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AN ANTIPODEAN LABORATORY OF REMARKABLE DISTINCTION

by

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SUMMARY

In an astonishingly short period in September 1939, while on a brief visit from England, F.P. Bowden (FRS 1948) conceived the need, and obtained the approval of the Australian Council for Scientific and Industrial Research (CSIR), to establish a wartime friction and bearings research laboratory within the University of Melbourne. He recruited a galaxy of young talent, which during the following six years made major contributions to four very diverse defence-related problems. The infant laboratory survived the peace and eventually evolved into the internationally admired Division of Tribophysics. Many of the original members of the group went on to distinguished careers in Australia, the UK and elsewhere. The story of the exciting early days of the laboratory and the subsequent achievements of its staff are briefly described.

INTRODUCTION

The year 2003 marks the centenary of the birth of F.P. Bowden FRS (figure 1). In September 1939, at the outbreak of World War II, Philip Bowden was on a brief family visit to Australia. He had been born in Hobart, Tasmania, in 1903 and obtained his BSc and MSc from the University of Tasmania.[1] He then went to Gonville and Caius College, Cambridge, as an Exhibition of 1851 Overseas Research Scholar to study for his PhD under Dr Eric Rideal (later Sir Eric Rideal FRS). He was to remain in Cambridge for the rest of his career except for the five-year period that is the subject of this paper.

Bowden, aged 36 years, was in his prime when he visited Melbourne in September 1939. He already had a substantial and growing reputation as a physical scientist. To quote David Tabor:[1]

> Bowden's researches were characterized by simplicity and elegance. His approach was direct, his conclusions clear and uncomplicated. He was recognized as an experimental scientist of great originality and in almost every field that he touched he provided some germinal idea of value and importance. He had no shortage of ideas.

In addition, Bowden had a deep insight into potential practical applications of his fundamental researches on friction and lubrication, and was already actively consulting for

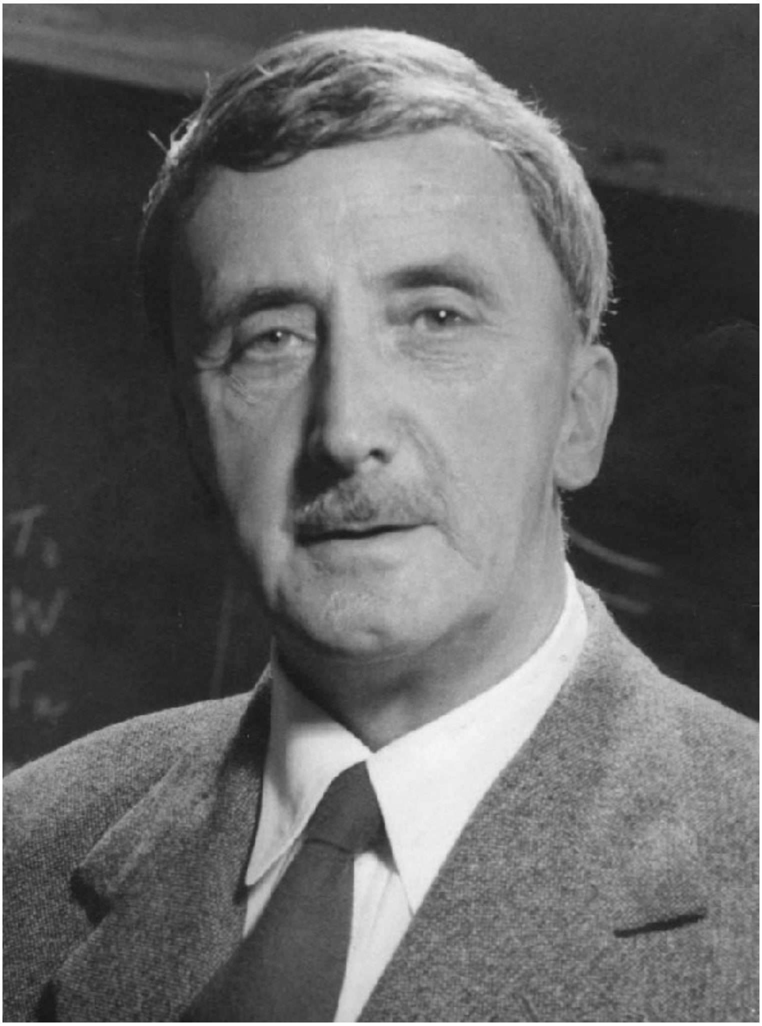

Figure 1. F.P. Bowden, FRS (1903–68). (Photograph: Edward P. Leigh.)

oil companies and industrial concerns in England. Furthermore, he had gained support from the Lubrication Committee of the Department of Scientific and Industrial Research and had attracted the interest of the Air Ministry Research Laboratory at Farnborough, the War Office and the Fuel Research Board. Above all, he was a scientific entrepreneur *par excellence*.[2] He was able to use his considerable personal charm and a shrewdly dogged persistence to convince a Minister of the Commonwealth Government, officers of the CSIR, and senior members of the University of Melbourne concerning the merits of setting up a laboratory within the university dedicated to studying fundamental aspects of lubricants and bearings related to the needs of the Australian Armed Services.

The first week of September 1939 was spent in a whirlwind of exploratory meetings during which Bowden met, successively: (i) L.P. Coombes, Head of the CSIR Aeronautical Research Laboratories at Fishermans Bend; (ii) L.J. Hartnett of General Motors

Holdens, the car manufacturers; (iii) senior officers in the Army's Mechanical Transport at Victoria Barracks; (iv) Dan McVey at the Department of Supply; (v) L.J. Wackett, Manager of the Commonwealth Aircraft Corporation; and (vi) Wing Commander Wackett, Chief Technical Officer for the Royal Australian Air Force (RAAF). During this week he also visited Professor Aubrey F. Burstall, Dean of the Faculty of Engineering at the University of Melbourne, who was so impressed with Bowden's ideas that he offered to make available the then considerable sum of £5000 plus accommodation in the School of Engineering if the plans were approved. Bowden also gave a lecture on his Cambridge work to a large number of scientists, engineers and industrialists in the School of Natural Philosophy hosted by its Head, Professor Thomas H. Laby FRS.

