

Superconductivity at CSIRO (Sydney) 1969-2009

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Abstract - This essay, prepared in recognition of the 2011 Superconductivity Centenary Year, gives an impression of work at CSIRO, Sydney, Australia, in the field of superconducting devices, with which the author was associated for a period of 40 years. Starting from the establishment of cryogenic facilities in the 1950s, work on superconductivity gained strength from the initiation of the Josephson voltage standard in 1969. Rapid expansion of the effort in high-precision metrology continued through the 1970s and was given a further stimulus from the high- T_c revolution in 1987. Applications in geomagnetic prospecting, high-frequency detectors and THz imaging are described.

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I. INTRODUCTION

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has supported a significant effort in cryogenics, initially within its National Standards Laboratory (NSL), later named the National Measurement Laboratory (NML) in Sydney, Australia, since the 1940s. Superconductivity research grew from 1969 onwards with the development of the Josephson voltage standard. I joined the effort at that time, having previously worked on thin-film dielectrics in Scotland (1960-64) and at NSL (1964-69) on the hydrogen maser frequency standard.

This essay is based on personal memories of the work in superconductivity with which I have been involved since that time. Any unintended errors and omissions are my responsibility. The Josephson effects [1] and their applications occupy much of this review, since they were responsible for my entry into and subsequent 40-year journey through the fields of cryogenics and superconducting technology, from 1969 to the present. The discovery by Bednorz and Muller of high-temperature superconductors in 1986, however, had for me a comparable career-determining impact.

II. CRYOGENICS AND SUPERCONDUCTIVITY AT CSIRO'S NATIONAL STANDARDS LABORATORY

The CSIRO work in superconductivity that I am about to describe would undoubtedly have been hindered, had there not already been a well-established on-site effort in cryogenics. Its origins can be traced back to a Cabinet (Australian Federal Government) decision in 1938 to set up a National Standards Laboratory, and to appoint as Officers in Charge: Norman Esserman (Metrology), George Briggs (Physics), and David Myers (Electrotechnology). These men, together with 5 or 6 later appointees, went to the National Physical Laboratory, Teddington, UK, in 1939 to gain relevant experience.

The 2nd World War intervened, but after 1946 Briggs was probably instrumental in setting up a cryogenics facility in Sydney, drawing on his experience at Cambridge where Kapitsa developed an expansion engine helium liquefier in the early 1930s, and subsequently in New York when Sam Collins and Howard MacMahon at MIT co-operated with Arthur D Little Inc to produce the first commercial "Collins" liquefier.

Back at the National Standards Laboratory (NSL) of the CSIRO, which was situated in the premises now known as the Madsen Building in Sydney University grounds, Alan Harper and Ron (WRG) Kemp took up the challenge to make a copy of the Collins machine, with the help of working drawings kindly donated by Collins and MacMahon.

Three Sydney graduates, Guy White, Paul Klemens and John Rayne were sent on CSIRO overseas studentships to gain relevant experience at Oxford, UK, and Chicago, USA. White returned in 1950, and when Kemp and Bill Smythe succeeded in producing the first liquid helium in the Southern Hemisphere, he initiated a research program concentrating on thermal properties of gold, silver and copper at temperatures between liquid helium and liquid oxygen, *i.e.*, 2K to 100K [2]. Klemens joined the group in 1953.

The cryogenics research initiated by Guy White and colleagues was carried out in what was then the Physics Division of NSL (under the overall direction of R. Giovanelli). Electrical metrology on the other hand, including the maintenance of the standards of time, frequency, voltage and resistance, was directed by F.J. Lehany, in the Division of Applied Physics.

Early in 1967, a paper by a group at University of Pennsylvania [3] appeared in Physical Review Letters:

"Using the ac Josephson effect, we have determined that $2e/h = 483.5912 \pm 0.0030$ MHz/microvolt. The implications of this measurement for quantum electrodynamics are discussed as well as its effect on our knowledge of the fundamental physical constants."

