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MEMOIRS

Sir Alan Cottrell FREng. 17 July 1919 –– 15 February 2012

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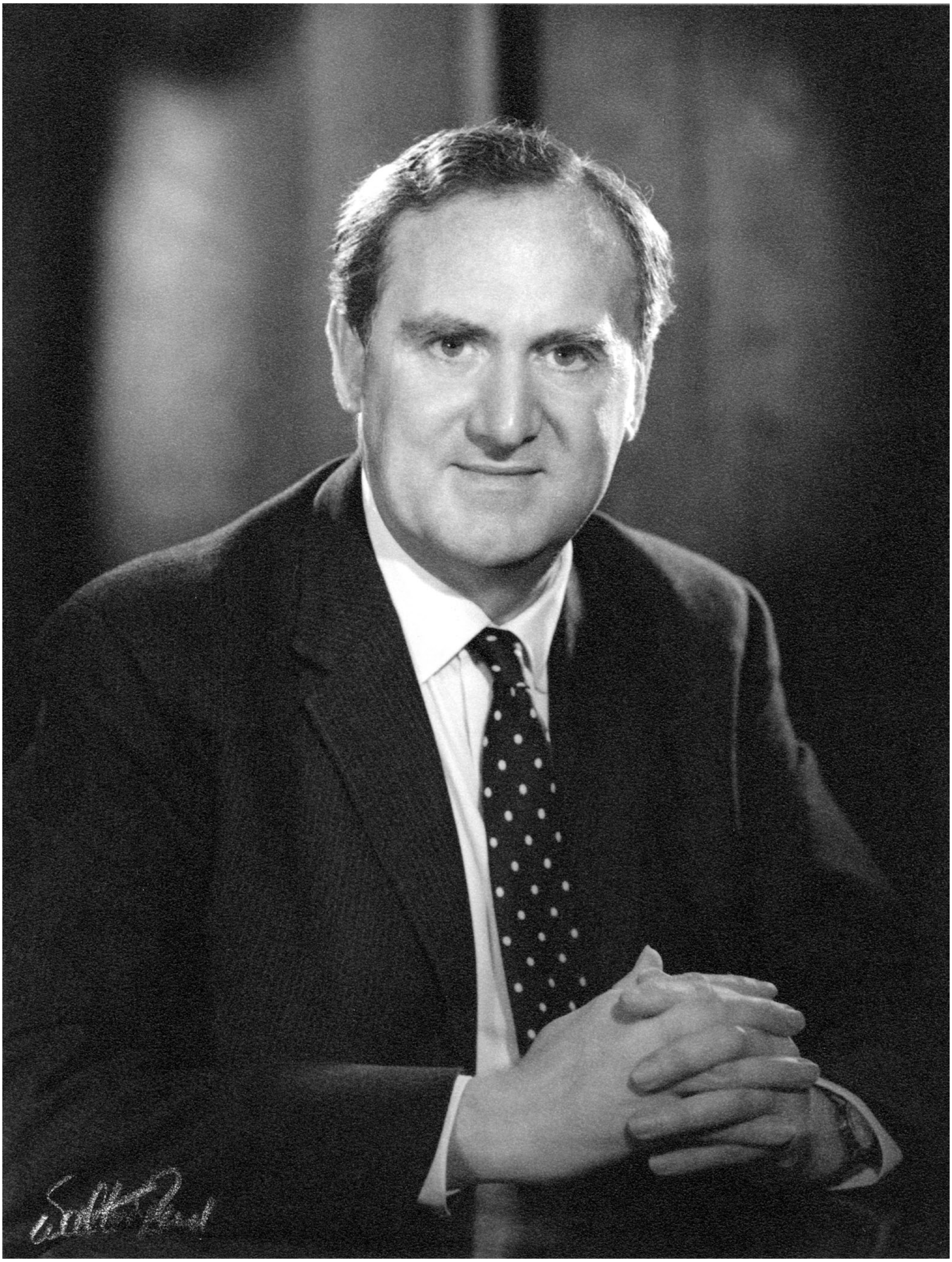

A. H. Cottrell

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Elected FRS 1955

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Sir Alan Cottrell was a man who achieved the highest possible distinction in a number of roles relating to science and education. He is rightly regarded as the outstanding physical metallurgist of the twentieth century. His career began at the University of Birmingham, where, first as lecturer, then as professor, he made two major contributions. The first was to relate the properties of metals and alloy systems to their electronic structures and to thermodynamical factors; the second was to relate the mechanical properties of solids to the defects that they contained: point defects such as vacancies and interstitials, and line defects such as dislocations. His work in both these topics proved to be instructional and inspirational for generations to come. He next spent a period at Harwell, making major contributions to the UK's nuclear reactor programme. He then moved to Cambridge to regenerate a somewhat moribund Department of Metallurgy. His success was such that, through the lines of research that he created and the people that he brought in, the Cambridge Department is now recognized as a world leader. His own research made great advances in the treatment of the brittle fracture of steel.

After Cambridge he moved to Whitehall: first as Deputy, then as Chief Scientific Advisor to the Ministry of Defence; this was then followed by a move to the Cabinet Office, as Deputy, then Chief Scientific Advisor to the government. A few of his achievements in these posts are described in the text, but it is abundantly clear that his advice was highly regarded by Ministers. One particular interest related to the safety of the pressurized water nuclear reactor (PWR), and the strength of the convictions that he held were eventually to be addressed by the industry and regulator to the extent that the care now taken in constructing and assessing PWRs for the UK leads the world. His spell in government was followed by a return to Cambridge, initially as Master of Jesus College, where he skilfully negotiated a change to co-education, and then as Vice-Chancellor of the university, a post that at the time was held sequentially by Heads of Houses. During this period he had close dealings with Prince Philip, Chancellor of the university, and when Cottrell returned 'full-time' to Jesus, Prince Edward

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was admitted to the college as an undergraduate. Throughout this latter period, Cottrell wrote several books and papers on applications of modern solid state theory to the properties of metals and alloys and was awarded the Copley Medal: the first time ever that this had been awarded to a physical metallurgist. Cottrell's career was indeed outstanding.

Introduction

We feel enormously privileged to have been asked to write this memoir of someone for whom we both held enormous respect and who, over the more than 50 years that we both knew him, had significant influence on our scientific careers. In his tribute at Sir Alan's funeral, Sir Peter Hirsch FRS put it simply: 'Alan was the most outstanding and influential Physical Metallurgist of the twentieth century … the only one to be awarded the Copley Medal.' It was with some trepidation that we approached our task, because Sir Alan achieved so much, in quite different areas. We have, however, been aided enormously by a copious set of autobiographical notes written by Sir Alan, and in places we have quoted directly from these notes, to allow his voice to come through. We are also grateful for inputs from Sir Alan's son, Dr Geoffrey Cottrell, and from Sir Peter Hirsch.

A significant part of Alan Cottrell's interests, both in science and in commenting on national policy, relates to the generation of electricity by means of nuclear power. The details of this may not be appreciated by all of those who read this memoir; rather than interrupt the general flow of the text, we have included a few paragraphs on nuclear power generation in the UK as an Appendix, to which the reader can refer if wished.

Family background and early years

Alan Cottrell was born in Birmingham on 17 July 1919, the elder son of Albert and Elizabeth Cottrell. His brother, Stanley, also a metallurgist, was born in 1925. His grandfather had built up a successful retail shoe business in the city and sold it at the end of World War I, investing the proceeds in a block of properties on the Moseley and Balsall Heath boundary, consisting of shops, houses and land. Alan's father took on the development and management of the property and they lived in one of the houses until 1932.

His primary school education was at Tindall Street elementary school, three minutes' walk from their house. He stayed at Tindall Street until the age of 10 years. Encouraged by an excellent schoolmistress, an early academic success was winning an essay competition and, later, the entrance examination to Moseley Grammar School. This was in Wake Green Road, about two miles away, and he was given a bicycle to get there. At age 15 years he was offered a sixth-form transfer scholarship to King Edward's, the premier school in the city, but he preferred to stay at Moseley. His talent depended more on logical consistency than on memory and his interests developed in the sciences rather than the arts, particularly in astronomy, electricity and engineering. His father, although not scientifically educated, had hobbies in radio and engines, and these aroused Alan's early interest. From his mother he developed a musical interest and learned to play the piano, at which he excelled in later life. His main sporting interest was in trout fishing, particularly dry-fly fishing, when the family drove to mid Wales in their car.

In the mid 1930s it was usual to leave school after School Certificate/Matriculation and get a job as an office junior or laboratory assistant. (Birmingham was still the 'city of a thousand trades'.) However, Alan was given a Birmingham Education Committee award to stay in the sixth form with only five or six other students to study physics, chemistry and mathematics. After Higher School Certificate, the traditional path to a degree in science was a job in industry, evening classes and an external London BSc. Accordingly in 1936 Alan took a job at ICI Metals, Witton, as a laboratory assistant and started a course at the local technical college. Within a few weeks an enlightened City Education Department wrote to offer Alan a university scholarship to read for a science degree. He accepted and intended to read physics, but at a farewell interview with Dr Maurice Cook, head of his department at ICI Metals, the suggestion of metallurgy was made. He visited the Departments of Physics, Mechanical Engineering and Metallurgy but was most impressed with Professor Daniel Hanson and decided on metallurgy at Birmingham.

The university and war years, 1936–45

Although the traditional metallurgy course at the time was based on ore extraction, analysis, processing (melting, casting and fabrication) and engineering properties, Hanson had introduced some scientific aspects of the subject, including metallography, X-ray diffraction, Hume-Rothery's alloy chemistry and the concepts of dislocations due to G. I. (Sir Geoffrey) Taylor FRS. This constituted a definite move towards understanding the basic science of metals and alloys.

Away from their studies, many undergraduates developed a passion for contract bridge at lunch times, and Alan was no exception. However, when the Barber Institute of Fine Arts was built with a splendid concert hall and a set of musical practice rooms, he gave up bridge and replaced it with piano practice sessions, becoming sufficiently good to give some student recitals. His *pièce de résistance* was a Beethoven sonata (Op. 90) but he was also fond of Ravel and Debussy, whose music he played well.

In June 1939 Alan graduated with first-class honours and was awarded a research scholarship to study the recovery of metals, on annealing, from the effects of deformation. However, the war changed that and after being earmarked for training in the Royal Armoured Corps he was transferred to a reserved occupation to do wartime research in the Department of Metallurgy. Many of the top science graduates were similarly directed and performed valuable wartime research work.

