Chapter 11: Wires and Tapes

11.3 History of Nb_3Sn and Related A15 Wires

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11.3.1 Introduction

Nb_3Sn occupies a special place in any history of superconductivity as the first material to show, 50 years ago in 1961, that superconductivity actually could exist in very high fields. It is both fitting and also perhaps remarkable that it so quickly made the transition from a *Physical Review Letter*[1] to high field magnets of 10 T or more that fulfilled Onnes's 50-year-delayed dreams. It was initially made as a few μm thick layers in tape forms on strong substrates, so as to allow application to magnets without performance being compromised by the hard and brittle nature of its A15 crystal structure. However, the electromagnetic instabilities of superconducting tapes were soon recognized. Following the development of filamentary forms of Nb-Ti in about 1965, the urge to develop a filamentary technology for A15 compounds occurred too. It was soon discovered that the presence of a small amount of Cu enabled formation of the relevant A15 compound, V_3Ga or Nb_3Sn, at temperatures of 600-700 °C, some 200-300 °C below the temperatures needed in the binary mixtures. Cu-Sn or Cu-Ga bronzes fulfilled this condition and allowed fabrication of wires containing many hundreds or even thousands of Nb or V filaments in the relevant bronze by conventional extrusion and drawing processes. This bronze route was the breakthrough that enabled Nb_3Sn multifilamentary conductor forms capable of producing stable 10-23 T field magnets required for fusion, NMR, and all manner of other systems. Due to these widespread applications, Nb_3Sn can thus be regarded as one of the key materials in science and technology. In this article the chronological progress of Nb_3Sn wires will be surveyed, together with some discussion of its brother A15 compound, V_3Ga, which played an important role too.

The A15 compounds, like Nb_3Sn, have the nominal composition ratio of A_3B, but although

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[1] J. E. Kunzler *et al.*, Phys. Rev. Let. 6:3 (1961) 89

the stoichiometric A_3B composition is obtained by diffusion, actually all possible compositions that are stable also form, thus producing a range of superconducting properties. For technology it is vital to work with at least ternary systems, since the formation temperature of Nb_3Sn is lowered from ~950 °C to ~700 °C by the addition of Cu. The constituent elements, Nb, Sn and Cu, have a favorable workability at room temperature, allowing multifilamentary composites to be assembled at larger size, co-drawn to final wire dimensions, and then reacted to form the A15 filament structure. Because optimum reaction conditions do not allow reaction to completion[2], the measured transition temperature T_c and upper critical field B_{c2} of Nb_3Sn wires have a width that depends on the variable stoichiometry of the filaments. A central compromise of all multifilamentary conductors is that grain boundaries provide the primary flux-pinning centers requiring a low reaction temperature, while the highest T_c and B_{c2} distribution requires a somewhat higher reaction temperature that enlarges the grain size and reduces the flux pinning. Third elements can also improve the performance of Nb_3Sn wires and commercial strand normally incorporates at least one of these. Most commonly, small amounts of Ti and Ta addition are used to enhance the B_{c2} by increasing the normal state resistivity of the A15 phase which results in higher critical current density at fields above 12 T (4.2 K). Moreover the addition of Ti appreciably accelerates the formation of Nb_3Sn.

11.3.2 Chronological Progress in the Fabrication of Nb_3Sn and V_3Ga Wires

At the 1982 Applied Superconductivity Conference John Hulm recalled the circumstances surrounded the discovery of superconductivity in the A15 compounds:[3]

> *"In the spring of 1952 I was working with a graduate student, George Hardy. We decided that the carbides and nitrides were more or less exhausted, so we moved down to silicides and germanides in the second and third periods. We also began arc-melting our samples. These were two very fortunate moves. Not only was the general quality of the samples improved over our earlier sintered materials, but we soon discovered a new high T_c superconductor, V_3Si, at 17 K.[4] It belonged to what was then known, erroneously, as the beta-tungsten structure; of course this was subsequently changed to A15. I told this news to Bernd Matthias almost immediately.*
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> *By then Bernd Matthias had teamed up with Ted Geballe, Ernie Corenzwit, and Seymour Geller at the Bell Laboratories. These investigators proceeded to execute a tour-de-force in creative synthesis by discovering about 30 new A15's, including several new high T_c materials, most prominently Nb_3Sn at 18 K, in 1954.[5]*

On December 15th 1960, a group at Bell Laboratories led by J. E. Kunzler tested the high field properties of a rectangular rod of bulk Nb_3Sn, that had been sintered and then melted at 2400 °C and to their "complete surprise" [6], found that it was still superconducting at their maximum field of 8.8 T. The details of the road to this discovery are covered in more detail in the ductile superconductor history 11.2 but it should be repeated here that this achievement represented a