It came to the attention of A.M. Thompson, who was well advanced at NSL in establishing the calculable capacitor as an absolute method for realizing the Farad and the Ohm [4], and Ian K. Harvey, who was working with Len Hibbard and me on the construction of a hydrogen maser frequency standard. Harvey grasped the significance of the Parker, Taylor, and Langenberg paper, which showed that Josephson's ac effect could in principle, provide a quantum-mechanical route for the definition of a voltage in terms of the frequency of an electromagnetic oscillation, depending only on the fundamental constants h and e : $f = (2e/h)V$. Because a frequency could be measured, with reference to an atomic frequency standard such as the hydrogen maser, to an accuracy of a few parts in 10^{10} , there was an obvious incentive to embark on this new route for the realization of

the volt. This would reinforce a trend towards realization of the SI Base Units in terms of the fundamental constants (Figure 1).

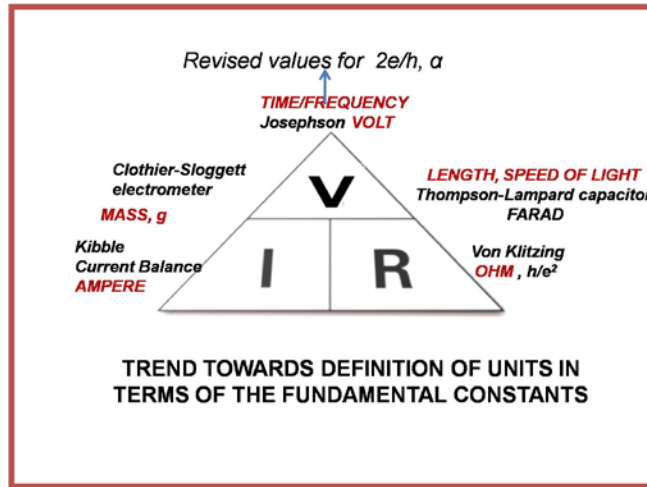


Fig. 1. Schematic realisation of the electrical units.

The adoption of cryogenic technology and superconductivity was a major revolution in the electrical standards section of NSL. Ian Harvey and I, neither of us having any previous cryogenics experience, spoke to Guy White about the breakthrough in fundamental metrology that was foreshadowed by Josephson’s theoretical paper and the Pennsylvania work. Within a few days, with help initially from John Birch who gave us a beginner’s crash course in practical cryogenics, we had a working cryostat and enough liquid helium to get started. Not many weeks later, following an overseas trip, Ian devised and constructed a simple point-contact Josephson junction from niobium wire, and mounted it inside a helium-cooled X-band waveguide. A later prototype point-contact junction is sketched in Figure 2.

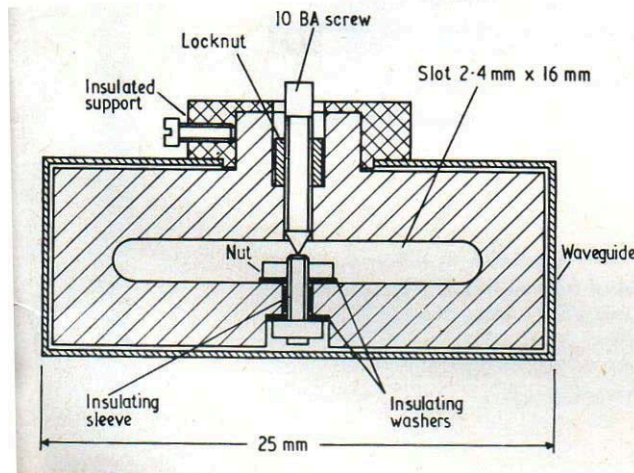


Fig. 2. Cross-section drawing of a prototype Nb point contact Josephson junction.

With microwave radiation applied from a borrowed Klystron source, the predicted Josephson/Shapiro constant-voltage steps were clearly displayed on the screen of an oscilloscope (Figure 3). I later prepared some thin-film PbIn and Sn tunnel junctions, which were shown to agree with the Nb point-contact result within the available precision of 2 in 10^7 , and subsequently demonstrated the equivalence of two point-contact junctions to 2 in 10^{10} [5].

