

## Emergence of Nb–Ti as supermagnet material

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The discovery and emergence of Nb–Ti as a high field superconductor is reviewed. The prehistory and setting for its discovery are described, and an anecdotal history follows its development up to the first successful large scale applications.

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*A group of young men so frenetic  
struggle with matters magnetic.  
Each day they conspire  
to wind super wire,  
a pastime which some deem pathetic.*

W.J. Tomasch

Today, more than 20 years since the discovery of the superior superconducting magnet potential of Nb–Ti, this alloy is widely utilized in medical, technical and scientific applications. It comprises the windings of supermagnets in some 800 magnetic resonance imaging systems which make possible medical diagnoses of unprecedented accuracy, safety and convenience. Prototype electric motors and generators with Nb–Ti field windings have achieved efficiencies and energy densities undreamed of with conventional technology. A Japanese experimental levitated train, which attained a record speed of more than  $500 \text{ km h}^{-1}$ , utilized Nb–Ti supermagnets for both levitation and propulsion. Enormous (hundreds of tons) Nb–Ti supermagnets are providing means for magnetic confinement of plasmas in controlled thermonuclear fusion experiments. In high energy physics experiments at the Fermi National Accelerator Laboratory more than one thousand 6 m long Nb–Ti supermagnets guide an energetic particle beam around the 6 km circumference of the world's most energetic accelerator, the Tevatron. Design studies for a three billion dollar 100 km circumference Superconducting Super Collider accelerator have selected Nb–Ti as the supermagnet material.

Despite the obvious importance of Nb–Ti the story of how it emerged from among the thousands of known superconductors to become the most widely utilized has not been written in any systematic fashion. Indeed, some modern accounts of high magnetic field superconductivity simply dismiss early Nb–Ti activity with a reference or two to an early Nb–Ti supermagnet patent by Matthias<sup>1</sup>, or to a paper by Hulm and Blaugher<sup>2</sup> which first reported the superconducting transition temperatures of Nb–Ti alloys, or to early papers by Hake and myself<sup>3–5</sup> on the upper critical fields and critical current densities of Nb–Ti alloys, or to the early commercial suppliers of Nb–Ti wires. This

leaves unsaid much that is of interest concerning the motivating circumstances during those times and the preconceptions which acted as barriers to the acquisition of the basic understanding which was required for progress to be made. In what follows, I attempt to fill in some of the missing background, to convey some of the excitement, urgency, suspense and frustration of those times, and to describe some of the missed clues, the serendipity and the behind-the-scenes activity. Primary focus is on events with which I had personal contact and which, by a circuitous route, finally converged on Nb–Ti. Although reference is made to pertinent published reports by others, the picture presented here is by necessity incomplete. No attempt is made to present events as they might have been perceived from the perspectives of others who also participated in the assault on high magnetic field superconductivity. In any event, it will be apparent that, while Nb<sub>3</sub>Sn and Nb–Zr brashly proclaimed their very considerable worth at the outset, Nb–Ti only reluctantly revealed its remarkable potential, almost as if it preferred anonymity.

My involvement with high magnetic field superconductivity began purely by chance. In 1955 I joined the Research Department of Atomics International (AI), a division of North American Aviation, Inc. (now part of Rockwell International), where a research contract administered by Donald K. Stevens of the Atomic Energy Commission (AEC) was in place. It was the goal of that contract effort to shed light on the basic electronic structure and properties of actinide metals. Along these lines I undertook electron transport measurements on pure Th and U from liquid helium temperatures up to room temperature and in magnetic fields up to 3 T. Being experienced in de Haas–van Alphen effect studies, I planned ultimately to use that powerful technique to determine the Fermi surfaces of pure single crystal specimens. My long range goal was thus to use the most explicit tool on the purest and simplest materials. Accordingly, it was with some reservation that I responded to a suggestion from Dwain B. Bowen, who had recruited me into his group at AI. Dwain suggested that I also investigate the electron transport properties of some