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[2] P. J. Lee and D. C. Larbalestier, Cryogenics, 48:7-8 (2008) 283
[3] J. Hulm, IEEE Trans. on Magnets, 19:3 (1983) 161
[4] George F. Hardy and John K. Hulm, Phys. Rev. 93:5 (1954) 1004
[5] B. T. Matthias *et al.*, Phys. Rev. 95:6 (1954) 1435
[6] J. Kunzler, IEEE Trans. on Magnetics, 23:2 (1987) 396

prize of 21 bottles of scotch whisky courtesy of a wager with Morris Tanenbaum. The 2400 °C bulk sample was impractical as the magnet material they had hoped to use for Masers. However, “super technician” [7] Ernie Buehler (Tanenbaum and Buehler formed the team that made the first Si transistor), devised the powder-in-tube (PIT) route to make wire, placing Sn and Nb powders in a Nb tube, a ductile combination that could be drawn to final size before the reaction heat treatment that would create the brittle Nb_3Sn. The first strand carried 50 times higher J_c than the bulk sample,1 and their best PIT strand (with 10% more Sn than was required to fully react the Nb powder to the stoichiometric ratio) reached almost 1500 A/mm² at 8.8 T (4.2 K) using a much more manageable heat treatment of 970 °C. Kunzler suggested that Nb_3Sn wires might enable a convenient and economical high-field magnet without the consumption of huge electric power and cooling water required in a water-cooled Cu magnet.[8]

The next major milestone was the development of a vapor deposition technique to produce Nb_3Sn by J. J. Hanak (who became the father of Combinatorial Chemistry) at RCA Laboratories.[9] Chemical vapor deposition produced a thin enough layer of Nb_3Sn on a wire or tape that was flexible enough to wind magnets. Furthermore, the use of substrates with thermal expansions greater than Nb_3Sn placed the brittle A15 layer under beneficial compressive strain. The technique involved production of gaseous $NbCl_4$ and $SnCl_4$ by direct reaction of Nb, Sn and Cl_2. The chlorides, together with H_2 and HCl were passed into a reaction chamber in which a continuously fed metallic substrate tape or wire was resistively heated between two carbon electrodes to ~1000 °C.[10] After growth of the Nb_3Sn, layer of Ag was applied as the stabilizer.

Figure 11.3.1 illustrates the industrial CVD facilities developed for the winding of 10 T-class superconducting magnets. A major effort was also underway at General Electric and in competition with RCA, they developed the Nb_3Sn diffusion process in which a Nb substrate tape was passed through a molten Sn bath.[11] Nb_3Sn layers were formed on both sides of the tape after the reaction heat treatment at 950 °C. Stabilizing Cu layers were soldered to the tape using the residual Sn left behind after reaction, as shown in Figure 11.3.2. Many 15 T-class superconducting magnets, mostly used for solid state physics research, were wound from these tapes by Intermagnetics General Co. (IGC), the spin-off company that emerged from GE. Thus the vision of Kunzler mentioned in ref.

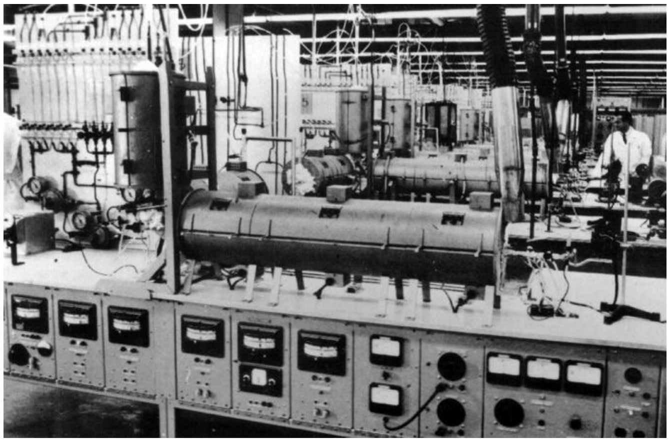

Figure 11.3.1: Production facilities for Nb_3Sn wires using the continuous CVD process were established at RCA already in 1966 [9].

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[7] Tanenbaum’s description of Ernie Buehler in “Oral-History: Goldey, Hittinger and Tanenbaum” interview conducted by Michael Riordan and Sheldon Hochheiser, Murray Hill, New Jersey, September 25, 2008, Interview #480 for the IEEE History Center, The Institute of Electrical and Electronics Engineers, Inc..

[8] J. Kunzler, Reviews of Modern Physics 33:4 (1961) 501

[9] J. J. Hanak, "Vapor deposition of Nb_3Sn," in Metallurgy of Advanced Electronic Materials, (AIME) 19, Ed. G. E. Brock. (New York: Interscience, n.d.) (1963) 161

[10] J. J Hanak, K. Strater, and G.W. Cullen, "Preparation and Properties of Vapor-Deposited Niobium Stannide", RCA Review, September 1964

[11] M.G. Benz, G.E. Research. & Development Center Report No. 66-C-044 (1966)

8 was realized rather quickly. Nb_3Sn diffusion tape was also used for a 110 m-long power transmission model cable operated at 7 K that was the forerunner of the many electric utility application dreams that flowered after the discovery of superconductivity in the cuprates in 1987.[12]

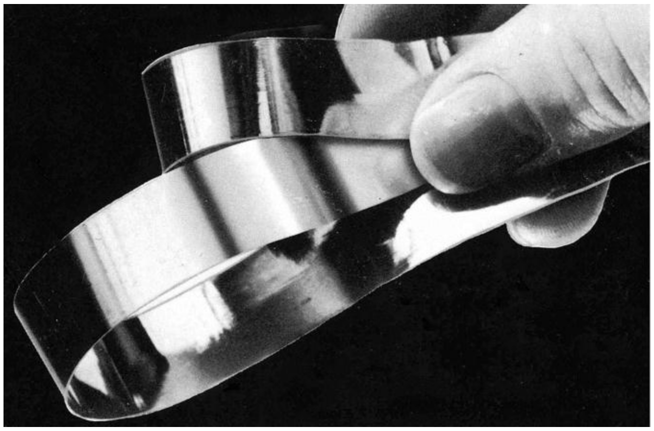

Figure 11.3.2: Nb_3Sn tape produced at General Electric using diffusion between a liquid Sn bath and a Nb foil, later the basis of magnets made by Intermagnetics General Corp.[11].