Having prepared the groundwork so thoroughly and informed himself of the existing situation in Australia, Bowden then wrote a crucial memorandum[3] to the Chief Executive Officer of the CSIR, Sir David Rivett (FRS 1941), who was himself a distinguished physical chemist and the former Head of the School of Chemistry in the University of Melbourne. On 14 September 1939 Rivett asked L.P. Coombes to comment on the memorandum and also sent it to the Minister in Charge of the CSIR, the Rt Hon. R.G. (later Lord) Casey, who had trained as an engineer and took great interest in the proposal, although he was inclined against it. He, in turn, referred it to Sir Colin Fraser, Chairman of the Advisory Panel on Industrial Organization, who strongly opposed the idea.[4] A flurry of correspondence (and no doubt telephone calls) ensued between Coombes, Rivett and Casey, with Casey and Sir Colin remaining unmoved.[5] At this point, in view of the divergent responses he was receiving, Casey decided to call Bowden to a personal interview on 25 September. Bowden seized the opportunity and, by a forceful combination of charm, persistence and a manifest commitment to solving practical problems of immediate concern to the war effort, managed to convince the Minister who immediately spoke with, and then wrote to, the Vice-Chancellor of the university, Dr J.D.G. (later Sir John) Medley.[6] Less than a fortnight had elapsed between the presentation of Bowden's memo to Rivett and Rivett's formal proposal to the University of Melbourne for a collaborative wartime project. Administrative details were quickly settled and Bowden was appointed as from 1 November 1939 as Officer-in-Charge of a new CSIR Section entitled Lubricants and Bearings. Bowden had characteristically suggested this severely practical and unromantic name to allay explicit fears and suspicions that the work proposed might prove to be too academic for immediate application.

The nascent Section was initially housed in the School of Engineering but was transferred after a few months to more spacious accommodation that was generously made available in the recently completed new School of Chemistry Building by its Head, Professor E.J. Hartung. The goodwill of the university was further demonstrated by its agreement, as part of the war effort, to pay half the salaries of three research scientists (a physicist, a chemist and an engineer) and two laboratory assistants, and to contribute a sum of £1250 towards the cost of apparatus and equipment. The initial appointees were W.B. Kennedy (engineer) and I. Lauder (chemist), the latter incidentally a New Zealand 1851 Overseas Research Scholar for 1937–39. Bowden had difficulty in recruiting a 'first-class' physicist locally but, within a month of the original job advertisements, had already sounded out David Tabor in Cambridge about taking on the position. In the event,

Figure 2. The New Chemistry Building, University of Melbourne, in 1956. (Copyright J.A. Spink.)

Tabor finally accepted and began duties in May 1940. Unfortunately, Kennedy and Lauder left within a year, Kennedy to go to the CSIR Aeronautical Research Laboratory and Lauder to a position in the University of Queensland where he had more freedom to develop his research and where he eventually became Associate Professor of Physical Chemistry. After their replacement and with Tabor on the staff, things began to stabilize, and continuing programmes of research were established in the space made available in the School of Chemistry (figure 2).

Ethos of the laboratory

The success of any laboratory not only depends on the level of funding and the quality of the staff but is also influenced in more subtle ways by an underlying ambience that is determined by the style of leadership and by the corporate philosophy of the institution itself. These are elusive and difficult matters to define, but it was singularly fortunate that, in the event, Bowden's style epitomized the principles so passionately espoused by the founding Chief Executive Officer of the CSIR, David Rivett.[7] Having identified a broad field that required investigation, Rivett's invariable procedure was to find the best possible person available in that field and then to clear the way for that person to develop his own team and methods with the minimum of interference or hindrance from administrators or accountants. It was not a philosophy that was universally welcomed by senior industrialists, government civil servants or even university scientists (some of whom feared competition from the CSIR's new laboratories and their expanding numbers of staff). But Rivett was adamant, from the very earliest days of the fledgling organization in 1926. His threefold credo was as follows:

1. appoint the best possible head of the laboratory and let him/her get on with it without interference;
2. give absolute priority to the scientist at the bench: if money was tight, as it undoubtedly was during the Great Depression of the early 1930s and later during the war, prune administrative costs to the bare minimum and eliminate all extravagances;
3. place unlimited trust in the judgement and actions of the leader chosen.

Bowden's leadership style matched these criteria admirably. He, himself, had an uncanny knack of seeking out and appointing young scientists and engineers who, in turn, responded magnificently to the opportunities and support offered. As will become evident, an astonishingly high proportion of these young appointees (most in their first job after graduation) went on to internationally distinguished careers. Bowden also had a flair for devising conceptually simple experiments that went to the heart of a problem, and he seemed able to transmit this approach and his own unbounded enthusiasm to his staff. At the same time, minds were inevitably focused on ends dictated by the imperatives of war in the fledgling Commonwealth that had previously had only limited industrial, technological and scientific experience to rely on. On occasion this led Bowden to an over-dirigiste attitude that some of the staff found unpleasantly constricting and confining.

One final aspect of the Lubricants and Bearings Section should be noted. This concerned the training and encouragement of support staff, particularly laboratory technicians. One attractive feature of the University of Melbourne was its extensive programme of evening lectures. These, coupled with the day release of technicians and laboratory cadets to take one additional daytime course each year in chemistry or another science or engineering subject, meant that it was possible to complete the standard ('Scottish style') four-year honours course in four or five years. Many bright teenagers availed themselves of this opportunity and several of them went on to become independent, internationally renowned scientists. It was seen as a great privilege to be able to participate in exciting scientific projects of national importance while working for a university degree. The hours were inevitably long because the CSIR wartime hours for a $5\frac{1}{2}$-day week were 8.45 a.m. to 5.15 p.m. (12 noon on Saturdays) and the university evening lectures and laboratory classes ran from 5.15 to 9.00 p.m. However, there was the great advantage that no time was lost in commuting from the CSIR Laboratory to the university classes because Lubricants and Bearings was housed within the School of Chemistry, and the other departments (such as Physics, Metallurgy and Mathematics) occupied essentially adjacent buildings on the campus.

The work of the laboratory developed along four rather diverse main themes, though there was always close interaction between the members of the individual groups. The four groups were concerned with:

1. friction, lubrication, bearings and surface damage;
2. initiation and propagation of explosions;
3. muzzle velocity of projectiles, and other transient events; and
4. physical metallurgy.

The important advances achieved in these areas will be described in a later section.

