APPLICATIONS AND SECONDARY FABRICATION OF PRACTICAL SUPERCONDUCTING MATERIALS

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Introduction

Two earlier papers in this symposium have dealt with the fundamentals of niobium-based superconductors and the processes which have been used to develop multifilamentary devices. This paper will cover some of the large-scale applications of Nb-based superconductors. Most of these require the construction of magnets of such a size that conductors in the form of fine wires cannot meet their requirements. Secondary fabrication of standard basic units of NbTi and Nb_3Sn wires has therefore to be performed to provide the necessary conductors. The types of secondary fabrication used in making the high current conductors will accompany the description of some of the applications.

First, a brief description of the fine wire units which are converted into the larger conductors by these secondary fabrication techniques.

NbTi

This is a ductile alloy which has been available in a fine multifilamentary form in a copper matrix for almost 15 years (1). It is still the basis of the majority of conductors used in large applications.

The wires are made by a single stage extrusion of billets containing various amounts of copper, most commonly 50 percent, 60 percent and 66 percent. Attempts have been made to standardize the number of copper tubes containing the NbTi rods which are packed into each billet to four ranges - around 60, 200, 500 and 2000. Figure 1 shows a 2100 filament NbTi conductor and Figure 2 a 500 filament NbTi conductor.

Nb_3Sn

Several techniques have been proposed for the manufacture of multifilamentary Nb_3Sn and these have been referred to elsewhere in the symposium (2). At the present time, however, the only method which has been used to produce tonnage quantities is the bronze approach (3). The starting materials can be either bronze tubes *(4)* or drilled bronze billets (3) containing a number of rods. The former can be cold drawn and successively rebundled or processed by extrusion in a manner similar to that used to make NbTi wires. The drilled bronze billets are generally extruded and then drawn to hexagonal rods which are then reextruded.

Attempts have been made to standardize the first extrusion units made from the drilled billets to contain 19, 55 and 187 filaments respectively (5, 6). Varying numbers of these first extrusions can be combined into second extrusions to give a series of small diameter basic unit conductors with different current carrying capabilities. Figure 3 shows one such wire containing 19 x 151 (2869) filaments (7).

Most of the basic units described above have two main shortcomings for large scale applications. They carry only a small current (a few hundred amperes under operating conditions), and they are inadequately stabilized for the high degree of protection required in large magnets.

Some of the large applications involving these magnets will now be described and in certain cases, the secondary fabrication techniques used to modify or consolidate the basic units into the desired conductor configurations will be mentioned.

Applications of Superconductors

While applications for transmission lines (8), quantum interference devices (9), RF cavities, and computer logic and memory systems could be significant in the future, they do not, at present, require multifilamentary materials and therefore will not be considered here. Most of the present, large scale applications involve superconducting magnets. Some of the more significant ones are used in high energy physics and fusion technology, although superconducting magnets are now being considered for use in magnetohydrodynamic, energy storage and rotating machinery applications.

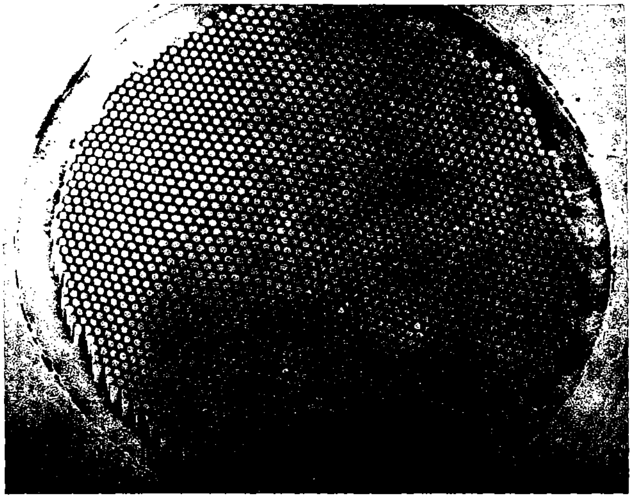

Figure 1 Typical basic unit of NbTi wire containing approximately 2100 filaments. Wire diameter 0.68 mm.

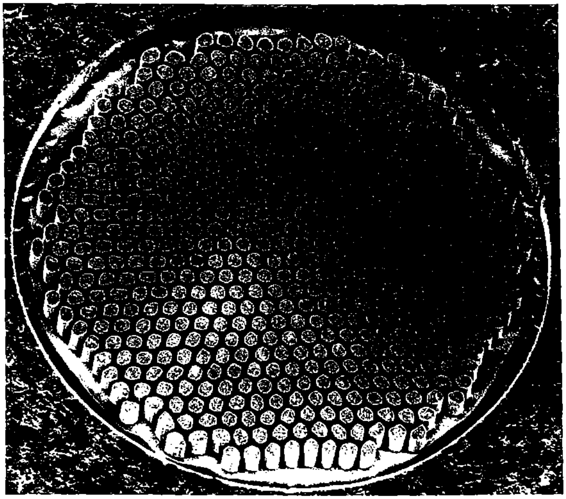

Figure 2 Typical basic Unit of NbTi wire containing approximately 500 filaments. Wire diameter 0.3 mm.

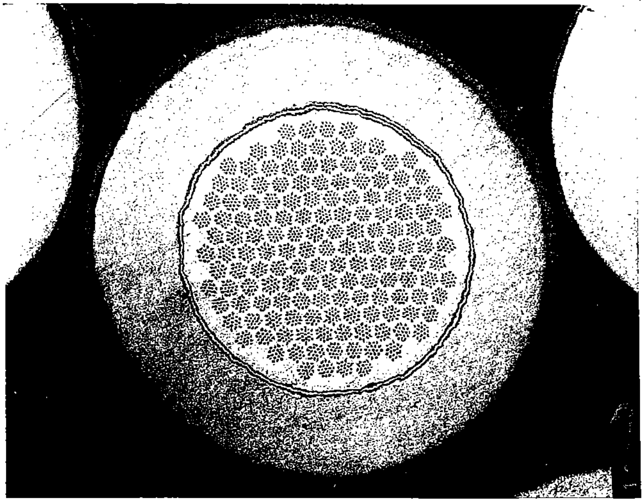

Figure 3. Typical basic unit of Nb_3Sn wire containing 19 x 151 (2869) filaments.

High Energy Physics

The high energy physics (HEP) community was the first large scale user of superconducting materials, first for detectors and then for beam handling equipment. The world's largest superconducting magnet is at the Organization for European Nuclear Research (CERN) in Geneva. It produces a field of 3.5 T over a bore of 4.7 m and is used in the Big European Bubble Chamber (BEBC) (10).

At present, the largest application in HEP is for numbers of much smaller magnets for use in the large accelerators now being built. The savings in electrical energy from the use of superconducting magnets leads to reduced operating costs, size reduction of the devices and auxiliary construction, and accompanying reduction in capital costs.

The Energy Doubler/Saver at Fermi National Accelerator Laboratory (Batavia, Illinois - Figure 4) requires 216 quadrupoles and 774 dipole magnets which have a peak field of 4.5 T and a field uniformity of a few parts in 10,000. These are arranged around an existing ring containing conventional magnets and the resulting total energy is 1000 GeV (hence the name Tevatron) (11).

