNL. The first one is an upgrade of the existing accelerator to 1000 GeV proton energy. The superconducting ring is installed in the same tunnel beneath the normal conducting rings (figure 4). It consist of more than 1000 s.c. magnets, the main part being dipoles of 22 foot length each. 30 full size dipole magnets and 100 of smaller ones have been built and tested. A string of eight, 22-ft dipoles have been excited to full current and met their specifications. The production process has been studied in great detail and a production rate of one 22-ft magnet per day has been demonstrated /19/. Isabelle is a proton-proton colliding beam facility with two 200 GeV proton beams being accelerated in opposite directions. Full size prototypes of s.c. dipoles (4.5 m, 4 T) and quadrupoles have been constructed and tested /20/.

Detector magnets with a large volume have been used in high energy physics since several years and
still hold the size record. One such development which is performed in collaboration by CEA Saclay and KfK Karlsruhe is a "thin wall solenoid". "Thin wall solenoid" means thin from a radiation standpoint. Particles should pass the magnet wall with only slight reduction in intensity. This calls for light wall materials with low density and low atomic number and high current densities in the coil. The solution makes use of a single layer of high purity aluminium stabilized NbTi conductor wound on a 3 mm thick aluminium bore tube. A wall less than half a "radiation length" thin results; this means a reduction of intensity less than 40%. The main solenoid has 1.5 m useful inner diameter and 4 m overall length (figure 5). The system includes two s.c. coils for magnetic field compensation of 1.4 MJ stored energy each. It is housed within a 1000 ton iron shield and is part of a large 4π magnetic spectrometer for e-p-collisions. It will be installed at the PETRA accelerator, with a large number of detectors deployed around the beam collision area. A similar solenoid is also under development and has been partly tested by Lawrence Berkeley Laboratory.

4.1.2. Solid state physics research.— Many effects in solid state physics show a linear or even quadratic dependence with the magnetic field. Therefore, very high fields are required. A well established technique used in high field magnetic laboratories involves continuous water cooled magnets with axially or radially cooled Bitter coils producing fields up to 25 T in a 4 to 5 cm bore. The power consumption is considerable and limits the fields obtained. An obvious idea is to surround such a magnet by a superconducting coil to enhance the magnetic field with the available power. In this approach the magnetic forces in the normal conducting inner part will limit the maximum field obtained. Such a high field hybrid magnet has been built and successfully operated by MIT. The superconducting coil has an inner diameter of 40 cm and contributes 8.5 T to the total field of 30 T. The total field is achieved with 9.2 MW. A similar hybrid magnet generating 25 T is operated at Kurchatov Institute. A new project is underway for the High Field Magnet Laboratory at Grenoble where the superconducting coil will contribute about 13 T to the total field of 30 T.

4.1.3. S.C. magnets in medical research.— The high fields and field gradients of suitably formed superconducting magnets have been used mainly for two purposes: to guide and position intravascular catheters to relatively inaccessible areas of the human body without major surgery for diagnostic and therapeutic reasons, or to fixate ferromagnetic material which has been infused in order to block anomalous passages of the blood-stream. Clinical experiments have been performed with dogs to treat arteriovenous fistulas and aneurysms or to guide and position a heart pacemaker probe along magnetic force lines into the ventricle of a dog's heart.

A new tool for cancer therapy, using two superconducting toroidal magnets, has been developed at Stanford University, and a similar device is under construction at SIN (Swiss Institute for Nuclear Research). It is a pion spectrometer which will be used to focus energetic pions from an accelerator to a patient's tumor. Pions are considered to be superior to γ- rays or neutrons for irradiation treatment because of their advantageous damage profile in human tissues, which is maximal at the end of their track. Thus, the particle energy can be varied so that the pions will stop in the tissue to be treated.

The double torus design focuses the useful beam, and at the same time, shields against unwanted particles. The two toroids are identical, and are made up of support rings and 60 triangular shaped individual superconducting coils. The Stanford system has a 2.1 m major diameter, produces a field 2.3 T and operates at 1.8 K. The Swiss system is
similar but has a larger diameter (3.3 m) and will be cooled with supercritical helium.

4.2 Superconductivity in Electrical Power Systems.-

4.2.1 Superconducting rotating machines.- Rotating electric machines with superconducting field windings have been proven to be feasible. There exist a lot of experimental machines, d.c. machines as well as a.c. generators, with power ratings up to several MW.

The application of superconductors has the most potential in very large machines and in cases where weight and power density are of prime importance. Its limitations are stability and energy dissipation in alternating load conditions.

Three types of machines have been studied:
- homopolar generators and motors
- a.c. generators
- superconducting linear synchronous motors.

The first s.c. machines to receive significant development effort were homopolar machines because of their simple field winding concept: A disc or drum is rotating in the field of a superconducting solenoid, the current is collected or supplied by brushes at the axis and outer circumference of the disc. The major limit is not with the superconducting coils, but rather with current collection. Motors of 2.5 MW have been built and operated and a motor-generator-set for a complete 1 MW ship propulsion system has been developed and tested /30/. The superconducting technique allows to produce very high torque motors with moderate terminal voltages.