However, all tape magnets suffered from flux jumps that made them slow to charge and sometimes irregular in performance. As monocore wires of Cu-clad Nb-Zr gave way to better-bonded Cu-Nb-Ti (see section 11.2) and then to metallurgically bonded, twisted multifilamentary Nb-Ti conductors, superconducting magnets became stable, capable of fast ramps and generally much more predictable. The drive to develop multifilamentary A15 wires was on!

A key study in this transition from tapes to wires was made on V_3Ga wires. A small Cu addition to molten Ga was found to change the diffusion mode for growth of V_3Ga from a grain boundary one to a bulk one, without the Cu impairing the properties of the growing V_3Ga layer. Cu accumulated at the diffusion boundary, decreasing appreciably the formation temperature of V_3Ga as illustrated in Figure 11.3.3.[13] The area fraction of V_3Ga with fine grains is much increased by the lower temperature reaction enabled by the Cu addition. The patent describing the effect of Cu on the promotion of V_3Ga and Nb_3Sn synthesis was filed in 1966.[14] The V_3Ga tape exhibits an appreciably better performance than pure Nb_3Sn tape in fields above 15 T. The 17.5 T superconducting magnet system shown in Figure 11.3.4, which held the field record for an all-superconducting magnet for ~10 years after 1975, was made by using a Nb_3Sn outer and a V_3Ga inner section.[15] Only in the 1980's was it possible to exceed this performance with multifilamentary conductors of Nb_3Sn with Ti addition.

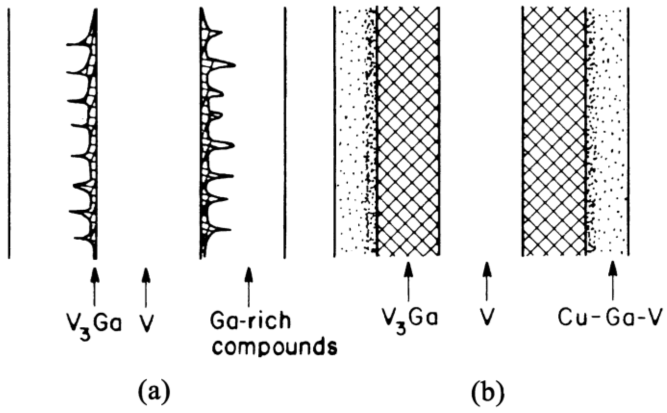

Figure 11.3.3: Formation of V_3Ga layer by a diffusion reaction between V and Ga. (a) diffusion at 800 °C without Cu addition, and (b) at 700 °C with Cu addition. The small dots represent the Cu in the Cu-Ga-V ternary alloy.[13]

The route to multifilamentary A15 conductors was greatly simplified by

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[12] E. Forsyth and G. Morgan, IEEE Trans. on Magnetics, 19:3 (1983) 652
[13] K. Tachikawa and Y. Tanaka Japanese J. Applied Physics 6:6 (1967) 782
[14] K. Tachikawa, Y. Tanaka and S. Fukuda, Japan Pat. 0670619 (Filed June 25, 1966)
[15] K. Tachikawa *et al.,* J. Cryogenic Soc. of Japan 11:6 (1976) 252

Figure 11.3.4. 17.5 T superconducting magnet system operated at the National Research Institute for Metals.[15]

the work with Cu additions to V-Ga tapes, and multifilamentary V_3Ga wires were soon fabricated using a Cu-Ga bronze matrix and V cores.[16] The first commercial multifilamentary V_3Ga wire was produced by Furukawa Electric in 1972 which was wound into a stable 10.4 T magnet, and by this time groups in Europe[17] and the USA[18] had also developed the bronze route to make multifilamentary Nb_3Sn wires. Because bronze wires required many anneals to allow wire drawing, interest rapidly grew in modifications of the bronze process, in which the more ductile pure metal components of Sn, Cu and Nb were used. The greatest longevity has come from variants of the internal tin (IT) process, in which a composite wire constructed from a Cu matrix, Sn and Nb cores (see Figure 11.3.5), which was initiated by Mitsubishi Electric in 1974.[19]

Some of the earliest work on multifilamentary conductors using the bronze process was performed at the UK Atomic Energy Research Establishment at Harwell, where Nb_3Sn tapes were also found to produce too much electromagnetic instability when in magnets. One of the young researchers in the Harwell group, Phil Charlesworth, recalls:[20]