arc-melted metastable  $\gamma$ -phase b.c.c. U-Mo and U-Nb alloys, which were considered to be potential nuclear reactor fuel materials, and which had been shown by Bleiberg, Jones and Lustman<sup>6</sup> to exhibit unusual negative coefficients of electrical resistivity between room temperature and liquid nitrogen temperature. I suspected that materials such as these would be hopelessly complex or, perhaps worse, simply not very interesting but, not wishing to offend Dwain, I proceeded with the measurements. This required only modest effort on my part, because arc-melted and quenched alloy specimens were provided to me through the courtesy of Roger Chang and James D. McClelland. For all four of the alloys I studied, the electrical resistivities continued to rise gradually as temperature was lowered from liquid nitrogen temperature to liquid helium temperature. This was not particularly surprising in light of the higher temperature results of Bleiberg *et al.* However, as temperature was reduced still further, below the normal boiling point of liquid helium, abrupt superconducting transitions took place in the vicinity of 2 K. I recall being mildly surprised, for, in light of the unusual behaviour of the resistivity at higher temperatures, the possibility of observing superconductivity simply hadn't occurred to me. I was more than mildly surprised, however, to find that at 1.2 K a magnetic field of 2.1 T was required to restore traces of resistance in some of the specimens, and that the maximum magnetic field at my disposal, 3 T, was insufficient to restore the full normal-state resistance<sup>7,8</sup>. Extrapolation of the resistive onset transition fields to absolute zero in temperature yielded values ranging from 3.4 to 3.6 T, or  $\approx 50\%$  higher than the earlier record value reported by de Haas and Voogd<sup>9</sup> in their studies of Pb-Bi alloys in 1930. Clearly, I was much indebted to Dwain Bowen for this advance!

It is also pertinent that Hulm and Chandrasekhar<sup>10,11</sup> at Westinghouse Research Laboratories independently observed the zero magnetic field superconducting transitions for these alloys, but not the magnetic field induced resistive transitions. We learned of each others investigations when we reported on them at the Fifth International Conference on Low Temperature Physics and Chemistry at the University of Wisconsin in August 1957. (That Hulm and Chandrasekhar should have studied the same alloys was not particularly surprising inasmuch as Bleiberg, Jones and Lustman were also associated with Westinghouse, and Hulm had earlier been deeply involved in superconductivity research.)

My subsequent journal report<sup>8</sup> on this work noted in the introduction that the negative temperature coefficient of resistivity behaviour was '... not confined to the metastable uranium alloys for it has been observed above liquid nitrogen temperatures for b.c.c. phases in the titanium-niobium system by Ames and McQuillan<sup>12</sup>, in the titanium-vanadium system by Brotzen *et al.*<sup>13</sup> and in the titanium-molybdenum system by Yoshida and Tsua<sup>14</sup>. An obvious extension of the U alloy work would have been to study these Ti-Nb, Ti-V and Ti-Mo alloy systems, especially in view of the fact that AI had acquired additional research contract support from the Air Force Office of Scientific Research for the purposes of studying the electronic structures of transition metals. However, the primary focus of my research was (and had been) on pure metals and I was eager to undertake pulsed magnetic field de Haas-van Alphen studies. Also, I was already heavily involved in electron transport measurements on a variety of actinide and transition metals and on transition metal hydrides.

It should be emphasized at this point that the high magnetic field behaviour of the U-Mo and U-Nb alloys

was regarded at that time more as something of a novelty than as offering the possibility of a high field supermagnet. Indeed, the widespread belief was that 'hard' superconducting alloys owed their high magnetic field properties to the existence of a sponge-like network of fine filamentary inhomogeneities, which, by virtue of small transverse dimensions, remained superconducting in high magnetic fields. Because these filamentary inhomogeneities were believed to occupy only a small fraction of the volume of this material, it was thought that in aggregate they could not support the large current densities needed for practical magnets. This model, conceived by Kurt Mendelssohn\*, had great appeal, for the high magnetic field Pb-Bi alloys studied by de Haas and Voogd were unquestionably highly inhomogeneous, consisting of eutectic mixtures of Pb-rich and Bi-rich phases, and they had been unable to support critical current densities at levels of interest for practical supermagnets<sup>16,17</sup>. The uranium alloys which I studied appeared to be quite homogeneous under metallographic examination and hence would be expected to possess still fewer filaments. In studying these alloys I had chosen very modest measuring currents quite arbitrarily for purposes of experimental convenience, and I had found that for a modest increase of measuring current the resistive transitions took place at significantly lower magnetic field strengths. In light of these factors, there appeared to be no reason to believe at that time that the uranium alloys might be made to support high critical current densities.