Recently homopolar machines have been investigated as fast discharging energy storage devices for use in plasma research. Machines with a storage capacity of 10 MJ have been built /31/, stored energies of several GJ seem to be feasible.

Experimental work on superconducting a.c. generators was initiated in MIT where a 45 kVA generator was first run in 1969. A 5 MVA machine has been successfully operated at Westinghouse /32/, others are operated at several places, including MIT (2 MVA). The Westinghouse machine will be upgraded to 15 MVA; two 20 MVA alternators are under construction at General Electric, U.S.A., and at All-Union Research Institute for Electrical Machinery, Leningrad, U.S.S.R. /33/. Presently at many places, investigations are performed including system studies and critical component developments towards a large power synchronous generator of several GVA. A model of several hundred MVA which is expected to cover most of the problems and which will allow extrapolation to the size required is considered at several big electrical companies.

In a.c. generators the superconducting part is the rotor. Therefore the superconducting winding and the helium experience huge centrifugal forces. Forced flow cooling with supercritical helium and a rotating helium transfer system must be used. The superconductor is exposed to changing load conditions, and therefore a.c. and eddy current losses will occur. On the other hand promising advantages are anticipated: Reduced capital and operation cost, enhanced efficiency (by about 1% to 99%), reduced size and therefore lower weight to power ratios (figure 6). The development of big superconducting alternators which have to compete with a well established technique in performance, reliability, and economy is one of the great challenges to this technology and to the engineers involved.

4.2.2. Energy storage and transmission.- Superconducting magnets as energy storage devices have rather low power density compared to chemical storage, but exceed that of a condenser bank by more than an order of magnitude. So for special applications, where high current pulses are needed, superconducting energy storage coils together with superconducting high power switchers have been developed /34/ and are technically feasible. It has also been proposed /35/ to include huge superconducting storage solenoids (about 100 m diameter) into the

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Fig. 6 : Specific weight of existing (solid) or planned (dashed) normal conducting and superconducting (double line) alternators. 1 direct gas cooled rotor, 2 direct gas cooled rotor and direct gas and water cooled stator, 3 direct water cooled rotor and stator; s.c. projected superconducting alternators.
power grid to store energy for peak power demands. This seems technically feasible but not yet economically attractive.

Superconducting a.c. or d.c. cables are able to transport large amounts of electrical energy. Models for a rated power of 3 GVA (a.c.) and above (d.c.) have been studied, e.g. /36/. At power ratings below a few GVA, which already exceeds present needs, no cost benefit compared to non-superconducting alternatives like forced cooled cables with oil impregnated paper insulation or compressed gas (SF$_6$) insulated cables will result /37/. Nevertheless investigations are further pursued to beat present limitations, e.g. /38,39/.

4.3. Superconducting Magnets for Other Applications.-

4.3.1. High speed ground transposition.- If a magnet moves along a conducting plate currents will be induced and repulsive forces are developed between the plate and the magnet. Above a certain speed the magnet will be levitated. If the field windings of a motor are rolled out on a track and energized the armature in a vehicle will be propelled along the track. This is the simple principle of magnetic levitation and propulsion by a linear synchronous motor. In both cases superconducting magnets prove to be useful.

Two projects are well advanced: The efforts of the ABC-Telefunken; Brown, Bovery & Cie and Siemens AG in Germany and of the Japanese National Railways (JNL). A test carrier weighing 17 tons and equipped with 4 s.c. lift magnets has reached a speed of 150 km/h on a circular track at Erlangen. Wheels are used at low speed. Ultimately, speeds of 500 km/h are expected /40/.

The JNL are planning to construct a high speed low environmental pollution railway for intercity service. A straight track of 1.3 km is available. Several test vehicles have been constructed and tested /41/.

4.3.2. Magnetic separation.- Magnetic separators are widely used for one separation or raw material purification. The magnetic force is a product of magnetic susceptibility, field-gradient and field. S.c. magnets allow increases in the two latter factors and therefore a reduction of the first. Thus weak magnetic materials can be separated with a suitably designed superconducting device. A series of new applications for magnetic recovery will offer: e.g. beneficiation of weak magnetic iron ores, cleaning of raw materials like kaolin, or water and coal purification. The existing superconducting magnet technology can be taken over, be combined with the existing processing of magnetic separation and adapted to the new conditions. Experiments performed at several places including our laboratory, show promising perspectives. Thus a new application of superconductivity may arise in the near future.

4.4 Superconducting Magnets For Future Power Stations.-

4.4.1. MHD Electrical Power Generation.- In MHD generators electric power is generated by direct conversion of heat. A hot conducting gas is expanding through a magnetic field perpendicular to the direction of flow. A potential increase of the electrical power output for a given amount of fuel by 60 % is expected compared to a conventional steam power plant. A commercial scale MHD channel is 15 to 25 m long with diameters of a few meters. The output power is proportional to the square of the magnetic field. The required magnetic field in this volume will be up to 6 T thus s.c. magnets are vital. However, rather than magnet problems others will turn out to be the critical ones, e.g. hot gas flow train or corrosion.