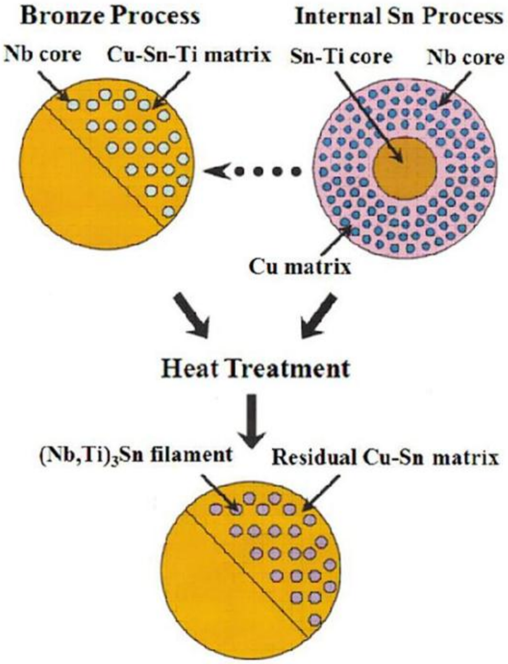

Figure 11.3.5: Schematic illustration of bronze and internal Sn (IT) process.

> *It also soon became clear that the critical problem in constructing superconducting magnets is ensuring stability against catastrophic quenching caused by small movements of flux vortices rearranging themselves against pinning sites during field ramping. For this purpose, a wire containing many thin filaments of superconductor embedded in a normal conducting matrix of low resistivity, providing dynamic stabilisation, is much more attractive than a tape, as the filaments, if fine enough are adiabatically stable and the matrix can help to damp out propagation of fluctuations to neighbouring*

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[16] K. Tachikawa, Proc. ICEC-3, Illife Sci. & Technol. Pub. (1970) 339

[17] Brian Howlett, Great Britain Pat. 52,623/69 (Filed Oct. 27, 1969). US Pat. 3,728,165 (Filed Oct. 19, 1970)

[18] A. R. Kaufman and J. J. Pickett, Bull. of American Phys. Soc. 15 (1970) 833

[19] Y. Hashimoto, K. Yoshizaki and M. Tanaka, Proc. ICEC-5, K. Mendelssohn, Editor, (1974)332

[20] Phil Charlesworth, personal communication for this article, October 17, 2010

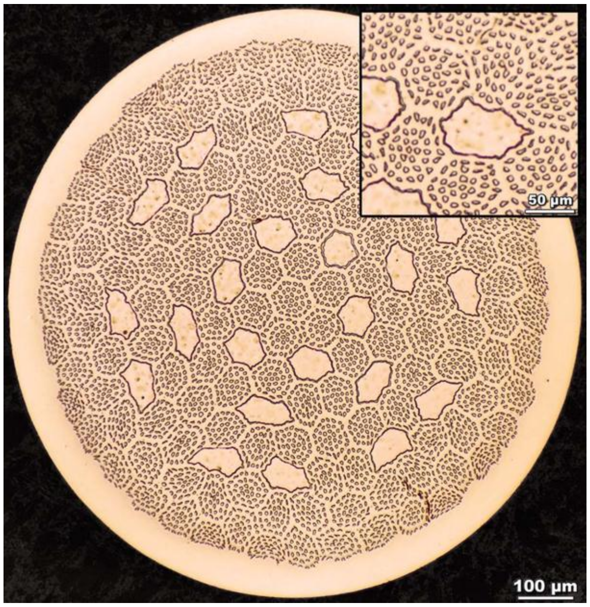

Figure 11.3.6: 5143 filament bronze process strand fabricated by Harwell/Rutherford group in early 1974. Application of a diffusion barrier is shown protecting internal stabilizer elements of Cu.[21]

> *filaments. Work along these lines was started in Brian Howlett's group at Harwell in 1969 with the progressive development of the so-called bronze-route, method of fabrication using niobium rods embedded in copper-tin bronze, the Nb_3Sn being created by heat-treatment to create a reaction layer between the tin and the niobium. In early 1971, the group moved into Chemistry Division with Jim Lee as group leader.*
>
> *I was involved in this program to the extent of measuring the properties of the material produced but the bulk of the effort went into development of a production line for ever more sophisticated composites. The fabrication route involved drilling a matrix of 37 holes in a cylindrical bronze billet, using a gun drill, inserting niobium rods and then swaging and drawing the material to bring the bronze into firm contact with the niobium and to reduce the overall diameter. The process could then be repeated, one or more times, using the previous stage composites as inserts. Many people worked on this program but Derek Armstrong, who toured the country acquiring second-hand machine tools to build up the industrial-scale fabrication shop we needed and threw himself with enthusiasm into developing the fabrication route.*
>
> *All along this work had been in collaboration with a team at the neighbouring Rutherford Laboratory interested in producing practical solenoids with possible particle accelerator applications in mind. Again there were several people involved but our liaison was chiefly through David Larbalestier and Chris Scott. A joint paper in 1974* [21] *describes composites with filament counts up to 42,439 and including regions of pure copper protected by a diffusion barrier to add extra stabilisation. Another paper of the same date describes the successful performance of several small solenoids made from our bronze-route material by winding the material as-fabricated and then heat-treating the whole coil to produce the Nb_3Sn.*

It is interesting that Howlett's bronze route patent was filed in 1969, and the work at Brookhaven National Laboratory in the USA was clearly ongoing at this time too. Having efforts in Japan, the UK and the USA led to competition that enormously enhanced progress. In particular the joint Harwell-Rutherford program had led to intrinsically stable multifilamentary conductors which had been wound into solenoid magnets generating more than 12 T in 1974.

