GRAHAM WOOD
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Graham Wood was a world-leading corrosion scientist who bridged both the aqueous (electrochemical) corrosion and high-temperature oxidation branches of the subject. His analytical predictions of depletion and enrichment profiles in substrate and scale during preferential oxidation have long been confirmed in practice. He also demonstrated that transient oxides can be vital solid lubricants in oxidative friction and wear processes. He elucidated ionic transport in amorphous anodic films, leading to precise models of pore initiation, development and closure, thus allowing the strict design of anodic films for practical application. He set up, and headed, the Corrosion and Protection Centre at the University of Manchester Institute of Science and Technology (UMIST) and was instrumental in initiating the Corrosion and Protection Centre Industrial Service, which, respectively, became the world’s largest academic centre on the study of materials degradation and the world’s largest corrosion consulting organization. While keeping active in research, he held increasingly senior administrative roles, where he established a specialist graduate school and helped prepare UMIST to full independence from the Victoria University of Manchester.

FAMILY BACKGROUND AND EARLY YEARS

Graham Wood was born in Farnborough, Kent, then a small village adjacent to open countryside some 15 miles southeast of London. Graham’s parents had met at Down House, the former home of Charles Darwin FRS, while it was being run as a school. Graham later ascribed his interest in science to childhood visits to Down House after it had become the

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Darwin Museum. He attended the local village school and enjoyed walking and exploring the nearby woods and fields and helping in his parent’s large garden. This early experience developed his lifelong love of hiking and for home-grown produce. At the age of 11 Graham attended Bromley Grammar School, excelling at cricket and football as well as academically.

The first of his family to attend university, he obtained a scholarship to Christ’s College, Cambridge, where he graduated in natural sciences (metallurgy) in 1956. He narrowly failed to get a first and a ‘blue’ (i.e. represent the university) in cricket, the latter being apparently one of the biggest disappointments of his life! After graduation, he undertook a PhD in the Cambridge Department of Metallurgy (figure 1) with Dr T. P. (Sam) Hoar, collaborating with Dr Ulick Evans FRS (the ‘father’ of corrosion science). In 1959 he continued as a postdoctoral researcher under Professor (later Sir) Alan Cottrell FRS.

Oxides at Cambridge (1956–1961)

An ineluctable consequence of the Second Law of Thermodynamics is that all material things are subject to decay. That advanced civilizations can use elements in their metallic state at all is solely down to the relatively slow kinetics of the decay (or corrosion) process. Indeed, the reaction rate for some metals is so slow as to be barely measurable. This cessation of reaction
(or ‘passivity’) was first observed by James Keir FRS for iron in concentrated nitric acid, a strong oxidizing agent (Keir 1790). Later, Michael Faraday FRS presciently stated of passivity (Faraday 1836): ‘My strong impression is that the surface of the iron is oxidised or that the superficial particles of the metal are in such relation to the oxygen of the electrolyte as to be equivalent to an oxidation.’ While stable passivity is generally either a transient condition or one that only exists for a specific metal–environment combination (e.g. steel in fresh concrete), for a few metals (e.g. aluminium alloys, stainless steels) passivity is the normal state of affairs. Aluminium is also one of the few metals where application of an oxidizing current in a suitable electrolyte can thicken the naturally formed passive oxide film, greatly improving corrosion resistance.

The electrochemical theory of aqueous corrosion was put on a sound footing at Cambridge by Evans & Hoar (1934). By the 1950s advances in instrumentation and microscopy were to realize novel opportunities for the study of both thin air-formed (passive) and thicker anodically grown (anodized) films on aluminium alloys. Graham’s PhD was concerned with the sealing of such films, with his first paper concluding that little was known of the mechanism of the process (1).* In later work he describes an apparatus for determining the resistance and capacitance (i.e. electrical impedance) of anodic films by use of an AC signal bridge by which the thickness and integrity of the film can be indirectly determined (2). The method and approach are sound, but the instrument, based on thermionic valves for both the oscillator and amplification circuits, would have required a considerable degree of technical knowledge to design and build. The last sentence in the paper promises that ‘impedance measurements made on anodic oxide films on aluminium during sealing are published elsewhere’, with the reference claiming to be ‘in press’. However, these results were not published until a few years later (4), by which time Graham had already moved to Manchester.