Interest in MHD power generation has declined in the past but has been revived recently by the fact that the MHD power plant U-25 near Moscow with a power output of 20.5 MW has been operated for more than 4000 h, including 200 h during which it supplied power to the Moscow grid /42/. In 1977 a superconducting magnet, designed and constructed at ANL, U.S.A., has been installed into a by-pass loop with 20 % of the total gas stream. The magnet is 2.5 m long with a 40 cm bore at the magnet inlet and 60 cm at the outlet and produces a field of 6 T /43/. It is part of the US/USSR high-field MHD studies. Another MHD device with a big s.c. magnet is operated by ETL, Tokyo, Japan /44/.

4.4.2. Superconducting magnets in fusion research.- The world's long term energy needs require the development of all relatively inexhaustible energy sources: solar energy, fission and fusion. For a fusion reactor based on magnetic confinement superconducting magnets are indispensable to get a positive energy balance. The development of the super-
conducting technology for use in large fusion devices is therefore essential. Two confinement concepts may finally lead to a reactor: a toroidal device, called Tokamak, or a linear device, called magnetic mirror. In the first, a series of circular or D-shaped coils are arranged to form a torus with a central field of 4 to 8 T (8 to 12 T at the conductor). Plasma diameters of several to ten meters are considered which lead to coils of 10 to 20 m in height. Coils for mirror machines are of similar size.

The magnets experience huge magneto-mechanical forces, changing magnetic fields from subsidiary coils and irradiation by neutrons during operation. They have to be fully stable in normal operating conditions and safe against fault conditions, e.g. against losing vacuum or helium, against shorting a coil to ground or developing a local hot spot. Large amounts of energy (several hundred GJ) are stored in the system which is two orders of magnitude beyond existing s.c. magnet systems.

In the past in fusion experiments superconductivity has been used only scarcely: A few outstanding experiments were made with levitated superconducting rings buried within the plasma, a baseball type coil with 1.2 m bore and generating a mirror field of 5.5 T was used in a neutral injection experiment, or a small toroidal system with 12 small superconducting coils was used for plasma heating and confinement experiments. Presently extensive development of s.c. magnets is being undertaken. A superconducting Tokamak, T-7, has been constructed and tested at the Kurchatov Institute, Moscow. 48 double pancakes divided into 8 sections produce a central field of 3 T and store a total energy of 20 MJ /45/. The mean coil size is about 1 m, the outer diameter of the torus is 4 m. A larger Tokamak, T10M, which has the size of JET and will be equipped with superconducting magnets is under development at Efremov Institute, Leningrad, and Kurchatov Institute, Moscow.

A superconducting Tokamak of smaller size, Tore II Supra, also using s.c. magnets but cooled by superfluid helium under atmospheric pressure is pursued in France /46/. In superfluid helium the heat transport by thermal waves can be utilized, which gives a better stability against transient heat pulses.

A technological experiment is pursued within the framework of the International Energy Agency (IEA) the goal of which is to design, construct and operate a set of 6 large s.c. coils in a toroidal assembly (Large Coil Task, LCT). The test facility will be installed at ORNL. The coils are D-shaped with a clear bore of 2.5 x 3.5 m² producing a field 8 T at the conductor. KfK has undertaken to design, construct and test one coil together with industry, other coils will come from Japan, Switzerland and U.S.A. (3). Part of the development is the composite conductor shown in figure 3, finite element stress calculations, design and test of a forced flow cooling concept. A forerunner, called TESPE (figure 7) /47/, which is of smaller size but

Fig. 7: Schematic view of the superconducting compact from TESPE with 6 D-shaped toroidal coils, poloidal field coils, and plasma simulation coil.

fully equipped with all measuring probes and subsidiary systems is under construction at Karlsruhe and is expected to go into operation within the next year.

5. CONCLUDING REMARKS.—Superconducting technology has experienced a steeply increasing interest within the last decade /48,49,50/. The problem to be faced with its application is the necessity to generate and maintain the cryogenic environment. This burdens all applications with specific cost which can only be encountered in large scale applications, sometimes too large to be within present needs.
That is only different where superconductivity is indispensible to obtain the development goal. Therefore applications in basic research will continue to be one of the main driving forces for further developing superconducting technology.

Presently superconducting magnets and cavities are well established within the research area. So far, however, superconductivity has not been employed for industrial applications. Developments of components which can be simply added to a system instead of changing the whole system are considered as especially promising. Thus s.c. alternators or s.c. magnetic separators will probably earlier replace its room temperature contenders than s.c. cables or s.c. levitated trains. A challenge for the development of superconducting technology is its application for controlled thermonuclear fusion. It is perhaps the most important use of large-scale superconductivity in the future.

ACKNOWLEDGMENT.- I cordially thank many of my colleagues for valuable discussions and for helping me with information and figures.

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