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[21] D. Larbalestier et al., IEEE Trans. on Magnetics 11:2 (1975) 247

[22] Courtesy of Osaka Alloying Works Co., Ltd. (2010)

11.3.3 Bronze-processed Nb$_3$Sn Wires

Figure 11.3.7: Typical bronze ingots for Nb$_3$Sn wires (Courtesy of Osaka Alloying Works Co., Ltd.).[22]

Figure 11.3.5 schematically illustrates the bronze and internal tin (IT) processes, while Figure 11.3.7 shows typical bronze ingots prepared on the industrial scale.[22] Diameter, length and weight of the ingots are ~200 mm, ~800 mm and ~250 kg respectively. Typically 19, 37 or some other hexagonal-array number of holes are drilled in the bronze ingot, into which Nb cores are inserted. The composite stack is then fabricated to hexagonal rods by extrusion and drawing. These hexagons are then restacked in a Cu cylinder which is protected from the bronze by a Ta or Nb diffusion barrier, whose purpose is to prevent poisoning of the high quality stabilization and protection Cu sheath by any Sn leakage. Bronze billets are normally hot extruded, and then drawn into multifilamentary wire. Wires are typically heat treated at ~675 °C for ~200 h to form the Nb$_3$Sn layers around each original Nb filament.

It was soon found that a small addition of Ti either to the bronze or Nb cores was favorable to J_c, as also was raising the amount of Sn in the bronze.[23] Tachikawa had originally intended the Ti addition to the bronze to improve the mechanical strength of the Sn-poor bronze left behind after the diffusion reaction was ended. Unfortunately the Ti was entirely incorporated into the Nb$_3$Sn layer or accumulated at the Nb$_3$Sn/bronze interfaces, and was not effective for reinforcement. Fortunately Ti incorporation into the A15 layer appreciably improved the high-field performance of Nb$_3$Sn by raising B_{c2}. A small amount of Ta added to the Nb filaments also enhances the high field performance. Both additions are still used today. Figure 11.3.8 shows bronze-processed

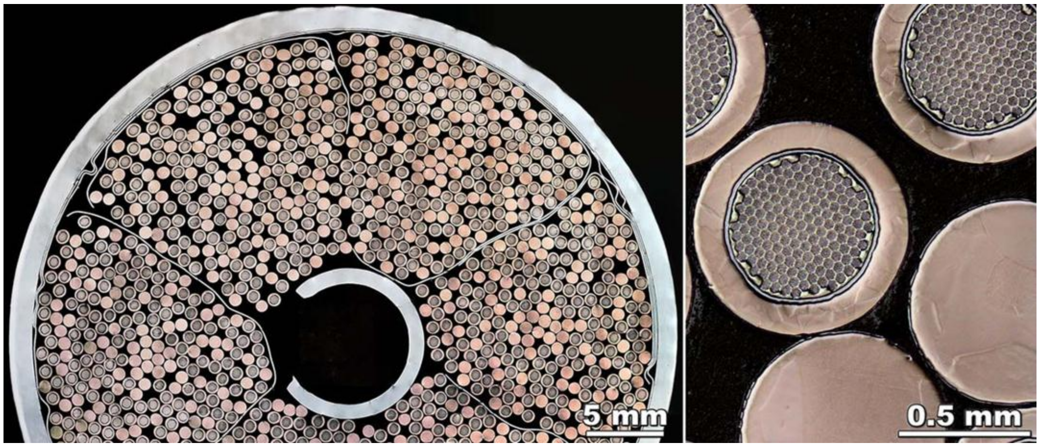

Figure 11.3.8: Partial cross-section (left) of a prototype ITER Toroidal Field Cable-in-Conduit Conductor (CICC) EUTF5 (ENEA) containing a mixture of bronze-process Nb$_3$Sn strands and Cu strands (right) within 6 cable petals (29.6% void fraction). Cable supplied to FSU after testing in the Sultan facility[24].

Nb_3Sn strands used in a prototype ITER Cable-in-Conduit Conductor (CICC).[24] ITER requires 502 tonnes of multifilamentary Nb_3Sn wires to provide the high magnetic fields (as high as 13 T) required to confine the plasma (Toroidal Field System) and induce the main plasma current (Central Solenoid). Both IT and bronze route wires are being manufactured for this program in a worldwide effort.

As the ITER use suggests, the bronze route to Nb_3Sn has had remarkable longevity. However, almost every part of the process has been subject to continuous development, resulting in a better, cheaper and longer piece-length product. A higher Sn:Cu ratio was recognized very early to be valuable for raising J_c but high-Sn bronzes were difficult to cast without inhomogeneity and difficult to draw without excessive bronze work-hardening. By such processes of continuous improvement and production, the Sn content of the bronze has been increased from 13wt% to 16wt% in the 1990's, allowing a doubling of the J_c at 4.2 K and 20 T. Such bronze wires have found wide application in NMR magnets, including the most recent delivery of a 1 GHz magnet by Bruker, as shown in Figure 11.3.9.[25] However, the specification of the wire used in this magnet is not reported. A variety of refrigerator-cooled magnets, vertical, horizontal and split pair magnets, have also been developed commercially using bronze-processed Nb_3Sn wires. The magnet shown in Figure 11.3.10 generates 15 T in a 171 mm room temperature bore.[26] In addition Nb_3Sn wires for the AC use have been fabricated by the bronze process. A 50 mm-bore 2 T Nb_3Sn magnet successfully operated at 53 Hz.[27] The diameter of Nb filaments in the wire has been reduced to as fine as 0.2 μm.