Alan's task was to study the problem of cracking associated with the arc welding of alloy steels for tanks. The steels, particularly in thick sections, developed extensive cracking along the heat-affected zones that bordered the welds. It was suspected that this was due to the formation of the hard, brittle martensite phase in these zones, but there was little evidence. It was necessary to solve this important practical problem to avoid the effect and produce strong, crack-free welded joints. Alan was initially under the direction of Professor E. C. Rollason, but later he led a team that included K. Winterton, P. D. Crowther and J. A. Wheeler. They established a working understanding of the scientific processes involved and devised methods for avoiding the cracking by a preheating treatment. The findings were accepted by the Ministry but their application remained secret. However, the work produced some interesting pieces of science, in particular the finding that metastable austenite could be decomposed to martensite and bainite by plastic deformation. They were able to publish some of the results, and Alan gained his PhD in 1942.

Between Home Guard duties and spending time up 'Joe', the university clock tower, on fire-watching duties, Alan carried on his war-based research, as a research fellow. In 1943 he was appointed to a university lectureship and became engaged to Jean Harber. They both lived in Kings Heath, where Jean's mother owned a pharmaceutical chemist's shop, and they travelled to Selly Oak on the same bus, Jean to a small corrosion research unit belonging to the Iron and Steel Institute and Alan to the Metallurgy Department. During the war the Lickey and Clent Hills were favourite locations for walks, and the City still held orchestral concerts and recitals. They were married on 5 April 1944 at St Agnes Church, Moseley, and honeymooned in Derbyshire. They set up home in a flat in Anderton Park Road in Moseley, eventually buying a house in Green Meadow Road, Weoley Hill, about a mile from the university.

In 1944 Hanson, anticipating the end of the war, began to construct his visions for the future. His ambition was to create a modern 'science of metals' department that incorporated all the new ideas of atomic physics, etc., and to have the department play a leading role in this. As a preliminary, he asked Alan to prepare a new course, basically on the physics of metals. This he did and began teaching it in 1945. A few years later it became the foundation of his book *Theoretical structural metallurgy* (1)*. His main aim was to get students to think about metals and alloys in terms of 'what the atoms were doing', instead of the mainly semi-empirical methods of the traditional approaches.

Postwar years, 1945–55

At the end of the war, G. V. Raynor (FRS 1959) joined the Department from Oxford, and Hanson gained a DSIR (Department of Scientific and Industrial Research) grant that funded both Alan and Raynor to start up new research: Raynor on the constitution of alloys, and Alan on the strength and plasticity of metals. After advice from Egon Orowan (FRS 1947) at Cambridge, his small group started to grow and strain single crystals of pure metals, initially Zn and Cd. The first success was to verify Andrade's $t^{1/3}$ law of creep with remarkable accuracy.

The department was strengthened with the addition of a theoretician, Maurice Jaswon, and an X-ray crystallographer, W. H. Hall. Interestingly, it was the national fuel crisis and power shut-down in the winter of 1946–47 that turned Alan in a more theoretical direction. The department was forced to shut down all experiments for several weeks. Following up a paper in which Frank Nabarro (FRS 1971) discussed the possibility of dislocation lines getting 'hung up' on foreign atoms distributed randomly through an alloy crystal, Cottrell considered the situation in which the atoms were mobile and allowed to diffuse. He conceived of the possibility of atoms migrating to the core of the dislocation and 'anchoring' it down. He realized that such segregation might be detectable by chemical etching, but it was not until some time later that one of his students, Neil McKinnon from Australia, looked at the problem. By then the technique of 'decorating' dislocations had been developed by P. Lacombe, J. W. Mitchell (FRS 1956) and others.

* Numbers in this form refer to the bibliography at the end of the text.

In 1949 both Cottrell and Raynor were appointed to professorships. Cottrell became Professor of Physical Metallurgy and Raynor became Professor of Metal Physics. It is rumoured that they tossed a coin to decide who should have which title.

The possibility of pinning dislocations, thereby strengthening the crystal, became Cottrell's major interest, and the spectacular yield point of structural steel became a focal point. Experimental evidence indicated that the yield drop might be associated with the presence of carbon or nitrogen and could be removed by a decarburizing anneal in wet hydrogen. Carbon and nitrogen atoms dissolve interstitially in iron and distort the lattice severely to give a strong elastic interaction with dislocations. With their high mobility they could migrate to dislocations even at room temperature; the interaction energy was about 1 eV. It was well known in industry that the yield point could be removed by small amounts of plastic deformation, but it would return when the steel was 'aged' either at room temperature or at slightly elevated temperatures. This, Alan recognized, could be explained if the yield drop was caused by the unpinning or freeing of dislocations from their impurity 'atmospheres' and not reappear until the dislocations had collected the migrating atoms and become immobilized. This was known as 'strain ageing'.

After discussions with Nevill (later Sir Nevill) Mott FRS, Charles (later Sir Charles) Frank (FRS 1954) and Nabarro at the Bristol School in 1947, Cottrell expanded his group to work exclusively on yield points in iron and other metals. Bruce Bilby (FRS 1977) joined the group to work on theoretical aspects of yielding, and several students were recruited to conduct research on other metals with different crystal structures and different impurities. It was recognized that the carbon and nitrogen atoms in the body-centred cubic (b.c.c.) transition metals enabled them to interact with both edge and screw dislocations, whereas the impurities in face-centred cubic (f.c.c.) metals produced symmetrical distortions and weaker yield points. In addition, the sites of maximum binding at the core of the dislocation are easily occupied and filled at room temperature by the mobile carbon or nitrogen in b.c.c. iron, but in the f.c.c. metals it is necessary to test at low temperatures, below the condensation temperature at which the 'atmosphere' changes from dilute to condensed.

By considering the thermally activated unpinning of dislocations from their impurity locking, Bilby and Cottrell deduced a strong temperature dependence of the yield stress (2). It was not until later that it was recognized that the Peierls stress of the lattice is also strongly temperature dependent. Indeed, in 1966, R. M. Fisher and Cottrell showed that in annealed mild steel the dislocations are so strongly locked that breakaway does not occur and the temperature dependence is due to the Peierls stress. Other work showed that in its early stages strain ageing should develop as $(\text{time})^{2/3}$ and this was later confirmed by S. Harper, a former Cottrell student, at Chicago, using an internal friction method due to J. L. Snoek. Attention was also given to the polycrystal aspect of yielding in iron. It was recognized that yielding is often triggered prematurely at inclusions and that the role of the grain boundaries is to contain the free dislocation in slip bands while the applied stress is quite small, eventually forcing yield to occur in the next grain. This feature is used in the development of our understanding of mechanical properties, for example grain-size dependence of the yield stress (N. J. Petch, FRS 1974) and fracture.

Cottrell also investigated, with Jaswon, the distribution of solute atoms around a slow-moving dislocation (3). The non-symmetry of the distribution causes a force opposing the dislocation motion. The force increases linearly with the speed of the dislocation at low speeds, and a critical range exists above which the dislocation accelerates. The characteristics of the plastic flow below the critical range were compared with micro-creep in tin containing iron and copper as impurities.

Cottrell later pointed out that the drag of substitutional solute atoms can occur not only in creep but also in ordinary tensile tests, when vacancies are generated to enhance the solute diffusion. He explained the well-known Portevin–Le Chatelier effect in aluminium alloys containing magnesium and copper, in which the stress–strain curves often begin smoothly but develop serrations (jerky flow) as strain proceeds. He considered the vacancies produced by plastic deformation to be responsible for the strain ageing. However, it is also possible to retain, temporarily, a large supersaturation of vacancies by quenching from elevated temperature. This is a feature of the standard heat treatment for precipitation-hardening aluminium alloys.

At room temperature the mobility of carbon and nitrogen atoms in iron is too low for them to keep up with dislocations as they move. However, at about 100–200 °C, the carbon and nitrogen can diffuse fast enough to allow strain ageing while plastic deformation is in progress. The relevant stress–strain curves show serrations and the ductility is reduced (termed 'blue brittleness', resulting from the discoloration of the iron at this temperature). The jerky flow arises because the dislocations do not glide with a steady velocity but are often held up, enabling the interstitial solute atoms to catch up and re-form atmospheres.

Other important aspects of dislocation theory apart from yield behaviour were studied. Cottrell, Nabarro and others were involved in the general consolidation of the elasticity theory of dislocations, and in calculations of elastic energies and interactions. One success was the explanation of Cahn's observations on continuously bent zinc single crystals after annealing. Cottrell suggested that the bending of the lattice was produced by randomly distributed dislocations of the same sign that, on annealing, rearranged by slip and climb into vertical walls to lower their elastic energy. The process was termed 'polygonization', with the resultant structure being a connection of slightly misoriented lattice regions. This subgrain structure may be identified with the 'mosaic' structure invoked by X-ray crystallographers. The work led to the first quantitative proof of the existence of dislocations when etch pitting of the dislocation separation in the subgrain walls was shown by Lacombe to be inversely proportional to the misorientation with the correct estimate of the Burgers vector.

In the 1950s, following Heidenreich and Shockley's paper on partial dislocations in the f.c.c. structure, the formation of the Lomer–Cottrell barrier was noted ((4); and see pp. 171–172 of (5)). This concerned the interaction of dislocations on intersecting slip planes, producing barriers that Cottrell suggested might contribute to increase work hardening. W. M. (Mick) Lomer considered the dislocation reaction of unit dislocations at the line of intersection of two active systems producing a barrier, but this was potentially glissile on a cube plane and Cottrell considered the interaction for the dislocations dissociated into partials. He showed that it led to a new type of partial dislocation (aptly named by N. Thompson a 'stair rod' dislocation because it joined two areas of stacking fault on intersecting planes, somewhat like the method employed at the time for fixing stair carpet). This had extremely low energy and was sessile because the Burgers vector is not coplanar with the fault. It would thus form a strong barrier to any further dislocation movement on the active slip systems. Lomer–Cottrell barriers were first observed by M. J. Whelan (FRS 1976) in transmission electron microscopy of stainless steel with low stacking-fault energy.

The concept of partial dislocations opened up several other areas. By using the mechanism for the creation of dislocations during deformation by the operation of a Frank–Read source, Frank, Bilby and Cottrell suggested a 'pole' mechanism for the growth of deformation twins. Another area was deformation in ordered alloys. With W. Rachinger, from the Aeronautical Research Laboratories in Australia, they pointed out that dislocations in disordered alloys were equivalent to partial dislocations in the ordered structure. Thus deformation in ordered alloys such as β-brass is achieved by super-dislocations consisting of pairs of dislocations coupled together by antiphase boundaries. That work started a tradition of study of intermetallic compounds in the Birmingham department that has continued for more than 50 years. Cottrell also became interested in how point defects interacted with dislocations and with Professor R. A. Maddin from Philadelphia demonstrated strengthening in quenched aluminium. This was an area followed up later at Harwell: exploring the roles of both vacancies and interstitials.

