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Howard Knox Worner 1913–2006

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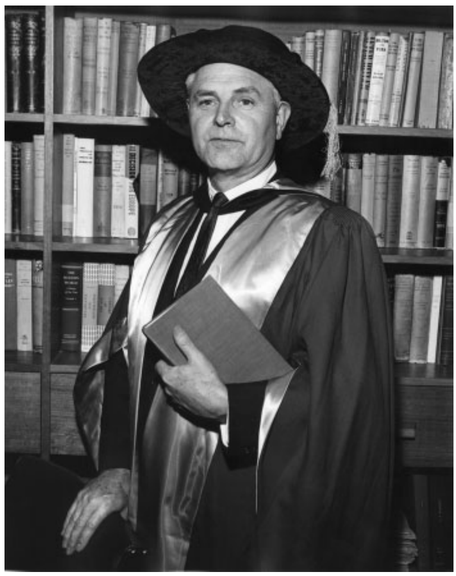
Howard Knox Worner was a renowned figure in Australian applied science and engineering. His successful career can be credited to his strong intellect, leadership and charisma. Coming from a humble farming background, he achieved a brilliant academic career in metallurgy and materials at the University of Melbourne. From the position of Dean of Engineering he moved into industry as Director of Research with BHP where his leadership led to significant improvements in conventional steel production and where he conceived his concept of continuous steelmaking. This was not put into practice but after moving to CRA he applied his concept to continuous copper production where it has largely been accepted around the world. Later he was a high-level adviser to Government on energy research and development, particularly the economic utilization of brown coal for liquid and gaseous fuels. In his 'retirement' he became deeply involved at the University of Wollongong in the application of microwaves to mineral processing and waste treatment. He died on 17 November 2006, aged 93.

Family Background and Early Life



Howard Knox Worner was born into a farming family at Swan Hill, Victoria on 3 August 1913. His grandfather, Josiah Worner, had migrated from Martock in Somerset, England in 1850. Josiah joined the gold rush at Bendigo but had no success and moved first to Swan Hill and then to farming in the Yassam district of the Mallee. Howard's father, John Worner, was Josiah's fifth child and married Alicia Stephens in 1890. They had six sons and a daughter before Alicia died in 1902. In 1912 John married again to Ida Castles with whom he had three sons, Howard, Neil and Hill, who all went on to achieve great professional distinction as engineers and technologists. The Worner family history had long been one of farming in England and Scotland, and Howard and his brothers seemed destined to follow the family tradition. As Howard noted in an interview in 2005, 'I very much enjoyed life on the farm. I was particularly interested in new aspects of farming, new ways of growing finer and finer wheat and methods of making better, stronger wool.' It was this spirit of scientific enquiry to practical ends that was to drive Howard in his professional career.

He and his younger brothers attended the Yassam West State School. However, the Mallee area was in drought in the 1920s and the ensuing harsh economic conditions of the Great Depression forced the family to move to Bendigo in 1928. There Howard and his two brothers attended the local technical school to learn practical skills in welding, fitting and turning, and carpentry that would fit them to be better farmers. However, it soon became clear that they all showed academic promise and they were encouraged to apply for scholarships to the Bendigo School of

Mines. Howard also enjoyed sports and was vice-captain of cricket and football and held the sprint championship of the Victorian Senior Technical Schools for two years. At the Bendigo School of Mines, Howard had a distinguished record and graduated with a Diploma of Applied Chemistry and Metallurgy in Industrial Chemistry in 1932, having studied chemistry, metallurgy and geology in his final year. He was awarded a Gold Medal for his outstanding performance in the final examinations. His two brothers followed similar academic paths and completed diplomas, Neil in Civil Engineering and Hill in Industrial Chemistry, and were awarded Gold Medals in their years. All three were awarded Senior Government Scholarships to attend the University of Melbourne. This was described by Melbourne's *Age* newspaper in 1935 as 'one of the most brilliant family records ever encountered in the educational history of Victoria'. All three went on to have outstanding careers, Howard and Hill in metallurgy and Neil in civil engineering.

Howard's scientific curiosity had been whetted during his course when the Principal of the School of Mines (J. R. V. Anderson) assigned him to work on gold amalgams coming from the local gold-mining industry. Howard was intrigued by the fact that although gold had such a high boiling point (2,970°C), it would nevertheless start to distil at the low boiling point of mercury (357°C) as the amalgam was heated.

Start of an Academic Career

In 1933 Howard started a Science degree at the University of Melbourne, majoring in Metallurgy. He was granted exemption for the first year based on his performance at Bendigo and graduated Bachelor of Science with First Class Honours and the Exhibition in Metallurgy in 1934. His love of sport continued and he was a member of the Intervarsity baseball team on two occasions.

In 1935 he took up a position at the Defence Standards Laboratory at Maribyrnong but soon returned to the University as Demonstrator in Metallography to carry out research with Professor J. Neil Greenwood, a notable figure in the history of metallurgy in Australia. In 1936 he was appointed Lecturer in Metallurgy and started publishing papers with Greenwood on the influence of alloying elements on the creep of lead (1–3). When a metal is put under a constant load or stress, it may undergo plastic deformation over time. This time-dependent deformation is known as creep. The creep of materials is very important for some types of engineering design, particularly those that operate at high temperatures such as gas turbine blades. Creep increases with temperature and becomes noticeable at $\sim 0.5\ T_m$ where T_m is the melting temperature in degrees Kelvin. For lead, this is around room temperature and this metal provided a model for Howard to study the effects of different alloying elements on creep behaviour without the need for using furnaces. In addition to developing new theories for creep, the results made possible lighter plates in lead-acid batteries, while the lead-tellurium alloys that he studied became the basis for delayed timing devices during the Second World War. For these studies, he was awarded a Master of Science degree with honours in 1938.

In 1937 Howard married Rilda Muller whom he had met at the University where she typed his MSc thesis. Rilda had come from Warracknabeal in western Victoria and was an instructor in business machines. They had three children—John, Colin and Ruth. John followed in his father's footsteps at the University of Melbourne, graduating with a Bachelor of Science with First Class Honours and the Exhibition in Physics in 1959. He continued his studies and graduated with a Master of Science degree in nuclear physics in 1962. Tragically, John and his wife Thais were killed in a car accident on the Olympic Highway in New South Wales in January 1963. Colin graduated in medicine from the University of New South Wales and went on to be a successful general practitioner and then an ophthalmologist in Sydney. Ruth pursued a teaching career and worked in Newcastle, New South Wales, and then in Wollongong where her husband, Gordon Proctor, was Librarian for the BHP company.

Research on Dental and Surgical Materials

While still working on creep of lead, Howard was asked to study the causes of failure of certain stainless-steel orthodontic arch wires and also dental amalgam fillings. The results were published in the *Australian Journal of Dentistry* and so captivated the dental profession that Greenwood was prevailed upon to release his young protégé to work solely on dental and surgical materials. To this end a Metallographic Research Laboratory was established in the Department of Metallurgy as part of an entity called the Dental Research Department. The Laboratory was later moved to the Prosthetics Laboratory at the Australian Dental College in Spring Street, Melbourne. In 1938 Howard was appointed Director of the new Dental Materials Research Laboratory with the status of a Senior Lecturer in Dental Materials. From the beginning of 1939 he became the first 'non-medical' Research Fellow of the National Health and Medical Research Council.