The Isabelle Intersecting Storage Ring at Brookhaven National Laboratory (Upton, New York - Figure 5) requires 720, 4.75-m long dipoles which must have a 5 T peak field, a larger bore than the Fermilab magnets, and a field uniformity of one part in 100,000, i.e. an order of magnitude more stringent than those required for the Tevatron. Two hundred seventy-six (276) 1.7-m quadrupoles are also required (12).

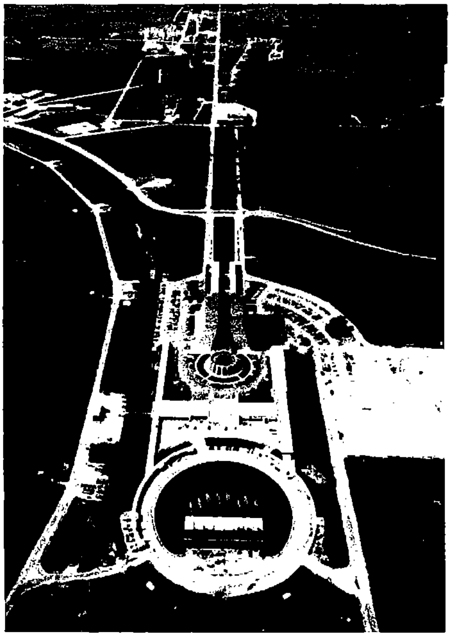

Figure 4. Photo of a section of the Fermilab accelerator ring. It is in this ring that the Energy Doubler/ Saver magents will be located.

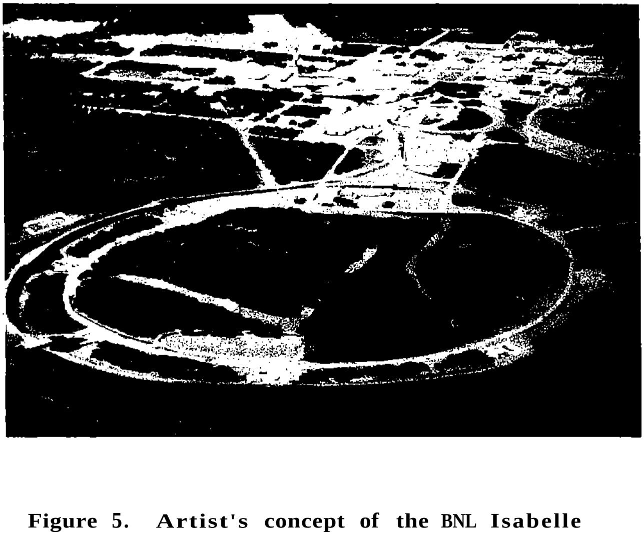

Figure 5. Artist's concept of the BNL Isabelle intersecting storage ring site.

One of the largest European HEP applications promises to be for the Hadron-Electron Ring Anordnung (HERA) to be built in the Federal Republic of Germany (FRG). It will employ 640 4.5-T dipoles and *164* quadrupoles of a design similar to those employed at Fermilab (13).

In the USSR there are plans for a very large proton accelerator, UNK, with an energy of around 3 TeV, to be located at Protvino near Moscow. Its peak field is 4 T and consequently it will have a large radius of curvature approx. 2.5 km.

In Japan, KEK has an expansion program, termed TRISTAN, which initially involves the construction of an electron-positron colliding ring. This will be followed by a superconducting proton ring in the same tunnel. High field, large aperture, warm iron and warm bore magnets are presently under development for this application (14).

These beam handling applications require conductors which are capable of carrying kiloamperes under rapidly pulsed conditions and these requirements have been traditionally solved by cabling or braiding the basic units described above. Figure 1 shows the wire used in the cable developed for the Fermilab Tevatron. This cable consists of 23 basic unit wires, each 0.68 mm in diameter and containing more than 2100 NbTi 8 μm diameter filaments in a copper matrix (Figure *6).* Some of the wires are coated with copper oxide insulation and others with a 95 Sn-5 Ag solder.

The braid for the BNL cosine theta braid magnets was fully transposed with 97 basic unit wires, each 0.3 mm in diameter and containing around 500 8-μm diameter NbTi filaments (Figure 2) in a copper matrix with 90/10 cupronickel around the outside. Problems were encountered, however, in the performance of the BNL cosine theta magnets and these led to the consideration of alternate designs for wide aperture accelerator magnets. The design selected employs cables similar to those used in the Fermilab magnets.

The accelerator magnets to be used in HERA or at KEK are also expected to employ conductors of a similar design to those used in the Fermi magnets, although it is possible that they will contain 27 rather than 23 basic wires.

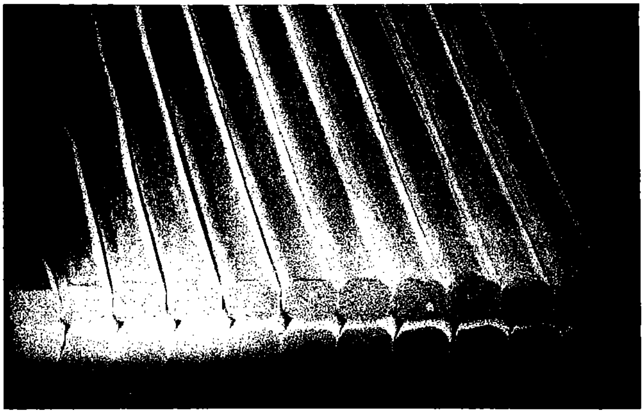

Figure *6.* Cable containing 23 basic units of conductor shown in Figure 1.

Up to this point, the maximum field required for these magnets has been 5 T, however, both the U.S. (15) and Japan are now developing designs which will go to 10 T for the next generation machines. These two countries are working separately and collaboratively on these programs.

In addition to the accelerator and storage ring magnets, similar magnets are required for bending and focussing in the experimental areas connected with the new, and also to a lesser extent, the existing accelerators.

Large magnets are also required for the detectors (16) and for analyzing and cyclotron magnets (17). Superconducting magnets are now being considered for specialized applications such as "thin" solenoids with a low radiation length and a high field quality (18), ion source lenses and magnets for synchroton radiation sources (19).

Magnetic Fusion

While in the past, high energy physics has always been the most significant user of superconducting materials, fusion technology has now developed to the stage where it promises to require large amounts of sophisticated superconductors for its magnetic confinement systems. These are essentially of two kinds: (a) toroidal confinement, and (b) mirror confinement.

Toroidal Confinement

The magnet systems employed for toroidal magnetic confinement have been reviewed recently (20). While most of the toroidal devices are tokamaks, the bumpy torus systems (e.g. EBT), which consist of linked mirror cells formed between adjacent toroidal field coils, will be discussed under this heading.

Superconducting Tokamaks. Although several major countries have been working on the development of superconducting magnets for tokamaks for many years, only one - the USSR - has operated a machine with superconducting toroidal field (TF) coils. The machine, T7, designed and built at the Kurchatov Institute, has 48 coils each with a 0.85 m bore. The conductor is NbTi, laid between copper tubes and joined to them by electroplated copper.

T15, which is now through the design stage, will have 24 coils each with a 2.2 m bore, and will use Nb_3Sn conductor at a current of 8 kA and a peak field of 6 T. The conductor will be internally cooled by helium flowing through two hollow tubes (21).