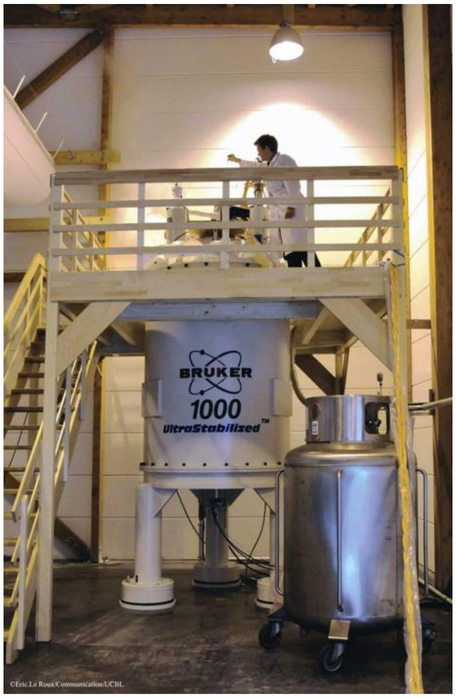

Figure 11.3.9: The 1 GHz NMR magnet constructed by Bruker now installed in Lyon, France.[25]

Figure 11.3.10: Refrigerator-cooled superconducting magnet.[26]

11.3.4 Internal Sn-processed Nb_3Sn Wires

The principle of the internal tin or IT process has been shown in Figure 11.3.5. In a bronze alloy the Sn solubility limit is ~15.8 wt.%, while a larger Sn fraction may be possible in the IT

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[23] K. Tachikawa, H.Sekine and Y. Iijima, J. Applied Physics 53:7 (1982) 5354

[24] P. Bruzzone, R. Wesche, and F. Cau, IEEE Trans. on Applied Superconductivity 20:3 (2010) 470.

[25] Bruker Biospin : http://www.bruker-biospin.com/pro091202.htmL?&L=11, March1(2010)

[26] R. Hirose *et al.*, IEEE Trans. on Applied Superconductivity 16:2 (2006) 953

[27] K. Tachikawa *et al.*, Proc. ICMC 17, D. Dew-Hughes, Editor, IOP Press (1998) 439

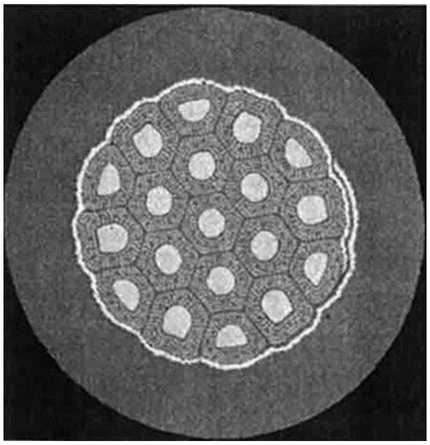

Figure 11.3.11: Typical cross section of 0.78 mm diameter 19 sub-element IT wire before heat treatment. The thin white ring is the diffusion barrier.[28]

process. Since the IT processed wire is composed of three components, a variety of cross-sectional designs are possible. Figure 11.3.11 is an example of an IT processed wire using 19 filamentary sub-elements protected by a single diffusion barrier.[28] Figure 11.3.12 shows a part of the Rutherford cable (see section 11.2) for the record breaking D20 dipole at LBNL [29] using IT processed strands like the one shown in Figure 11.3.11. Wires composed of as many as 100-200 sub-elements, each covered by the diffusion barrier (distributed barrier) have been also developed. Design of IT wires is still rapidly evolving as the tradeoffs between high J_c (favored by a small Cu fraction in the Cu-Sn-Nb composite needed to increase Nb_3Sn fraction) and a small effective filament diameter (favored by a large fraction of Cu to keep the A15 filaments separated) are explored. The requirements for high field magnets for NMR, for ITER and for high energy physics applications are still driving this not yet mature technology.

In the heat treatment of IT wires, the Cu and Sn elements are first converted into high-Sn bronze phases at temperatures up to about 500 °C, and only after this is the wire heated to 600-700 °C to react with the Nb filaments. The IT reaction thus requires a multi-step heat treatment in which the filaments move away from the Sn cores during heat treatment, often resulting in bridging of the filaments, increasing the effective filament diameter and the hysteresis loss. The arrangement of Nb filaments can be designed to account for this change as in the example.[30]