With the outbreak of the Second World War, Howard was appointed Honorary Scientific Consultant to the Australian Defence Forces and set up control standards for dental materials for the forces. He continued research on plaster of Paris and amalgams, and introduced plastics into dentistry. His publications continued unabated. In 1940 he was joint recipient, with Professor E. S. Hills, of the David Syme Research Prize of the University. Two years later he was awarded the degree of Doctor of Science for which he submitted 22 published papers and two unpublished theses. He remains probably the youngest recipient of this degree at the University of Melbourne. His links with the defence forces led to work on applications of polyvinyl resins for facial prostheses, splints and dental restorations for wounded servicemen. Here he worked closely with specialists in hospitals with some remarkable results. In 1944 he was attached to the Services Tropical Research Unit to investigate corrosion problems with medical equipment in tropical environments. As a scientific liaison officer with the status of a major, he visited operational areas in New Guinea and Bougainville. His work led to improved packaging and protection of a wide range of stores and became the basis of new Australian Standards for the protection of goods and equipment in the humid tropics. He continued at the Dental Materials Laboratory until 1946 when he made his first overseas visit, to the UK and the USA, with National Health and Medical Research Council support. His pioneering work on dental materials was acclaimed at the British Dental Association's annual meeting in Edinburgh. His contributions were recognized later by the award of the Docking Award of the International Association of Dental Research in 1983.

Leadership at the Department of Metallurgy, University of Melbourne

In July 1946 Howard was appointed to the position of Professor of Metallurgy and Head of the Department of Metallurgy, taking over from Professor Greenwood. Greenwood had led the Department through the war years and made valuable contributions to production of strategic materials such as tungsten, but he wished to return to research and, with strong industry support, had secured the establishment of a Chair in Research Metallurgy to which he was appointed in 1946. Greenwood also secured the support of the Council of Scientific and Industrial Research (CSIR, later CSIRO) to establish a Physical Metallurgy Section within the Department and was appointed Officer-in-Charge. This Section gained a notable research reputation, particularly in chemical and physical metallurgy of titanium. Unfortunately, the technology developed here was not taken up in Australia but was put into production in England.

Howard was an excellent lecturer, presenting his ideas as flights of imagination and delivering with great gusto and passion topics normally seen as dry. He carried a heavy teaching load while still pursuing his research interests. In 1947 he turned his attention to new techniques of casting high-strength alloys and pioneered both investment casting and shell moulding in Australia (55–58). The foundry industry benefited greatly from this work.

In 1948 Howard became interested in the possibility of extracting titanium metal from its ores by molten salt electrolysis. (This would be his first move into research in the area of mineral processing that dominated most of the rest of his career.) The only commercial method at that time was the Kroll process whereby titanium tetrachloride was reduced to titanium metal by reacting it with magnesium. This was an expensive batch process and Howard felt that molten salt electrolysis had the potential to be operated as a cheaper, continuous process. At that time there was very little information available in the literature. Howard approached Consolidated Zinc Ltd and obtained sufficient funding to employ several graduate students on an extensive programme of research over the next seven years. His brother Hill, who at the time was a Research Officer with CSIRO working in the Baillieu Laboratory next to the Metallurgy School, also became involved in the programme.

Early success was obtained with the production of titanium trichloride, dissolving this in molten salts and producing a cathode deposit of metallic titanium. Subsequent work was published in several papers and summarized in a detailed paper in 1956 (54). The work included research into methods of producing titanium trichloride, extensive investigations of the optimum conditions for the cathode deposit and the demonstration that an anode of titanium carbide could be used in the process to introduce titanium chlorides to the molten salts, thus avoiding the need to produce titanium tetrachloride before converting ti to titanium trichloride. This work was the subject of a provisional patent but unfortunately funds were insufficient to proceed to completion of the patent. It is interesting to note that this work was largely conducted in a basement laboratory with very poor ventilation. Titanium tetrachloride was used during the war to make smoke bombs as on exposure to air it hydrolyses to a fine smoke of titanium dioxide. Whenever a research student dropped a glass flask of the liquid material, as happened occasionally, within minutes the laboratory would be filled with thick smoke. The only solution was to retire to the University cafeteria for several hours while the smoke cleared!

In subsequent years several groups undertook extensive research in this area leading to pilot-plant testing in both Italy and Japan, including the use of titanium carbide anodes. In 1988 a feasibility study was undertaken by an Australian firm (Minproc Ltd) into establishing a plant in Australia under licence from the Italian group but this did not proceed. None of the subsequent work acknowledged the pioneering work done in Melbourne. As so often happened during his career, Howard had been ahead of his time.

From Academia to the Steel Industry

Howard's talents in management were recognized when he was appointed as Dean of Engineering in 1953. This brought him into close contact on the Engineering Faculty Board with Mr (later Sir) Ian McLennan who was a Director and Senior General Manager of The Broken Hill Pty Co Ltd (BHP), which had major steel-making plants in Newcastle and Port Kembla, New South Wales, based on Australian coal and iron ore. McLennan was convinced that increased research on steel production was needed to improve efficiency and offered Howard the position of Director of Research with a brief to head the new Central Research Laboratories being built at Shortland, a suburb of Newcastle. Howard's strong desire to see application of research in industry outweighed his potential future as an academic administrator and he resigned from the University of Melbourne and moved to Newcastle in 1955. Again the remarkable Worner brothers achieved a first at the University of Melbourne when Hill was appointed Professor of Metallurgy in direct succession.

The Central Research Laboratories (CRL) were some distance from the BHP steelworks but were close to the site of the later development of the University of Newcastle. With his academic background Howard was extremely supportive of the concept of a university in Newcastle and immediately joined the body that had set itself up to promote this concept. Later he was appointed to the first council of the University of Newcastle and served for seven years. In 1966 his services to the new university were recognized by the conferring of an honorary degree of Doctor of Science.

In a very short time, several highly qualified staff were working at CRL in three main areas of research, namely raw materials, processing and finished products. The work on titanium at the University of Melbourne had changed Howard's area of interest in metallurgy from products to metal extraction processes and from now on he concentrated on problems of pyrometallurgy.

The traditional method of making steel had evolved by that time into a batch process in which iron ore (iron oxide containing around 65 per cent iron), coke and limestone were smelted together at a high temperature in a blast furnace (a vertical chamber lined with refractory bricks) using air forced into the mixture to maintain a temperature high enough to reduce the iron oxide. This process produced molten high-carbon iron that was then transferred to an open-hearth furnace operating at high temperatures where the carbon content was lowered by controlled oxidation. Alloying elements were added to produce steels of different compositions that were cast into ingots for further fabrication. The batch nature of these processes constrained the rates of production and there was considerable activity in steel companies around the world to improve productivity.

In the case of iron making, the group at CRL recognized that uniformity of lump size of iron ore was critical to the rate of the smelting process and proposed the use of a sintering process to amalgamate fine particles of high-grade Australian iron ore into larger pieces to enable better penetration of the air blast. Installation of sinter plants led to significant increases in production rates in the blast furnaces in the plants at Port Kemble and Newcastle. Similarly the strength of the coke was seen to be critical and improvements to the coking process also led to increased production rates.

In the case of steelmaking, Howard made several visits overseas while at CRL and became aware of exciting new developments in steelmaking in which small furnaces using oxygen (which became available cheaply in large tonnages) were producing high-quality steel very rapidly. At that time Port Kembla had installed the largest open-hearth furnaces in the world at 550 tons capacity but Howard showed that smaller basic-oxygen furnaces of 200 tons capacity could produce five times as much steel per day. Later BHP introduced the Austrian L. D. (Linz-Donawitz) basic-oxygen steelmaking process but steelmaking was still a batch process. However, Howard could see the possibilities of continuous steelmaking and in mid-1961 he developed his ideas on a pilot scale using a small furnace into which molten iron was continually poured and then oxygen was injected using water-cooled lances. The temperature increased and the iron was rapidly transformed into low-carbon steel on a continuous basis. This was accompanied by a significant rise in temperature that Howard and his team controlled by adding lump iron ore, thus achieving a continuous bath smelting of the added ore. This led Howard to seriously consider other possibilities with non-ferrous smelting where sulphur (from sulphide ores) could be the internal fuel rather than carbon.