Tore Supra, a French tokamak with superconducting coils, bas been designed and construction will start shortly (22). This machine has 18 coils, each with a 1.8 m bore. The aim is to achieve a peak field of 9 T using a NbTi conductor cooled with pressurized superfluid helium. The conductor is a rectangular monolith containing CuNi barriers.

The reason why cables and braids of the type described above, for beam handling magnets, were not chosen for this application was that there is a tendency for the individual basic unit wires to move under the high magnetic fields. Such movement tends to drive the magnet normal prematurely. A monolithic conductor, which can be insulated by coating or wrapping, is generally preferred when it is available with the necessary properties. In the case of Tore Supra, the requirement is for a high current density and many fine filaments separated by CuNi as well as copper.

Due to the fact that in the single stage extrusion process usually used for basic units of NbTi, the number of filaments is limited to approximately 3000, it is not possible to make this small filament, high amperage conductor from such a normal basic unit. The solution is then to carry out a double extrusion in a manner similar to that described briefly for the bronze process above.

Such a conductor is shown in Figure 7. It contains 10,285 20-micron diameter filamets in 55 groups of 187, its dimensions are 2.8 mm x 5.6 mm, and it is designed to carry about 3 kA at 9 T and 1.8K. Each filament is surrounded by copper and separated from its neighbors by cupronickel, which helps to reduce eddy current losses in the matrix under the pulsed conditions experienced in Tore Supra. One problem with the double extrusion process is that, because of the material losses at each step of the process, the resultant conductor is expensive. A yield of 85 percent is typical of the extrusion process and a double extrusion therefore gives only a 72 percent yield at best. Since the NbTi alloy cost is frequently more than half the price of the finished conductor, material losses are particularly significant.

Another drawback to large monoliths is that, because they experience only a small amount of cold work compared with fine wires, it is more difficult to develop high curent densities in the larger cross-section materials, although recently techniques have been developed to reduce this effect (23).

In order to overcome the above drawbacks a new consolidation process termed the "compacted monolith" method has been developed. Several basic units which have been drawn to fine crossections, where high current densities (J_c) can be achieved, are wrapped with copper strip which is welded in line and the sheathed assembly then reduced to achieve copper to copper bonding. Due to the fact that material losses are insignificant in this process and the high J_c's in the basic units can be relied upon, the resulting conductor is less expensive than the doubly extruded monolith.

Figure 8 shows a compacted monolith with 6919 filaments in 37 groups of 187 made for Tore Supra. This conductor has been extensively tested and shown to be at least equivalent to that illustrated in Figure 7.

The principal US effort for the development of superconducting coils for tokamaks is to build the Large Coil Test Facility (LCTF) at Oak Ridge National Laboratory (ORNL) which will house a six-coil toroidal array (Figure 9) (20). The U.S. will supply three of the six coils under the Large Coil Program (LCP). Under the auspices of the International Energy Agency (IEA), an agreement was made for the remaining three coils to be supplied by Euratom, Japan and Switzerland, respectively. Each of the coils has a bore of 2.5 x 3.5 m and a peak field of 8 T with conductor currents in the range of 10-19 kA and with the five similar coils at 80 percent of design current. Three of the coils, one of which is made from Nb_3Sn conductor (Figure 10), are internally cooled conductors and the other three NbTi coils are to operate in

A magnet is said to be cryostable when the superconductor is paralleled with sufficient high conductivity copper in close contact with liquid helium that when a local loss of superconductivity occurs, the resistive heating of the copper is small enough for the heat to be dissipated by the helium

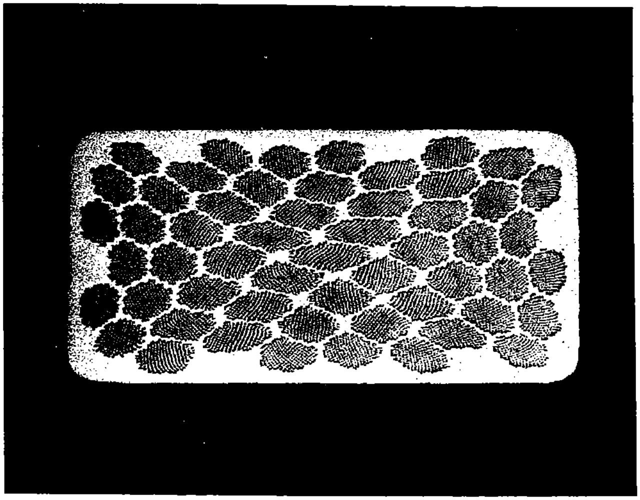

Figure 7. Tore Supra Conductor 2.8 mm x 5.6 mm made by double extrusion.

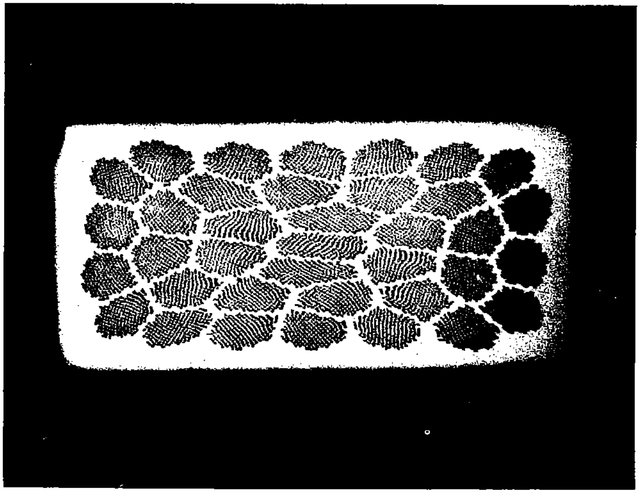

Figure 8. Tore Supra conductor 2.8 mm x 5.6 mm made by compacted monolith technique.

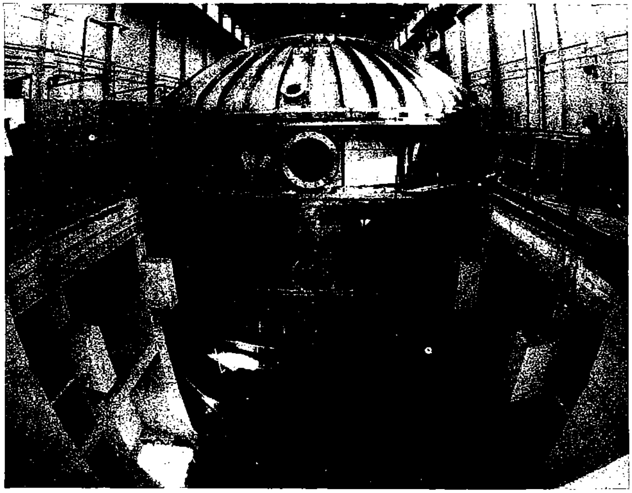

Figure 9. Large Coil Test Facility at Oak Ridge National Laboratory.