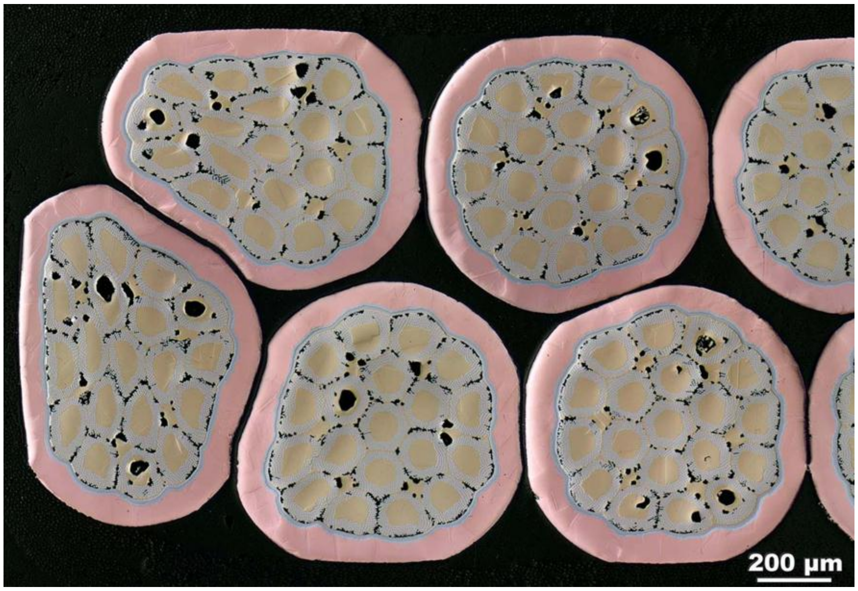

Figure 11.3.12: IT strands cabled for the record breaking 13.5 T D20 dipole magnet at LBNL (cable supplied to FSU by Dan Dietderich - LBNL) imaged in transverse cross-section after heat treatment.[29]

Figure 11.3.13 shows the non-Cu J_c versus magnetic field curves of the distributed barrier IT-

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[28] M. B. Field *et al.*, Adv. in Cryogenic Eng. Materials 54 (2008) 237

[29] R. Benjegerdes et al., Proc 1999 Particle Accelerator Conference, 5 (1999) 3233

[30] Y. Kubo et al., IEEE Trans. on Applied Superconductivity16:2 (2006) 1232

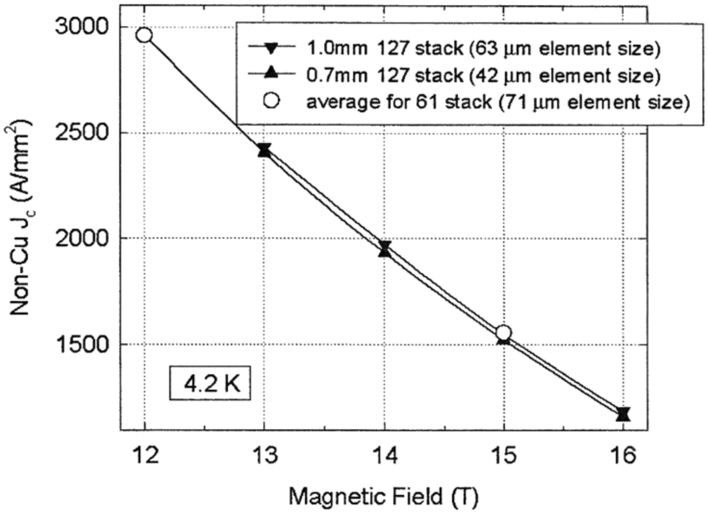

Figure 11.3.13: Non-Cu J_c of distributed barrier IT wires as a function of magnetic field. The J_c-B curves are nearly identical for strands containing either 61 or 127 subelement rods.[28]

processed wire[28] in which ~3000 A/mm² is achieved at 12 T, as part of the US DOE HEP Conductor Development Program, nearly 3 times larger than that in bronze-processed wires. However, increasing the separation of Nb filaments by enhancing the Cu:Sn ratio to avoid filament bridging reduces the J_c to the level of bronze-processed wires. High-field accelerator magnets are being developed using IT-processed Nb_3Sn wires due to their large non-Cu J_c. IT-processed Nb_3Sn wire is used also for fusion magnets, e.g. ITER and KSTAR (Korea Superconducting Tokamak Advanced Research) facilities.

Comparing the bronze and IT process, a clear advantage for the IT process is in the wire fabrication, since the bronze process requires frequent intermediate anneals to soften the work-hardened bronze. However, it is not possible to extrude composites containing Sn cores because of the danger of melting the Sn, so temporary cores must be used which can be replaced by Sn at a later stage. The heat treatment profile is also simpler for bronze wires. The J_c is larger in IT-processed wires, while AC loss is smaller in bronze-processed wires. The *n*-value and the irreversible strain tend to be better in bronze-processed wires. Thus there are advantages and disadvantages to both processes. Figure 11.3.14 illustrates the Nb_3Sn layer J_c, reflecting the intrinsic quality of the Nb_3Sn, versus magnetic increase in Sn supply available in bronze processed wires[31]. Furthermore the strain effect in Nb_3Sn wires which is practically an important topic has been extensively studied.[34]