Electrochemical corrosion in aqueous solutions, the subject of Graham’s PhD, covers only one-half of corrosion technology. Metals also deteriorate at high temperature by direct interaction with oxygen and other corrosive gases, where the damage mechanisms are significantly different. Graham’s postdoctoral work with Cottrell considered the high-temperature thermal oxidation of iron–chromium alloys then being considered for higher performance steam-raising plant (5). These experiments also introduced him to the opportunities offered by the application of high-resolution analytical tools to corrosion and oxidation studies (3).

Graham met his wife Freda (nee Waithman) during his undergraduate studies in 1958, while she was working as a teacher. Subsequently, in 1961, they moved to the then Manchester College of Science and Technology (which, in 1966, became the former University of Manchester Institute of Science and Technology, UMIST, and is now part of the University of Manchester), with Graham taking up a position as lecturer in corrosion science in the Department of Chemical Engineering.

**Manchester College of Science and Technology**

In 1956 the Manchester College of Science and Technology (also the Faculty of Technology of the Victoria University of Manchester, through which body the College awarded degrees)

* Numbers in this form refer to the bibliography at the end of the article.
gained its Royal Charter. Vivian Bowden, the principal of the college, invited Professor Frank Morton and T. K. (Ken) Ross to move from Birmingham and establish a new Department of Chemical Engineering bringing together the college’s existing interests in applied chemistry. Ross had become aware of corrosion problems in industry around 1947 during his PhD in London. He was among the first to recognize that the adverse effect of corrosion on industry also directly affected everyday life by increasing costs and reducing service life. After moving to Manchester, Ross established a vibrant research activity within the new Department of Chemical Engineering that eventually became the largest in the UK concerned with the study and practical prevention of corrosion in the chemical and process industries.

In 1961, anticipating Hoar’s report on corrosion some 10 years later, Ross established the first purely postgraduate MSc programme in corrosion science. It was into this environment that Graham arrived, not only to assist in the growth and delivery of the new MSc programme, but also to develop the research interests of Ross’s group beyond the corrosion of industrial chemical plant to the science and mechanisms of oxide film growth on metals and alloys.

**Corrosion Science Division, Chemical Engineering (1961–1972)**

Far from being a narrow subject, one of the attractions about corrosion protection and control is that it has always operated at the interfaces where science, engineering and technology interact. For example, the study by Alessandro Volta FRS of the ‘pile battery’ (Volta 1800), comprising zinc and copper sheets separated with salt-soaked paper, showed that current was caused by the disappearance (i.e. corrosion) of the zinc element of the pile. Likewise, the work of Sir Humphry Davy PRS for the Navy Board (Davy 1824) on preventing the corrosion of copper-sheathed vessels by use of iron attachments was the first application of galvanic (now known as cathodic) protection. Electrochemical phenomena, including corrosion, were explored experimentally by Faraday and many others over the next 100 years. However, despite the pioneering contributions of Evans and colleagues (Evans et al. 1931), Wagner (1933, 1936) and others from the 1920s to the 1950s, no universal mechanism was found for oxidation or corrosion. Rather, many ‘special cases’ were determined by the variability of the environments in which materials need to survive.

In the 1960s, when Graham started to build his personal group at Manchester, a topic of interest was the oxidation and high-temperature corrosion of materials. This was encouraged by: (a) the electricity industry’s drive to improve the thermal efficiency of generation requiring higher temperatures; (b) the expansion and mass production of internal combustion engines for personal and goods transportation; and (c) a similar expansion of air transportation requiring advanced materials for gas turbines. Consequently, there were significant research funding opportunities from government and industry. During this period Graham functioned as a traditional academic leading a large personal research group within the Corrosion Science Division headed by Ross. In the 11 years to 1972 he published over 80 papers and was progressively promoted from lecturer through to reader. Around two-thirds of this output was concerned with high-temperature oxidation, the remainder on anodic films and anodizing, reflecting the balance of interests and funding.