For the work to be internationally accepted, the reliability of the existing working standard of voltage had to be ascertained. The immediate priority then at NSL, was to deploy the ac Josephson effect in a long-term, week-by-week monitoring of the in-house voltage working standard, which consisted of a group of electrochemical cells which had been carefully maintained at 20.00°C in a constant-temperature oil bath over several decades. In fact some of the cells were part of the original 1938 bequest from NPL, Teddington. This monitoring routine was carried out by Ian Harvey, Bob Frenkel and myself with technical assistance from Norm Ancher, Harry Collins and others.

A major effort was then required to compare the voltage output of about 1 millivolt from the single Josephson junction, at the temperature of liquid helium, with the standard cell voltage of 1.018... volts at room temperature. With traceability of our resistors to the Thompson-Lampard absolute resistance standard, and by means of regular calibrations using a series-parallel "Hamon" resistive ratio divider, the 1:1000 voltage ratio was reliably maintained with a precision of 2 in 10^7 [6].

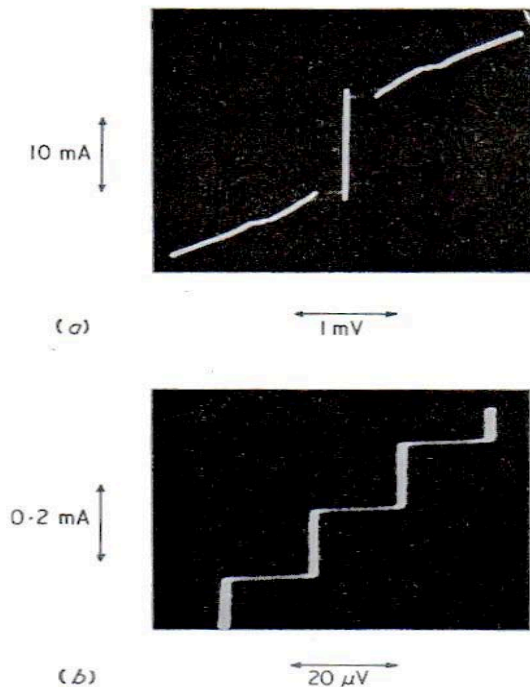


Fig. 3. Current-voltage characteristics of our point-contact Josephson junction (a) without and (b) with applied 9.8 GHz radiation.

The later invention by Ian Harvey of the superconducting current comparator established a new principle in electrical metrology, based on the Meissner effect and the quantization of magnetic flux, and enabled a ratio of currents to be established to a few parts in 10^{10} [7]. The absolute value of $2e/h$ was at that time known to an accuracy of only several

parts per million, and the challenge was opened for a series of $2e/h$ inter-comparisons by several independent national laboratories - to the highest possible precision. The US National Bureau of Standards (NBS) [8], the UK's National Physical Laboratory (NPL) [9] and NSL [10] each published their determinations within a few months of each other in 1970. The quoted NSL precision (0.1 ppm) was state-of-the-art at that time. The development of the cryogenic current comparator (Figure 4) by Harvey [11] improved the available precision to 0.02 ppm. A further reconciliation of international voltage standards took place following the Absolute Volt determination at NSL by Sloggett and Clothier (see below).



Fig. 4. Ian K. Harvey's superconducting current comparator [11].

THE JOSEPHSON JUNCTION AND THE SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE (SQUID)

When two pieces of superconductor are separated by a very thin barrier (~ 1 nm thick) their wave-functions can interact by quantum-mechanical tunnelling through the barrier. The state of each superconductor is determined by a quantum-mechanical wave-function with a phase parameter, ϕ , which is uniform throughout the superconductor. By this interaction, supercurrents can tunnel, without any voltage drop, across the barrier, provided the current does not exceed a value called the critical current. This value can range from a few micro-amps to several milli-amps depending on temperature and other parameters. When the applied current exceeds the critical value, a voltage difference V appears (Figure 3a) and the quantum mechanical wave-functions in the two superconducting electrodes experience phase slippage, such that an alternating supercurrent with frequency $f=2eV/h$ is set up, which can interact with an applied microwave signal f_0 to produce constant-potential (Shapiro) steps Fig. 3(b). The separation between neighbouring steps is precisely $V=hf_0/2e$, and this equation is the basis of the Josephson volt.