In 1961 he gave a paper at the Annual General Meeting of the Australasian Institute of Mining and Metallurgy in Newcastle on his ideas for continuous steel-making processes. This aroused much interest and discussion tempered with a considerable degree of scepticism among the traditional steelmakers.

Howard now faced a dilemma. He could see that the future of steelmaking was in the basic oxygen process, possibly on a continuous basis, but BHP had no plans for change in the immediate future. Further, at that time, BHP was not in the non-ferrous business and had no interest in continuous processing of non-ferrous ores. Howard, however, could see the enormous potential for his inventions in the non-ferrous metals industry. About mid-1962, after much agonizing, Howard decided to resign from BHP with effect from the end of the year and to look elsewhere for his future.

From the Steel Industry to the Non-Ferrous Metals Industry

In early 1963 Howard lodged his basic patent applications and travelled overseas to promote his new concepts. Several companies in the USA and Europe showed keen interest but, after discussions in London with Mr (later Sir) Val Duncan, Chairman of Conzinc Rio Tinto Corporation Ltd, Howard was invited to join the Australian arm of the company (later to known as CRA Ltd). The following year he was appointed Director of New Process Development. The CRA chairman, Mr (later Sir) Maurice Mawby, was an enthusiastic supporter of Howard's ideas and gave him space for a pilot plant at a CRA plant at Cockle Creek, near Newcastle. This suited Howard's wife and family as they did not need to move from Newcastle.

The continuous process envisaged by Howard was named the WORCRA process and initial experiments in small furnaces in1963–4 showed the feasibility of the concepts of smelting and refining in the same bath. New concepts of counterflow refining and composition control were developed. The next step was to scale up to a 3/4 ton pilot furnace at Cockle Creek and then a semi-commercial plant at Port Kembla. Several thousand tonnes of copper were produced and many technical problems were solved in the course of work in 1969–71. Howard was somewhat frustrated in this period since there was a perception in senior management in CRA during the 1960s that oxygen was too expensive for non-ferrous smelting-converting and so the WORCRA team used only air. This reduced the production rate with concurrent higher fuel costs.

Since CRA had no copper smelters of its own, negotiations were entered into with several overseas companies. At this time, Sir Maurice Mawby, who had been a great supporter of Howard's work, stepped down as Chairman and was replaced by Mr Arthur Rew who announced at an early stage that 'CRA would no longer be in the business of inventions'. This led to tensions in the top management as there were some who strongly supported the concept of CRA moving into copper production based on the WORCRA process and felt that CRA should retain absolute control of the technology. This bedevilled negotiations on licencing and Howard was again frustrated at this time.

Howard still had an interest in continuous steelmaking and tested the principles developed in the WORCRA work at several steel plants in Europe as well as at Cockle Creek. There was a ferment of activity around the world in the field of pyrometallurgy in the 1960s and 1970s and Howard's ideas and experience fed into the general field. While he was disappointed that no commercial WORCRA furnace was commissioned in Australia at that time, he had the satisfaction of seeing his ideas for continuous smelting adopted in several later technologies in Europe for non-ferrous metals and in Japan and China for steels. Subsequent research in Australia by CSIRO and CRA led to commercial applications based on his work. He continued at CRA, researching other processes such as continuous vacuum refining of zinc and cadmium until August 1975 when he retired and moved to Melbourne.

Working with Governments

Because of his background in energy-related processing, Howard's services were sought by both the Victorian Government and the Australian Government to oversee new activities in the energy area. In the former case the Victorian Government was acutely aware that the Victorian reserves of lignite (brown coal) constituted some 20 per cent of the world's resources with an estimated economic life of some 500 years. A problem was the high water content, which necessitated drying. Although extensive work had been carried out on drying and briquetting of this coal as a solid fuel to produce the major part of Victoria's electricity supplies since the early 1920s, there was a need to improve the drying process and to look to production of higher-value energy products, for example chemicals and liquid fuels. In August 1975 the Victorian Government set up the Victorian Brown Coal Research and Development Committee with Howard as chairman. There was a sense of déjà vu for Howard in that some twenty years previously he had published a paper on 'Metallurgical Fuel from Victorian Brown Coal' (120) while at the University of Melbourne!

The terms of reference of the committee were broad but the major task was to make recommendations on conversion of brown coal into transport fuels. This picked up the theme of the future oil supply for Australia that Howard developed later during his chairmanship of the National Energy Research Council. The concept of oil from brown coal was not new and had been examined in the 1930s but was abandoned because of the high cost of the product. However, industrial-scale plants had operated in Germany during the Second World War to provide fuel for the German military forces. One of the first tasks of the committee was to set up a major project with industrial partners to characterize the physical, chemical and petrological variability of the huge Victorian brown coal reserves. At the same time the committee studied proposals from governments, consortia or individual companies in the USA, Japan, South Africa and Germany. A significant step was the building of co-operation within the scientific community in Victoria in order to have pilot-plant facilities available for testing of possible liquefaction processes using high-pressure hydrogenation.

This intense activity led the Victorian Government in January 1979 to upgrade the committee to a new statutory authority, the Victorian Brown Coal Development Authority (later the Victorian Brown Coal Council) with Howard as part-time Chair. Numerous proposals were considered with the major thrust coming from Japan. A consortium comprising Kobe Steel, Mitsubishi Chemical Co., Nissho Iwai, Idemitsu Kosan and Asia Oil formed a company, Nippon Brown Coal Liquefaction Ltd, which negotiated an agreement with the Victorian Government to further develop the technology of high-pressure hydrogenation by constructing a 50 tonnes per day pilot plant. The major funding of over \$300 million was provided by the Japanese Government through its New Energy Development Organisation, with the Victorian Government providing a fully serviced site and engineering support. The plant was built from 1981 to 1985 and operated until 1988. However, world economics did not justify further investment. By this time Howard had retired, in mid-1981. Again he had been involved in the development of a process that did not reach commercial application. The cycle still continues with the Victorian Government setting up a new group, Brown Coal Innovation Australia, in 2009, and the announcement of a \$90 million project for oil from brown coal jointly with the Australian Government in 2012.

Howard's involvement with the Australian Government was with the National Energy Advisory Committee (NEAC), established in the Department of National Development in May 1977 to provide advice on energy matters and to assist in the formulation of a national energy policy for Australia. Howard was appointed chairman with a council comprising eighteen experts from industry and academia. Again the Worner brothers were teamed together, with Hill Worner representing CSIRO where he had become a member of the Executive after leaving the University of Melbourne. Under Howard's leadership, NEAC produced eleven significant reports from 1977 to 1980. The first report highlighted the issues relating to the future supply of petroleum products in Australia and this theme was taken up in detail in later reports. The second report was a major assessment of Australia's energy resources that provided the basis for future energy research and development and policy development. Subsequently, in 1978, the Australian Government established the National Energy Research Development and Demonstration Council (NERDDC) with significant funding to identify and fund projects related to new approaches to energy generation and use in Australia. Howard was appointed a member of the first council of NERDDC and retired in mid-1981. His contributions to energy policy in Australia were recognised by the award of a CBE in the 1978 New Year Honours List.

The Creation of an Australian Academy of Technological Sciences and Engineering

While the spirit of scientific enquiry towards practical ends motivated Howard throughout his career, he recognized that there was a need to build bridges between university researchers and industry for national benefit. A starting point was his support while at BHP and CRA of the Australian Industrial Research Group, formed in 1964 to link research managers of major Australian companies. In 1969 there were moves in AIRG to give greater recognition to technologists in Australia through the formation of an Australian Academy of Applied Science. Howard was a member of a small committee set up to develop the concept. The committee moved cautiously at first, hoping that an agreement could be reached with the Australian Academy of Science on the addition of an applied science division. However, it became clear that this would not be possible and the committee then moved to engage prominent engineers and technologists from industry and academia. The committee also consulted a range of Australian professional associations. Reactions ranged from enthusiasm through apathy to antagonism, but there appeared to be general recognition of the need for an academy in the realm of technology. In 1972 the AIRG formally withdrew from the process while the committee continued its activities, including consulting the Royal Swedish Academy of Engineering on the constitution and operation of an Engineering Academy. Interestingly, despite the reluctance of the Australian Academy of Science to admit technologists, Howard was elected a Fellow in 1973. He served as a Member of AAS Council from 1983 to 1985. Later, in 1994, at the age of 81, he was awarded the Ian Wark Medal of AAS for his contributions linking science and industrial technology.