Work hardening was a continuing complex problem that challenged researchers worldwide for many decades. At that time, little progress, apart from the Lomer–Cottrell barrier, had been made since G. I. Taylor's time. It was well known that metals hardened with strain more rapidly at low temperatures, but it was not clear whether this was due to a more rapid build-up of dislocations at such temperatures or to a steep temperature-dependence of the flow stress in a standard work-hardened state. Cottrell and R. J. Stokes studied this in aluminium crystals by imposing step changes of temperature during plastic deformation (6). The experiments showed that the flow stress for a given work-hardened state was relatively insensitive to temperature. They suggested a 'forest'-cutting model to account for this, with the temperature-independent part due to the repulsive elastic interaction between interacting dislocations and the temperature-dependent part due to the thermally activated formation of jogs during the cutting process. This proposal led to the forest (rather than the long-range pile-up stress) model of flow stress. The finding that the temperature-dependent part of the flow stress is proportional to the temperature-independent part (after correction for the temperature dependence of the shear modulus) has become known as the Cottrell–Stokes law.

A further observation was that much of the work-hardening produced at low temperature disappeared in a yield drop when strained at a higher temperature. This was due not to any impurity effect but to the development of a work-hardened state characteristic of that temperature. At the higher temperature, work-softening occurs initially, but with continued plastic deformation a work-hardened state characteristic of that temperature is developed, eventually producing yield strengths above that at which the low-temperature work-hardened state had been eliminated.

The Metallurgy Department, 1945–55

Throughout the period, Hanson's leadership and support was remarkable, not only to his staff but also to the graduating students. It was a very happy environment in which to work. The research students and staff were on good terms, there were no antagonisms or rivalries, and all shared the pleasures of the various individual successes. The department soon became famous as a leading centre for the science of metals and attracted many distinguished researchers, such as Nabarro, Robert Cahn (FRS 1991) and Bilby. There was a very active weekly seminar that most students attended to familiarize themselves with all aspects of the new science. There was tremendous excitement when visiting lecturers came: Mott and Frank from Bristol, Herb Holloman from General Electric, Schenectady, and Cyril Stanley Smith (a graduate from Birmingham) from Chicago.

Alan's personal life with Jean was also very happy. They bought a succession of old cars—all that could be obtained in those days—and took holidays in north Wales, staggering up Snowdon. They also became regular visitors to the theatre at Stratford during the Shakespeare season. Jean was a violinist and, at home, they played Beethoven's sonatas (and much more music) together. On 7 October 1951, Alan and Jean's son Geoffrey was born and life was complete, with regular visits to the USA and elsewhere. Then quite suddenly, in June 1953 Hanson died unexpectedly of heart failure. Despite this, the momentum of the department kept things going well and distinguished visitors came, notably Professor Charles Barrett from Chicago and Professor Robert Maddin from Pennsylvania. J. D. (Jock) Eshelby (FRS 1974) joined the department to maintain the theoretical strength after Nabarro left for a professorship at Witwatersrand in South Africa. Alan published his second book, *Dislocations and plastic flow in crystals*, in 1953 (5). This was the first book relating mechanical properties to dislocation mechanisms in a meaningful way. It was, and still is, a classic containing much material that at the time was completely new and intellectually exciting.

With Hanson's death, the department lost a powerful influence in the university. A. J. Murphy came in to be Head of Department, and although all continued to get on well together, the 'chemistry' was not the same. In 1955 Alan was elected to the Fellowship of the Royal Society for his work on dislocations. Then came an invitation from H. M. (Monty) Finniston (FRS 1969) to become Deputy Division Head of the Metallurgy Division at the Atomic Energy Research Establishment, Harwell. After 19 years at Birmingham, Alan resigned his chair to take up the post. For the family, the move to lovely countryside near Oxford was a pleasant change from the 'sombre' suburbs of Birmingham only just recovering from the aftermath of the war. They moved to an Authority-owned house on the Fitzharry's estate in the market town of Abingdon. The work at Harwell seemed ideal for Alan, applying his expertise in lattice defects to understand 'radiation damage' of metals and to help develop radiation-resistant materials for the construction of nuclear power reactors. So began the next phase of his career.

Atomic Energy Research Establishment, Harwell, 1955–58

The Metallurgy Division

Cottrell moved to Harwell in the spring of 1955. After the friendly, interactive atmosphere at Birmingham, it was something of a shock to find that the establishment was full of cliques, rivalries and 'class' structure. The 'superior' class were (self-defined by) the physicists, especially the nuclear physicists, who generally made policy and planned experiments, and then there were 'the others', among whom metallurgists were included, who generally made hardware, etc., for the experiments. Monty Finniston was a forceful Division Head and wanted a strong fundamental science arm to his Division, recognizing that the problems of radiation damage and materials with novel crystal structures required both a practical and a scientific approach. Cottrell agreed with this approach and thus it was unfortunate that soon after Cottrell's joining Harwell, Sir John Cockcroft FRS, Establishment Director, invited him to take his radiation damage group out of the Metallurgy Division and unite it with the neutron diffraction people and other small physics groups to form a new Solid State Physics Division. To his credit, Cottrell made no attempt to implement this proposal, firmly believing that radiation damage research should be kept close to the practical reactor problems. This proved to be a crucial decision for the success of the future Magnox reactor programme, but the incident weakened relations between Monty and Alan.

Alan soon gathered around him several scientific officers from across the Division and also several researchers from the Central Electricity Generating Board (CEGB), seconded while the Berkeley Nuclear Laboratories were being built, and from other generating companies. These included Robert Barnes, Trevor Churchman, Dennis Rimmer, A. C. Roberts, Derek Hull (FRS 1989), Ray Smallman (FRS 1986), John Makin and Mike Thompson, many of whom went on to forge highly successful careers in later life.

Radiation damage research

Alan's research aim at Harwell was to concentrate on the scientific understanding of radiation damage in those areas most helpful to the development of nuclear power reactors. Much of the research worldwide was in determining the energies of formation and migration of vacancies and interstitials and identifying the various stages of annealing. Although this was important, Alan instead concentrated on two problems: the behaviour of uranium under irradiation, and the hardening and embrittlement of structural steel used for reactor pressure vessels. A problem with uranium as fuel rod material is 'swelling' due to the formation of gas 'bubbles' or pockets from the vacancies and fission products krypton and xenon. An aim was to get the gas into a large number of small 'bubbles' in which the surface tension of the metal would hold the gas at high pressure and reduce the swelling. This led to uranium alloy research to produce fine intermetallic precipitates on which the bubbles could be nucleated. Another uranium problem was the growth of grains due to the preferential clustering of interstitials on particular planes. Cottrell showed that grains growing into one another would lead to a total loss of yield strength and would eventually behave as a Newtonian fluid. The rate was such as to imply serious practical consequences for the buckling of fuel rods in the reactor.

The most significant experiment arising from this was one with A. C. Roberts on irradiation creep deformation, conducted by winding a thin uranium wire into the form of a soft spring, sealing it in a silica tube and lowering it into the reactor at the end of a fishing line for periods of one week. (The fishing line would not have been difficult to acquire!) The sample was withdrawn and the irradiation creep was viewed indirectly through a mirror. During irradiation in a flux of about 10^{12} thermal neutrons $cm^{-2}\ s^{-1}$, at temperatures as low as 100 °C the uranium was observed to creep ($10^{-7}\ h^{-1}$) under an external stress as small as 10^{-2} yield stress (7). The observations proved all the theoretical predictions that the creep rate was sufficient to produce a large bend in the fuel rod within a few weeks' irradiation. At the time the designs for the Magnox power reactors (see the Appendix) were being finalized, and it was intended to stack the fuel rods vertically in the channels through the graphite core. It was estimated that the weight of the stack would be sufficient to cause irradiation creep, buckle the rods and jam the channels within the first two weeks of operation. Dr A. K. Hardy at the northern group of the Atomic Energy Authority (AEA) checked the predictions, and his team redesigned the fuel elements with supporting lugs on each to carry the load (11).

This development was undoubtedly the most important contribution that Cottrell made to the UK nuclear power programme. Without it, the Magnox reactor programme would have run into serious operational difficulties within a few weeks of starting up. Apart from the problem of removing buckled fuel rods from the channels, there could well have been overheating and bursting of the fuel cans.

The other main topic studied by Cottrell's group was the irradiation embrittlement of steel, a potentially important problem for the steel pressure vessels of Magnox (and later PWR) reactors (11). It was known that prolonged exposure to fast neutrons could significantly raise the ductile–brittle transition temperatures of structural steel. In this case the irradiation produced a hardening of the metal (by forming clusters of irradiation defects in the lattice as shown by electron microscopy) that hindered the movement of dislocations. For the amount of hardening produced, the increase in the brittle temperature was similar to that produced by other methods of hardening, such as alloy precipitates, without irradiation. On this basis Cottrell proposed a semi-empirical relation to give the rise in transition temperature as a function of fast neutron dose, as a guide to behaviour in reactor pressure vessels.

Irradiation embrittlement studies led to the problem of brittle cleavage fracture of steel. Experimental evidence, particularly in the USA by J. R. Low, suggested that the cleavage cracks were nucleated by plastic deformation. Cottrell, in a paper published in 1958, developed a model of crack nucleation involving the coalescence of glide dislocations on intersecting slip planes to form edge-type dislocations that structurally resembled a wedge of material, made up of several of the new edge dislocations forced between the faces of the (100) cleavage plane (10). Because coalescence occurred with a decrease in energy, the nucleation process was not the most difficult stage of the fracture; it was instead the propagation of the embryonic crack within a grain. Introducing the grain-size dependence of the yield stress, Cottrell developed a mathematical relationship for the ductile–brittle transition in terms of composition, grain size, irradiation hardening and stress state. Independently, Petch also recognized that early growth of a nucleated crack was more difficult than its nucleation and developed somewhat similar equations. An important outcome of the work was the recognition of the importance of grain size in providing both increased yield strength and greater toughness as the grain size is refined. This is now one of the fundamental features of the development of modern steels.

Through this work and also because of some other problems, such as the grain boundary failure of magnesium alloy fuel cans which could potentially lead to the escape of radioactive material into the cooling system, Cottrell became interested in fracture generally. D. Hull and D. E. Rimmer in the group established the parameters and mechanisms controlling the growth and coalescence of grain boundary voids during high-temperature creep by grain boundary diffusion. Another area was fatigue failure. Experiments by D. Hull at the nearby Clarendon Laboratory, University of Oxford, showed that extrusions and intrusions formed in 'persistent' slip bands even at 20 K. Cottrell recognized that at such low temperatures a purely mechanical process of cyclic slip must be involved in the nucleation and growth of fatigue cracks from the intrusions, and he proposed a new ingenious mechanism (9).