When a Josephson junction is inserted into a superconducting ring, the structure displays the unique property of Superconducting Quantum Interference. In this configuration, the critical current of the Josephson junction undergoes a periodic modulation as a function of the magnetic flux threading the ring (Figure 5).



Fig. 5. Ian Harvey observes the triangular voltage vs. flux trace of an rf SQUID.

The period of the field corresponds to a change of one magnetic flux quantum Φ_0 in the ring, where $\Phi_0 = 2 \times 10^{-15}$ Wb. The sensitivity of the SQUID as a magnetometer [12] depends primarily on designing an electronic read-out which can resolve flux changes on the order of $10^{-6} \Phi_0$.

III. THE MOVE TO THE NEW NATIONAL MEASUREMENT LABORATORY, LINDFIELD.

Shortly after the successful realization of the Josephson volt, all staff and equipment at NSL (by now re-named the National Measurement Laboratory (NML)), were re-located to a new, purpose-built laboratory complex in West Lindfield, some 20 km north of Sydney University. A major effort over a 6-month period was required to ensure the safe dismantling, transportation, and re-establishment of a vast array of complex, sensitive apparatus at its new destination (Figure 6).

In the case of the voltage standard, the crucial components were the standard cells and their constant-temperature bath, the 1000:1 resistive ratio divider, the liquid-helium cryostats, and various irreplaceable galvanometers. All due care was taken to avoid exposing the gear to shocks such as excessive vibration and extreme temperature changes. We were by now confident, however, that in a worst case scenario we could always re-establish the volt in terms of the atomic constants by means of the Josephson technique; a task which would have been impossible just a few years earlier.

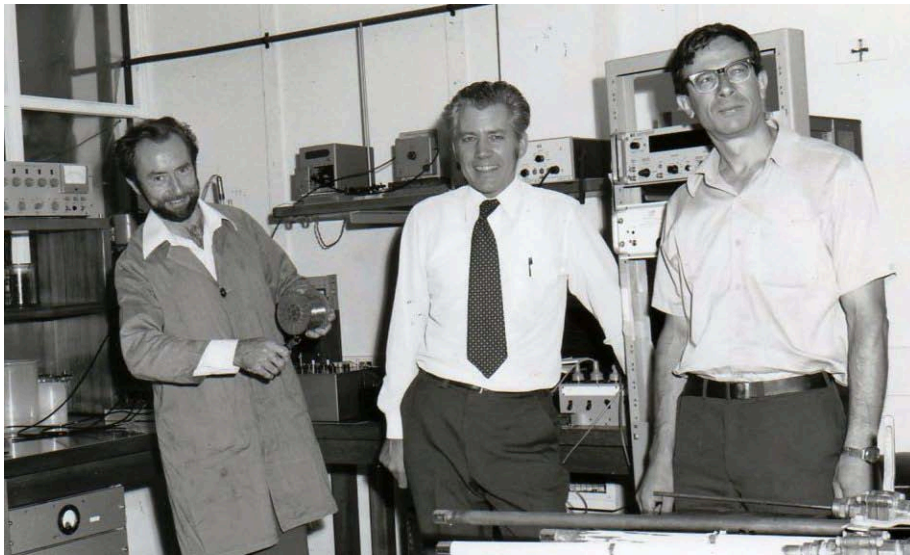


Fig. 6. John Macfarlane, Ian Harvey and Robert Frenkel prepare to re-locate with the Josephson volt equipment to the new Lindfield laboratory complex in 1977.