However, there were clues which should not have been overlooked. In a pure (chemically homogeneous) but highly strained Nb specimen I had observed a resistive transition field of 1.1 T<sup>18</sup>. By the reasoning of that era, the high field superconducting filamentary sponge was believed to be associated with dislocation networks and was not expected to yield useful critical current densities. But, in spite of this, George B. Yntema, with whom I had earlier shared laboratory space and facilities when we were graduate students in Cecil T. Lane's group at Yale University in the early 1950s, had in 1955 reported constructing a small 0.7 T iron-core electromagnet with superconducting Nb windings<sup>19</sup>. His results, published only as an abstract for the New York meeting of the American Physical Society (APS), attracted relatively little attention at that time, even though he also reported that a 0.002in diameter Nb wire had supported a critical current of 1.5 A in an applied field of 0.5 T at 1.7 K. Stated in those terms, it didn't appear to be particularly noteworthy, but it is interesting in hindsight to speculate on what the response might have been had Yntema stated instead that his Nb wire supported a critical current density of 74 000 A cm<sup>-2</sup> at 0.5 T. Curiously, even Yntema himself did not further exploit this most significant clue! To me, in the late 1950s, de Haas-van Alphen effect studies appeared to offer more scientific promise than did high magnetic field superconductivity, which appeared at best to arise from a phantom sponge structure not amenable to rigorous quantitative analysis and interpretation.

Fortunately, I did not have to choose between those two lines of investigation, for one of my AI colleagues viewed superconducting alloys as presenting very interesting challenges. Richard R. Hake, who had done his doctoral thesis on superconductivity at the University of Illinois, decided that Ti-Mo alloys would be interesting materials for study with his newly established capability

\*An excellent account of early papers which appeared to support this perspective appears in Reference 15

for conducting low temperature heat capacity measurements. His primary goal was to test, for alloys, the electronic specific heat predictions of the Bardeen–Cooper–Schrieffer theory, but he was also interested in studying the transport properties of the Ti–Mo alloys. He invited me to collaborate in this latter aspect and I agreed enthusiastically. Thus began a most productive collaboration. So complementary were our talents and interests that significant milestones in our research almost invariably rested on essential contributions from both of us. In what follows, my use of the terms ‘we’ and ‘our’ is intended to reflect our roles in that sense.

Rounding out our collaboration was the late Donald H. Leslie, a graduate of Northrop Institute of Technology, who had acquired valuable experience in cryogenics and metallurgy before joining AI. Leslie addressed the problems of preparing the alloys of interest. In a remarkably short time he designed and assembled a very versatile water-cooled copper hearth arc melter which was on-line prior to October 1957. This was to become the mainstay of our refractory alloy preparation capabilities, allowing us to examine a wide variety of alloys with great agility. Leslie also rapidly mastered the electrical and magnetic instrumentation and so participated actively in the transport property measurements.

Our initial experimental data on the electron transport properties, the specific heat and the superconductivity of b.c.c. Ti–Mo alloys appeared in an abstract<sup>20</sup> which Hake prepared for the Honolulu meeting of the American Physical Society (APS) in late August 1959\*. Among the Ti–Mo alloy compositions studied was one which, for a current density of  $34 \text{ A cm}^{-2}$ , showed no restoration whatsoever of resistance in magnetic fields up to 3 T at 1.2 K and hence represented an advance over the uranium alloys.

Although we regarded the Ti–Mo results as noteworthy scientifically, we still thought in terms of the electric current strictures discussed above with respect to the filamentary sponge model. Thus, it did not occur to us that the Ti–Mo results might offer a step toward a high field superconducting magnet. Others thought otherwise, however, for shortly thereafter Richard H. Kropschot and Vincent D. Arp of the National Bureau of Standards, Boulder (NBSB), had a large beer mug sized billet of Ti–Mo prepared from which they hoped to fabricate a superconducting magnet<sup>21</sup>. This very tough billet stubbornly thwarted their most vigorous attempts to reduce it to wire; and so the Ti–Mo supermagnet was not to be. From what we now know of the properties of Ti–Mo<sup>22,23</sup>, had the fabrication problems been overcome, Kropschot and Arp probably could have produced a 5 T supermagnet. That recalcitrant billet, which Kropschot and Arp subsequently shipped to us (on 27 March 1961) doubtless still exists in a configuration only slightly deformed from its original geometry.