In the autumn of 1957 the planned research that Cottrell was leading was totally interrupted as a result of a fire in one of two graphite moderated reactors at Windscale. These were not power reactors but air-cooled reactors built to produce plutonium (^{239}Pu) for the British atomic bomb project. The reactors were also used for the production of isotopes and other nuclear experiments. During irradiation, point defects are created in the graphite moderator: displaced carbon atoms create interstitials and vacant atom sites (vacancies), which build up a significant stored energy. To prevent the spontaneous release of this energy, a controlled anneal of the moderator was performed at about 250 °C, to allow the displaced carbon atoms and vacancies to diffuse and annihilate. This was a new and unresearched process with which the engineers had little experience. Unfortunately, the rate of (Wigner) energy release was so rapid that the temperature got out of control and the graphite caught fire in some channels. Cottrell was asked to lead a research programme throughout the AEA to provide a better understanding of the physics and engineering of radiation damage in graphite and its removal by annealing. It was a crash programme organizationally separate from the Metallurgy Division. The senior people in the team were J. H. W. Simons and W. N. Reynolds of the Physics Division, Lomer in Theoretical Physics at Harwell, J. C. Bell and H. Bridge at Windscale, and G. B. Greenhough at Springfields. The team had, with some urgency, to establish safe and effective conditions for the annealing of graphite in the Calder Hall and planned Magnox power reactors. In the short term, graphite annealing was planned for the Harwell reactor British Experimental Pile 0 (BEPO) in early 1958. A new laboratory was set up, with all its specialized equipment working and ready in six weeks. The BEPO annealing was successfully performed on 8 March 1958, confirming the protocol developed by the team. That was one of the last tasks that Cottrell completed at Harwell.

Throughout his short time at Harwell, Alan led a group conducting scientifically and technologically important research, often with brilliant design of experiments to obtain fundamental information on mechanisms. He also used his exceptional talents in his papers to convey complex phenomena in simple terms. His review article 'Effects of neutron irradiation on metals and alloys' (8), published soon after he joined Harwell, made a great impact on the scientific community in the field.

Cambridge, 1958–64

On 18 January 1958 the Vice-Chancellor of Cambridge University, Lord Adrian FRS, wrote to Cottrell, offering him the Goldsmiths' Chair and the Headship of the Department of Metallurgy. Cottrell records that 'This was in scratchy handwriting, on a half-sheet of notepaper. It was (and remains) my only legal contract with the University of Cambridge.' He 'of course' accepted this offer and moved with Jean to a house in Luard Road, close to Nevill and Ruth Mott, who were already friends of theirs. Sir Alex (later Lord) Todd FRS persuaded Alan to become a Fellow of Christ's College. Despite forming many new friendships, notably one with Peter (now Sir Peter) Hirsch and his wife, Steve, that was to last 50 years or more, Alan and Jean initially found Cambridge life, with its formal dinners and college functions, 'rather stiff and strange after the informalities and jollities of Harwell and Abingdon: but we soon got used to it.'

Taking up the reins in October 1958, Cottrell realized how much he needed to do to build up the status and reputation of the department. It was housed in scattered bits of Victorian buildings. The university increased the amount of accommodation when the Department of Chemistry vacated space in Pembroke Street, but the buildings were still Victorian: wooden floors, wooden benches, timbered ceilings; hardly suitable for metallurgical research, involving high-temperature furnaces for melting and heat treatment. Fires were almost inevitable, and occurred, but more of that below. The department had a small staff, and rather little equipment apart from some fatigue machines. There was research on mechanical properties, corrosion and the beginnings of the application of transmission electron microscopy to the study of alloys, but Cottrell's initial impression was that the overall level of research needed significant improvement.

The CEGB and the AEA provided significant research funding, and the Science Research Council awarded grants for the purchase of new equipment, in particular a state-of the-art transmission electron microscope. The university permitted the establishment of additional academic posts, enabling Cottrell to make new appointments, in particular Robin Nicholson (FRS 1978) in electron microscopy, Tony Kelly (FRS 1973) in metal physics, and Jim Charles in process metallurgy. Cottrell felt strongly that, although the main aim for the department was to improve its standing in the science of metals ('*à la* Birmingham'), he considered that it should also have a strong section in practical metallurgy, encompassing advances in oxygen steel-making, for example. He interested himself in the teaching of extraction metallurgy, and taught a Part I course (see below) based on the underlying thermodynamical principles and reaction kinetics. This material was incorporated in a much-expanded version of his earlier work *Theoretical structural metallurgy* to produce a new textbook, *An introduction to metallurgy* (which was, however, not published until 1967).

Cottrell set up research teams in two new research areas: field ion microscopy (FIM), initially led by David Brandon and later by Brian Ralph and Mike Southon; and superconductivity, with David Dew-Hughes, Jan Evetts and Archie Campbell. In the department's 'Tributes to Sir Alan Cottrell', produced for his Memorial Service (in Great St Mary's on 9 June 2012), David Brandon explains that FIM, which had been demonstrated by Müller only in 1958, was recognized by Cottrell as a technique able to examine radiation damage and defects such as dislocations at the atomic level. When Brandon eventually met Müller, in 1961, the latter complained that the Cambridge samples were 'no good—they contained defects'. It had to be explained carefully that that was the whole point of the exercise. Campbell emphasizes Cottrell's recognition that superconductivity was emerging from the realms of pure physics to an interdisciplinary subject requiring materials science. In Campbell's words, 'It was inspired timing.' Superconductivity research at Cambridge was to go from strength to strength: initially in developing the concepts of 'pinning' of flux vortices by defects (closely analogous to the pinning of dislocations) through to extensive research on high-temperature superconducting materials and thin-film technology, which has produced a wide range of devices and nanomaterials and now involves some 60 researchers in materials and engineering. Again quoting Campbell: 'This is all the result of Alan's remarkable foresight fifty years ago.'

Cottrell's own research concentrated on three topics: (i) elastic–plastic deformation and fracture at the tips of sharp cracks; (ii) experimental observations of deformation and fracture in notched bars of steel; and (iii) fibre-reinforced composites. The first topic involved the theory of continuous distributions of dislocations: 'real' dislocations ahead of the crack and 'virtual' dislocations within the crack. The details of the analysis involved collaboration with Bilby and K. H. Swinden, at the University of Sheffield, and later with Ted Smith (FRS 1996) at Leatherhead. The first results were available in early 1960, and the concept that the initiation of fracture was determined by the attainment of a critical crack-tip displacement was used by Cottrell, at a meeting of the Iron and Steel Institute in December 1960, to explain size effects on fracture (12). The classic 'Bilby, Cottrell, Swinden (BCS)' paper was not, however, published until 1963 (13). The analysis was used, in modified form, for many years to provide a theoretical basis for the 'failure' line on the 'failure assessment diagram' (FAD), commonly accepted by industry as the means of assessing the likelihood of failure in cracked engineering structures. Failure can occur either by 'fast fracture' (the unstable propagation of a pre-existing crack-like defect) or by 'plastic collapse' (gross yielding of the section ahead of the crack: the 'uncracked ligament'). The proximity to fast fracture is given by the ratio, K_r, of the applied stress intensity factor K (a function of applied stress and crack length) to the materials 'fracture toughness' K_{1c} (a quantitative measure of resistance to fast fracture, as determined from the failure loads of standard, precracked test pieces). The proximity to plastic collapse is given by the ratio, L_r, of the applied stress on the uncracked ligament to the collapse stress for that ligament (this depends on geometry and the material's flow strength). The FAD plots K_r as ordinate against L_r as abscissa, and the assessment point is given by the values of K_r and L_r for a given applied stress and crack/section geometry. The important finding is that the two failure criteria are not independent: the 'failure' line (representing the achievement of the critical crack-tip displacement) decreases from unity on the K_r axis, at $L_r = 0$, to zero on the K_r axis at $L_r = 1$, with the form being given by the BCS theory. More recent developments, including effects of work hardening, have somewhat redefined the line, but the contribution of the BCS concepts to the underpinning of practical assessments was of major importance for 20 years or more.

The theoretical work was accompanied by experimental work performed by John Knott (FRS 1990) and John Griffiths, to demonstrate that even the most brittle fractures in steel, at very low temperature, were always preceded by small amounts of plastic deformation, whether slip or twinning (14, 17). Knott's research included measurements of notch-tip and crack-tip displacements, but it also began to establish a critical local tensile stress criterion for the propagation of micro-cracks initiated by local plastic deformation. This was later interpreted in terms of Cottrell's 1958 model for cleavage crack propagation, and was then extended to include effects of brittle second-phase particles, such as carbides. In 1963 Cottrell delivered the Bakerian Lecture 'Fracture', in which he presented and discussed both the theoretical and experimental findings (15). In 1964 he published *The mechanical properties of matter* (16).

His interests in fracture at a crack tip ranged from the macroscopic scale, using the BCS theory to explain size effects in large engineering structures, through the microscopic scale (with Knott and Griffiths) to the atomic scale, in work with Bill Tyson and Tony Kelly. In a classic and highly influential paper (19), they considered the factors that might determine whether a material would fail in a brittle manner or a ductile manner. Ahead of an atomically sharp crack tip in an annealed solid, dislocation sources are likely to be relatively remote (up to 1 μm away), and the situation was therefore analysed in terms of the balance between fracturing the crack-tip bond at the theoretical fracture strength (of order $E/10$, where E is Young's modulus) or creating a dislocation at the tip, able to glide away and thereby blunt the crack. This would occur at a stress of order $\mu/10$ (where μ is the shear modulus), with some modification to take account of permissible slip systems. Using these concepts, they were able to classify materials as 'inherently brittle', such as diamond, with its very high Peierls stress; layer silicates such as mica; or 'inherently ductile', such as f.c.c. metals (for example gold). It is of interest to note that b.c.c. iron turned out to be a borderline case—and iron, of course, exhibits brittle behaviour at low temperatures but ductile behaviour at higher temperatures. This paper stimulated much further research, both theoretical and experimental, on the emission of dislocations from crack tips, and the concepts have been adapted in recent years to explain the properties of metallic glasses. The trend now is to refer to the bulk modulus, K, rather than Young's modulus, E, and a general finding is that material is ductile if the ratio μ/K is less than about 0.4.