After everything had settled down in the new, temperature-controlled, electromagnetically-screened labs, in mid-1978 we resumed our weekly calibrations of the standard-cell group against the Josephson voltage. It became clear that, despite all the precautions, something had changed! The slow, uniform drift of about 0.04 microvolts per annum in the mean electromotive force (emf) of the group, which had been continuously monitored from the inception of the Josephson experiment in 1969, underwent an abrupt upward shift of about 1 microvolt. A convincing explanation was never found, and after some months, the readings gradually resumed their original long-term trend line. Without the benefit of the Josephson experiment, and its intrinsic traceability to the fundamental constants, this excursion and eventual recovery in the voltage of traditionally-maintained standard cells would not have been reliably detected.

At about the same time, also at NML, the quest for an absolute voltage standard by an entirely different, non-Josephson, route was under way in the work of Keith Clothier, Graeme Sloggett and others. An immensely difficult and multi-disciplinary experiment, it relied on state-of-the-art optical interferometry, measurements of the gravitational acceleration, g , mercury-liquid densitometry, and vibration isolation, as well as high-precision electrical metrology. In 1983, this work finally yielded an absolute value for the volt in terms of $2e/h$ with a precision of 3 parts in 10^7 . Moreover, the new value differed by a relatively enormous 8 parts in 10^6 from the then internationally-agreed figure [13]. This determination, together with results from Josephson-volt experiments which by now had been set up and internationally verified in a number of standards institutes around the world, made a vital contribution to a revised definition of $2e/h$ which was internationally agreed upon in 1990. The endeavours of many CSIRO scientists and technicians, working individually on several quite independent, highly challenging experiments over a period of decades, thus converged within a year or two to produce a world-class contribution to the knowledge of the fundamental physical constants, thereby confirming the place of Australian metrology at that time amongst the top 2 or 3 electrical-standards labs in the world.

IV. TOWARDS HIGHER FREQUENCIES

The Josephson effect experiment not only established a link between dc voltages and high-frequency electromagnetic radiation, it also catalysed a transition in the careers of those involved in its development. The high-frequency, broadband capabilities of Josephson junctions were becoming recognized for demanding applications, including radio astronomy, where low noise, ultra-sensitive detectors were in demand. A collaborative project, initiated around 1982 with the Division of Radiophysics, Marsfield, enabled us to recruit from the Australian National University, Canberra, a dynamic researcher, Lew Whitbourn, to activate this work. Involving the manufacture and testing of prototype SIS (superconductor-insulator-superconductor) diodes operating at 40 GHz in liquid helium, preliminary results were published in 1986 in the Australian Journal of Physics [14]. Lew then, in collaboration with Brian James and colleagues at Sydney University, went on to greatly extend the scope of the project by designing and building an optically-pumped far-infrared laser, with which we carried out a number of innovative quasi-optical experiments at wavelengths around 400 microns, equivalent to a frequency of 750 GHz. In Lew's words, we were now covering the electromagnetic spectrum "from dc to daylight". A spin-off from this work enabled a local company to develop and market a range of quasi-optical components.

V. TOWARDS HIGHER TEMPERATURES

While this lively laser work was in progress, the high-temperature superconductivity breakthrough announced in 1986 by Bednorz and Müller triggered the next surge of activity at CSIRO/NML. Driven initially by the understandable desire to extend the Josephson work up to liquid nitrogen temperatures, we quickly realized that it would be essential to have in-house access to the new and strange rare-earth oxide materials that were just being reported, particularly by Paul Chu's group at the University of Houston, and by workers at Bell Labs. As soon as the stoichiometric composition of the YBCO compound was clarified by the Bell Labs group in Physical Review Letters [15], I took the reprint round to Bob Driver, one of the few "chemists" then working at NML (Figure 7). By chance, Bob had done some of his PhD work on oxides closely related to this compound. He seemed instinctively to know the process, including the critical firing and annealing in an oxygen atmosphere that would be required. Within a few weeks, we were testing samples of this black ceramic, and when we achieved superconductivity at a temperature of 90K, a front-page article appeared in the Sydney Morning Herald - such was the public interest at that time.