Personnel

During 1940 and 1941 Bowden recruited a steady stream of young graduates to the Section and these new members of the research staff set the tone of the work done during the subsequent three or four years. Several already had their Master's degree. (It should be recalled that, at that time, there were no PhD programmes at any Australian university; these were developed after the war.) In addition, as indicated in the preceding section, Bowden turned to Cambridge, where David Tabor had recently (1939) been awarded his PhD under Bowden's supervision and had remained a member of the group there, studying aspects of friction and lubrication. Tabor arrived in May 1940 and stayed on in Melbourne to become acting Head of the Section after Bowden's own return to Cambridge in December 1944. Tabor himself returned to Cambridge in February 1946 and spent the rest of his career there in the research group on the Physics and Chemistry of Solids (PCS). He subsequently became a Fellow of Gonville and Caius College, Head of PCS, a professor of physics in the Cavendish Laboratory and was elected to the Fellowship of The Royal Society in 1963. Another Cambridge recruit was A.A. Townsend, who had gone to the Cavendish Laboratory from the University of Melbourne in 1938 on an Exhibition of 1851 Overseas Studentship. He interrupted his PhD studies to return to Melbourne during the war but, after barely six months in Lubricants and Bearings, joined the staff of the CSIR Aeronautical Research Laboratories. He subsequently returned to Cambridge, completed his PhD (1945–47), and became a Fellow of Emmanuel College, Reader in Experimental Fluid Mechanics at the Cavendish Laboratory and was elected a Fellow of The Royal Society in 1960.

To help in the development of satisfactory casting techniques for the production of aircraft bearings, a recent Melbourne graduate, Hill W. Worner, was recruited (September 1940) from Professor J. Neill Greenwood's Department of Metallurgy. However, he increasingly came to feel that his role was, in his words, little more than 'a tame metallurgist', and he left in June 1942 to join Dr (later Sir) Ian Wark's CSIR Division of Industrial Chemistry at Fishermans Bend. Worner subsequently had an outstanding role in Australian metallurgy (DSc 1953) becoming Professor of Metallurgy in Melbourne (1956–75) and a member of the CSIR Executive (1976–82). He was elected a Fellow of the Academy of Technological Sciences and Engineering (FTS) in 1978 and received the honour AO in 1981. Other indigenous talent recruited at about this time (March 1941) included the young Tasmanian engineering graduate Jeofry S. Courtney-Pratt, an extraordinarily ingenious inventor of ballistic instrumentation and devices for high-speed photography. Although his behaviour in the laboratory sometimes bordered on the eccentric, his productivity was phenomenal. In February 1946 he resigned from the CSIR to join Bowden's new PCS Laboratory in Cambridge (where he received his PhD in 1949 and his ScD in 1958) and during the course of a glittering career he received many prizes and awards. From 1969 he was Head of the Applied Physics Department of Bell Telephone Laboratories, USA.

Two further staff appointments in late 1941 should be mentioned. Abraham D. Yoffe, a Melbourne chemistry graduate who had just completed his MSc degree with Dr Erich Heymann, undertook a fundamental study of the factors that crucially influenced the initiation and propagation of explosions in nitroglycerine and other liquid explosives (1941–45). In 1941 Yoffe had been the first recipient of the newly instituted University of Melbourne Travelling Scholarship but had deferred taking this up until 1945, when he went to Cambridge as the first research student with Bowden in PCS (PhD 1948, ScD 1961). He spent his subsequent career there (having resigned from the CSIR in February 1947) apart from a five-year appointment as Senior Scientist at the Weizmann Institute Rehovoth, Israel. In a distinguished career he was successively Mackinnon Research Student of The Royal Society, an ICI Fellow, and Assistant Director of Research at the Cavendish Laboratory. In 1964 he became a Founding Fellow of Darwin College, which was the first graduate college to be established in Cambridge as well as the first mixed college. He was appointed a Reader in Physics in 1968 and was Head of PCS from 1981 to 1987.

The other appointment was Alan J.W. Moore, who had just graduated BSc in 1941 with a double major in chemistry and metallurgy. He joined David Tabor in studying the ploughing and adhesion of sliding metals, a problem of urgent relevance to the wear of aircraft cylinder barrels. Moore, like Yoffe and Courtney-Pratt, then went to Cambridge in May 1945, ostensibly to gain further research experience (PhD 1948) but in fact largely to assist in the setting up of the new PCS Laboratory. In November 1947 he returned to Melbourne, where he made his career in the CSIR/CSIRO (Commonwealth Scientific and Industrial Research Organisation) Tribophysics Laboratory (the successor to Lubricants and Bearings) and its successor, the Division of Materials Science.[8] In 1962–63 Moore spent a year at the Carnegie Institute of Technology in Pittsburgh, USA. There he came into contact with Professor Erwin Muller, the inventor of field ion microscopy, who was by then at the nearby University of Pennsylvania. On his return to Melbourne, Moore, with the help of John Spink (see below), set up a field ion microscope to study the arrangement of atoms in net crystal planes on spherical metal crystal surfaces. This led to the use of CSIRAC, Australia's first computer (which from 1955 had been relocated in the Physics Department at the University of Melbourne), to calculate the position of all the atoms on the surface. Moore and Spink developed several field ion microscopes and made extensive studies on the influence of crystallographic environment on the stability of individual surface atoms. Moore rose to become Senior Principal Research Scientist (1965–82). He retired in 1982 and, with the assistance of a Royal Society Anglo-Australian Research Fellowship, spent two years (1982–83) at the Department of Materials Science, Oxford, where he worked closely with George D.W. Smith (FRS 1996), now Head of the department, on computer simulations of FIM patterns.

By the end of 1941 the staff of Lubricants and Bearings comprised seven graduate scientists and a similar number of technicians and laboratory assistants (see below). Expansion continued steadily throughout 1942 with further appointments to each of the main research groups. Jack N. Gregory, a recent Melbourne chemistry graduate, joined Tabor in studying the mechanism of boundary lubrication and also studied electroplating methods for bearing surfaces. He was subsequently seconded to the Atomic Energy Research Establishment at Harwell, UK, and on return to Australia worked in the Australian Atomic Energy Commission's Laboratories at Lucas Heights, NSW, eventually becoming Chief of the Isotopes Division. E. Brent Greenhill, another Melbourne chemist (MSc 1944), was also in this group, studying extreme-pressure lubricants and then investigating the effect of tropical conditions on thickened fuels for use in flamethrowers. In September 1945 he joined Moore at PCS in Cambridge to undertake research and to help in establishing the new laboratory. He completed a PhD and returned to Tribophysics in April 1948. In 1953 he resigned from the CSIRO and took a research position with Monsanto Chemicals Ltd. In 1966 he moved to a senior chemist position with Australian Portland Cement Ltd, where he remained until retirement in 1984.