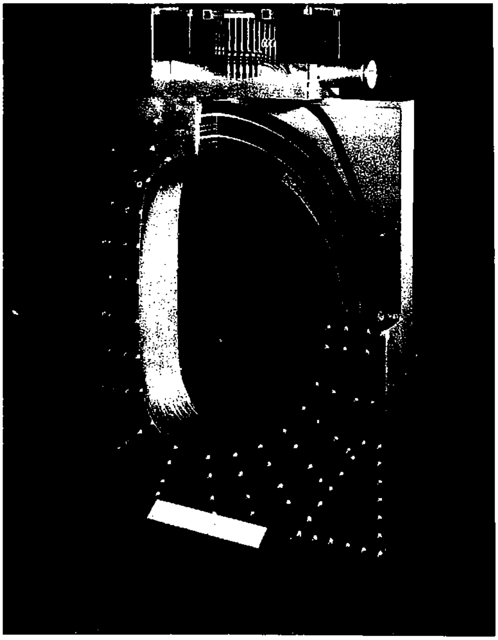

Figure 10. Westinghouse-Airco Large Coil. The only Nb_3Sn coil in the set of six internationally built coils. The conductor is also internally cooled.

coolant and the superconducting state restored. This measure of stability is very desirable for large magnets with stored energies of greater than 10 MJ as a rapid total loss of superconductivity would produce catastrophic effects.

One proposed solution, to provide increased stability, is to create passages in the superconductor through which helium can flow. Such conductors have been called by many different names, but they will be referred to here as internally cooled conductors (ICCS) *(24)*. They are basically of two kinds: cable-in-a-conduit conductors (7) and hollow conductors (21).

Figure 11 shows a cross section of the cable-in-a-conduit conductor for the Airco-Westinghouse Large Coil Project. This is the only coil in the six-coil array which is made from a Nb_3Sn conductor. It operates at *17.6* kA, *4 K* and *8.4* T, and has a square cross-section 20.7 mm x 20.7 mm with rounded corners. The cable is made from *486* (6×3^4) of the basic strands shown in Figure 3 (7) and the tube through which the helium flows is made of a special variant of the iron-based superalloy A286, termed JBK75.

The maximum field for which all the conductors for this Large Coil Program (including the Airco-Westinghouse Nb_3Sn ICCS) have been designed is *8* T.

It is as yet uncertain at what field the next generation of tokamaks will operate, but both the U.S. and Japan are building test facilities, the High Field Test Facility (HFTF) at Livermore (Figure 12) *(25)* and the Cluster Coil Facility at the Japan Atomic Energy Research Institute (JAERI) (26), designed ultimately to go to 12 T and 10 T, respectively. These facilities will be able to test conductors which are designed to be used in the next generation machines.

Figure 13 shows the conductor to be used in the coils for HFTF at the Lawrence Livermore National Laboratory (27). It is made by cabling *54* ($6 \times 3 \times 3$) strands of a basic unit of Nb_3Sn conductor containing (187 x *85)* filaments. This cable is wrapped with copper strip which is welded in line and the sheathed assembly made into a rectangular cross-section. Two stabilizer strips, tinned on one side, are added to the HFTF core to form the final conductor. The design current for the conductor is *7.5* kA at 12 T and *4.2 K*, although the operating current for the magnet is *5* kA. This "compacted cable" is similar to the "compacted monolith" used for Tore Supra and EBT-P but in the case of the "monolith", the basic units are fed into the sheath in a parallel array.

The U.S. 12 T program, although plagued with funding problems, has been aimed to produce conductors capable of operating at 12 T for tests in the HFTF magnet. The LCP conductor shown in Figure 11 has been proposed for the Airco-MIT 12 T coil *(28)*. Figure *14* shows the "compacted monolith" proposed for the Airco-GD 12 T model coil (29). This conductor is similar to the one developed for HFTF and consists' of a 199-strand compacted monolith joined to a copper stabilizer.

In addition to the work described above directed towards the development of superconducting toroidal coils, work is also underway, if to a somewhat lesser extent, on the development of poloidal coils which will also be an essential part of some superconducting tokamak machine.

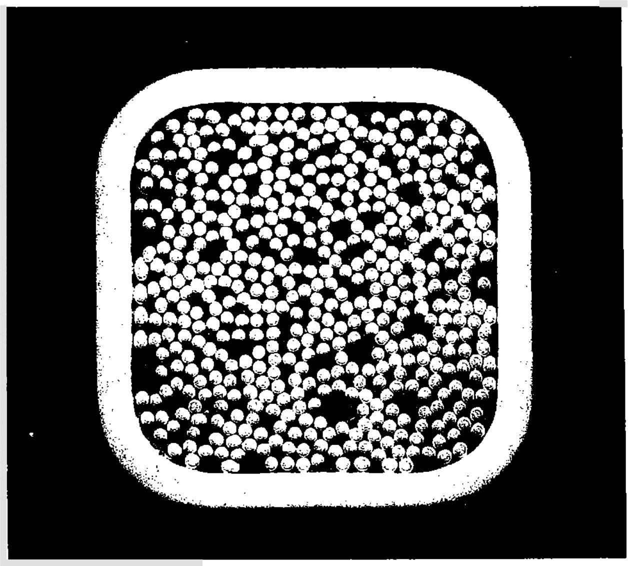

Figure 11. LCCS Nb_3Sn cable-in-conduit conductor for the Westinghouse-Airco coil. It measures 20.7 mm x 20.7 mm and contains *486* strands *of* the basic unit shown in Figure 4.

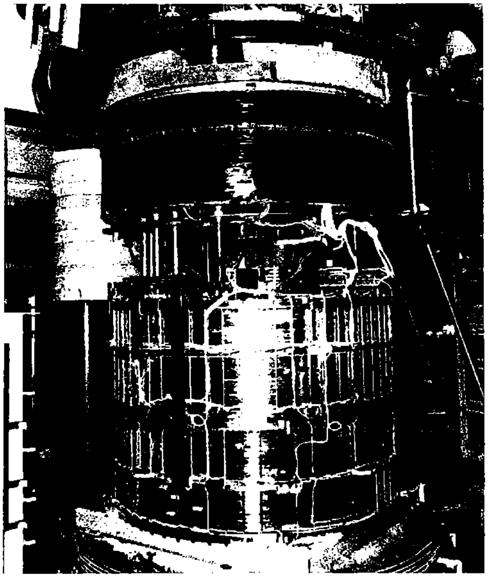

Figure 12. The NbTi back-up coils for the HFTF magnet at LLNL. The Nb_3Sn coils will be inserted inside these coils.

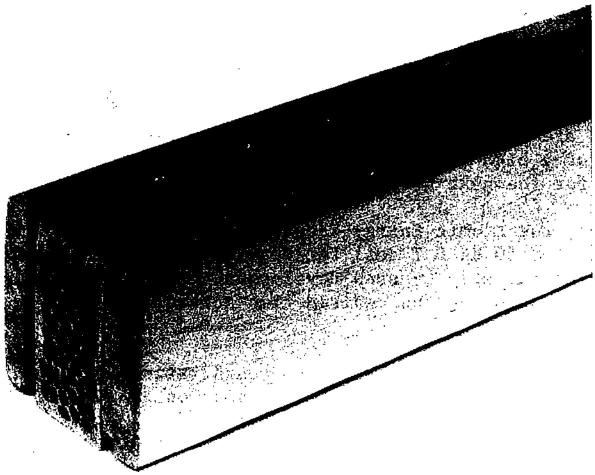

Figure 13. Complete Nb_3Sn compacted cable HFTF conductor with stabilizer strip added.