The third area of interest was that of fibre composites. Cottrell was aware of discoveries in the USA of dislocation-free 'whisker' crystals, which exhibited near-theoretical strengths, and was also intrigued by the increase in the viscosities of fluids that had long fibres embedded in them. From this he developed the idea of fibre 'pull-out' as a means of providing a high work of fracture. He again collaborated with Tony Kelly. They established that dislocation-free fibres were not essential and they emphasized the importance of (relatively) weak interfaces between fibre and matrix, which could split open and impede the propagation of sharp cracks (18). Kelly explained these concepts in depth in his book *Strong solids*, and they have proved extremely useful in the design of high-performance components made in composite materials.

The overall achievements of the 'Cottrell years' at Cambridge are impressive and are rightly regarded as such by those who experienced them. He 'led from the front' in no uncertain manner, continually encouraging his staff and impressing the students. His newly appointed staff members, Nicholson and Kelly, became Fellows of the Royal Society, and Jim Charles became a Fellow of the Royal Academy of Engineering. It is, however, clear in his notes that his time was by no means trouble-free: much politicking was necessary to maintain the standing of the department with respect to both the other natural science subjects and engineering. There were also very practical concerns to face. Above, mention was made of the unsuitability of the buildings for metallurgical research, and indeed there was a rather serious fire in the summer vacation of 1959. This was followed by another fire about a year later. After this, the research group responsible for both fires was relocated in a new extension, at the top of the Pembroke Street building. What then happened, however, was that, shortly after the decorators had finished covering up fire damage and left the premises, two members of the group contrived to flood the building. Gallon upon gallon of water flowed down through all the newly decorated rooms. In later life, equanimity restored, Sir Alan was wont to refer to these incidents in terms of the tribulations of Egypt in biblical times 'fire, flood: we were waiting for frogs, flies, locusts, plague and pestilence', but at the time his reaction was better described (by the two research students who had just been given a severe dressing-down) as 'near-apoplectic'.

An interesting consequence of these disasters relates to the steady stream of visitors, from all over the world, coming to the department to pay their respects to Cottrell. When, after fire and flood, his office was finally refurbished, it was fitted with a rubber-backed carpet, such that visitors, walking across to shake his hand, and later to take their leave, tended to build up a substantial static electrical charge. On reaching for the brass door handle to leave the office, discharge occurred and a spark flew. They assumed that it was the handshake with the great man that had charged them up, and who in the department was going to disabuse them? The effect was quite disconcerting for Cottrell himself, who had to leave his office every day, and—sadly from the point of view of preserving the legend—a remedy had to be sought. This was provided by his secretary, who ensured that there was always a bowl of flowers in water in the room, to prevent the air from becoming too dry.

Cottrell readily recognized that a major strength of metallurgy at Cambridge was the existence of the Natural Sciences Tripos (NST), which ensured that undergraduates during their first two years (to Part I) were exposed to teaching not just in chemistry and physics but also in subjects such as metallurgy (before 1965, counting as a 'half-subject'), crystallography and others. Metallurgy was therefore able to teach quite large numbers of science students and attract them into the final-year (Part II) single subject. Attraction was all-important and it was doubtless for this reason that Cottrell gave those lectures in Part I: 'leading from the front'. There was a continuing battle to preserve the NST system in the face of chemistry and physics, which both wanted to stream students into their specialist subjects from the first year, but some adroit manoeuvring and the formation of alliances contrived to preserve the NST when its structure was revised, starting in October 1965. The new subject 'the crystalline state' was introduced in the first year: Part IA of the Tripos, taught jointly by metallurgy and mineralogy/petrology. In addition there was Part IB metallurgy in the second year. The strategic importance of these developments can scarcely be overemphasized. Not only did they greatly increase the amount of material taught by the department in the first two years, but the undergraduates were also physically present in the department for much longer (for example for laboratory classes and supervisions) and so were able to form a much better view of what the department had to offer. This was very beneficial in terms of recruitment to the final-year Part II subjects, which, from 1965, included both metallurgy and a new course, materials science. The new structure and courses have stood the test of time in a highly successful manner and it is perhaps ironic that Cottrell, who had applied himself vigorously to their establishment, was no longer in the university when they were first implemented.

During his time at Cambridge, his energies were by no means confined to university matters, although, as described above, he worked tirelessly for the department in building up research, teaching, attracting final-year undergraduates and generally maintaining the department's standing in the university. He also served on the Council of the Senate, and one of the achievements that he notes was his role as 'intermediary' between the university and Fred (later Sir Fred) Hoyle FRS, who was becoming disillusioned and threatening to resign his chair. The Cottrells were close friends of the Hoyles, and Alan was given the task of finding out what might persuade Hoyle to stay at Cambridge. The matter was thrashed out during a Sunday afternoon 'chat', and the result was the establishment of the Institute of Astronomy. Outside the university, Alan acted as Consultant to both the AEA and the CEGB and became a part-time member of the AEA board. He became a Vice-President of the Royal Society and, as noted above, gave, among many other lectures, the Bakerian Lecture in 1963. He also became a member of the Advisory Committee on Scientific Policy, where he first met Sir Solly (later Lord) Zuckerman FRS.

Corridors of power, 1964–74

In 1964 Zuckerman approached Cottrell with an invitation to become one of his two deputies at the Ministry of Defence (MoD) (Sir William Cook FRS was the other). This invitation was more forcefully repeated a little later at a College Feast in Christ's College, by Lord Louis Mountbatten (FRS 1966), who was an Honorary Fellow of the college. According to Cottrell's notes, the invitation was almost at the 'Your Country Needs You' level. Eventually Cottrell agreed to the move, which caused great distress (and some bewilderment) to the members of staff in the Cambridge department. His main reason for the move was that he had become strongly interested in national scientific and industrial policy, especially in the need to strengthen and invigorate British industry by infusing it with modern scientific technology. The MoD was not the ideal base for Cottrell's reforming zeal, but Zuckerman had suggested that 'things would broaden out in Whitehall'. This turned out to mean that Zuckerman himself would very soon (in mid 1966) move to the Cabinet Office to become Chief Scientific Advisor (CSA) to the government, leaving Cottrell in the MoD. About 18 months later, Cottrell also moved across, to become Zuckerman's deputy. Cottrell's move to the MoD was noted in *The Times* in a short article entitled 'Not a tadpole'—a reference to Zuckerman's interests in biological science. In the article, it was stated that Cottrell 'smoked cheroots and enjoyed fishing'. The cheroot smoking was at best a passing phase, but the fishing was, of course, one of Cottrell's passions, from his youth (figure 1).

Figure 1. ‘Not a tadpole’—Sir Alan on one of his many fishing trips. (Online version in colour.)

In his new post he was able to attend various committees more or less concerned with the issues of the links between science, technology and industry in which he was interested, but he was constrained to be present simply as an MoD observer. One technical enterprise that he notes was that for the provision of a low-level, long-range strike fighter to replace the cancelled TSR2. This was to add extra fuel tanks to the naval ‘Buccaneer’ aircraft. Cottrell’s support for this stratagem led to its being referred to in the House of Commons as ‘Cottrell’s Buccaneer’.

His main role was concerned with defence issues and particularly with Denis Healey’s defence reviews. These were eventually to lead to a withdrawal of a (visible) British presence east of Suez. The inescapable consequence of such a presence was the need to be able to provide air cover. In turn, this required either more aircraft carriers or highly complicated in-flight refuelling systems, neither of which Britain could afford. Cottrell chaired several of the study groups that came to this inevitable conclusion and was highly complimented by Healey for the work that they had done: the word ‘brilliant’ was used. In an addition to Sir Peter Hirsch’s obituary of Cottrell in *The Independent* (16 March 2012), Sir Tam Dalyell recalls an occasion following a dinner after a meeting of the Parliamentary and Scientific Committee, at which Cottrell had made a presentation. When, as Secretary, he had thanked Cottrell, he received the semi-joking, semi-serious, reply, ‘It is my job to educate you politicians in military and scientific issues.’ When Dalyell later mentioned this to Healey (then Secretary of State for Defence and hence Cottrell’s ‘boss’), Healey replied, ‘You aren’t the only ones he educates—Alan educates me too.’ Dalyell concludes by saying that Cottrell ‘was indeed a powerful influence—for the good.’

In late 1967 Cottrell accepted an invitation from Zuckerman to move to the Cabinet Office as Deputy CSA to the government. He was already Zuckerman's deputy as Chairman of the Central Advisory Council for Science and Technology. This addressed an impressive range of issues, including the 'brain drain', national statistics for R&D, the transfer of government resources from defence to civil industry, European collaboration in science and technology, environmental pollution, food and agriculture research, the Advanced Passenger Train, UK participation in the Centre Européenne de la Recherche Nucléaire (CERN), and, most importantly, national priorities in science and technology. A report was produced on technological innovation; Cottrell wrote the first draft, but it was then modified and re-modified by other hands, including those of Zuckerman. Cottrell was greatly disappointed by the final version. He had many other matters with which to busy himself, including the government's forays into space-related activities and environmental issues: he represented the UK at the UN Stockholm Conference on The Environment. In January 1971 Cottrell received a knighthood in the New Year's Honours List.

The early period of the Heath government proved difficult. Victor Rothschild FRS, 3rd Baron Rothschild, had been brought in by Edward Heath as head of the newly formed Central Policy Review Staff (CPRS), which operated as an independent unit in the Cabinet Office (popularly known as the 'think-tank'). Rothschild was given *carte blanche* to expand more or less as he wished. He began to take over several of the CSA's functions, including the giving of advice to the Prime Minister on scientific aspects, *Concorde*, computer policy, and nuclear power. Zuckerman was by now infirm and was not maintaining the grip on affairs that he had previously held. He had not retired but was treated as though he had, and the plan was apparently that when Zuckerman was finally persuaded to retire, Cottrell and the team would be assigned to Rothschild. Cottrell was forced to state that he would resign unless the post of CSA were retained and given to him. This was accepted and eventually, Zuckerman retired, at least 'officially', Cottrell became CSA on 1 April 1971. The date was not auspicious and Cottrell felt that the situation in which he found himself was not good. He was directed to work in close partnership with the CPRS. In addition, Zuckerman, although now officially retired, retained an office in the Cabinet Office, with special responsibility for nuclear weapons policy. Cottrell was left with space policy, the environment and communications. Much time was spent with the European Economic Community, trying to coordinate European R&D activities. This led to the setting-up of the Scientific and Technical Research Committee (CREST) in Brussels.