The explosives group was strengthened by three appointments. Dr Frederick Roland Eirich, who had been working in Rideal's laboratory after escaping from Germany, was interned in the UK as an enemy alien and sent to Australia in August/September 1940 on HMT *Dunera*. He was extracted from the internment camp and was a member of the group for about two years before returning to Cambridge in 1944. In 1947 he moved to the Polytechnic Institute, Brooklyn, New York, where he became Professor of Polymer Chemistry (1951–69) and subsequently Distinguished Professor. At the same time Maurice F.R. Mulcahy and Robert G. Vines also joined Yoffe in studying factors influencing the initiation and propagation of explosions in liquids. Both were recent Melbourne chemistry graduates. Mulcahy had just completed an MSc with Erich Heymann (1942) and subsequently gained a DPhil at Oxford University (1948) for research on chemical kinetics under Sir Cyril Hinshelwood FRS. After his return to Melbourne he held parallel appointments in the CSIRO Division of Tribophysics and the University of Melbourne Department of Chemistry, continuing his research programmes in explosives and chemical kinetics. In 1959 he transferred to the CSIRO Coal Research Section at North Ryde near Sydney, NSW, becoming Assistant Chief in 1981. His publications include the well-known book *Gas kinetics* (Nelson, London, 1973; 305 pages) and, during a distinguished career, he held several visiting professorships overseas and received numerous awards including the Rennie Medal of the Royal Australian Chemical Institute (1948), DSc (Oxon.) (1971), and the Royal Society of Chemistry's Award in Combustion Chemistry (1983). He was elected to the Australian Academy of Technological Sciences and Engineering (FTS) in 1980 and retired from the CSIRO in 1983.

R.G. (Bob) Vines, BSc 1941, MSc 1944, was recruited in July 1942 to join the explosives group. He continued with this work until 1948 when he went to work with J.D. Lambert in Oxford for a year, gaining an Oxford BSc. Back at Tribophysics he began work on the physical properties of organic vapours. In 1956 he transferred to the CSIRO Chemical Research Laboratories at Fishermans Bend to work initially on bushfire research and later on the prevention of evaporative loss of water from the surface of storage reservoirs. He was then transferred to the Division of Building Research and finally, in 1980, to the CSIRO Division of Forest Research. He became a Senior Principal Research Scientist in 1968 and was a visiting associate professor at Massachusetts Institute of Technology in 1954 and again in 1960–61.

Two engineering graduates greatly strengthened the capabilities of the Section at this time by contributing to the design and construction of the specialized apparatus being developed by the various groups. Arthur E. Ferguson's expertise was in electrical engineering (BEE 1941, MEE 1949), initially with thermionic valves and high-speed electronic counters (in the days before the discovery of the transistor at Bell Labs, Murray Hill, New Jersey, in 1947). He left in 1945 to join the CSIR Aeronautical Research Laboratories and then returned to the Melbourne University Department of Electrical Engineering, where he subsequently became a Reader (1956–82). Trevor V. Krok was a Queensland graduate in mechanical engineering. He was a prime mover in the design and installation of the Section's much enlarged mechanical workshops and interacted very effectively with the expanding research groups. He left in 1951 to go into industry before returning ultimately to the University of Queensland in Brisbane, where he became a Senior Lecturer.

R.W.K. Honeycombe (later Sir Robert Honeycombe FRS FEng*) replaced Hill Worner in mid-1942. Like Worner he had been a research student in Professor J. Neill Greenwood's Department of Metallurgy, and was involved initially with the examination of bearings and other parts from Japanese planes and torpedoes, with the manufacturing details of bearings for Allied planes, and with the electropolishing of metals. After the war, in December 1947, he went to the Cavendish Laboratory on an ICI Fellowship and his PhD research was done in the group led by Egon Orowan FRS. He then held the Royal Society Armourers and Brasiers' Fellowship in Metallurgy, also in the Cavendish (1949–51). His subsequent very distinguished career developed entirely in England and included appointments as Professor of Metallurgy at Sheffield University (1955–66) and Goldsmiths' Professor of Metallurgy at Cambridge (1966–84; now Emeritus). He was a Fellow of Trinity Hall, Cambridge (1966–73, Honorary Fellow from 1975), President of Clare Hall, Cambridge (1973–80, now Honorary Fellow), President of the Institution of Metallurgists (1977), President of the Metals Society (1980–81), Prime Warden of the Goldsmiths' Company (1986–87) and was awarded numerous prizes, honorary degrees and visiting professorships. He was elected FEng in 1980 FRS in 1981, was Treasurer and a Vice-President of The Royal Society (1986–92) and was knighted in 1990.

By the end of 1942 the number of graduate staff in Lubricants and Bearings had grown to 14 and there were a further half a dozen laboratory assistants working in the Section while studying part-time for an undergraduate science degree. These assistants and other persons associated with the work of the laboratory form the subject of the next section, after which the main results obtained by the various groups will be described. A photograph of the personnel in 1943 is shown in figure 3.

Laboratory assistants and others

In the introduction we referred to the university's agreement to provide laboratory space for the Lubricants and Bearings Section and to contribute to the salaries of three research scientists and two laboratory assistants. These assistants were able to study part time for a pass or honours degree in chemistry or metallurgy. In the event, the School of Chemistry seconded three full-time technician posts to the infant Section and contributed half of their salaries, as part of the university's 'war effort'. Accordingly, Dalway

* Following approval by the Privy Council, as of June 1999 Fellows of the Royal Academy of Engineering are now referred to as FREng.

Figure 3. The CSIR Lubricants and Bearings Section, Melbourne, 1943. Back row (from left): M.A. Stone, R.W.K. Honeycombe, Dr Ph.J. de Kadt, J.F. Peart, G.K. Tudor, D.D. Fisher, H.J.L. Mitchell, Sgt J. Laurent, W.J. Thiele. Second row: A. Yoffe, M.F.R. Mulcahy, S.J. Lloyd, T.V. Krok, J.R. Johnson, J.L. McNab, A.J.W. Moore, A.E. Ferguson, J.N. Gregory, E.B. Greenhill. Third row: R.G. Vines, N.N. Greenwood, D.J. Swaine, J.G. Argall, R.R. Hughan, I.H. Schroeter, J.A. Spink, A. Ewan, E. Winter, H.B. Morley. Front row: E. Angus, J. Collins, Dr D. Tabor, Dr F.P. Bowden, J.S. Courtney-Pratt, D. Pettigrew, G. Holmes. (From the private collection of N.N. Greenwood; photograph taken by Kerr Bros, formerly of 533 Collins Street, Melbourne.)