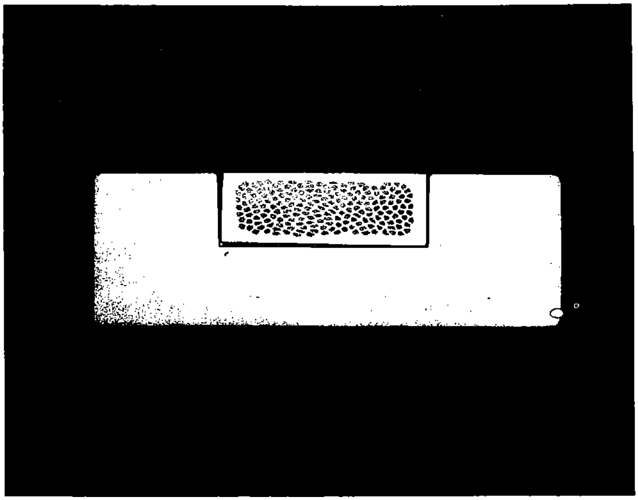

Figure 14. Nb_3Sn compacted cable conductor proposed for the Airco-General Dynamics 12 T coil.

Tokamak Poloidal Coil Development. The Los Alamos Scientific Laboratory (LASL) has a program to produce a conductor for the pulsed induction windings of the tokamak. A 20 MJ coil is being built by Westinghouse (Figure 15) with a conductor capable of carrying 50 kA with a field swing from -7 to +7 T in a few seconds (30).

Efforts are underway, at Argonne National Laboratory, towards the development of a high current, high pulse rate superconducting ohmic heating coil needed for the next generation of tokamak (31).

In Japan, the Atomic Energy Research Institute (JAERI) has a tentative plan for a 100 MJ 50 kA 8 T coil for testing in the next few years (32). They already have a step by step development program underway designed to produce the conductor on the desired time schedule.

FED and INTOR. Over the past few years various groups in the U.S. and abroad have been considering how the tokamak concept can be embodied in a practical, electricity-producing power plant.

The U.S. domestic effort is directed towards a device termed FED (the Fusion Engineering Device) (33), whereas the international team, which meets under the auspices of the International Energy Agency (IAEA), is working on a concept called INTOR (International Tokamak Reactor) (34). This team has representatives from Euratom, Japan, the U.S. and the USSR.

The toroidal magnets for both machines are large in comparison with the coils which have been built up to this time (Figure 16).

Elmo Bumpy Torus. As mentioned earlier, there is an alternate confinement system, the Bumpy torus system (EBT) which consists of linked mirror and toroidal field coils. The EBT-P proof-of-prinicpal experiment is to be built at Oak Ridge National Laboratory with McDonnell Douglas as the principal contractor (Figure 17). The machine will have 40 circular coils each with a winding bore of 0.48 m. The peak field is 7.4 T, and because of the constraints of the machine design, a current density in the windings of at least 10,000 A/cm^2 was originally considered necessary. A metastable design using NbTi cooled in boiling helium at atmospheric pressure was chosen and two prototype coils have been built and operated successfully at ORNL (35).

Figure 18 shows a cross-section of the conductors used in these coils. The 6 T conductor consists of 9 basic units each containing 517 NbTi filaments and the 8 T conductor contains 37 basic unit strands (36). Both were continuously sheathed in copper strip, welded, compacted, drawn and made into rectangles. The technique used was the "compacted monolith" one described above for Tore Supra, although in this case no cupronickel was included in the structure.

Conductors with apparently simpler configurations and lower specifications are now being made for further prototype coils to be built both by ORNL and General Dynamics-Convair (GD). The latter is under contract to McDonnell Douglas to build the coils.

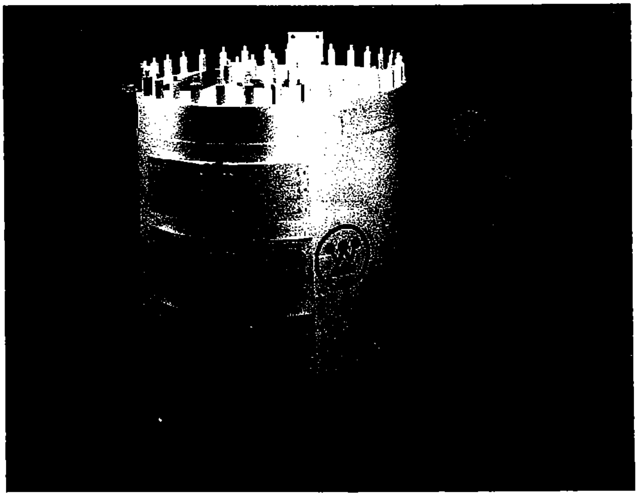

Figure 15. The Westinghouse 20 MJ coil to be used to test the applicability of a conductor to tokamak poloidal systems.

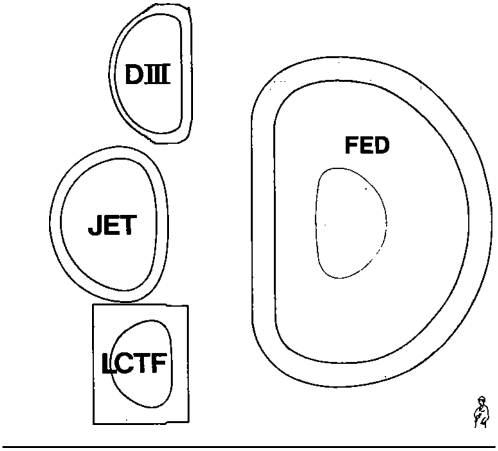

Figure 16. Relative scale of the Large Coil Test Facility and FED toroidal field systems. The conventional magnet coils for Doublet III and JET (Joint European Torus) are shown for comparison.

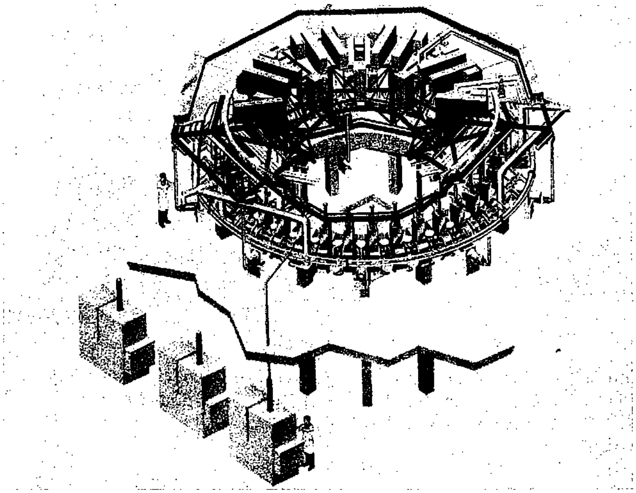

Figure 17. Schematic drawing of EBT-P proof of principal machine to be built by McDonald Douglas at the Oak Ridge National Laboratory.