11.3.5 Conclusions and Future Outlook

We have described a remarkable development of the A15 compound Nb_3Sn from its “accidental” discovery as a high-field superconductor 50 years ago in 1961 through rapid implementation as a tape conductor made either by CVD or by diffusion-processed Nb_3Sn tapes and then to its replacement by multifilamentary conductors, starting in the early 1970s. The discovery that Cu could allow synthesis of V_3Ga and Nb_3Sn at much lower temperatures than was possible for binary mixtures enabled this move to a multifilamentary technology. Additions such as Ti, which enhanced B_{c2}(4.2 K) of Nb_3Sn from ~21 T to ~26 T further enhanced the high-field capability of Nb_3Sn wires. Industrial fabrication of Nb_3Sn wires was well established in the 1970’s on so that

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[31] P. J. Lee, A. A. Squitieri and D. C. Larbalestier, IEEE Trans. on Applied Superconductivity 10:1 (2000) 979

[32] J. A. Parrell et al., Adv. in Cryogenic Eng. Materials 48 (2002) 968

[33] A. Godeke *et al.*, Cryogenics 48:7 (2008) 308.

[34] J.W. Ekin, Adv. Cryogenic Engineering: Materials 30 (1984), 823

[35] E. Gregory *et al.*, Adv. Cryogenic Engineering: Materials 54 (2008) 252

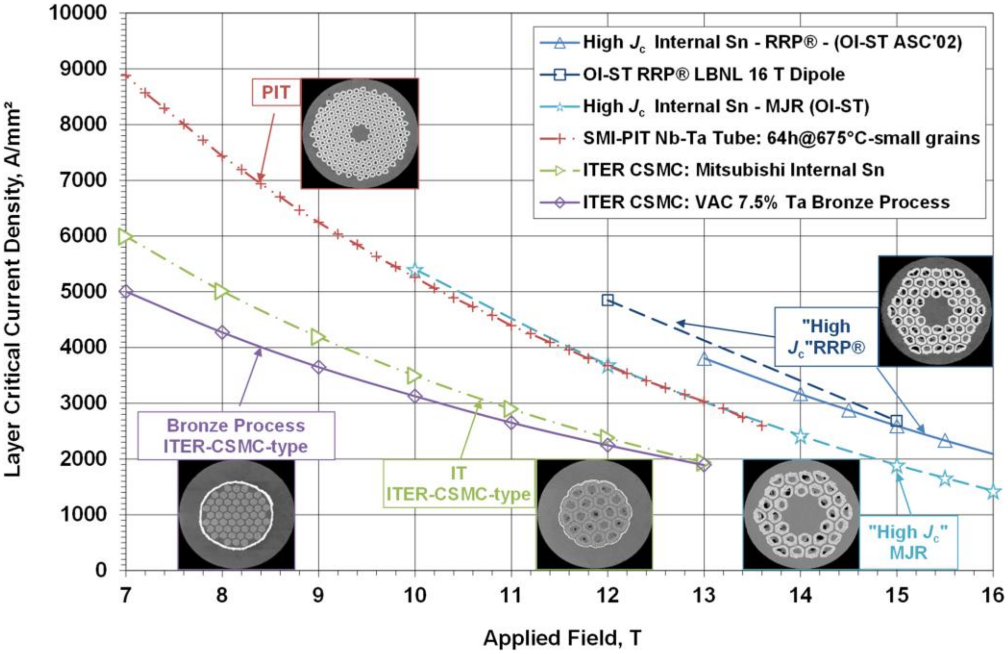

Figure 11.3.14: The layer J_c of the Nb_3Sn in a variety of Nb_3Sn strands. The higher Sn contents available in PIT and high-J_c type IT strands can double the intrinsic J_c of the Nb_3Sn.[31] RRP®: Restacked Rod Process (IT)[28], MJR: Modified Jelly Roll (IT)[32], PIT: Powder in Tube[33].

it was not disrupted by the discovery of high-T_c cuprates in 1987. In the 1990's and the 2000's marked improvements in the performance of Nb_3Sn wire continued to be achieved using the usual techniques of gaining a better understanding of manufacturing improvement and better understanding of how to best package the mixture of Sn, Cu, Nb and Ti or Ta needed to produce the superconducting A15 phase.

Because Nb-Ti cannot provide fields greater than 10-12 T, there is a clear market for high field superconducting coils in the range up to now ~23 T that Nb_3Sn can address. In fact alternative processes to high performance conductors are still being explored. Besides the bronze and IT processes, the PIT process, using powders of Sn-rich compounds such as $NbSn_2$ or Nb_6Sn_5,[33] and the Nb tube process,[35] yield Nb_3Sn wires with excellent J_c performance and a well-defined and small filament diameter. Such innovations show clearly that Nb_3Sn has not yet lost its place as the high-field superconductor, a rather remarkable state for the "original" high-field superconductor 50 years on. Fresh water may still come out from an old spring in the future.

Further Reading

1. In 1986 the Applied Superconductivity Conference celebrated the 75th Anniversary of the discovery of superconductivity with a symposium on the history of superconductivity. The symposium is published in full in IEEE Trans. Magn., 23, pp. 354-415, 1986

2. In 2008 a special edition of the journal Cryogenics brought together articles on the current

state of the art of low temperature superconductor science and technology: Cryogenics 48 (2008)

3. A history of technical superconductors in Russia, including Nb_3Sn, is covered in: A.K. Shikov et al., "The History of Technical Superconductors Development in Russia," IEEE Transactions on Applied Superconductivity 17, no. 2 (2007): 2550-2555.