In July 1974 a meeting of eminent engineers and technologists endorsed the establishment of a Council with Sir Ian McLennan as President and Howard as Honorary Secretary, a post he was to hold for ten years. Incorporation of the Australian Academy of Technological Sciences (ATS) was granted in November 1975 and the original committee and invitees were designated as Foundation Fellows. The Academy was renamed the Australian Academy of Technological Sciences and Engineering (ATSE) in 1987.The early years of the Academy were a period of intense activity with many new initiatives set in train under the general guidance of Sir Ian McLennan, strongly supported by Howard. The first few years saw the preparation of a series of important reports on Australian science and technology (impact of climate change, developing high technology enterprises, and a space policy for Australia), the initiation of the Academy's Annual Invitation Symposium, the receipt of a grant of $100,000 per annum from the Australian Government to assist with the basic operation of the Academy and the appointment of the Academy's first permanent staff. During the second half of 1979 and early 1980, the Academy established Regional Divisions in New South Wales, the Australian Capital Territory and Victoria.

In addition, the first formal links were developed with sister academies overseas, leading to ATS being one of the five founding academies of the International Council of Academies of Engineering and Technological Sciences. As a result, the Second Convocation of Engineering and Like Academies was hosted in Melbourne in 1980. These links entailed numerous overseas visits and Howard was in the Academy's first delegation to China in 1982 led by Sir Ian McLennan. Howard relinquished his position as Foundation Honorary Secretary when he moved from Melbourne to Wollongong in 1985. For his services to ATSE, Howard was elected as an Honorary Fellow in July 1993, joining a small group of eminent Fellows to be so honoured by ATSE.

Activities with Professional Societies

From his early days at the University of Melbourne, Howard played a role in many professional societies in the metallurgical, materials, engineering and geological fields. Thus he was an active member of the Melbourne University Metallurgical Society, which later linked up with groups in Melbourne and other states to form the Australian Institute of Metals (AIM) in 1947. Howard was a Vice-President and then President while Professor of Metallurgy at Melbourne. In 1978 he was awarded the AIM Silver Medal in recognition of outstanding service and achievement in the industry and profession of metallurgy.

Howard was also an active member of the Australasian Institute of Mining and Metallurgy from his early days as a researcher. In 1977 he was awarded the Institute Medal of the AusIMM and in 1989 he was elected an Honorary Fellow.

Since all the Worner brothers had outstanding careers in technology and engineering, it is hardly surprising that they all were elected Fellows of the Institution of Engineers Australia. However, it must be unique to have three brothers honoured for their achievements in engineering by being elected as Honorary Fellows over a four-year period—Neil in 1983, Hill in 1986 and Howard in 1987.

The Wollongong Period

Beyond the technical committee work and his ATSE responsibilities during his period in Melbourne, Howard's activities included his election as National Chairman of the Committee for Australia-China Relations and his serving as Crosbie Morrison Lecturer at Museum Victoria. He found little time for his hobbies of painting and collecting minerals. In 1985 Howard and Rilda decided to move to Wollongong to be near their daughter Ruth and to allow time for his other interests.

However, towards the end of his time in Melbourne Howard had become interested in possible applications of microwave heating to mineral processing. After settling into their new home, Howard started experiments in their kitchen microwave oven. After producing a strong sulphurous smell with an experimental smelting of a copper ore, he was banned from the kitchen! After some further work in his garden shed he obtained permission to use the foundry at the Wollongong TAFE for further experimental work. Whilst this was proceeding he was approached by Professor Ken McKinnon, Vice-Chancellor of the University of Wollongong, who invited him to join the University as an Honorary Professor and to start up a research centre in the applications of microwave heating to industrial processes. The Centre was called the Microwave Applications Research Centre, and was placed within the commercial arm of the University (first Uniadvice Ltd and then the Illawarra Technology Corporation Ltd). At the age of 74, when most scientists had moved to retirement, Howard was launching into a new career in a new field! He very quickly obtained over $2 million of research grants from mining companies and government and built a group that peaked at about twenty staff including several postgraduate students. Howard was the initial director but in 1990, due to his wife's illness, he handed responsibility to Dr Douglas Bradhurst while still maintaining a very active role. The Centre worked in a wide variety of applications of microwave heating. Key areas were:

- Sterilization of sewage waste (funded by a grant from the Sydney Water Board). This project led to a major pilot plant at the Shell Harbour Sewerage Plant but, although the pilot plant was successful, Sydney Water elected not to proceed to a full-scale plant.
- Production of oil from Australian shales
- Smelting of oxide minerals with coal
- Sintering of ceramics
- Surface coating of metals
- Drying of wool bales before processing. A commercial plant was installed successfully at an Italian wool processor.

The high standard of the work at the Microwave Applications Research Centre was recognized when it organized an international conference in 1989 on microwave power applications that was attended by over one hundred delegates including several from overseas. The activity generated a company that still operates from the University of Wollongong site, namely Australian Microwave Technology Ltd, which provides feasibility studies and engineering design for applications of microwave heating to industrial processes. It is interesting to note that although none of the mineral processing investigations led to commercial outcomes, Rio Tinto Ltd is currently investing large budgets in the application of microwave heating to mineral comminution. Again Howard was ahead of his time!

The EnvIRONment Process

During the investigations into sterilisation of sewerage, Howard observed that the sludge could possibly be a source of carbon for metal reduction. Preliminary experiments confirmed this and led Howard to the concept of a new process, based on his research on continuous smelting, to combine this material with the fines produced by oxygen steelmaking to produce an iron product and simultaneously solve two environmental problems. The steelmaking fines are a problem in most steel plants and consist primarily of iron oxides that cannot be processed in normal steel furnaces because of their high zinc content. Funding was obtained to build a 100 kw experimental arc furnace and patents were taken out for the process, which was christened the EnvIRONment process. In the process, the iron ore fines are pelletized with the sewerage sludge after preheating and fed into the arc furnace. The zinc is fumed off the melt and collected in a baghouse, the potentially harmful organics in the sewerage are burnt off in the furnace, and cast iron and a usable slag, which contains the potentially harmful sulphur and phosphorus, are produced and tapped off at opposite ends of the furnace. Funded by the Sydney Water Board, the New South Wales State Electricity Commission and BHP, a considerable test programme was undertaken to refine the process and a proposal to BHP to conduct a major pilot plant was submitted and accepted. Unfortunately a management change at BHP resulted in cancellation of this project, and efforts to pursue the concept elsewhere in Australia were not successful.

An American company, Molten Metal Technology Inc., which had been set up to develop techniques for economic disposal of industrial wastes, expressed interest and for many years Howard (now in his eighties) acted as their consultant and travelled to Boston several times a year to work with them on various projects. Unfortunately they ran out of funds before commercializing any new process.

In 1995 an Australian company, Ausmelt Ltd, which had successfully commercialized continuous smelting furnaces for several base metals, approached Howard to work with them on a proposal to smelt iron ore, which had been discovered near Cooper Pedy, with coal from a deposit in the same area, using a modification of the EnvIRONment process. Patents were applied for and a detailed proposal prepared, with support from the South Australian Government and Meekatharra Minerals Ltd, to raise funds for a major pilot plant. Unfortunately, in spite of significant interest from Japanese companies, sufficient funds could not be raised and the project did not proceed.