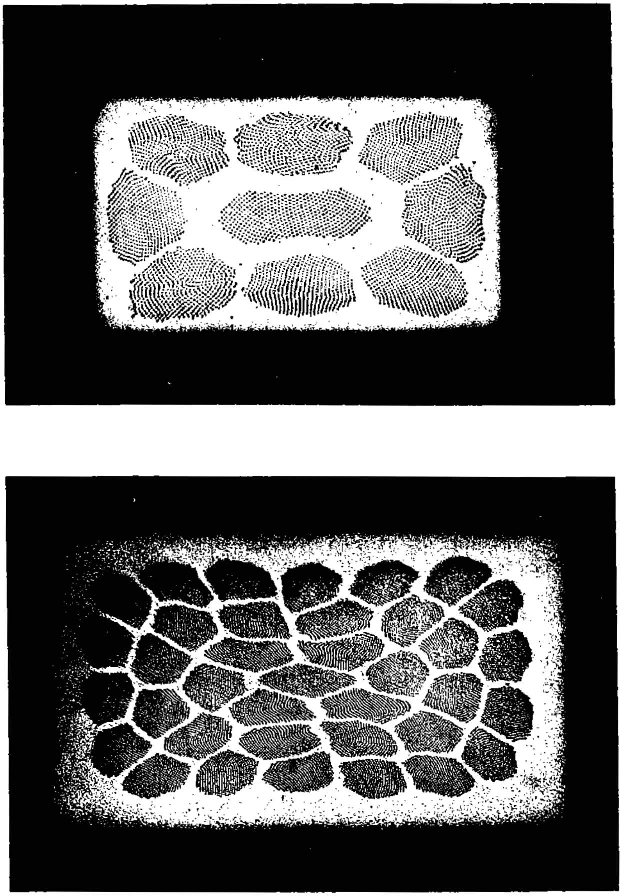

Figure 18. Compacted monolith EBT 7 and 8 T conductors containing 9 and 37 basic units, respectively. Dimensions are 2.9 mm x 5.0 mm and each basic unit contains approximately 500 filaments.

Mirror Confinement Systems

From the beginning of research in mirror fusion, it has been recognized that, when the mirror machines are compared with the closed toroidal systems described above, they are subject to plasma end losses and this is an inherent disadvantage. Despite considerable developments in design, leading to field reversed mirrors or tandem mirrors such as the Mirror Fusion Test Facility-B (MFTF-B) at Lawrence Livermore National Laboratory (LLNL), these end losses can still occur. The use of the highest possible magnetic fields has always been contemplated as a way of compensating for this.

In view of this and particularly because miror machines are fundamentally DC machines, they have always been good candidates for superconducting magnet systems.

Through the Sixties and Seventies, baseball magnets were built at LLNL and Kurchatov and work on floating rings was done at LLNL, Princeton and Culham.

The work at LLNL progressed the most rapidly and led to the tandem mirror device MFTF-B (37), the coils for which are now being built by General Dynamics/Convair. When completed in 1985, this magnet system will be the largest in the world with a stored energy of 3000 MJ - more than three times that of the present largest (BEBC magnet at CERN (10)). MFTF-B consists of two Yin-Yang magnets, one of which has been completed as MFTF-A (Figure 19), four other similar coils for the end plugs and fourteen solenoids which create a central solenidal section about 30 m long, the overall length of the vacuum system being 64 m (Figure 20).

The very large amount of stored energy in the coils demands that appreciable quantities of copper must be in the conductors. Long twisted lengths are always required and it is expensive to co-process large amounts of copper with the composite containing the superconductor.

While one solution to the problem is to wrap with copper as in the "compacted monolith" method, even this approach is not economical for the addition of large amounts of copper. One solution is to make a composite containing a low percentage of copper and then join it by crimping, soldering, brazing or welding to a piece of suitable high resistivity ratio copper usually in the form of a channel.

The solenoids for the MFTF-B machine are expected to be made from a conductor of this type. Figure 21 shows a sample of this type of conductor which was produced for a rapid cycling bubble chamber at CERN. It carried 4.5 kA at 6.5 T and 4.5 K and measured 14.8 mm x 8.7 mm overall.

One of the drawbacks of adding the stabilizer in a manner illustrated in Figure 21 is that only one surface of the composite is in close contact with the liquid helium bath. Since liquid helium is a better heat transfer agent than copper, it is desirable that it should be as close as possible to all parts of the superconductor. One way of achieving this is to make an extended surface area conductor. Figure 22 shows such a cryostable pool boiling conductor (38) with internal cooling channels and a simple rigid outside configuration for easy insulation and winding. The internal channels are formed by wrapping an embossed copper strip around the core and soldering the two together. This is the conductor for the Yin-Yang magnets of MFTF-B. The other four end plug coils have the same configuration with a modified core. The conductors have a monolithic 6.5 x 6.5 mm core containing several hundred filaments each several hundred micrometers in diameter. The conduc-

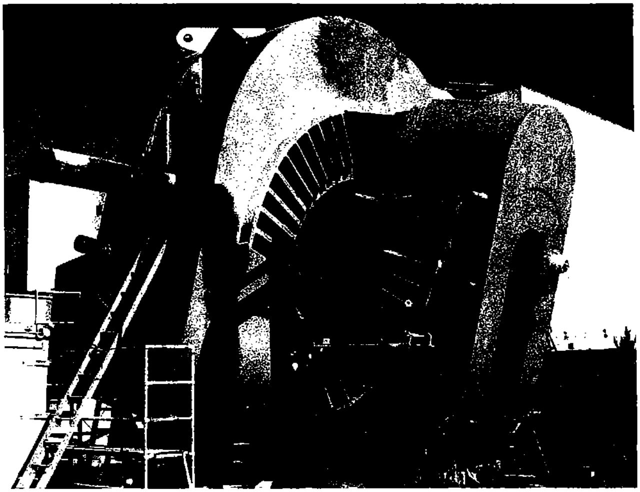

Figure 19. **MFTF–A Yin–Yang Magnets now being completed at Lawrence Livermore National Laboratory.**

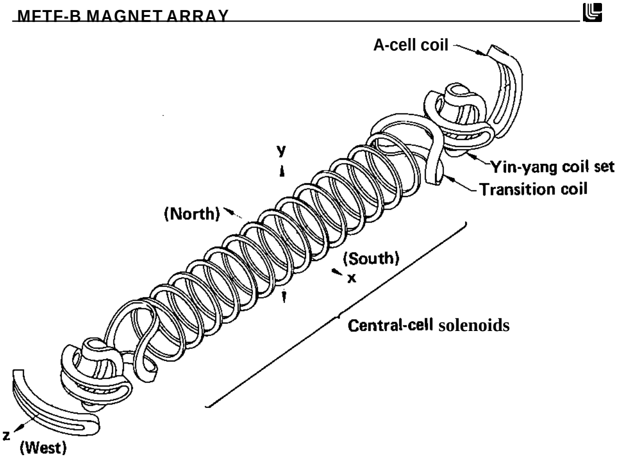

Figure 20. **Schematic lay out of the MFTF–B machine at LLNL.**

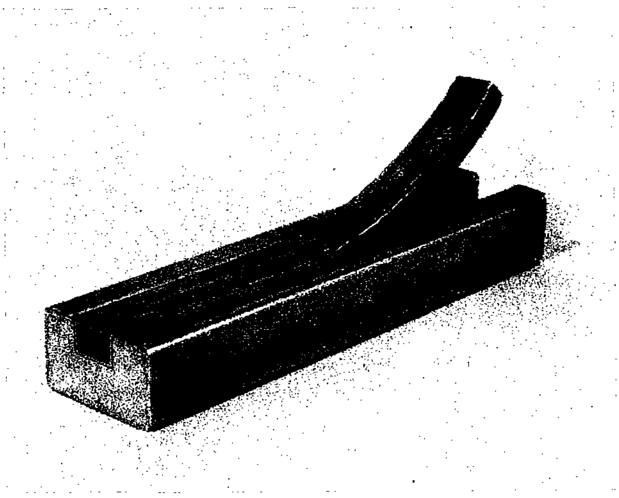

Figure 21. NbTi conductor 14.8 mm x 8.7 mm developed for the rapid cycling bubble chamber at CERN.