A big topic in Cottrell's later years in the Cabinet Office was the organization of governmental R&D. Rothschild was keen to bring the research councils under the control of government departments, but both the Agricultural Research Council and the Medical Research Council (MRC) were able to provide robust opposition to these plans: the Department of Health and Social Security had said that they did not want to take over the MRC. Rothschild saw no way forward until Cottrell pointed out that the key issue was not where the research councils were located but who paid their bills. This principle became embedded in Rothschild's report on the 'customer–contractor' relationship. The issue of this caused quite a furore, and much of Cottrell's time in late 1971 and early 1972 was spent 'clearing up the mess'. In mid 1972 Cottrell and Lord Jellicoe (Lord Privy Seal) produced a draft White Paper (Cmnd. 5046) explaining that what was envisaged was not 'an arms-length contractual arrangement, but a partnership between the Research Councils and the executive Departments, held together financially.' They insisted that the departments should employ Chief Scientists with responsibilities to make the partnerships work effectively. The Select Committee for Science and Technology came out with a counter-proposal, advocating the appointment of a Minister for

Research and Development. Decisive arguments against this were set out in a second White Paper (Cmnd. 5177, December 1972) largely written by Cottrell.

A major issue, and one that was to occupy much of Cottrell's energies during his last period in the Cabinet Office and for most of his subsequent career, was that of the UK's policy for civil nuclear power. Towards the end of the 1960s, the CEGB was becoming concerned at the total amount of generating capacity available, because demand seemed to be increasing sharply while progress, particularly with the promised advanced gas-cooled reactors (AGRs), was slow. (For a brief description of the different types of reactor involved, see the Appendix.) In 1972 Heath became impatient with the general slow rate of progress with civil nuclear policy, and Cottrell wrote him a memorandum making two recommendations: (i) consider a steam-generating heavy water reactor (SGHWR), largely based on the Canada Deuterium Uranium (CANDU) system; and (ii) consider a commercial 'fast-reactor' system, which would make use of U/Pu transmutation and would, *inter alia*, make use of the 99.3% ^{238}U present in natural uranium, which is not fissile but can be transmuted to ^{239}Pu, which can then undergo a fission sequence. It is of interest that fast reactor systems are currently being reassessed in the 'Generation IV' programmes. Heath was besieged by other views: Rothschild favoured the AGR; Weinstock favoured the PWR. Eventually the CEGB opted for the PWR.

Cottrell was, however, worried about the safety aspects, with respect particularly to the avoidance of brittle fracture of the large, thick reactor pressure vessel (diameter about 4 m, wall thickness about 200 mm, ratio of height to diameter about 4:1). He wrote a strong minute to this effect to the Nuclear Power Advisory Board in the autumn of 1973. This was in strong contrast to his positive views on the CANDU system that he had formed as a result of taking a UK team to Canada in February 1974. Again, in 1974, he appeared before the House of Commons Select Committee on Science and Technology to express his concerns on the 'unforgiving' PWR system, warning of the possibility of rapid fracture; the lack of 'leak-before-break' protection; the need for rigorous manufacturing and quality control standards, coupled with effective and repeated non-destructive inspections with ultrasonics; and further investigations of the effects of ageing, corrosion and thermal shock. In response to Cottrell's minute in autumn 1973, Sir John Hill (who at the time was Chairman of the AEA) asked Sir Walter (later Lord) Marshall FRS to head a Study Group to address Cottrell's points in detail. Marshall set this up in November 1973, enlisting Sir Peter Hirsch and others from outside the AEA to provide independent views. Reports were published in 1976, 1982 and (the 'Hirsch Appendix') in 1986. Even as late as 1980 (*The Times*, 21 February), the year after the 'Three Mile Island' incident at Harrisburg, Pennsylvania, Cottrell told a Select Committee that he was 'uneasy' about the safety of the PWR system and that he considered it unnecessary to change from AGRs. As a quote: 'He refused, however, to be drawn into saying that it was impossible to operate a PWR safely.' From his time at the MoD, Cottrell would have been well aware that the UK had been using PWR systems successfully in submarines since 1960. Eventually, in the early 1980s, Cottrell agreed that all the necessary controls were being put in place for the proposed PWR at Sizewell (Sizewell B).

Jesus College, Cambridge, 1974–86

Out of the blue, Cottrell received a confidential enquiry into whether he would be interested in taking up the Mastership of Jesus College, Cambridge. The College and its Fellowship

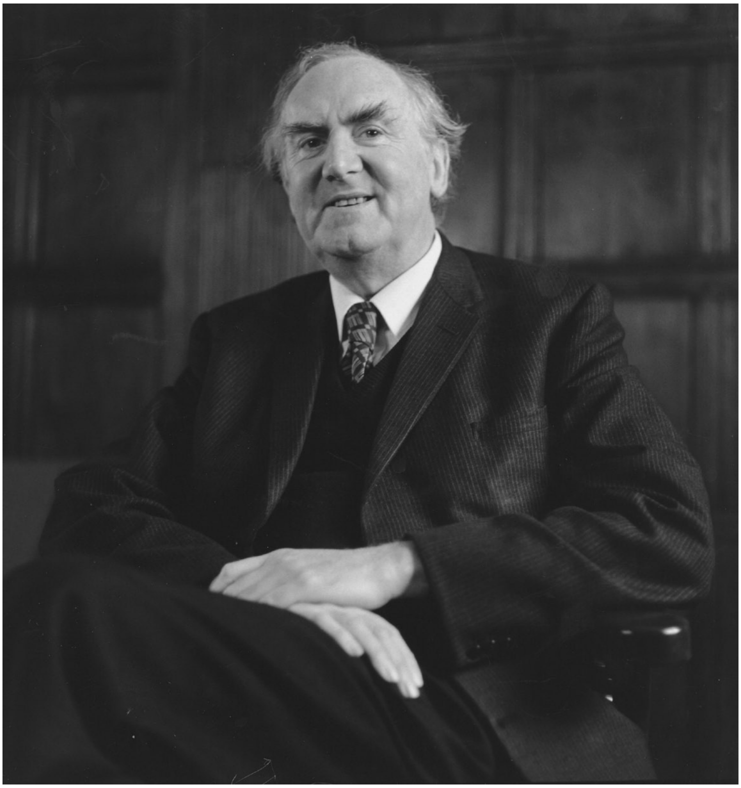

Figure 2. Sir Alan, when Master of Jesus College, Cambridge. (Photograph by courtesy of Jesus College.)

(apart from Brian Ralph) were unknown to him, but several 'familiarization' dinner parties were arranged, on Friday evenings, when he returned from London. The Cottrells moved into the Master's Lodge in the spring of 1974 (figure 2). In June 1974 he, Jean and Geoffrey visited Israel, where Cottrell was to receive the Harvey Science prize. They had a happy and memorable holiday, and Cottrell notes that the premium attached to the award helped to pay for some of the new furnishings that they needed for the Lodge.

In October the College Council, on a major revision of its Statutes, focused on the admission of women (following the trends set a few years earlier by Churchill, Clare and King's). The first woman Fellow to be elected was Lisa Jardine (daughter of Jacob Bronowski and now a widely read historical biographer), but women undergraduates were not admitted for another two years, at the request of the women's colleges (Girton, Newnham and New Hall), which asked for extra time to adjust to the new situation. Cottrell notes that the admission of women was a great success, changing the ethos of the college for the better. 'Before, it had been a bit schoolboy-ish: it became more adult after their arrival.'

Cottrell's duties as Master fell into four main areas: (i) running the formal business of the college, through its Council and Committees; (ii) representing the college in the university; (iii) solving 'as best I could' problems of personal relationships that arose in the college—Cottrell describes the college community as being like a large, and sometimes fractious, family, of which he, as Master, was Head, and so was responsible for sorting out 'family problems'; and

(iv) providing and attending a large number of social functions. Here he acknowledges the crucial role played by Jean, who shouldered most of the responsibility for social matters. There were many dinner parties and musical evenings in the Lodge, and Cottrell remarks particularly on the sherry parties that they gave for first-year undergraduates: 'Their youthful enthusiasm, intelligence and high spirits were very refreshing.'

He had hoped that he would be able to concentrate on some 'serious scientific research' but found that any spare time that he had was fragmented into short spells, such that he could not do deep concentrated work. He gave several public lectures, kept up his interest in PWR safety (23) and wrote two further books aimed at a wide public readership: *Environmental economics* (21) and *How safe is nuclear energy?* (22). He had already written *Portrait of nature* (20) before moving to Jesus. Among other awards during this period, he received the *Acta Metallurgica* Gold Medal. This was presented at a conference, 'Fatigue '77', held in Pembroke College, Cambridge; in his speech of acceptance Cottrell noted that he was subjected to 'medal fatigue'.

Soon after becoming Master, Cottrell was approached to see whether he would be willing to be considered as a candidate for Vice-Chancellor of the university (at that time, the Vice-Chancellor was chosen from a 'Head of House' who would serve for two years at a time). The college had not had a Vice-Chancellor since the mid nineteenth century and were fully supportive. Cottrell was pre-elected and became Deputy Vice-Chancellor (to Dame Rosemary Murray) in 1975. This role was usually little more than a formality, but in 1976 the Vice-Chancellor accepted an invitation to visit New Zealand for a few weeks and Cottrell was left 'holding the fort'. It turned out that he had to deal with an undergraduate 'sit-in' at the university library in protest at a change in library opening hours. He was admitted as Vice-Chancellor on 1 October 1977 and, interestingly, one of his first acts, at his first degree-giving congregation, on 15 October, was to confer the degree of PhD on his son, Geoffrey. Geoffrey had read physics at Sussex University as an undergraduate but had returned to Cambridge in 1973 to become a research student in radio-astronomy.

Cottrell quickly settled into the role of Vice-Chancellor, which was similar to that of Master but on a larger scale. He was surprised by the amount of time that had to be spent on 'behind-the-scenes trouble-shooting' with respect to personal grievances, 'whether real or imagined' felt by staff or research students. Many such issues were dealt with quietly, within the university, but Cottrell had a rather more publicized encounter with the Faculty of Economics over their procedures for making an appointment. The Faculty sought the views of undergraduates on the respective candidates, and Cottrell declared their actions invalid. This brought a spate of protests.

The social, ceremonial and representational expectations for the Vice-Chancellor were, of course, extensive, and Cottrell quotes the words of one of his predecessors: 'I don't mind being the eyes, ears and mouthpiece of the university, but I do object to being its stomach', agreeing strongly with this sentiment. Again, much of the burden fell on Jean, who had to arrange 'innumerable' dinner parties in the Lodge, ably assisted by the College Kitchen Manager, John Fairhurst. As a result of this, Alan and Jean became acquainted with several members of the Royal Family (Princess Anne, Princess Margaret and Prince Charles) on their visits to Cambridge. Above all, they formed a very close connection with Prince Philip, who had become Chancellor of the University at much the same time that Cottrell was appointed as Vice-Chancellor. Prince Philip would visit twice a year and stay overnight at the Lodge. The visits continued for some years after Cottrell had stepped down as Vice-Chancellor, and the Cottrells were the hosts for Prince Philip's 60th birthday on 10 June 1981. They also provided accommodation for several distinguished honorary graduands of the university and gave receptions for speakers at the Cambridge Union, ranging from Cabinet ministers to stars of light entertainment.