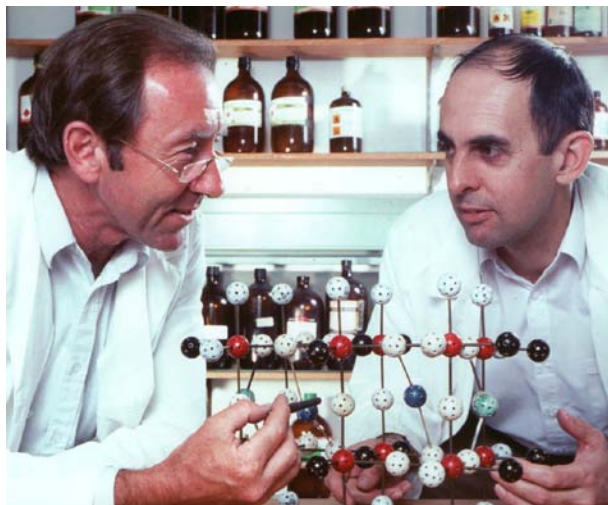


Fig. 7. Robert Driver (right) and I discuss the structure of YBCO (1987).

Rapid progress was achieved in the years 1986-91. Our ready access to the in-house expertise and facilities for reliable electrical and magnetic measurements, together with insightful calculations by Karl-Heinz Müller, contributed to a series of papers which made fundamental advances in understanding the response of the superconductor to magnetic fields [16]. Valuable experimental support by Harold Welch, Steve Collocott, Ron Roberts, Chris Andrikidis, Cathy Foley, Corinna Horrigan and others, added to the effort. Theoretical contributions were also made by John Bell and David Eagles. Immediately after we learned how to make and measure the HTS materials, the possible applications envisaged for Josephson devices such as SQUIDs multiplied overnight. The first HTS SQUID in Australia was demonstrated at CSIRO by Ian Harvey [17], and subsequent improvements made over the next 10 years have been summarised by Graeme Sloggett *et al.* [18] and by Cathy Foley *et al.* [19]. Early doubts about the feasibility of unskilled operators using liquid nitrogen and deploying relatively unproven equipment in the field situations were largely overcome by the ingenious adaptation of low-cost, ruggedized Dewar flasks as described by Keith Leslie, Rex Binks *et al.* [20]. Although the original principle of the SQUID as applied to magnetometry was conceived by Silver and Zimmermann in the 1960s, its use had been restricted for many years to the laboratory, due to the necessity of operating the original devices at liquid-helium temperatures. Now, the easy availability and relatively low cost of liquid nitrogen caused an explosive growth around the world in superconductivity research. In the thin-film area, Nick Savvides at CSIRO developed an unbalanced magnetron sputtering process which was used to fabricate high quality a-b aligned c-axis oriented $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thin films [21]. Parallel work was done by Steven Filipczuk on an ion-beam sputtering method. Although the preferred method to form Josephson junctions in HTS materials was to use bicrystal substrates, we opted instead to develop step-edge junctions on single-crystal MgO (001) substrates. These substrates were relatively cheap, and had the advantage that the junctions could be placed at arbitrary positions. Later refinements allowed us to control the junction critical current over four orders of magnitude by

variation of the step angle. Some of these achievements are summarised in [19]. Equally vital to the success in making reproducible junctions and SQUIDs, of course, was the contribution of skills in the micro-lithographic clean-room (Figure 8).



Fig. 8. The CSIRO clean-room team ca. 2003.

VI. COLLABORATIONS

From 1986 until 1992, our “Superconducting Devices Group” grew in size to well over a dozen. The spirit of enthusiastic co-operation that emerged between people working on theory, materials, measurement standards, cryogenics, X-ray diffraction and scanning electron microscopy, was truly magnificent. It was a privilege to work with those people (Figure 9) and to be, for a time, their Project Leader.