Greater success with supermagnet fabrication had been enjoyed elsewhere. The April 1960 issue of *The Review of Scientific Instruments* carried an account by Autler<sup>24</sup> which described a 0.43 T iron core electromagnet with superconducting Nb wire windings. Ironically, Autler appears to have been unaware of Yntema’s pioneering work, although he was aware of my observation<sup>18</sup> of a 1.1 T resistive critical field in strained Nb, and he also referenced the Ti–Mo alloy work of Hake, Leslie and myself<sup>20</sup>.

\*Although this abstract appeared in the *Bulletin of the American Physical Society*, Hake did not attend this meeting because of the imminent birth of his son, Clifford

As 1960 proceeded, I focussed my efforts on developing a 20 T pulsed copper wire magnet for use in de Haas–van Alphen studies. Although I undertook this task with no thought of making superconductivity measurements at such high fields, this pulsed magnet facility was destined to become a key capability in our high magnetic field superconductivity studies. In developing this capability I profited greatly from assistance most generously provided by David Shoenberg of Cambridge University and Israel S. Jacobs of the General Electric Research Laboratory, both of whom were highly experienced in pulsed magnet technology.

In the late summer of 1960, at the Seventh International Conference on Low Temperature Physics in Toronto, I celebrated the operational status of the pulsed magnet capability by reporting data on the de Haas–van Alphen effect in Ca<sup>25</sup>. At the same conference, Hake<sup>26</sup> reported more extensive specific heat data on Ti–Mo alloys, and Goodman, Hillairet, Veyssie and Weil<sup>27</sup> reported specific heat data on U–Mo and U–Nb alloys. Not yet appreciated was the fact that our electron transport data (transition temperature and normal-state electrical resistivity), together with these specific heat data (normal-state electronic specific heat coefficient), were sufficient for calculations of the upper critical magnetic fields of the above alloys in terms of the truly remarkable theoretical structure developed between 1950 and 1959 by the Soviet scientists Ginzburg and Landau<sup>28</sup>, Abrikosov<sup>29</sup> and Gor’kov<sup>30</sup> (GLAG). Curiously, Hake had pointed out Abrikosov’s paper to me and we had wondered if it might have some connection with the high magnetic field superconductivity which we were observing, but we didn’t pursue it in any depth at the time. Indeed, from among the many complex, abstract and lengthy theoretical superconductivity papers being published in that very exciting post-Bardeen–Cooper–Schrieffer era it was no easy task to select and focus on those which were exceptionally significant.

Also in 1960 a highly significant publication appeared, which, apparently unknown to its authors, actually anticipated the discovery of large superconducting critical current densities at high magnetic fields. In magnetization studies of Nb<sub>3</sub>Sn, Bozorth, Williams and Davis<sup>31</sup> of Bell Telephone Laboratories (BTL) found evidence for the survival of superconductivity in magnetic fields at least as high as 7 T at 4.2 K. They took little note of the observed hysteresis in the magnetization other than to point out that after initial flux penetration the magnetization exhibited trapped flux ‘irregularities’. We now refer to such irregularities as ‘flux jumps’. Moreover, with the advantage of hindsight, and using their data, I have since determined that the critical current density which sustained the trapped flux in their Nb<sub>3</sub>Sn specimen at 7 T must have been  $\approx 6000 \text{ A cm}^{-2}$ . The low temperature physics community had again failed to recognize what appears, in hindsight, to have been a very obvious clue! Clearly, it would take a direct measurement of critical current to make the point. That would soon be forthcoming.

The next escalation in our high magnetic field superconducting studies at AI was triggered by a letter from Donald Stevens and addressed to John P. Howe, Director of Research at AI. It was dated 6 January 1961 and requested that I participate in a meeting to be held in Washington, DC on 16 January 1961. The stated purpose of this meeting was ‘. . . to consider what part should be played by the Division of Research, AEC, in advancing knowledge of superconducting alloys which withstand high magnetic fields’. A notation at the bottom of the letter

indicated that a copy had been directed to Arthur E. Ruark, who, at that time, was Assistant Director of the AEC Controlled Thermonuclear Research Program. Now there was a programme in critical need of more efficient higher field magnets!