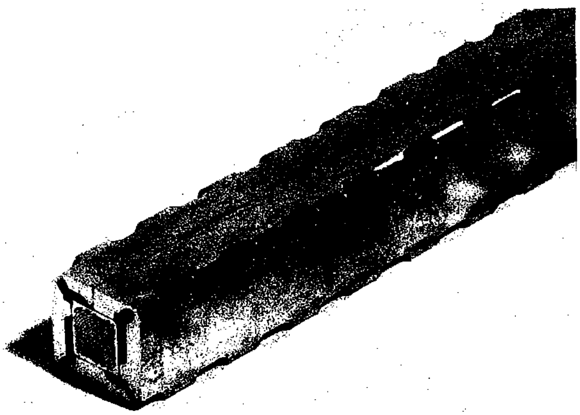

Figure 22. Extended surface area conductor for the MFTF Yin–Yang, A-cell and Transition coils.

tors for the Yin–Yang and A–cell carry currents of 10 kA and 11 kA respectively at 7.5 T and 4.5 K. The conductor for the Transition coils of this device carry 7.2 kA at 5.1 T and 4.5K.

Figure 23 shows an indication of the type of equipment required just to plate the core, wrap the stabilizer around it, and solder the whole conductor together.

Even as construction of MFTF-B is taking place, preliminary design studies are already underway on the Tandem–Mirror–next–Step (TMNS) (39) which will employ magnets where the maximum field on the conductor will be increased from 7.5 T to 12 T. The coil assemblies for TMNS will be twice the size and ten times the weight of the MFTF-B coils. A possible conductor for parts of this system may be a Nb_3Sn one similar to that shown in Figure 14.

Magnetohydrodynamics

One large scale commercial application of superconductivity which has been under development for some time is magnetohydrodynamic power generation, or MHD (40). Unfortunately in the U.S. funding has been spasmodic, resulting in slow progress.

In some of the early work, a magnet was developed at Argonne National Laboratory which had a stored energy of 32 MJ, a field strength of 5 T, and a working volume of approximately one cubic meter (41). As part of a US-USSR collaboration program, this coil was delivered to Moscow and incorporated in a prototype MHD generator with a power capacity of 25 MW. A conductor similar to that shown in Figure 21 but of a smaller cross–section was used in this device.

A similar 6 T magnet has been designed and built at ANL for use in the Coal–Fired Flow Facility (CFFF) at the University of Tennessee Space Institute (UTSI). The conductor, which is a soldered assembly of a superconducting cable that fits into a longtiudinal groove of OFHC copper stabilizer, is in three grades carrying 4.4 kA at 4.5 T, 6.5 T and 7.5 T, respectively.

The Stanford Magnet, Figure 24, which was to consist of a 7.3 T, 79-MJ coil for an MHD research facility at Stanford University (42), was cancelled due to shortage of funds. Figure 25 shows a cable–soldered–in–a–channel type conductor developed for this application; it carried 6.5 kA at 8 T and 4.2 K (43).

The next largest magnet to be built under the US MHD program is for the DOE Component Development and Integration Facility (CDIF) under construction in Butte, Montana (40). This is to be built by General Electric, but it is plagued by funding problems and delays and its completion date at the time of writing is therefore in question. Figure 26 (44) shows extended surface area conductor to be used in this application. It carriers 8 kA at 7 T and 4.5 K.

The next step after CDIF is an Engineering Test Facility (ETF). Design alternatives have been suggested by Francis Bitter National Magnet Laboratory (FBNML) at MIT for a facility rated at 20 MWe which will require a magnet with a field of 6 T, an inlet bore of 2 m^2, an outlet bore of 4 m^2 and the stored energy of the magnet will be 6000 MJ (40).

Figure 23. Equipment required to plate the core, wrap the stabilizer around it, and solder the whole MFTF Yin-Yang type conductor together.

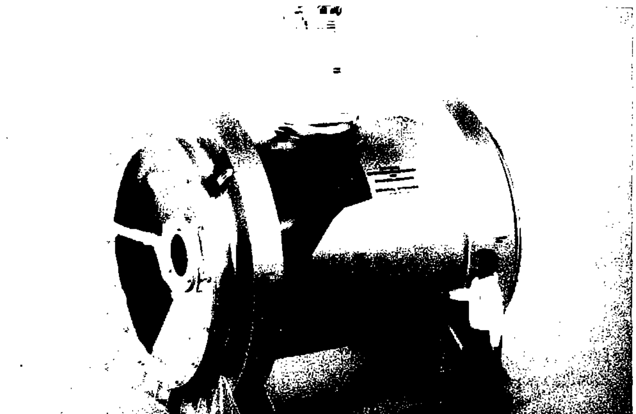

Figure 24. Schematic representation of the Stanford MHD Testing Magnet.

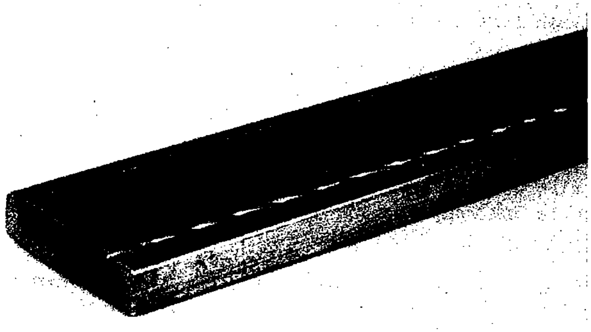

Figure 25. Cable-soldered-in-a-channel type conductor, 18.9 mm x 4.24 mm, developed for the Stanford MHD magnet.

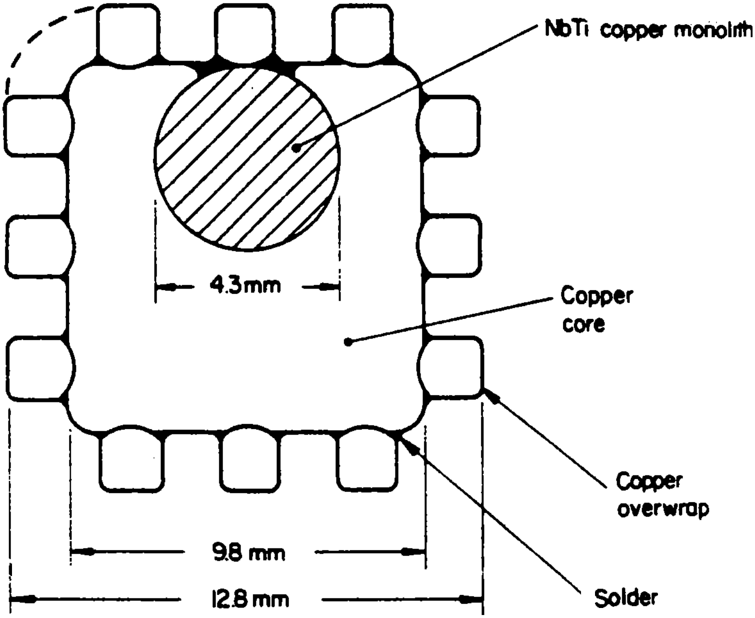

Figure 26. Schematic cross-section of an extended area NbTi conductor for the CDIF MHD.