Fig. 9. Some members of the Superconducting Devices team in 1990. Clockwise from left: I. Harvey, G. Sloggett, W. Wright, L. Whitbourn, A. Collings, C. Foley, N. Scheepers..

The opportunity of more widespread collaboration emerged in 1987 during a workshop meeting at Warburton, Victoria, where I met Dr John Watson, then the Research Director at BHP Melbourne Laboratories¹. More or less over dinner, we sketched out a research program, which in due course, brought CSIRO, BHP, and AWA (Amalgamated Wireless Australasia) together in a successful application for Commonwealth government funding. The outcome of this and successive collaborations (described in the next paragraph) proved that cryogenic techniques can be successfully deployed in real-world field situations. Other collaborations were set up, for instance, with Metal Manufactures and the University of Wollongong. Meanwhile, in 1992, I moved for a time to the University of Strathclyde, Scotland, and the National Physical Laboratory, UK, but maintained my links both personal and scientific with CSIRO, where I have recently, with Dr Jia Du, resumed a part-time collaboration on the radio-frequency and THz properties of HTS Josephson devices [22,23].

VII. LANDTEM

It is impossible to expand here on all the outcomes of the HTS work, so I shall mention only one project which evolved from the early industrial collaboration, and which came to be known as LANDTEM. Great credit for this outcome is due to the inspirational leadership of Graeme Sloggett, who succeeded me in 1991 as Project Leader; Cathy Foley, who took over this role following Graeme's untimely death; and Keith Leslie, the current Project Leader (Figure 10).



Fig. 10. Keith Leslie and Cathy Foley at the Applied Superconductivity Conference, Jacksonville, USA, in 2004.

Valuable experience in geomagnetic techniques was contributed by the CSIRO Division of Exploration and Mining. The TEM (Transient Electro-Magnetic) method is one of many mineral exploration techniques. It is widely used for the detection and delineation

¹ BHP has been an important and major player in the mineral resources industry, since 2001 known as BHP Billiton.

of highly conducting ore bodies such as nickel sulphides, silver and gold. In the “traditional” ground-based TEM methods, a square loop of wire, about 100 x 100 m² in size, is placed on the ground. When current is pulsed through it, eddy currents are induced in any electrically-conducting materials under the soil. These eddy currents generate transient magnetic fields, B , which in turn, induce transient secondary currents in a detecting coil located at some distance. In the case of LANDTEM [24], the sensing of B -fields is accomplished by means of a radio-frequency (rf) SQUID. The history of LANDTEM is therefore closely linked to the history of SQUID development at NML, which can be traced back to the work initiated on Josephson-effect devices in 1969, and was extended to high-temperature superconductors (HTS) from 1987 onwards. The SQUID in the meantime has travelled a long way from its experimental beginnings in a cryogenics laboratory towards the realisation of a fully-operational commercial implementation in the geo-exploration field, which was recognized by the award of the CSIRO Medal to the LANDTEM Team in 2007².

VIII. PRESENT

In 2004, the National Measurement Institute separated from CSIRO, but the superconductivity work continues in the CSIRO Centre for Materials Science and Engineering (CMSE). Activities at the Centre include the further development of HTS and LTS superconducting instrumentation; applications in geo-magnetic and sub-ocean detection; HTS active and passive radio-frequency devices; quantum computing applications; design and testing of cryogen-free THz imaging sensors.

ACKNOWLEDGEMENTS

Some of the photographs (Figs 5, 6, 7) were taken by staff of the then-existing CSIRO Photolab.

I am grateful to Dr Guy White for providing background notes on the development of cryogenics at NSL/NML/CSIRO; to Cathy Foley and colleagues at CSIRO; to Gordon Donaldson and Colin Pegrum, University of Strathclyde, for their pioneering work on SQUID applications; to John Gallop and Ling Hao, NPL Teddington, for their hospitality and collaboration on many occasions; and indeed to all my colleagues, past and present, for their inspiration and support.