At AI it still had not occurred to us that superconductivity might hold the key to those needs. Nevertheless, to give that possibility the benefit of the doubt we decided for the first time deliberately to test materials which might be expected to yield the very highest field superconductivity and to determine just how much current density they could support without dissipation. Once that direction had been set, the choice of materials was straightforward, viz. those with the highest known superconducting transition temperatures. After all, if U-Mo alloys, with transition temperatures of  $\approx 2$  K, could remain superconducting to 3.4 T, then truly enormous transition fields might be expected for alloys and compounds with transition temperatures ranging up to 18 K. However, we had no such grand expectations regarding critical current densities. We decided to concentrate on alloys and compounds having between four and five valence electrons per atom, a composition region which Matthias<sup>32</sup> had found to be favourable to the occurrence of high transition temperatures. We were of course also aware of the Nb<sub>3</sub>Sn work of Bozorth *et al.*<sup>31</sup>, although not of its revolutionary implications.

On 12 and 13 January 1961 we obtained data<sup>33</sup> on a number of materials having valence electron concentrations between four and five per atom, and all exhibited zero resistance at 3 T. The highest critical current densities were obtained for Nb<sub>3</sub>Sn, Ti-Ta and Ti-V, with values at 3 T ranging up to 560 A cm<sup>-2</sup>, or significantly higher than had been our expectation. It thus became evident that these materials should be suitable (although not particularly exciting) for supermagnet application. We noted, however, that the observed critical current densities at 1.2 K were almost identical to those observed at 4.2 K. This suggested that the electrical contacts to the specimens, rather than the specimens themselves, were most likely limiting the currents. We reasoned that if superconductivity had been the limiting factor then significantly larger critical current densities should have been observed at the lower temperature. Moreover, the contact arrangement and specimen holder had been designed and fabricated in great haste (in two days) without any anticipation that exceptionally high critical current densities might be possible. My report of these encouraging, but not spectacular, findings at the AEC meeting in Washington, DC on 16 January 1961 was received by those present with cautious optimism. It appeared that 3 T supermagnets would be feasible with winding thicknesses of  $\approx 40$  cm. Also discussed at the meeting were reports on a 1 T Nb supermagnet developed by Arp and Kropschot<sup>34</sup> at NBSB and a 1.5 T Mo-Re alloy supermagnet developed by Kunzler, Buehler, Hsu, Matthias and Wahl<sup>35</sup> at BTL (although to the best of my memory, no BTL representative was in attendance). It was the consensus at the meeting that additional work on high magnetic field superconductivity was highly desirable. Indeed, Drs Stevens and Ruark expressed interest in receiving proposals for such activity. Time was of the essence because they were required to present their budget requests to their superiors by 6 February 1961.

Upon returning to California, I prepared a research proposal which was mailed on 27 January 1961. Concurrently, we undertook steps to develop an improved specimen holder with electrical contacts capable of supporting much larger currents. However, before that task

was completed the truly spectacular results of Kunzler, Buehler, Hsu and Wernick<sup>36</sup> of BTL were reported in the 1 February 1961 issue of *Physical Review Letters* (PRL). They found that critical current densities greater than 10<sup>5</sup> A cm<sup>-2</sup> could be supported in Nb<sub>3</sub>Sn at 8.8 T! It is an understatement to remark that this gained the attention of the low temperature physics community.

The BTL paper had been received by PRL on 9 January 1961 and hence their investigations clearly predated our hurried and less spectacular Nb<sub>3</sub>Sn observations. I have since heard that Arthur Ruark was called out of the 16 January 1961 meeting mentioned above to receive a telephone call from BTL regarding their Nb<sub>3</sub>Sn data. If that is true, Ruark was a remarkable poker player, for during the meeting he made no mention of it nor did he show any signs of the excitement it should have evoked! Perhaps he was simply invited to a meeting at BTL at which their Nb<sub>3</sub>Sn results were to be disclosed.