The Howard Worner Mineral Collection

Howard developed an early interest in mineralogy and started a collection of minerals in 1932 that by 1995 amounted to over 3,000 items. He published papers from time to time on aspects of mineralogy and in 1982 he edited and made significant contributions to a definitive book entitled *Minerals of Broken Hill* (96). This was widely acclaimed and ran to several editions. In 1995 he donated the best part of his mineral collection to the University of Wollongong, where ~1,000 specimens are on permanent display in the foyer of the Science Building. Howard worked with the curators, Professor Paul Carr and Dr Penny Williamson, to catalogue and arrange the display. This is regarded as the best collection within an Australian university and is widely used by students and staff.

Awards and Honours in his Later Years

During his career Howard received many honours and awards as noted in the earlier text but in his later years these intensified. Thus in May 1988 the University of Wollongong conferred an honorary degree of Doctor of Science on Howard in recognition of his activities. In the same year a major symposium 'Frontiers in Pyrometallurgy, the Inaugural Howard Worner Symposium' was organized by the Newcastle Branch of the Australasian Institute of Mining and Metallurgy.

In 1993, to coincide with his 80th birthday, a 'Symposium to Honour the Life and Work of Howard Worner' was organized by the University of Wollongong in collaboration with Illawarra Technology Co Ltd, the Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering. The papers in the symposium reflected the wide range of topics on which Howard had engaged himself during his career. At the symposium the Worner brothers linked up yet again as Hill Worner chaired one of the sessions, while the President of ATSE, Sir Rupert Myers, presented Howard with his Certificate of Honorary Fellowship.

This contribution to technology in the broad sense was reinforced in a subsequent symposium in Howard's honour, namely the Howard Worner International Symposium on Injection in Pyrometallurgy held in Melbourne in July 1996, organized by the G. K. Williams Co-operative Research Centre for Extractive Metallurgy in conjunction with the Minerals, Metals and Materials Society of the USA and the Iron and Steel Institute of Japan. Here Howard gave a fascinating presentation on his career entitled 'Some Trials and Tribulations of an Inventor' in which he acknowledged that 'Unfortunately, several of these inventions were ahead of their time'! A further recognition of Howard's achievements came in July 1997 during a major international conference on thermomechanical processing of steel and other materials, held in Wollongong attended by some 350 Australian and international participants. Tributes were paid by colleagues from Australia and North America and Professor Gerard Sutton, Vice-Chancellor of the University of Wollongong, presented Howard with a specially struck gold medal bearing the University's crest.

A continuing tribute to Howard and his brothers is the Worner Lecture Series instituted in 1988 at the Bendigo campus of La Trobe University. (This institution is the successor to the Bendigo School of Mines where the Worner brothers commenced their careers.) In 1994 Howard was awarded an honorary degree of Doctor of Science by La Trobe University. The Worner Research Lecture is part of an annual programme of public lectures and aims to publicize research carried out at La Trobe University, Bendigo. The subjects have been diverse but in 1997 the topic was 'Bendigo Gold: Past, Present and Future' with two parts, the first on 'History and Geology' given by H. K. Worner and the second on 'Refractory Gold Ores' by R Findlay Johnson!

In 2002, at the age of 89, Howard was presented with the Benjamin F. Fairless Award by the American Institute of Mining, Metallurgy and Petroleum Engineers for contributions to the steel industry, the first time this award went to someone outside the USA. In 2003 the Australian Government awarded him a Centenary Medal for services to science.

A lasting tribute to Howard was the creation in 2008 of the Howard Worner Memorial Scholarship Fund at the University of Wollongong. This provides an annual $10,000 scholarship to a student from a rural background studying at the University of Wollongong. The fund is intended to preserve Howard's legacy and recognises his rural origins, his contribution to the scientific community and his passion for new challenges.

The Final Years

Rilda's health was failing during the later years of Howard's career and for the last three years of her life she was confined to a nursing home where she died in 2001. Howard and Rilda had a wonderful partnership of over sixty years and Howard readily acknowledged the enormous support she provided to his career.

Following the closure of the Microwave Centre and the failure to commercialize the EnvIRONment process, Howard continued an active involvement with students at the University of Wollongong, giving an occasional inspirational lecture and helping with the supervision of PhD students. His fame did not affect his open and generous nature and the sight of 'the Prof' wandering the university grounds, eagerly examining the world around him, discussing ideas with young researchers and generally spreading goodwill made him a much loved figure at Wollongong. He maintained an office in the ITC building, which he attended for several hours each day, and maintained an active correspondence with contacts around the world until very close to his death. He died on 17 November 2006 following a short illness. He was survived by his daughter Ruth Proctor, his son Colin, eight grandchildren and nine great-grandchildren.

Acknowledgements

The authors wish to acknowledge the extensive help that they received from Howard's daughter, Ruth Proctor, who provided extensive background material including diaries and unpublished material together with detailed information on Howard's family and early life. Excellent assistance was also provided by Susan Jones, Archivist at the University of Wollongong Library. The photograph was taken on the occasion of the conferring on Howard of an honorary degree of Doctor of Science by the University of Newcastle in 1966, and has been made available through the University's Cultural Collections office.

Bibliography

Howard Worner published over 200 research papers and technical articles and had 35 patents to his credit. The following listing of 132 of these papers, and the patent applications, illustrates the wide range of his research. The research papers and the patents are arranged separately, generally in chronological order within their groupings.

Creep and Other Properties of Lead and its Alloys

1. "The lnfluence of Tellurium on the Creep Rate of Commercial Lead" (with J Neill Greenwood). Proc. AusIMM., NS **101**, 57 (1936).
2. "The Influence of Composition of the Creep Rate of Industrial Lead" (with J Neill Greenwood). Proc. AusIMM. NS, **104**, 385 (1936).
3. "Types of Creep Curve Obtained with Lead and its Dilute Alloys" (with J Neill Greenwood). Jl Inst. Metals, London **54**, 135 (1939).
4. "An Analysis of the Deformation and Hardening of Lead Effected by Rolling and Pressing". Proc. AusIMM, NS **116**, 491 (1939).
5. "The Influence of Some Variables on the Brinell Hardness of Lead". Proc. AusIMM, NS **117**, 29 (1940).
6. "Some Factors Affecting the Behaviour of Lead During and Subsequent to Deformation by Rolling and Pressing". Proc. AuslMM, **118**, 111 (1940).
7. "The Preparation of Lead and Lead-Rich Alloys for Microscopic Examination" (with H W Worner). Jl. lnst. Metals (London) **66**, 45 (1940).

Dental and Surgical Materials and Related Subjects

8. "The Failure of Stainless Steel lnlay Retention Posts" (with C H Down) Aust. J. Dent., **41**, 73 (1937).
9. "The Properties of Dental Amalgams". Aust. J. Dent., **41**, 117 (1937).
10. "The Influence of Some Manufacturing Variables on the Properties of Dental Amalgams" (with J S Anderson). Aust. J. Dent., **43**, 269 (1939).
11. "The Composition and Properties of Commercial Dental Amalgam Alloys". Aust. J. Dent., **43**, 347 (1939).
12. "Gnathodynamics". Aust. J. Dent., **44**, 381 (1939).
13. "Some Aspects of Dental Significance from Recent Research in the Dental-Metallographic Research Laboratory, University of Melbourne". Proceedings 10th Congress ADA (1939).
14. "Specifications for Dental Amalgams". Aust. J. Dent., **44**, 37 (1940).