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² Editors note: after this article was accepted by ESNF, the author informed us that Cathy Foley and her CSIRO team received the ““Mineral Industry Operating Technique Awards (MIOTA)” of the Australasian Institute of Mining and Metallurgy (AUSIMM), see [PA3](#). The award presentation is scheduled for March 2011.

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APPENDIX: 1911 IN RETROSPECT

Heike Kamerlingh-Onnes found to his astonishment in 1911 that a sample of mercury attained a state of zero electrical resistance at the temperature of liquid helium. What had started out as a methodical, if unexciting, endeavour to catalogue the low-temperature electrical properties of various metals, opened a door to a totally new, and anomalous, aspect of Nature. It would be a further 20 years before theory even began to glimpse a possible explanation for this behaviour. The enlightenment was arguably triggered by the discovery in 1933 by Meissner and Ochsenfeld of an equally surprising effect: perfect diamagnetism, accompanied by the expulsion of magnetic flux from a solid as it makes the transition into a superconducting state. A phenomenological theory based on the two-fluid model, consisting of normal and superconducting electrons co-existing side by side, was introduced by Gorter and Casimir in 1934. Then in 1935, F. and H. London proposed two equations which govern the motion of the superconducting “fluid”, while the normal

fluid obeys only Maxwell's equations. This approach led to the notion of the London penetration length for magnetic fields at the surface of the sample. Not all superconductors however behaved in the same way - in some, it appeared that superconductivity persisted even when magnetic fields penetrated large distances. Type I and Type II superconductors were thus recognised. Abrikosov in 1957 explained the magnetic penetration of Type II materials by conceiving the existence of vortices arranged in a periodic lattice. Each vortex consisted of one flux quantum, equal to $h/2e$. In 1950 Ginzburg and Landau produced a phenomenological theory which embodied the ideas of a wave function and an order parameter, confirmed the expression for the London penetration length, and introduced a second characteristic dimension called the coherence length. The G-L Theory explained the magnetic behavior and many other experimental observations on the basis of this "hydro-dynamic" model. Independently, following an entirely different microscopic approach to the problem, H. Fröhlich proposed that superconductivity occurs due to an interaction between the electrons and the ions of the crystalline lattice mediated by phonons. He suggested that pairs of electrons were in some way able to attract each other, despite their Coulomb repulsion, to form charged Bosons. Moreover, as electrons "condensed" into the superconducting state, an energy gap opened up, which was later confirmed both by thermal and electrical measurements. Experimental evidence in support of Fröhlich's hypothesis was soon established by Bardeen. The microscopic approach, based on a weak electron-phonon interaction as formulated by Bardeen, Cooper and Schrieffer, quickly gained acceptance as a vital part of the mechanism, and the BCS Theory was shown to be consistent with all then-known phenomena observed in "conventional" superconductors. But more was to come: still more intriguing aspects of superconductivity were, as yet, unknown to the authors of the G-L and BCS theories. In 1962, Brian D. Josephson, a PhD student at Cambridge, England, proposed that quantum mechanical tunnelling of Cooper pairs could occur across thin insulating barriers, giving rise to phenomena at least as remarkable as any yet seen since Onnes described his surprising observations in 1911.

About the Author:

John C. Macfarlane graduated with B. Sc. (Hons) in Natural Philosophy from the University of Glasgow in 1958, then spent 2 years as a Health Physicist with the UK Atomic Energy Authority. From 1960 to 1964 he carried out research at the University of Strathclyde on thin-film dielectrics, which led to the award of his PhD in 1964. Later that year, John moved to Sydney, Australia, with his wife and daughter, to accept an appointment with the CSIRO as a Research Scientist, where he remained for the next 27 years. He returned to the UK in 1992 and worked there for some 15 years on short-term appointments at Strathclyde, and at the National Physical Laboratory. In 2009 he retired to Tasmania, Australia, to live near his wife, 3 grown-up children, and 5 grand-children. He still maintains part-time interactions with CSIRO as an Honorary Research Fellow.