At this juncture, recognizing the considerable problems of fabricating and utilizing the very brittle Nb<sub>3</sub>Sn compound in magnet configurations, we decided at AI to emphasize ductile alloys in our investigations. On 17 April 1961 we obtained data<sup>37</sup> showing interesting critical current densities in cold rolled Nb-Ti, Nb-Hf and Ta-Ti alloys. For the Nb-Ti alloys critical current densities ranging up to 5000 A cm<sup>-2</sup> were observed for a magnetic field of 3 T. We noted also that these Nb-Ti alloys were exceptionally ductile and easily worked. The next day we obtained comparable results for Ta-Hf and Ta-Zr specimens<sup>37</sup>. Then on 19 April 1961 we observed critical current densities an order of magnitude greater for cold rolled Nb-Zr alloys<sup>37</sup>. The excitement from these results was compounded when, during the same period, my pulsed magnet collaboration with Arthur C. Thorsen<sup>38</sup> yielded de Haas-van Alphen oscillations for the first time in an alkali metal, viz. potassium. But, in any event, our superconductivity efforts turned to optimizing Nb-Zr and AI very promptly (24 April 1961) engaged the services of Chase Brass and Copper Co. to produce long lengths of Nb-Zr alloy wire suitable for supermagnet fabrication. The high toughness of the test specimens we had fabricated suggested that this task would not be easy.

Unknown to us, on 24 April 1961 (i.e. one week after our first Nb-Ti measurements), Matthias<sup>1</sup> filed for a patent on a 'Superconducting device consisting of a niobium-titanium composition'. Also unknown to us, on 24 April 1961 (i.e. five days after our first Nb-Zr measurements), Kunzler and Matthias<sup>39</sup> filed for a patent on a 'High field superconducting magnet consisting of niobium-zirconium composition'. Their data, obtained in fields up to 8.8 T, also revealed great superiority in the critical current densities of Nb-Zr alloys over those of Nb-Ti alloys. Although we did not know it at that time, at 3 T the AI and BTL data showed reasonable agreement for both alloys. Our data were publicly announced on 24 April 1961 and again on 26 April 1961 in colloquia which I presented at Iowa State University and at Case Institute of Technology, respectively, during stopover visits as I travelled to Washington, DC to attend a meeting of the APS and also to attend another AEC meeting on high magnetic field superconductivity to be held at the Naval Research Laboratory. At the APS meeting on 27 April 1961, Kunzler<sup>40</sup> presented an invited paper entitled 'Superconductivity in high magnetic fields and at high current densities', in which he elaborated on the BTL Nb<sub>3</sub>Sn results and, to my surprise, announced the BTL results on Nb-Zr. After his talk I approached him and showed him graphs of our Nb-Zr data. Our AI Nb-Zr results<sup>41</sup> were subsequently reported in the 15 June 1961

issue of PRL.

Meanwhile, on 11 May 1961 we received a half metre length of 0.028 cm diameter Nb-Zr alloy wire from Alan H. Springmeyer of Chase Brass and Copper Co., enough for us to fabricate and test a small 56 turn 0.12 T supermagnet<sup>42</sup>. Shortly thereafter we were visited by James Wong, an MIT-trained metallurgist from Wah Chang Corporation who, upon learning of the highly favourable superconducting properties of Nb-Zr had begun efforts to produce Nb-Zr wire in quantity. By September, Wah Chang was producing long lengths of Nb-Zr on a commercial basis, and Westinghouse was producing long lengths for their internal use. In a few more months, small Nb-Zr supermagnets generating fields up to  $\approx 6$  T became commonplace in scientific research laboratories. Patent interference negotiations between AI and BTL in the matter of Nb-Zr superconducting devices lasted for four years and, in the final resolution, BTL was awarded priority and AI received non-exclusive royalty-free rights.

It should be emphasized at this point that in early 1962 Nb<sub>3</sub>Sn and Nb-Zr occupied centre stage, and Nb-Ti appeared to be destined to obscurity. We had not sought patent coverage on Nb-Ti nor were we aware of the Matthias patent application on Nb-Ti, not that it would have mattered at that time, for references in the scientific literature to Nb-Ti either ignored<sup>43,44</sup> its current carrying capacity or revealed an unfavourable comparison<sup>45,46</sup> with Nb-Zr.