J. Swaine was appointed in January 1940, Jack F. Peart in 1941 and Norman N. Greenwood in January 1942. The arrangement turned out to be administratively untidy because the university and CSIR pay scales were different, annual increments were made at different times of the calendar year, other salary adjustments and pay awards were incommensurate in time and amount, and the entitlement to part-remission of university undergraduate fees for staff had to be apportioned between the two organizations. Matters were further complicated by the intrusion of part-time day release during university term time only and the differing holiday leave entitlements. A prolonged correspondence of Byzantine complexity developed between senior officers of the university and the CSIR that was rendered all the more ludicrous by the essentially trivial sums of money involved in the almost monthly adjustments that were required. For example, Greenwood (just before his 17th birthday) was appointed at a basic salary of £50 p.a., which later increased to £96 p.a. (nominal). It was finally agreed to transfer the three posts wholly to the CSIR establishment as from 1 January 1943 and to have a simplified agreement with the university concerning day release and fees. In reviewing the voluminous correspondence about these three teenage technical assistants for the purpose of the present article it is hard to imagine that these negotiations and computations were performed against a background of a country at war both in Europe and in the Pacific. It has to be said, though, that the three youths concerned were blissfully unaware of the massive volume of letters and memos that were exchanged between the two organizations. In time, all three graduated.

Dal Swaine and Jack Peart both worked in Tabor's group on problems of friction, wear and lubrication and stayed in the Section until early 1945. Peart took leave during the 1944 academic year to complete his BSc in chemistry. In 1945 he resigned to take a position in the Post Master General's Research Laboratories and later joined the Laboratories of the Melbourne and Metropolitan Board of Works. Swaine completed his BSc in 1945 and then stayed on as a postgraduate student (MSc 1947) with Gustav A. Ampt, who was generally regarded as the finest analytical chemist in Australia at that time. He also held a position as Senior Demonstrator in the Chemistry Department until 1949, when he joined R.L. Mitchell's group at the Macaulay Institute for Soil Research (PhD Aberdeen, 1952). He stayed at the Macaulay Institute as a Senior Research Officer until 1959, when he returned to the CSIRO's Division of Mineralogy in New South Wales. In 1972 he was appointed Head of the Geochemistry Section of that Division and then served as Leader of the Geoscience Section of the Division of Fossil Fuels (1980–85). Since 1984 he has been a Professorial Fellow of the University of Sydney. Swaine is renowned as a world authority on trace elements in coal and has authored several influential monographs on this and related subjects. His expertise has ensured numerous visiting professorships in Europe, Asia, America and Australia. His many honours and awards include the Archibald D. Olle Prize of the Royal Australian Chemical Institute, the Medal of the Royal Society of NSW and its Liversidge Lectureship, and the P.H. Given Award in Coal Science of Pennsylvania State University, USA. He retired as Chief Research Scientist in 1985 and then continued as Honorary Research Fellow, now in the Division of Energy Technology.

Norman Greenwood worked as a laboratory assistant on the impact sensitivity of nitroglycerine with Abe Yoffe and Maurice Mulcahy, being particularly involved with the photographic recording of the events subsequent to the initiation and propagation of explosions. On graduation at the end of 1945 he resigned his cadetship and then did research for an MSc in solid state chemistry in the department with J. Stuart Anderson (FRS 1953). The award of an Exhibition of 1851 Overseas Studentship enabled him to go to Cambridge, where he took a PhD in inorganic chemistry under the guidance of H.J. Emeléus FRS. His subsequent career developed almost entirely in England and included appointments at the University of Nottingham (1953–61) and then the Foundation Chair of Inorganic Chemistry at the University of Newcastle upon Tyne (initially part of the University of Durham), 1961–71. From 1971 to 1990 he was Professor of Inorganic and Structural Chemistry in the University of Leeds (now Emeritus) and served at various times as Chairman of the School of Chemistry and Dean of the Faculty of Science. He has received numerous awards, prizes, honorary degrees and visiting professorships throughout the world. His other appointments include Vice-President of the Royal Institute of Chemistry, President of the Dalton Division of the Royal Society of Chemistry, President of the Inorganic Division of the International Union of Pure and

Applied Chemistry, Chairman for many years of the International Commission on Atomic Weights, and President of the Chemistry Division of the British Association. He was elected a Fellow of The Royal Society in 1987 and a Foreign Member of the French Academy of Sciences in 1992.

Other laboratory assistants appointed in 1942 include June Collins and John A. Spink. June Collins (now Lady Honeycombe) worked in the metallurgy section and completed her BSc in that subject in 1947. She married Robert Honeycombe just before they set off for England at the end of 1947. In Cambridge she worked in the PCS Laboratory and conducted metallography for David Tabor's investigations on hardness and wear. After a decade in Sheffield she returned to Cambridge in 1966 and joined The Welding Institute (now TWI) in 1968. She worked with Trevor Gooch on a wide range of research problems concerned with the welding and corrosion resistance of stainless steels, which led in 1978 to an award from the American Welding Society (AWS). She retired in 1985 as a Principal Research Scientist. John Spink joined the lubrication and friction group and graduated BSc in chemistry in 1946. Promoted to the research staff (Senior Research Scientist 1960–87), he continued work on the properties of monomolecular and multimolecular films on liquid and solid surfaces. In 1955 he was awarded his MSc and spent that year with J.H. Schulman at Colloid Science in Cambridge, the laboratory where almost 30 years previously Bowden had undertaken his initial researches under E.K. Rideal. His subsequent research on solid surfaces involved (with Alan Moore) the development and use of field ion microscopy and, in later work, Auger electron spectroscopy in the analysis of intergranular/fracture surfaces of metals and ceramics. In 1982 he completed a BA (Hons) at the University of Melbourne, majoring in history and philosophy of science. After retirement in 1987, he was awarded a CSIRO Post-Retirement Fellowship to conduct in-house archiving and to work on a history of the early days of the laboratory. He has been active within the Royal Australian Chemical Institute, initially with the Solid State Division and later with its History and Archives Committee, of which he was the founding Chairman in 1987. Currently he is a Fellow in the History and Philosophy of Science Department at the University of Melbourne.

Of other laboratory assistants, particular mention should be made of Geoffrey Brinson, who joined the CSIR Lubricants and Bearings Section in 1944: he graduated BSc (metallurgy) in 1951 and gained his MSc in 1958. He left the (by then) CSIRO Division of Tribophysics in 1958 to take up a position in the Metallurgy Department in the University of Sheffield and obtained his PhD there in 1961. His subsequent career was at the University of Wollongong, NSW, first as a senior lecturer and then as Professor of Metallurgy (from 1969). He was particularly influential in university affairs and was Chairman of the Academic Senate at Wollongong from 1975 to 1983.