Energy Storage

Superconducting Magnetic Energy Storage (SMES) is being considered for applications in electrical utilities as well as in the poloidal coil applications for tokamak fusion devices described above.

An immediate utility application is a 30 MJ system to be used to dump power oscillations occurring in the Bonneville Power Administration electric transmission lines. Los Alamos National Laboratory (LANL) is engineering such a SMES device (30), which will be built by General Atomic.

LANL is also working to determine applicability of superconducting magnets in static VAR compensation systems used in the electric utility industry.

The above applications are small compared with the diurnal load leveling SMES systems being considered by both LANL and the University of Wisconsin (45). It has been shown (46) that there is a clear advantage for SMES when systems to store in excess of 6 GWh or to deliver in excess of 1750 kWh/yr per kW are required. One suggested system (45) is to store 10 GWh at 1.8 K in a dewar structure supported by bedrock underground. One proposed system consists of 15 tunnels arranged in a circular pattern with a minor radius of 40 m and a major radius of 120 m. The maximum field in this system is 4.2 T. A second design consists of a 560 m radius single tunnel solenoid with a maximum end field of 5.2 T (Figure 27). This second system need not be buried very deep as the radial pressures on the rock are an order of magnitude less than in the case of the 15 tunnel system. The conductor proposed is a complex design of aluminum stabilized NbTi 10 cm in diameter designed to carry 400 kA (45).

Rotating Machinery

Large turbogenerators seem to be attractive candidates for the application of superconductivity. The main advantages being; a considerable reduction in weight and volume and a significant increase in efficiency over conventional machines.

Although electrical losses, that occur in present day superconductors at power frequencies, forbid their use in the stators of generators, they do appear to be attractive for use in rotor magnets which are excited by direct current.

The main problems have been connected with designing a magnet with surrounding vacuum vessel which must rotate at around 3600 rpm and be constantly supplied with liquid helium through a rotary seal.

The first machines were built in the late 60's by MIT (47) and followed closely in the early 70's by a 5 MVA generator built by Westinghouse. The success of the early work and the expected advantages led to development work in many laboratories around the world including the Electrical Machine Institute in Leningrad USSR, General Electric USA, Siemens in Germany, Brown Boveri in Switzerland, Ansaldo in Italy, IRD-Parsons in the UK, Alstrom in France and Mitsubishi and Hitachi in Japan.

There are at the present time three major programs underway in the U.S. The largest is the joint EPRI-Westinghouse program to build a 300 MVA generator (Figure 28) (48). It has NbTi windings in the rotor which will yield a maximum field of 5.2 T. The prototype conductor for this 300 MVA device was

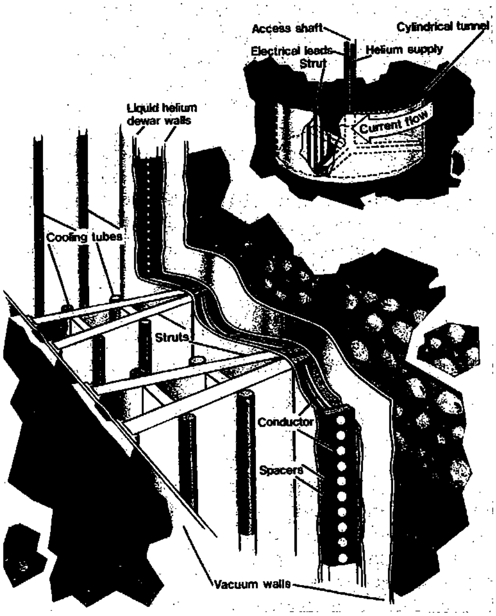

Figure 27. Artist's concept of underground storage of 10 GWh for diurnal load leveling. (Courtesy of University of Wisconsin).

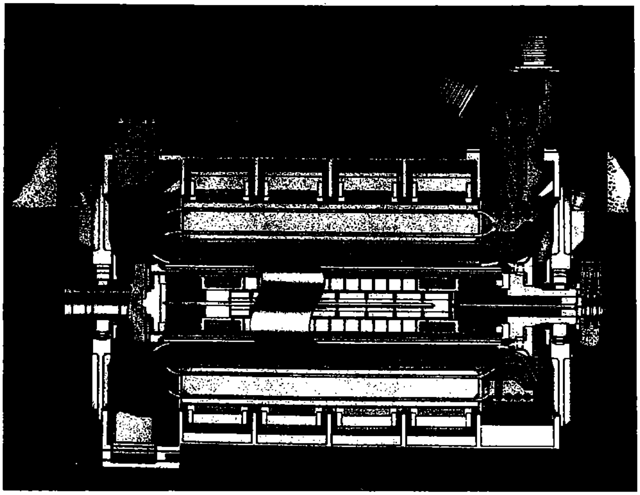

Figure 20. Schematic designs of the 300 MVA Westinghouse generator to be built on the EPRI-Westinghouse program.

made by the "compacted monolith" technique. It consists of 7 basic units each with 517 filaments surrounded by copper and it carries 4 kA at 5 T and 4.2 K. When the generator is finished in 1984, it will be tested in an electric utility power plant and if it succeeds, it will constitute one of the first major industrial applications of superconductivity. GE is at present completing their 20 MVA machine (49), and MIT is committed to the construction of a 10 MVA generator to demonstrate advanced concepts (50).

The reductions in size and weight which result from the use of superconducting materials are paticularly attractive for airborne and shipboard applications. The USAF has a program to develop a 400 Hz generator and the US Navy has tested a 400 hp direct current rotor.

Several prototype motors using the homopolar principle have been built by IRD in the UK (51) and GE and the Garrett Corporation have contracts for development of motors and generators for ship propulsion.

Magnetic Levitation

The high fields and light weight of superconducting magnets make them ideally suited to tracked high speed ground transportation systems for speeds of 500 km/h and above. In the past, levitated train programs existed in the U.S., Canada, Germany and Japan, but at the present time only the Japanese National Railway (JNR) program is still active (52). In 1982, JNR expects to start experimental operation of a manned three-car train.

Magnetic Separation

Superconducting magnets may also find commercial applications in high gradient magnetic separators. These can be used for separation and benefication of weakly magnetic materials, purification of water, desulphurization of coal and several other chemical and biological applications. Imperial College - London, Kernforschungzentrum Karlsruhe (Kfk) and several German companies are active in the field.

Summary

A description has been given of some of the large scale applications of niobium-based multifilamentary superconductors. Most of these require the construction of magnets of such a size that conductors in the form of fine wires cannot meet their requirements. A description has been given of how several standard basic units of NbTi and Nb_3Sn wires can be subjected to secondary fabrication to form the necessary high current carrying conductors. An attempt has been made to show that commercially available Nb-based superconductors can meet the requirements of these ambitious application programs.

Acknowledgements

I would like to acknowledge the support of both BOC Group and Airco, Inc.'s top management over the years and the continued effort on the part of all the employees of Airco Superconductors. Without their work, much of this review would not have been possible.

I would also like to thank the U.S. Department of Energy, both the headquarters and the national laboratories, who have sponsored the work on many of the conductors described.

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