In late 1961 and early 1962 our high magnetic field superconductivity research at AI continued in several directions. We addressed the technical problems inherent in attempts to achieve short sample critical current densities in practical supermagnets. We also continued our search for other superconducting materials with still better properties, extending our measurements to magnetic fields up to 16 T by adapting the pulsed copper magnet techniques developed earlier for de Haas-van Alphen studies. We also sought deeper understanding of the basic mechanisms of high magnetic field superconductivity, which was still generally believed to arise from a sponge-like, filamentary, inhomogeneous structure.

The first clue that the high magnetic field superconductors of technological interest might be explained in terms of the GLAG theories had appeared in a paper by Goodman<sup>47</sup> at the IBM Conference on Fundamental Research on Superconductivity held in June 1961. Using the GLAG theory together with my U-Mo alloy experimental data for the transition temperature and normal state electrical resistivity and his own normal state electronic specific heat data for U-Mo of the same composition, Goodman deduced a theoretical upper critical field of 2.7 T for 1.2 K. This value fell at the very centre of the magnetic field range over which I had observed the magnetic field induced restoration of resistivity in this alloy at 1.2 K and for a measuring current density of 4 A cm<sup>-2</sup>. In discussing this remarkable result with Goodman after his talk I cautioned that, while it appeared to be a very important observation, it could have been a fortuitous coincidence, for the magnetic field induced resistive transitions I had observed were sensitive functions of measuring current density. Moreover, I suspected that for different magnetic field and current orientations, and for different mechanical and metallurgical treatment, I might have observed quite different transition fields. Indeed, cold working was known to affect the resistive transition field very markedly in Nb<sup>18</sup>.

Some months later at AI we investigated the influences of these variables for alloys under study in the

pulsed magnet. Significantly, so long as very low current density ( $\approx 10$  A cm<sup>-2</sup>) was employed, the resistive transition field for a given alloy composition was found to be nearly independent of mechanical working, and field and current orientations. It thus appeared that the low current density resistive critical field was intrinsic, i.e. related to fundamental electronic structure, not simply a capricious parameter dependent upon a presumed inhomogeneous filamentary sponge structure. This suggested that a serious comparison of our low current density resistive critical field data with upper critical field predictions of the GLAG theories should be meaningful. This was now possible not only for U-Mo and Ti-Mo alloys but also for Ti-V alloys, for specific heat data on the latter were kindly provided to us prior to their publication by Cheng, Gupta, van Reuth and Beck<sup>48</sup>. For wide ranges of alloy composition we found remarkably good quantitative agreement with the GLAG predictions *with no arbitrary adjustable parameters*. For some compositions we noted discrepancies but we were able to account for them by invoking electron spin paramagnetism energy considerations\* which had been ignored in the formulation of the GLAG theories. Also, the until-then puzzling fact that the low current density resistive critical field was nearly insensitive to cold working in the concentrated alloys, but was a strong function of cold working in pure Nb, could now be understood in terms of the GLAG formalism. Our findings<sup>4,5,23,52</sup> left no doubt in our minds that the GLAG approach to high magnetic field superconductivity was indeed the correct one, needing only modest refinement to take account of electron spin paramagnetism and related effects. Although transport supercurrents were not explicitly considered in the GLAG theories, Abrikosov<sup>29</sup> had suggested that macroscopic inhomogeneities in non-ideal materials would perturb the vortex pattern of the mixed state and hence account for trapped flux. This was tantamount to saying that inhomogeneities would stabilize transport supercurrents. Nevertheless, our interpretation of our experimental results in terms of the GLAG theories was so foreign to the prevailing tide that publication of our results in PRL<sup>52</sup> was delayed for a month by referees who still subscribed to the filamentary sponge viewpoint.