Others were associated with the work of the Section from time to time although they were not formally employed by the CSIR. Among these can be mentioned two young Melbourne graduates in mathematics and physics, respectively: Elizabeth Mann and Richard H. Dalitz. Both made their careers in England: Elizabeth Mann (later Mrs Abraham Yoffe) in Cambridge and Richard Dalitz in Oxford, where he became Royal Society Professor in Physics (FRS 1960). There was also substantial collaboration with the Head of the Department of Pure and Mixed Mathematics, Professor T.M. (later Sir

Thomas) Cherry (FRS 1954; knighted in 1965). He made a powerful contribution to our understanding of the flow and generation of heat in compressed films of viscous liquid in connection with the initiation and propagation of explosions in nitroglycerine. Cherry became a Founding Fellow of the Australian Academy of Science and a Member of its first Council (Secretary A 1956–59, President 1961–65).[9]

Scientific achievements, 1940–45

Much of the fundamental work of the Lubricants and Bearings Section during its six years of existence has been published in some 50 papers in the primary scientific literature—an astonishingly large number considering that the Section started from scratch and was dealing primarily with urgent practical problems related to the war effort. Further details were contained in nearly 200 CSIR internal Laboratory Reports, which varied in length from brief technical notes to very substantial documents of 100 or more pages in length. The main outlines of the work have been briefly reviewed in the context of the role of Australian science and industry in the war of 1939–45,[10] and as part of the history of Australia's CSIR, 1926–49.[11] It is therefore only necessary to describe some of the more significant achievements and to supply leading references for further details. The results obtained by each of the four main research groups will be dealt with in turn.

Friction, lubrication, bearings and surface damage

Bowden's interest in friction and lubrication began in the early 1930s[1] and had developed by 1939 into a fundamental and penetrating study with his graduate students in Cambridge, L. Leben and D. Tabor. This involved measurement of the real (as distinct from the geometric) area of contact between stationary and sliding surfaces, and an elegant study of the 'stick–slip' nature of sliding between clean metal surfaces.[12–19] The influence of lubricants was also systematically investigated.

With the arrival of Tabor in Melbourne in May 1940 the Cambridge instrumentation and techniques were rapidly duplicated and extended. The metallurgist Hill Worner was already working in the Section on problems of aero-engine bearings,[20] and their joint efforts made a vital contribution to a crucial aspect of aircraft production in Australia. This has been well summarized by C.B. Schedvin:[11]

> As was so often the case in the early phase of the war, the first task of Lubricants and Bearings was to fill a critical gap in the country's technological capability. Before the war, all bearings for aero engines were imported, and it was obviously necessary to develop productive capacity for replacement parts, as well as for new engines when supplies were terminated in 1940.... By the end of [1941] Bowden's team had been successful in developing the appropriate casting techniques in association with the Commonwealth Aircraft Corporation.... For example a prototype of the silver-lead-indium bearing for the single- and twin-row Wasp engine used in the Beaufort and other aircraft was tested in the laboratory, developed in the annex, and subsequently placed with the manufacturers for large-scale production.... A precise knowledge of casting technique and the physical properties of the metals was required. Subsequently, alloys for more exacting operational conditions were developed, such as the copper-lead bearing for heavy loads and high speed, and the special bearing for the Rolls-Royce Merlin engine. It is no exaggeration to say that the aircraft production programme, which aimed at a high level of self-sufficiency in operational aircraft for the R.A.A.F., depended on the technical expertise of Bowden's team.

Fundamental studies were also undertaken by Tabor in association with A.J.W. Moore on the ploughing and adhesion of sliding metals[21] and with J.N. Gregory on the lubrication of metal surfaces under extreme conditions.[22] They were assisted in this by D.J. Swaine and J.A. Spink as laboratory assistants and later by E.B. Greenhill. At the same time J.S. Courtney-Pratt and G.K. Tudor were developing a cathode-ray technique to measure the electrical resistance between a piston ring and the cylinder wall of a running engine, as a means of investigating lubricating conditions operating while the engine was running, and the way in which these conditions were affected by temperature, viscosity, compression ratio and other variables.[23] These and other similar studies have been very helpfully reviewed elsewhere in the context of contemporary studies on friction and lubrication.[24]

In a parallel study, not published until after the war,[25] the occurrence of high temperatures between rubbing surfaces was demonstrated by means of the thermal electromotive force developed between the rubbing surfaces of dissimilar metals. If one of the surfaces was polished glass or quartz, the incidence of high surface temperatures could be directly observed by visual or photographic means:[26] tiny stars of light appeared at the interface, corresponding to local hot spots. The temperature at which they first became visible was *ca*. 500 °C. As shown in more detail in the next section, the initiation of an explosion in some solid and liquid explosives can be caused by the development of localized hot spots. With the use of nitroglycerine it was found that, when this was rubbed between solids, the incidence of explosions was determined by the thermal conductivity of the solids and their melting points. Explosions resulted only if the melting point was above 480 °C; with metals of melting point below 480 °C, explosion of nitroglycerine could not be obtained even under severe conditions of load and speed.[25]

Initiation and propagation of explosions

One aspect of this work has already been alluded to in the preceding paragraph. However, the main programme of research was performed initially by A.D. Yoffe and M.F.R. Mulcahy, with N.N. Greenwood as laboratory assistant. Later members of the group included F.R. Eirich, R.G. Vines and M.A. Stone. The work began in response to an unexplained explosion of nitroglycerine at the Deer Park factory of Imperial Chemical Industries of Australia and New Zealand, which suggested that the liquid was far more susceptible to detonation than had previously been supposed. In fact, although the impact sensitivity of nitroglycerine had been the subject of many studies since the original classic work of Alfred Nobel in the 1860s, values quoted for the sensitivity ranged widely from 14 000 g cm down to 500 g cm (1 g cm is the potential energy dissipated by a mass of 1 g falling through 1 cm). By an ingenious set of carefully designed experiments[27] it was shown that, in the presence of a minute bubble of air or other gas, explosions could occur when a metal weight of 40 g fell as little as 0.5 cm onto a metal anvil, corresponding to the astonishingly small energy of 20 g cm. In the absence of such bubbles, or the possibility of entrapping them during impact, very much higher energies were required.[28–30] The initiation was caused by heating due to the adiabatic compression of the gas bubble(s), which could be as small as 0.1 mm in diameter.