15. “Heat Generated in Cavity Preparation” (with H F Willis). Aust. J. Dent., **44**, 62 (1940).
16. “The Influence of Temperature of Trituration on the Properties of Dental Amalgams”. Aust. J. Dent., **44**, 81 (1940).
17. “The Properties of Commercial Zinc Phosphate Cements”. Aust. J. Dent., **44**, 123 (1940).
18. “A Investigation of the Properties of Some Hypodermic Needles used In Dentistry” Aust. J. Dent., **44**, 205 (1940).
19. “The Properties of Dental Silicate Cements”. Aust. J. Dent., **44**, 277 (1940).
20. “The Physical and Mechanical Properties of Copper Cements – Part 1”. Aust. J. Dent., **44**, 411 (1940).
21. “The Physical and Mechanical Properties of Copper Cements Part 2”. Aust. J. Dent., **45**, 1 (1941).
22. “Excessive Expansions in Dental Amalgams, Hand Milling shown to be a Cause”. Aust. J. Dent., **45**, 161 (1941).
23. “An Investigation of the Cause of Crevices Around Teeth in Vulcanite Dentures”. Aust. J. Dent., **45**, 263 (1941).
24. “Base Metal Alloy Substitute for Dental Inlay Casting Gold”. Aust. J. Dent., **45**, 293 (1941).
25. “Dental Plasters, Part 1 – General Manufacture and Characteristics Before Mixing with Water”. Aust. J. Dent., **46**, 1 (1942).
26. “Dental Plasters, Part II -The Setting Phenomenon, Properties After Mixing with Water, Methods of Testing.” Aust. J. Dent., **46**, 35 (1942).
27. “Plaster of Paris as a Cast Material.” Aust. J. Dent., **46**, 84 (1942).
28. “Some Observations on the Strength of Dental Plasters as Vulcanising Investments”. J. Dent. Res., **21**, 340 (1942).
29. “A Study of the Behaviour of Plaster of Paris and Hydrocal as Investments in the Process of Vulcanising Dental Rubber.” Aust. J. Dent., **46**, 132 (1942).
30. “Acrylic Resins in Dentistry, Part I – Introductory. General Chemical and Physical Considerations.” (with B D Guerin). Aust J. Dent., **46**, 202 (1942).
31. “Acrylic Resins in Dentistry, Part II – Their Use tor Denture Construction” (with B D Guerin and W J Tuckfield). Aust. J. Dent., **47**, 1 (1942).
32. “Investigations on Dental Materials in the Research Laboratory at the Australian College of Dentistry”. Aust. J. Dent., **47**, 157 (1943).
33. “Acrylic Resins in Dentistry, Part III – (Introductory) – Artificial Teeth, Inlays, Crowns and Flexible or Rigid Facial Restorations” (with W J Tuckfield and B D Guerin). Aust. J. Dent., **47**, 172 (1943).
34. “Consistency Tests on Dental and Surgical Plasters and Casting Investment” [with M N Anderson). Aust. J. Dent., **47**, 217 (1943).
35. “Biting Force Measurements on Children” (with M N Anderson). Aust. J. Dent., **48**, 1 (1944).
36. “Some Observations on the Effect of Styrene and Polystyrene on Dental Acrylic Resins” (with B D Guerin). Aust. J. Dent., **48**, 12 (1944).
37. “Impression Materials with an Alginate Base.” Aust J Dent., **48**, 49 (1944).
38. “Alginates as Substitutes for Tinfoil for Acrylic Resin Dentures.” (with W J Tuckfield). Aust. J. Dent., **48**, 43 (1944).
39. “The Fundamental Principles of Vision Applications to Dentistry” (with J F Richardson). Aust. J. Dent., **48**, 100 (1945).
40. “The Effect of Temperature on the Rate of Setting of Plaster of Paris”. J. Dent. Res. (USA) **23**, 305 (1944).
41. “Acrylic Resins in Dentistry. Part III – Obturaters, Flexible or Rigid Facial Restorations, Splints and Artificial Teeth.” (with W J Tuckfield). Aust. J. Dent., **49**, 10 (1945).
42. “Polyvinyl Resins in Dentistry, with Special Reference to their use tor Facial Prostheses” (with W J Tuckfield). Aust. J. Dent., **49**, 25 (1945).
43. “Changes in the Composition and Setting Characteristics of Plaster of Paris on Exposure to High Humidity Atmospheres” (with A S Buchanan). J. Dent. Res. (USA) **24**, 65 (1945).
44. “Impact Tests on Some Dental Vulcanites and Acrylic Resins using a Guillotine Type Machine.” (with J F Richardson). Aust. J. Dent., **49**, 96 (1945).
45. “A Micro-Hardness Instrument for Studying Surface Hardness” (with J F Richardson). Aust. J. Dent., **49**, 217 (1945).
46. “How to Get the Best Out of Your Materials.” Aust. J. Dent., **49**, 227 (1945).
47. “Plastics in Dentistry and Surgery. Part I – Historical. Part II, ” Chemistry, Part III – Acrylic Resin Dentures, Part IV – Applications of Acrylic Resins in Dentistry, Part V – Applications in Surgery and General Medicine”. Aust. Plastics. Vol I (Nos. 8–12] Nov. 1945, April 1946.
48. “A Study of the Action of Borax in Retarding the Setting of Plaster of Paris” (with A S Buchanan). Jl. Soc.Chem.Ind., **65**, 23 (1946).
49. “Materials Research and Development of Dental Standards.” (with A R Docking). Aust. Dent. Jl., **3**, 215, (1955).
50. “Dental Materials in the Tropics.” (with A R Docking). Aust. Dent. Jl. **3**, 215 (1958).

Titanium Extraction

51. “The Extraction of Titanium” (with G D Cordner) Proceedings of the AusIMM *158–159*, 65–87, Sept–Dec 1950.
52. “Titanium Extraction Metallurgy” (with H N Sinha). Trans.Indian Inst. Metals **119**, 265 (1956).
53. ‘Titanium Research at the University at Melbourne” (with F L Bett). Proc.AusIMM. **178**, 1 (1956).
54. “The Extraction of Titanium by Fused Salt Electrolysis” (with F L Bett, B S Hickman and G M Willis). Institution of Min. & Met. Symposium on Extraction of Less Common Metals, 1956 (London), p. 21.

Special Foundry Techniques

55. “Precision Casting”. Aust. Engineer. pp. 60 – Aug. 1947.
56. “Investment Casting”. Proc. Inst. Aust. Foundrymen, **3**, 193 (1951).
57. “Shell Moulding Copper Base Alloys” (with S S Brown). Proc. Am. Foundrymens Soc., **54**, 39 (1954).
58. “The Shell Moulding Process” (with S S Brown). Proc. Inst. British Foundrymen (Australian Branch), **5**, 39 (1950).

Mining, Metallurgical and Engineering Education

59. “Mining and Metallurgical Education in Victoria (with H H Dunkin). Proc. Aus IMM, **158–9**, 297 (1950).
60. “Metallurgical Education in the University of Melbourne”. Bull. Inst. of Metallurgists (London). pp. 19–25, Sept. (1950).
61. “The Education of Mining and Metallurgical Engineers in Australia.” Proc. Fifth British Empire Min. & Met. Congress, *5*, chap. 6. pp. 165–185 (1953).
62. “Engineering Education in Australia”. Paper presented to Third Convocation of Engineering and Like Academies in Oaxaca, Mexico. Sept. 1951, published separately by Australian Academy of Technological Sciences (p. 14).