The search for understanding recounted above proved to be a crucial step in the identification of the technological potential of Nb-Ti, for it was in the course of the pulsed field measurements that we discovered that, among all of the ductile high magnetic field superconductors we studied, Nb-Ti alloys possessed the highest upper critical fields ( $\approx 14.5$  T). This factor, together with our better understanding of the theoretical basis of high magnetic field superconductivity, gave us confidence that through appropriate metallurgical and mechanical processing Nb-Ti could in fact be made to support high critical current densities. This proved to be the case. In a post-deadline paper<sup>3</sup> at the Washington, DC meeting of the APS in late April 1962 and in a regular contributed paper<sup>4</sup> at the Evanston meeting of the APS on 21 June 1962 we reported greatly enhanced critical current densities for heavily worked Nb-Ti and pointed out the suitability of Nb-Ti for supermagnets generating 10 T. We reported additional results<sup>5</sup> on high critical current density Nb-Ti specimens at the VIII International Conference on Low Temperature Physics in London in late September

\*The importance of electron spin paramagnetism energy considerations at very high magnetic fields had been anticipated by Pippard and Heine<sup>49</sup>. That such considerations would impose a limit on the filamentary sponge model was pointed out by Chandrasekhar<sup>50</sup> and Clogston<sup>51</sup>.

1962. Included in this report were data we obtained on Nb-Ti wire specimens prepared by James Wong, who, among the commercial superconducting wire producers, maintained the closest ties with our activity. At 4.2 K and 3 T these early Nb-Ti wires supported critical current densities of  $4.4 \times 10^4$  A cm<sup>-2</sup>, or greater than observed for the earliest Nb-Zr wires at 3 T. But, more importantly, the Nb-Ti alloy specimens supported critical current densities of  $\approx 10^4$  A cm<sup>-2</sup> at 4.2 K and 10 T, well above the useful 6-7 T magnetic field limit of Nb-Zr. At this point Nb-Ti was far from being optimized, but we had no doubt that it would ultimately replace Nb-Zr. Not only did Nb-Ti possess superior superconducting properties, but it was also much more easily drawn to wire. Nevertheless, the transition from Nb-Zr to Nb-Ti occurred much more slowly than we anticipated. Extensive investigations by commercial producers, among them Atomics International, Wah Chang, Supercon and Westinghouse were required to establish the most appropriate compositions and metallurgical structures to optimize performance for various applications. In one way or another we made modest contributions to each of these efforts, conducting evaluations of specimens prepared by James Wong at Wah Chang and later Supercon, transferring pulsed magnet technology to B.S. Chandrasekhar at Westinghouse, and assisting Roger Boom in his efforts to launch the Atomics International commercial Nb-Ti wire and cable venture. Modest quantities of Nb-Ti wire were first marketed in 1964 by Westinghouse, but it was 1966 before commercial superconducting Nb-Ti wires and cables were available in significant quantities.

The first supermagnet to utilize Nb-Ti to achieve 10 T was realized in 1964 by Coffey, Hulm, Reynolds, Fox and Span<sup>53</sup> at Westinghouse. By using Nb-Ti for the high field windings and Nb-Zr for the lower field regions, this magnet set an example which was followed in other early magnets<sup>54,55</sup>. But by 1967 complete conversion from Nb-Zr to Nb-Ti was widely recognized as being inevitable. In a review of superconducting magnet materials at the Applied Superconductivity Conference held that year in Austin, Texas, Laverick<sup>56</sup> remarked that, 'Nb-Zr is now obsolescent and current practice favours the use of the cheaper, lighter and more ductile Nb-Ti'. The term 'higher performance' should also have been included among his descriptors!

The suitability of Nb-Ti for truly large scale projects was soon proven in an audacious project undertaken by John Purcell<sup>57</sup> to develop a hydrogen bubble chamber supermagnet at Argonne National Laboratory. This pioneering 1.8 T, 4.8 m i.d., 80 MJ behemoth, begun in 1966 and first operated in December of 1968, utilized US \$2.5 million worth of Nb-Ti/Cu composite conductor, and it was an unqualified success. For 10 years it served its original purpose and more recently has been turned on its side for use in a colliding beam experiment at the Stanford Linear Accelerator Center. The subsequent widespread application of Nb-Ti has been marked by exquisite engineering challenges and accomplishments which far surpass anything we might have anticipated during the early 1960s.

Will Nb-Ti itself be displaced? Given the diversity of the elements of the periodic table and the far greater diversity of their possible combinations, there should be little doubt that better materials await discovery. The challenge is to attain, in a single material, the fabricability typical of Nb-Ti and the superior superconducting characteristics typical of the brittle compounds.

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