Further insight into the sequence of initiation and propagation of explosions in liquid nitroglycerine were obtained by studying the blast patterns remaining on the impacting flat surfaces. By using a brass projectile and anvil, both electroplated with various thicknesses of the softer metal lead, and then chemically dissolving off the lead layer, it was possible to record the blast patterns at varying stages of the explosion. Further, by inserting a transparent slit of Perspex into the anvil it was possible to record electrically and photographically the period of impact, the initiation of the explosion and its subsequent velocity by means of a camera with a rotating drum.[30] More general accounts of this epoch-making work were later made available,[31,32] and the whole programme affords a classic illustration of the synergic interaction of fundamental science and technological practice.

Muzzle velocity of projectiles, and other transient events

The ability to measure accurately the muzzle velocity of projectiles was essential for the determination of the range of artillery when firing at unseen targets located by radar. The velocity could be measured, in principle, by measuring precisely the time taken for the projectile to pass successively over two points that were separated by a fixed and accurately known distance. At the outbreak of the war it was necessary for the fixed points to be at least 40 m apart to achieve the required accuracy of 0.1%. The baseline could be reduced to *ca*. 20 m by using an electronic timing system involving a photocell and high-gain amplifier coupled with an electronic cycle counter to measure the time interval between signals. However, such a long baseline required recalibration each time the system was moved and was obviously completely impractical for measuring muzzle velocity on naval vessels.

The challenge was taken up by two recently graduated engineers, J.S. Courtney-Pratt and A.E. Ferguson. They succeeded in increasing the speed of the electronic cycle counter to 400 000 cycles per second by pushing existing valve technology and circuitry beyond previous limits. So great an improvement in the timing device was achieved that a baseline of only 3.05 m (10.0 feet) became feasible.[33] This made the apparatus completely mobile[34] and, after sea trials,[35] it was adopted by the British Admiralty. Indeed, improvements in accuracy and reliability were such that Courtney-Pratt was lent to the Admiralty in an advisory capacity during 1944–45. He did not return to Australia but subsequently joined Bowden's PCS Laboratory in Cambridge and then went to the USA (see page 91). He was replaced by another young engineering graduate, R.W.R. Muncey (1944–46), who subsequently moved to Building Research (1946–66). Muncey was then appointed Chief of the Division of Forest Products (1966–71) and when this Division amalgamated with Building Research he became Chief of the thus enlarged Division of Building Research (1971–78). Muncey also had an important role in education and was President of the Victorian Institute of Colleges. He was awarded DApplSc, DEd *honoris causa* and was a Foundation Fellow of the (Australian) Academy of Technological Sciences and Engineering (FTS).

The contributions of Courtney-Pratt and Ferguson to the work on friction, lubrication and bearings, and on the time-resolution of rapid events during the initiation and propagation of explosions have already been mentioned in the preceding two subsections.

Physical metallurgy

As indicated on p. 90, Hill Worner was initially concerned with the technical problems of manufacturing alloy bearings and the metallographic examination of the wear and performance of used bearings.[20] These extensive studies were the subject of over a dozen CSIR Laboratory Reports between September 1940 and March 1942. Alan Moore and others also performed much work in this area. In May 1942 Robert Honeycombe joined the Section and was concerned initially with the metallographic study of numerous recovered Japanese aero-engine bearings and related parts; some 10 CSIR Laboratory Reports appeared during the next two years. He also studied the electrolytic polishing of metals.

During his studies on casting procedures and the properties of bearing alloys, Honeycombe had noticed some unexpected deformation characteristics produced by the repeated heating and cooling of samples. In collaboration with Walter Boas (p. 101), a senior member of the university's Department of Metallurgy, this developed into a classic piece of fundamental research on the internal stresses produced in certain pure metals and alloys by thermal cycling.[36] Thus, when pure samples of the non-cubic metals zinc, cadmium and tin were subjected to cyclic thermal treatment between 30 and 150 °C, they showed signs of plastic deformation after a small number of cycles. However, the phenomenon was not observed in the face-centred cubic metal lead. They showed that the deformation was due to the anisotropy of thermal expansion in the crystals of the non-cubic metals. Implications of this behaviour were exemplified by comparing various tin-based and lead-based bearing alloys.[37]

In further work it was shown that the deformation increases with increase in temperature range on repeated heating and cooling of non-cubic metals within the overall range of −190 to +250 °C. Cadmium needed only 20 cycles between 30 and 75 °C for deformations to appear. With pure zinc, cadmium and tin between room temperature and liquid-air temperature, complex slipping and twinning appeared but grain boundary migration was practically absent.[38] An elegant series of experiments was also conducted on a series of tin-rich tin–antimony alloys (two-phase 'duplex' alloys). In these there is a (non-cubic) tin-rich matrix in which particles of a hard second phase of cubic crystal structure are embedded. Deformation near the boundaries of the two phases was much smaller than near the crystal boundaries of the anisotropic matrix. Similar results were obtained with tin-based bearing alloys.[38] These novel effects were also shown to occur in the most familiar example of a duplex alloy containing two deformable phases, namely brass (60% copper, 40% zinc).[39] As with the work described in the preceding sections these results illustrate yet again how, under the right conditions, results of deep fundamental significance can be obtained while working on the solution of urgent and purely practical problems in a comparatively isolated wartime laboratory.

Towards the end of the period under review, another physical metallurgist who was to have a major impact on the subject joined the Lubricants and Bearings Section. Max Hargreaves (BMetE 1944) was appointed in February 1945 as an Assistant Research Officer to work on the plastic deformation of metals. He was awarded a CSIR Overseas Studentship in 1947–49 to work with W.H. Taylor at the Cavendish Laboratory on the X-ray crystallography of alloys (PhD 1949). On his return to Tribophysics he continued to work (from 1949 to 1963) on the plastic deformation of metals and short-range order in alloys. By 1961 he was a Senior Principal Research Scientist and in that year was awarded the David Syme Research Prize (jointly with L.M. Clarebrough and M.H. Loretto). In 1964 he was appointed inaugural Professor of Physical Metallurgy at the University of Melbourne (1964–76) serving also, during that time, as Dean of the Faculty of Engineering (1967–70), Pro-Vice-Chancellor (1969–73) and Chairman of the Professorial Board (1972–73).