Iron and Steel Research

63. “The Work of BHP Central Research Laboratories.” BHP Technical Bull. **1**, 2 (March 1957).
64. “Some Researches into the Sintering of Fine Hematite Ores”. AusIMM Sintering Symposium, Port Pirie, p. 71 (1957).
65. “The BHP-AIS Research Programme with Particular Reference to Coke Quality and Iron Production”. BHP Technical Bull. **3**, 3 (March 1959).
66. “Some Experiences in Sintering Rich Hematite Ores in Australia.” AIME Blast Furnace and Raw Materials Proc. (New York) **19**, 648 (1950).
67. “Structures and Bonding Mechanisms in Sinters made from Fine Grained Australian Hematites” (with L C Bogan), Internat. Symposium on Agglomeration (Philadelphia) April 1961.
68. “Revolutions in Iron and Steelmaking”. Aust. Engineer p60 June 1961 and Jl. Aust. Inst. Metals **6**, 167 (1961).
69. “The Physical Degradation of Ores and Sinters During Simultaneous Abrasion and Chemical Reduction- (with BO Holland and J B Lean). AIME Blast Furnace and Raw Materials Proc. (New York), **21**, 269 (1962).
70. “Some Developments from the First Five Years Work of the Central Research Laboratories”. BHP Tech. Bulletin **6**, 2 (February 1962).
71. “Steelworks Research”. Aust. Mech. Engineering **49**, 33 (1962).
72. “Australian Research Features Continuous Coking and Steelmaking.” Jl. of Meta1s (New York) **14**, 375 (May 1952).
73. “Continuous Processes being investigated in Australian Steel lndustry Research”. Nature **195**, 15 (July 1962). Also New Scientist *283*, 79 (April 1962).
74. “EnvIRONment and other Bath Smelting Processes for treating organic and ferrous wastes.(with S Street, G. Brooks and L Reilly JOM, **50**(4), 43–47, (April 1988).
75. “Recovering iron and zinc values from steel plant dusts with simultaneous destruction of organic wastes; the EnvIRONment process” Technical Proceedings of the AusIMM Annual Conference 1995, pp. 195–198, Newcastle.
76. Pyrometallurgical treatment of wastes; an Australian contribution (with G A Brooks) Pyrometallurgy Conference 1995 proceedings. Institute of Mining and Metallurgy, London.
77. “The EnvIRONment process, towards commercialisation; A decade of gestation”, (with S Street, G Brooks) Proceedings of Second International Symposium on Extraction and Processing for the Treatment and Minimisation of Wastes-1996, pp. 73–83, Minerals Metallurgy and Materials Society.

New Continuous Methods of Smelting and Refining

The following 16 papers are representative of over 30 papers on WORCRA technology that were presented at international symposia and conferences around the world and published as indicated.

78. "Continuous Copper Converting." Letter to Jl. of Metals (USA) **16**, 614 (1964).
79. "Some Principles Governing CRA Research in Pyrometallurgy". Mining and Chem. Eng. Rev., **57**, 50 (1965).
80. "The WORCRA Processes for Continuous Smelting and Refining". Institution of Mining and Metallurgy Symposium on Advances in Extractive Metallurgy, London 1957 (p. 20).
81. "WORCRA Copper Smelting". Paper presented to Meeting of United Nations lndustrial Development Organisation (UNIDO), Vienna, November 1957 (p. 35).
82. "Kupferschmelzen nach der WORCRA Verfahren". Contribution to the Berg-und-Huettenmaennischer Tag, Bergakademie Freiberg, Germany July 1968 (p. 22).
83. "WORCRA (Continuous) Steelmaking." AlME National Open Hearth and Basic Oxygen Steelmaking Conference, Toronto; published in Jl. of Metals (USA) **21**, 50(1969)
84. "Continuous Steelmaking". Jl.Iron and Steel Inst, (London), **207**, 1420 (1969).
85. "WORCRA Iron and Steelmaking". Chapter in "Alternative Routes to Steel," published by Iron and Steel Inst. (London) p. 41 (1971).
86. "Applications of the Levenspiel Dispersion Model to Metal Flow in Pilot Plant WORCRA Continuous Steelmaking Furnace." (with T W Jenkins and N B Gray), Met. Trans AIME (USA) **2**, 1255 (1971).
87. "Measurement of the Residence – Time Distribution for the WORCRA Steel Refiner." (with T A Engh), Jernkonterets Annaler (Sweden) **155**, 93 (1971).
88. "One Dimensional Model ol the WORCRA Steel Refining Launder" (with T A Engh, C E Crisp and L Hansson). Jemkonterets Annaler (Sweden) **155**, 553 (1571).
89. "WORCRA Copper and Nickel Smelting". Paper presented in Tokyo, May 1972 and published in Joint MMIJ and AIME Symposium Proceedings 1972 (16 pp).
90. "Continuous Copper Smelting – Convertng by the WORCRA Process" (with B S Andrews). Paper presented in Santiago, Chile, Aug. 1973 and published in Proceedings of Chilean lnst. of Mining Engineers 1973 (13 pp).
91. "Integrated Smelting – Converting-Slag Cleaning in a Single Furnace." Paper presented at TMS-AIME Annual Meeting, Dallas. Texas, USA, February 1974 and published in Meeting Proceedings (p. 12).
92. "Modern Vulcans", Search **6** (5), 157–166 (1975).
93. "Extra Clean Steel via WORCRA Continuous Steelmaking." Iron and Steelmaker (USA) **15**, 23 (1988).
94. "Continuous Ferrous and Non-Ferrous Bath Smelting." Proc. Savard/Lee International Symposium on Bath Smelting, Montreal, Oct. 1992, 83–101. Published by TMS, Warrendale, PA, USA.

Geology and Mineralogy

95. "Nephrite Deposit of the Great Serpentine Belt of New South Wales (with J J Hockley and W D Birch) Jl.Geological Soc. of Aust, **25**, 249 (1978).
96. "Minerals of Broken Hill", AM&S Ltd. Melbourne. (H K Worner principal editor and also contributor) (1982).
97. "Early Australian Mineralogy" (with T G Vallance). The Mineralogical Record **19**, 357 (1989).
98. "Variable Morphology in Synthetic Zincite." Aust. Jnl of Mineralogy, **2**(1), 28 (1996).

Microwave Processing

99. "Some Pioneering Pyrometallurgy". AuslMM Bulletin and Proc. **293**, 36 (1988).
100. "Microwave Drying of Brown Coal Agglomerates" (with N Standish and H R Kaul). Jl Microwave Power and Electromagnetic Energy." **23**, 171–175 (1988)
101. "Microwaves in Pyrometallurgy" (with L Reilly and J Jones). Proc. Symposium on Microwave Power Applications, Univ. of Wollongong, Feb 1989, pp. 179–188.
102. "Microwave Energy as an Aid to Smelting." Proc. Non- Ferrous Smelting Symposium, Port Pirie, Sept. 1989, 17–20 (AusIMM and IEAust).
103. "Effect of Microwave Drying on the Results of Subsequent Analytical Results" (with N Standish). Analyst **114**, 115–116 (1989).
104. "The Applications of Microwave Energy in Mineral Processing" (with D H Bradhurst). TIZ International, **114**, 246–249 (1991).
105. "Temperature Distribution in Microwave Heated Iron Ore-Carbon Composite" (with N Standish and G. Gupta). Jl Microwave Power and Electromagnetic Energy **25**, 59 (1991).

106. "Microwave Applications in the Reduction of Metal Oxides with Carbon" (with N Standish). Iron & Steelmaker (I&SM) **18**, 59–61 (1991).
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108. "Microwave Energy used to Smelt Mixtures of Low Rank Coals and Oxidic Materials" (with D H Bradhurst). Fuel **72**, 685 (1993).
109. "Reduction of Stannic Oxide with Carbon by Microwave Heating" (with D H Bradhurst). Proceedings of AusIMM Extractive Metallurgy Conference, Brisbane 1994 pp. 225–232.
110. "Evaluation of Oil Produced from Microwave Retorting of Australian Shales" (with D H Bradhurst). Fuel **75**(3), 285–288 (1996). Pollution Control, Waste Processing. Recycling.
111. "WORCRA Metallurgy Promising tor Pollution Control in Copper Plants." Eng. and Mining Journal **172**, 64–68 (1971).
112. "New Use for Sewage Sludges in Smelting." Search **21**, 245–246 (1990).
113. "Putting Wastes to Work", Chemistry in Australia **58**, 432–433 (1991).
114. "Iron Bath Melting-Smelting in the Treatment of Wastes"'. Proc. Mervyn Willis Symposium, Univ. of Melb. (July 1992) p. 9.
115. "Putting Pyrometallurgy to use in Waste Processing", Proceedings of GK Williams Research Centre Conference 1994. Published by The Minerals, Metals and Materials Society pp. 49–58.