In 1980 Cottrell was informed that Prince Edward (then at Gordonstoun School) was expressing interest in coming to Cambridge. A visit and college 'tour' with undergraduates was arranged, resulting in a request that he be admitted to the college in October 1983. After some initial misgivings, the college followed the recommendation of the Senior Tutor, and Prince Edward duly arrived, accompanied by his two detectives: 'most personable individuals who fitted in easily'. The security arrangements were discreet and hardly noticeable, so that the college continued to function normally. Cottrell was, however, critical of the attitude of the Press, which followed Edward everywhere in the hope of obtaining unflattering photographs. They identified one or two girls in the college whom they thought might be forming some sort of relationship with Edward, and made their lives a misery; they encouraged the Head Porter to say things out of context and gave them as headline comments in the papers. Edward settled down quickly and enjoyed his time at college. He was popular with the college staff because he was invariably polite and took an interest in them. He participated in the college play and wider theatrical activities in Cambridge, and was largely responsible for running the Jesus May Ball in his final year. He graduated in 1986 with a respectable 2(ii) degree and presented himself, together with other Jesus graduands, for his degree at the Senate House on Saturday 28 June. By chance, Cottrell was officiating that day and so was the person who conferred the degree on Prince Edward. Prince Philip was able to attend the lunch given in Jesus for the new graduates and their families.

Cottrell retired as Master of Jesus College in 1986, moving from the Lodge to a house in Maids Causeway on 5 August. It had been an eventful 12 years: admission of women to the college; Vice-Chancellor of the university; having Prince Edward as an undergraduate. On the lighter side, there are two stories: one apocryphal, and the other vouched for by Cottrell himself. The first is of a telephone call made to the college, and answered by Cottrell's son, Geoffrey, as 'Jesus here.' After finding that the caller wanted to speak to Cottrell himself, his words were 'I'll get my father.' The second is of Jean answering the telephone on a Christmas Day. On replying 'Yes' to the question 'Is that Jesus?' she was treated to a rendering of 'Happy birthday to you!'

Cambridge, 1986–2012

Retirement from the Mastership did not imply any cessation of activity in scientific and technological fields. He was given an office in the Department of Materials Science and Metallurgy and returned to his scientific interests in the electronic structure and properties of metals, writing *Introduction to the modern theory of metals* (Institute of Metals book 403) in 1988, *Electron theory in alloy design* with David Pettifor (FRS 1994) in 1992, and *Chemical bonding in transition metal carbides* (Institute of Materials book 613) in 1995; in addition he wrote several papers in *Materials Science and Technology* in 1993 and 1994, dealing with bond energies, cohesion and grain boundary strength (for example (24)). His return, to make significant contributions in areas with which he had not been involved for some 40 years, and that had changed drastically over this time, was genuinely remarkable. He realized the power

Figure 3. Sir Alan and some of the Management Advisory Committee to the Independent Validation Centre (IVC). Seated, from left to right: Professor W. McEwan OBE, Professor J. F. Knott OBE FRS FREng, Sir Alan Cottrell, Professor F. M. Burdekin OBE FRS FREng, Mr R. H. Bond FREng. Directly behind Sir Alan is Dr C. Waites, Director of the IVC, and, to the right, Mr B. George FREng, Project Director for Sizewell B. (Online version in colour.)

of the 'embedded atom' concept and was able to exploit this in his calculations of bond energies. He also familiarized himself with new theories of high-temperature superconductivity and explained these clearly in his books. Such achievements are of the very highest order. It is highly likely that this spectacular return to the front line of research was a factor in the decision of the Royal Society to award him the Copley Medal in 1996 (see below).

As Master he had taken up some consultancy work with the AEA, the Nuclear Installations Inspectorate and Rolls-Royce, and he began to be able to devote more time to these. One activity related to his concerns with respect to the presence and detection of small defects in PWR pressure vessels. There was planned to be a variety of 'quality-control' inspections at each stage of manufacture and fabrication, but there was also to be a major ultrasonic inspection after the hydraulic over-pressure 'proof' test, to serve as a 'fingerprint', to be compared with periodic ultrasonic inspections during service. These would have to be made remotely, involving custom-built inspection assemblies. All the proposed inspection procedures, equipment and personnel had to be validated, and this was achieved through an Inspection Validation Centre (IVC), located at AEA Risley. To provide further reassurance, the IVC instituted an independent Management Advisory Committee (MAC), of which Sir Alan was the chairman, from 1983 to 1993. The first of the conclusions in the final report of the AEA in 1993 reads: 'Inspection Validation has provided assurance that the ultrasonic inspections carried out on Sizewell B RPV are capable of achieving the required quality of inspection needed to ensure

Figure 4. Sir Alan (far right) on site at Sizewell, 5 June 1989; next right is Mr R. G. Warwick, an independent member of the IVC. (Online version in colour.)

that the vessel starts its operating life free from significant defects.' This assurance was a major factor in persuading Cottrell to give his blessing to the Sizewell PWR. The MAC not only met regularly as a committee (figure 3), it also made a memorable visit to Sizewell B while the power station was under construction (figure 4).

In 1988 Brian Eyre (FRS 2001), Chief Executive of the AEA, set up a Committee—the Technical Advisory Group on Structural Integrity (TAGSI)—to follow on from the Marshall/Hirsch Study Groups and give advice on structural integrity issues in nuclear plant. Cottrell became a founder member of TAGSI and contributed energetically to its deliberations for more than a decade. He retired on 21 June 1999, and the minutes of that meeting state:

> The Chairman (Sir Peter Hirsch) noted that Sir Alan Cottrell had announced his decision to retire from TAGSI and that this would be his last meeting. On behalf of TAGSI, the Chairman said that everyone had been extremely sorry to learn of Sir Alan's decision, although the reasons for it were appreciated. Sir Alan had been a member of TAGSI since its inception in 1988, during which time he had been TAGSI's most influential member. Indeed, the very existence of TAGSI could be traced to Sir Alan's concerns about the safety of PWRs that he had first expressed in 1973. The Chairman noted that Sir Alan's guiding influences had had an enormous impact on reactor safety within the UK and elsewhere. This unique contribution would be sadly missed.

Sir Alan's interests in structural integrity were not confined to the nuclear industry. From 1988 to 1995 he was Chairman of the Rolls-Royce Materials and Process Advisory Board. Although the topics mainly concerned the manufacturing of components and the properties of materials, assurance of fitness for purpose throughout service entailed several 'lifing' studies:

for turbine discs, blades and thermal barrier coatings. Consideration was also given to the properties of organic matrix fibre composites and of ceramic matrix composites. Sir Alan laid the foundations for what is now the Rolls-Royce Materials, Manufacturing and Structures Advisory Board, spanning the whole range of materials and structural integrity issues.

The year 1989 marked Cottrell's seventieth birthday. In addition to a dinner given by the then Institute of Metals, this was celebrated by symposia held in both Cambridge and Birmingham. The Cambridge papers were published in book form as *Advances in physical metallurgy* (edited by J. A. Charles and G. C. Smith) (Institute of Metals book 495, 1990); the Birmingham papers appeared in the October 1990 edition of *Materials Science and Technology*. In the latter are two articles by J. E. (Jack) Harris FRS: one on the history of civil nuclear power in the UK; the other on the physical metallurgy of the Magnox fuel element. There is also an article by Kingsley Williamson, entitled 'The moderator's moderator', which recalls time spent in the Cambridge Metallurgy Department (1959–61), seconded from the CEGB, while the Berkeley laboratories were being completed. Cottrell encouraged Williamson to look at radiation damage in graphite, a topic that is still of major interest with respect to the integrity of graphite moderator blocks in AGRs. Cottrell's eightieth birthday was marked by a TAGSI Symposium, with the papers published in book form as *Fracture, plastic flow and structural integrity* (edited by Peter Hirsch and David Lidbury) (IOM Communications Ltd, 2000). The symposium was held at the Welding Institute, near Cambridge, and Cottrell was presented with a silver plate on which was engraved a schematic drawing of Sizewell B. His ninetieth birthday was a quiet affair, in Cambridge, but the editorial in the July issue of *Materials Science and Technology* gives due recognition to his standing in the metallurgical community: 'If anyone can be said to bestride the World like a Colossus, it is Sir Alan Cottrell.'

Throughout the early 1990s Cottrell continued to be active on many fronts. In 1991 he was invited by the Institute of Materials to give the Inaugural Finniston Lecture (in memory of his former Harwell Colleague, Monty Finniston) and he readily accepted, despite not always having been on the best of terms with him. Entitled 'Sunlight and shadow in applied science', his lecture used the development of the uranium fuel element as a case study to describe the way in which the solving of practical issues ('applied science') throws up so many challenging, previously unencountered scientific problems that the scientists are stretched to their utmost (25). The point that he made is that science of this sort needs to be understood by the general population, industry and politicians alike, and to be better supported at a national level. He urged the engineering institutions to play a proactive part in this, although he was not optimistic that the message would get through to the nation.

In 1996 Cottrell received many marks of personal success. In December 1995 Cottrell had been invited by the Vice-Chancellor of Cambridge to accept the Honorary Degree of Doctor of Law and this was conferred on 28 June 1996. He was asked by the Chairman of the AEA to give the Commemoration Lecture to celebrate the 50th anniversary of Harwell, and this he gave, as 'Harwell: the first fifty years', on 10 May 1996 in the Cockcroft Hall. Jean and Geoffrey were in the audience. The University of Oxford invited him to give the first Hirsch Lecture, which he delivered on 4 October 1996: 'Surprises in materials science' (26). On 18 July 1996 he received a letter from the Royal Society, announcing that he had been awarded the Copley Medal (the first physical metallurgist ever to receive this award) and he was presented with this on 29 November. On 21 August he took a telephone call from the USA, telling him that he had been awarded the Von Hippel Award of the Materials Research Society. His notes use phrases such as 'This must be my year', 'Annus Mirabilis'.