Subsequent evolution of the laboratory

Philip Bowden returned to Cambridge in December 1944 and founded the research group on the Physics and Chemistry of Rubbing Solids (PCRS) in early 1945. The name was later shortened to the Physics and Chemistry of Solids and, as PCS, became a sub-department of the Cavendish Laboratory. David Tabor became acting Head of the Lubricants and Bearings Section in Melbourne until February 1946, when he too returned to Cambridge. In thinking ahead to the postwar future of the Section, Bowden had suggested that a more scientific and euphonious name might be found to replace the uncompromisingly rugged and somewhat restrictive title of Lubricants and Bearings. Tabor devised the neologism 'Tribophysics',[1] and the laboratory became the Section of Tribophysics in January 1946. This continued until 1948, when it was given full divisional status as the CSIRO Division of Tribophysics.

In September 1945 Stewart H. Bastow (1908–64) was appointed Officer-in-Charge of the Section. Like Bowden before him, Bastow had gone to the Hutchin's School in Hobart, Tasmania, studied at the University of Tasmania (BSc 1929) and then done research on surface chemistry under Eric Rideal in Cambridge (PhD 1932). The award of an Exhibition of 1851 Senior Studentship enabled him to stay on to work with F.P. Bowden on the physical properties of solid and liquid surfaces. After a period with the Anglo-Iranian Oil Co. Ltd (1938–40) he was commissioned in the Royal Engineers and had the task of laying smoke screens to cover assaults during the Allied advance across northeast Europe (DSO 1945).

Bastow's leadership and wisdom enabled him to transform the Section's wartime programme of research and development into one geared to peacetime needs. He planned a new building for the laboratory to be adjacent to the Chemistry Building and established groups to work on metal physics, chemical reaction kinetics and the properties of drilling-clay suspensions. In May 1949 he was appointed a full-time member of the Executive of the CSIRO, becoming Chief Executive Officer from January 1957 to June 1959. He died of a cardiac arrest in 1964, just one month before his 56th birthday.[40]

Bastow was succeeded as Chief of the Division of Tribophysics in 1949 by Walter Boas, a noted authority on deformation and crystal plasticity and on lattice defects. Boas was born in Berlin in 1904, educated at the Technische Hochschule, Berlin (DrIng 1930), and then did research at the Physics Departments of the University of Fribourg and the Technische Hochschule, Zurich. In 1937 he came to England as a Research Associate at the Royal Institution, London, and then went to Australia in 1938 on his appointment as

Lecturer in Metallurgy in the University of Melbourne (Senior Lecturer 1940–47). He joined the CSIR Division of Tribophysics as a Principal Research Officer (1947–49) and succeeded Bastow as Chief of the Division in 1949. He was elected a Fellow of the Australian Academy of Science in 1954 and retired in 1969.[41] In 1978 Tribophysics was enlarged and renamed the Division of Materials Science. By 1985, with staff numbers approaching 100, the laboratory was moved to a new site adjoining Monash University at Clayton in the eastern suburbs of Melbourne. The building that had housed the Tribophysics Laboratory was taken over by the University of Melbourne and renamed the Walter Boas Building. Earlier (in 1974) the university had also recognized Boas's contributions to science and the university by awarding him the degree of DApplSci *honoris causa*.

Conclusion

The story of the Lubricants and Bearings Section of the CSIR during its brief existence in World War II illustrates how much can be achieved by the creative drive and enthusiasm of a highly motivated group of young scientists. Most of the staff recruited by Philip Bowden were in their early twenties and in their first job after graduation. The research programmes were designed to solve urgent and severely practical problems but the penetrating approach adopted in each case ensured that significant advances in fundamental science were also achieved. The generous cooperation of the University of Melbourne in supplying personnel, accommodation and other support was also notable. In particular, the system of part-time day release, coupled with the availability of evening lectures and laboratory classes, enabled several teenagers to study for university degrees while still working long hours as laboratory assistants. The subsequent distinguished careers of many of the research staff and laboratory assistants afford impressive testimony to the remarkable quality of the laboratory at that time. Its subsequent growth and development into the CSIRO Division of Tribophysics and later incarnations during the following 55 years are briefly indicated.

Acknowledgements

We are grateful to many of our former colleagues in the CSIR Section of Lubricants and Bearings for supplying personal information and recollections with which we have been able to supplement the archival records and our own experiences.

Notes

1 D. Tabor, 'Frank Philip Bowden', *Biogr. Mems Fell. R. Soc. Lond.* **15**, 1–38 (1969).

2 J.A. Spink, 'Frank Philip Bowden—scientific entrepreneur', *Chem. Aust.*, May 1989, 157–160.

3 F.P. Bowden, 'The testing and improving of lubricating oils and use of substitutes. The development of bearing materials and the reduction of metallic wear and corrosion'. September 1939. *CSIRO Archives: Ph/Bow/93 – TZ370/2*.

4 Sir Colin Fraser, letter to Rt Hon. R.G. Casey, 18 September 1939, *CSIRO Archives: TZ370/2*. (By contrast, Coombe's comments proved most favourable: he already had an intimate knowledge of Bowden's research and organizational skills from prewar contacts between Bowden's Cambridge laboratory and the Royal Aircraft Establishment, Farnborough, from which latter establishment Coombes had been recruited to the newly established CSIR Aeronautical Research Laboratories a year previously.)

5 L.P. Coombes to A.C.D. Rivett, 19 September 1939, *CSIRO Archives: Ph/Bow/93—TZ370/2*. R.G. Casey to A.C.D. Rivett, 25 September 1939, *CSIRO Archives: TZ370/2*.

6 A.C.D. Rivett to J.D.G. Medley, 27 September 1939, *CSIRO Archives: TZ370/2*.

7 Rohan Rivett, *David Rivett: fighter for Australian science* (Dominion Press, Melbourne 1972), pp. 91–93.

8 CSIRO (the Commonwealth Scientific and Industrial Research Organisation) replaced the CSIR by Act of Parliament in 1949. The consequential changes in organization and underlying philosophy were bitterly opposed by Sir David Rivett and polarized many of the scientists working in the Council's various laboratories throughout Australia. Some of the more extreme concerns appear, in hindsight, to have been exaggerated, although the changes were deeply resented by many. One of Australia's most senior government scientists, Sir Ian Wark, himself a devoted admirer of Rivett, believed the fears were unfounded and expressed this as a mathematical equation:

$$\text{C.S.I.R.O.} = \text{C.S.I.R.} + \text{O.}$$

The matter is well summarized in Rohan Rivett, *op. cit.*, note 7, pp. 188–212.

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11 C.B. Schedvin, *Shaping science and industry: a history of Australia's Council for Scientific and Industrial Research, 1926–1949* (Allen & Unwin, Sydney, 1987), pp. 201–205, 293–296.

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