Miscellaneous including Reviews

116. "Plastics and Metals". Aust. Engineer p. 34 – June 1945.
117. "Plastics v Metals" Aust. Plastics pp 25, August 1945 and p. 16 October 1945.
118. "The Progress of Secondary Metallurgy." Aust. Engineer p. 52. May 1948.
119. "Sponsored Industrial Research" (with G V Cullen). Aust. Engineer p. 20. April 1956.
120. "Metallurgical Fuel from Victorian Brown Coal". Proc. AuslMM **177**, 49 (1956).
121. "Some Achievements in Modern Metallurgy", (Presidential Address) Jl. Aust. Inst. Metals **1**, 10 (1956).
122. "Metallurgical Research in Australia" (Presidential Address). Jl. Aust. Inst. Metals **2**, 1 (1957).
123. "Australia's Iron and Steel Industry." Proc. RACI p 571 November 1958.
125. "The Romance of Metal Winning in Australia." Min. and Chem. Eng. Review. **57**, I6 (1965).
126. "Australia's Mineral Wealth – A Forecast." Aust. Mining **58**, HE (1966).
127. Pilot Scale Copper Precipitation Using Particulate Iron in a Pulsed Column." (with M B Altman and J A Harris) Proc. Commonwealth Mining and Metallurgical Congress. 5th Edition, M J Jones Ed. pp. 95–106 (1970).
128. "Continuous Vacuum Refining of Crude Cadmium Metal." (with D E Fitzgerald and M G Tavernor). Vacuum **22**, 393–397 (1972).
129. "Dental Standards in Australia" International Dental Jl. **24**, 368–71 (1974).
130. "Energy-the Australian Scene AusIMM Bulletin **427**, 17–19 (1979).
131. Australian Coals as Feedstocks for Liquid Fuels." (with G H Taylor). Review prepared for The American Association of Petroleum Geologists Volume on World Oil Resources p. 9 (1981).
132. "Advances in Science and Technology Stemming from Broken Hill." Keynote Address at Centenary Conference of AuslMM, Broken Hill (with I E Newnham). AuslMM Bulletin 476. p. 9 (1983).

Patents and Patent Applications

Arranged generally in chronological order within categories. Australian Patent Numbers only are listed. Many international patents granted.

Iron and Steelmaking

1. Process and Apparatus for Autogenous Grinding (with J B Lean)* No 245.543. Continuous simultaneous chemical and physical reduction of Hematite Quartzites.
2. Continuous Oxygen Steelmaking No 257,155. Sequential oxygen lancing in simple launder furnace.
3. Smelting Ferrous Materials. No 5531805 (1996). The EnvIRONment process.

Gypsum Products (High Strength Plaster)

3. Continuous Production of Alpha Plaster.* No 275,443. Single stage process.
4. Continuous Production of Alpha Plaster No 67I42/65. Two stage process. Mechanical movement of slurry.
5. Continuous Production of Alpha Plaster No 67143/65. Multistage, slurry pumped.
6. Production of Alpha Plaster No 35674/68. Slurry process in sloping autoclave.

Glass Production

7. Continuous Production of Furnace Products.* No 273,494. from cheap particulate materials.

Direct Continuous Smelting and Refining

8. Direct Smelting of Ores and Concentrates.* No 281,236. Called WORCRA smelting-refining. Applicable to most commercial metals Fe Cu Ni Pb etc.
9. Reverberatory Smelting of Copper Concentrate.* No 66820/65. Continuous, direct to metal.
10. Continuous Direct Smelting of Sulphide Concentrates (with B S Andrews).* No P1302/56. Specially applicable to continuous Cu and Ni production.
11. Direct Smelting of Oxide Ores and Concentrates. No P3172/66.* Mainly direct ore to steel called CIMAS (Continuous iron making and steel making.)
12. Continuous Bath Smelting and Refining. No P14484/66. Mainly relates to direct ore to steel (CIMAS)
13. Tin smelting.* No P34576/68. Direct from ore to tin metal.
14. Shaft Furnace Smelting of Oxidic Ores, Concentrates or Calcines. No. P4434/68. Uses vertical perforated columns in combustion zone.
15. Suspension Smelting and Refining. No 47558/68. Suspension smelting combined with WORCRA refining.

Continuous Electric Smelting-Refining

16. Continuous Production of Iron and Steel. No P47333/68. Uses ladle type induction furnace with launder furnace.
17. Continuous Production of Iron and Steel. No P54530/69. Uses barrel shaped induction furnaces.
18. Continuous Production of Liquid Steel using Arc Furnaces (with R Siddons) No P14483/66. Uses modified arc furnaces with integral launder refining furnace.

Continuous Refining of Matte or Pig Iron

19. Refining of Metals and Alloys.* No P48138/64. Continuous production of copper or steel.
20. Refining of Metals and Alloys No P3170/66. Improvements on 48138 with particular reference to steelmaking.
21. Method and Apparatus for Refining Metals. No P33751/68. Improvements on 48138 and 3170 with particular reference to concurrent and countercurrent slag/metal refining.

Continuous Vacuum Degassing and Deoxidation

22. Degassing metals and Alloys.* No 279,591. Sloping ribbed vacuum chamber, particularly applicable to steel and aluminium.
23. Continuous Degassing of Metals. No 27983/67. Uses bell jar and electric stirring.
24. Continuous Degassing of Steel. No 27984/67. Uses fixed chamber, inlet and outlet legs, electric stirring.

Continuous Vacuum Refining of Metals

25. Vacuum Separation and Refining of Metals (with D E Fitzgerald). No. P1371/66. Particularly applicable to separation and refining of metals like Zn, Cd, Pb.

Separation of Molten Materials Continuously

26. Separation of Molten Materials. No P35728/68. Pyrometallurgical liquid-liquid extractions. Production of Composites of Low Rank Coals, Peat etc. and Minerals for Smelting.
27. Metallurgical Composites and Processes (with A S Buchanan).* No P54395/86. Brown Coal + Lignite blends with fine ores and concentrates for smelting.
28. Upgrading Plant Material and its use for Metallurgical Processes (with A S Buchanan).* No P7944/66. Use of peat and plant material in metallurgical composites for smelting.

Microwave Treatments for Processing of Minerals and Coal

29. Microwave Irradiation of Composites No. 49062909. (1990) Precursor treatment ahead of high intensity bath smelting.
30. Microwave Irradiation of Mineral Ores and Concentrates. No. P1623/87, 875414/89. Microwave smelting of mixtures of ores and coals.
31. Microwave Heating of Oil-containing Shales (with P. Burton) No. P 32534/87, 624369/89. To maximise production of alkanes and alkenes.
32. Direct Reduction Ores and Concentrates. No. P9876/88. To accelerate metallisation by microwave aided reduction.

Accelerated Fixation of Biopsy Specimens

33. Method and Apparatus for fixing biopsy specimens (with D Mclean) No. P21131/90. To greatly speed up biopsy specimen fixation using microwaves.

Processing of Wastes

34. Co-treatment of Sewage and Steelworks Wastes.* No. 5364441(1994). To achieve recovery of iron, zinc oxide useable slag from such as steel plant dusts, sewage sludge and other carbon-containing wastes.

*Patents granted in several countries.