Yet 1996 was a year of great personal distress: that earlier title ‘From sunlight into shadow’ could hardly have been more apt. In early 1996 Jean first began to experience the effects of Parkinson’s disease. Alan devoted himself to looking after her full time, so that she could stay at home. Over the next years her condition continued to deteriorate and Cottrell became more and more physically exhausted through trying to cope. Sadly, she died in 1999. Alan was devastated, and only got through it by strong family support. But he missed her greatly and never really got over her loss. During this period he also became very deaf, and this ended his enjoyment of music and lectures. Nevertheless, his mind remained as sharp as ever and he continued publishing on the plasticity of metals during the last few years. He retired from TAGSI in 1999, and the symposium that year was dedicated to him. In April 2013 another joint TAGSI/FESI (Forum for Engineering Structural Integrity) symposium was dedicated to his memory.

On 20 June 2003 a meeting was held in St Catharine’s College, Cambridge, to celebrate the 50th anniversary of the publication of *Dislocations and plastic flow in crystals*. Hosted by Derek Fray FRS, then Head of the Cambridge Department of Materials Science and Metallurgy, members of the department and former colleagues of Sir Alan were invited to attend and listen to several (prearranged) ‘readings’ of different chapters of the book by Mick Brown FRS, followed by a brief review and discussion of how each topic had developed over the 50-year period. It was a splendid occasion, with a lunch of grilled salmon: it was Cambridge in the summer. Cottrell thoroughly enjoyed the proceedings and the company of so many friends of long standing. There was a very nice touch at the end. Several of us had clearly had the same thought and had brought along our personal copies of the book, many of them the original 1953 first edition. A lasting memory is that of the end of the meeting: seeing a dozen or so eminent scientists, many an FRS amongst them, meekly forming a queue to have Cottrell autograph their copy. He had deservedly earned the respect of all those present, often having played a major part in their scientific development.

As further recognition of Sir Alan’s standing, the Department of Materials Science and Metallurgy at Cambridge launched an appeal, shortly before his ninetieth birthday, to raise an endowment for a Chair to be established in his name. The appeal was led by Sir Graeme Davies, with Prince Edward as its patron. In early 2013, by grace of the Regent House of the university, the Sir Alan Cottrell Professorship of Materials Science was formally created. This provides a continuing tribute to, and memory of, someone who was undoubtedly the foremost materials scientist of his age. The department is now faced with the problem of trying to find someone of sufficient quality to fill the Chair—the task will not be easy.

Sir Alan Cottrell, 1919–2012

We are aware that we have been trying to summarize the enormous lifetime achievements of a truly remarkable individual and that what we have written is only the ‘tip of the iceberg’. Described as the ‘most outstanding and influential Physical Metallurgist of the 20th Century’ by Sir Peter Hirsch, here was someone who, through his writings and lectures, influenced generations of undergraduates over more than 60 years; who, through his interest in their research, inspired so many who were later to become Fellows of the Royal Society or otherwise achieve high academic distinctions; who, through his personal research, vastly increased our understanding of the electronic structure of metals and alloys, the mechanical properties of metals and

Figure 5. Sir Alan in later life, with 'trusty steed' (an electric bicycle). (Online version in colour.)

alloys in terms of dislocation mechanisms, and mechanisms of fracture, from the macroscopic scale to the atomic scale; who, by 'leading from the front' invigorated the departments at both Birmingham and Cambridge; who gave the very best of advice (if, often, unheeded) to ministers when in Whitehall; who presided capably, not only as Master of Jesus College but also as Vice-Chancellor of Cambridge University, awarding degrees to both his son, Geoffrey, and Prince Edward. His views on the safety of the PWR eventually led to much improved standards of both quality of build and inspection of steel pressure vessels. 'Bestriding the World like a Colossus' is by no means inapt. Yet Alan's life was rooted in his family, his love of music and the outdoor pleasures of walking in the rugged countryside, and, of course, fishing. His devotion to Jean and care for her during her illness was clear to all, and the devastation that he experienced when she died was extremely hard to overcome. He was so clearly delighted to have been the person to present Geoffrey with his PhD degree. Alan Cottrell was a brilliant man, devoted to his family. The close family includes not only Geoffrey, his wife, Jo, sons Edward, Nicholas and daughter Rebecca, but also their mother Arabella, and Ioana Davies (*née* Westwater), her husband, Roger, and their children, Frank and Helen. Alan and Jean had taken Ioana into their family when she lost her own parents at an early age. Ioana, Edward and Helen all gave readings at Sir Alan's funeral service, held on 27 February 2012 in the Chapel of Jesus College, Cambridge. They, and we, will continue to miss him sorely. Fortunately, many memories remain, and his books and other publications will provide inspiration for many in the future. A final memory of Sir Alan is shown in figure 5, which appeared on the final page of the order of service for his funeral.

Appendix. Nuclear power in the UK

The essence of a power reactor, in contrast to that of a bomb, is that the neutrons ejected by fission of the ^{235}U isotope have to be slowed down ('moderated') so that they can produce a succession of controlled fissions in other ^{235}U nuclei in a 'chain reaction', gently releasing energy in the form of heat, which is then used to raise steam and drive a conventional turbo-generator. Moderating materials are those with low atomic number. Heavy water can be used with natural uranium (which contains 0.7% of the ^{235}U isotope), but ordinary light water is rather too effective for natural uranium (it stops reactions completely) and a degree of enrichment (up to about 4.5% ^{235}U) is needed. Both the production of quantities of heavy water and the enrichment of uranium require very large facilities, and it was not practicable to locate these in the UK during the early part of World War II. Uranium enrichment was sited in the USA and heavy water production in Canada. At the end of the war, the UK concentrated initially on bomb production by a route that transmuted uranium to plutonium. This was the purpose of the Windscale piles, the annealing of which had been such a crucial part of Cottrell's time at Harwell.

By mid 1952 consideration was being given to the construction of 'dual purpose' reactors (for both plutonium production and power generation) and work began at Calder Hall on these reactors in August 1953. In February 1955 the White Paper 'A programme of nuclear power' was presented to Parliament, and on 17 October 1956 the Queen opened Calder Hall power station, to deliver electrical power to the National Grid. As a result of the early lack of either enriched uranium or heavy water, the first commercial reactors used solid graphite as a moderator, with carbon dioxide gas as a 'coolant' to take heat to the steam generators. They employed metallic uranium fuel, clad in a magnesium alloy containing a small amount of aluminium to provide oxidation resistance: hence the term 'Magnox' (magnesium, no oxidation). As described above, some of Cottrell's work at Harwell had led to the bracing of the clad fuel elements with stainless steel supports to prevent excessive distortion. Bradwell and Berkeley came into operation in the mid 1960s. Uranium enrichment facilities were established at Capenhurst in 1953; a suite of AGRs was designed by the AEA and commercial orders were placed. The AGRs were designed to operate at temperatures comparable to those for fossil-fuelled plant: steam delivery at 565 °C. They retained solid graphite as moderator, with carbon dioxide gas as coolant, but the fuel was now enriched (to about 3% ^{235}U) uranium dioxide pellets clad in stainless steel. The thermal efficiency of the AGRs is about 43% compared with about 30% for Magnox plant, whose output temperatures are about 350 °C.

The USA had made good use of its enrichment facilities and had developed two versions of light-water systems, the light water serving as both moderator and coolant. One was the boiling-water reactor (BWR) in which the water was allowed to boil, and the steam was then taken directly to drive the turbo-generator before being condensed and recirculated. A problem with early BWRs was that it was difficult to control water chemistry at the 'steam line', and corrosion of stainless steel cladding became a problem. The second US system was the PWR, in which the water was maintained in liquid form (at about 320 °C) in a pressure vessel and primary circuit, transferring its heat to a secondary circuit that then went to the steam generator. The pressures in the pressure vessel were necessarily high: up to some 17 MPa. The Canadians had developed a system employing natural uranium (dioxide) enclosed in pressure tubes, with heavy water as moderator and coolant: the CANDU system. All three systems employ a zirconium alloy to clad the oxide fuel. None of these have efficiencies much better than that of Magnox, but they all have the advantage of being compact compared with the very large volumes required for the gas-cooled systems. They could be used not just for land-based power generation but also for propulsion. The USA uses PWR systems to power its aircraft carriers and, notably, submarines, where there is the possibility of remaining submerged for very long periods without having to come to the surface. Such 'nuclear' (-powered) vessels may, or may not, carry nuclear weapons. In the UK, HMS *Dreadnought* entered service on 21 October 1960 (with a US PWR) and HMS *Valiant* (with a PWR manufactured by Rolls-Royce) entered service on 6 December 1963.

Honours

1955 Fellow, Royal Society (Vice-President 1964, 1976 and 1977)
1960 Foreign Honorary Member, American Academy of Arts and Sciences
1970 Foreign Fellow, Royal Swedish Academy of Sciences
Honorary Fellow, Christ's College, Cambridge (Fellow 1958–70)
1972 Foreign Associate, National Academy of Sciences, USA
Honorary Member, American Society for Metals
1974 Honorary Fellow, American Society for Metals
1976 Foreign Associate, National Academy of Engineering, USA
Honorary ScD, University of Cambridge
1977 Honorary Member, Metals Society
1981 Honorary Member, Japan Institute of Metals
1986 Honorary Fellow, Jesus College, Cambridge
1989 Honorary Fellow, Institute of Metals
1991 Honorary Fellow, Imperial College, London
Member, Academia Europaea
1996 Honorary LLD, University of Cambridge

Alan Cottrell was also awarded honorary higher doctorates from the following universities and institutes: Columbia (1965), Newcastle (1967), Liverpool (1969), Manchester (1970), Warwick (1971), Sussex (1972), Bath (1973), Strathclyde (1975), Aston (1975), Cranfield Institute of Technology (1975), Oxford (1979), Essex (1982), Birmingham (1983) and Technical University of Nova Scotia (1984).

Awards

1961 Rosenhain Medal, Institute of Metals
Hughes Medal, Royal Society
1963 Bakerian Lecture, Royal Society
1964 Réaumur Medal, Societé Française de Metallurgie
1965 Platinum Medal, Institute of Metals
1967 James Alfred Ewing Medal, Institute of Chemical Engineers
1969 Holweck Medal, Société Française de Physique
Albert Sauveur Achievement Award, American Society for Metals

1974 James Douglas Gold Medal, American Institute of Mining, Metallurgy and Petroleum Engineers
Rumford Medal, Royal Society
Harvey Prize, Technion, Israel
1976 Acta Metallurgica Gold Medal
1977 Guthrie Medal and Prize, Institute of Physics
1980 Gold Medal, American Society for Metals
Brinell Medal, Royal Swedish Academy of Engineering Sciences
1986 Kelvin Medal, Institute of Chemical Engineers
1990 Hollomon Award, *Acta Metallurgica*
1996 Copley Medal, Royal Society
Von Hippel Award, Materials Research Society

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