**Metals at high temperature**

Among the papers published shortly after his appointment in 1961–1962 was a monograph on the oxidation of binary alloys (6), the mechanisms of which were then little understood. It
also exemplified his fundamental approach, which was to work with industry on a system of commercial interest, to simplify the problem to its basics, then to study this with scientific rigour using the most advanced tools available. In other words, to identify, categorize and isolate the ‘special cases’ and study them in depth by the best available techniques, then to develop their understanding and inter-relationship in a realistic, semi-quantitative or quantitative manner. Ensuring system realism was key, and an important component of this approach was to pioneer or adapt novel experimental tools from other disciplines to characterize materials and environments.

The main task over this time was to start to elucidate the mechanism(s) underlying oxidation of binary and more complex alloys for high-temperature applications. The traditional kinetic tool was thermogravimetry, whereby the mass gains of alloys were measured as a function of time, temperature and environment. Occasionally this was complemented by X-ray diffraction (XRD) of the resulting bulk oxide scales for phase identification. Although the thermally activated diffusion of ions within oxide lattices had been identified by Wagner in the 1930s as the underlying rate-controlling mechanism for oxide growth, it did not explain many practical phenomena, such as loss of adhesion, oxide spallation or reaction with other chemical species. Graham’s initial approach was to apply the relatively novel method of electron-probe microanalysis (EPMA) to the study of oxidized alloys. In this way he confirmed the chemical composition of oxide scales that were too thin to be analysed by bulk XRD and, importantly, identified compositional variations within the alloy and the scale (8, 9), see figure 2. Such new measurements provided previously unavailable insight and were key to developing mechanistic, rather than phenomenological, studies of high-temperature corrosion and oxidation phenomena in more complex alloy systems of practical significance.

A critical factor limiting service life of materials at high temperature is ‘breakaway’ oxidation, whereby an apparently stable and protective oxide scale suddenly fails, leading to premature component failure. Graham believed that this was due to the depletion in the protective scale-forming elements in the underlying alloy, and he was among the first to demonstrate this using analytical microscopy (10, 11). Focusing on the interface between the oxide and the underlying metal, while pushing the resolution limits of EPMA, a thin protective oxide layer lying underneath the main oxide scale (styled the ‘healing layer’) was identified (14) as being critical in whether the main scale survived or not. Research on this early ‘transient’ oxidation process (i.e. before the main scale is fully established) required higher resolution than EPMA could provide. Thus, transmission electron microscopy (TEM) with electron diffraction was applied to the analysis of these ultra-thin scales using a careful selection of binary alloy compositions and environments to build up a picture of oxide nucleation and growth (12, 14). This enabled the first detailed analytical investigations into the oxidation of commercially important ternary alloys (15).

Anodic oxides
During anodizing of aluminium, ‘barrier’ films form where the oxide is relatively insoluble (e.g. in near-neutral solutions), and thickness depends directly on the DC voltage. Alternatively, in solutions where the oxide is slightly soluble (such as sulfuric acid), ‘porous’ films form with thickness dependent on anodizing time. Thick and porous films on aluminium alloys enhance overall corrosion protection but can become rapidly soiled on atmospheric exposure. Sealing of such porous films can prevent this discolouration, and this was the topic
of Graham’s PhD at Cambridge. After moving to Manchester, and in view of the successful application of EPMA to the analysis of oxide scales on alloys, it seemed a good idea to examine anodized films using EPMA (7). Sealing of anodized films can be accomplished by thermal hydration or by reaction with metal salts such as nickel or chromium, and Graham noted in the paper that: ‘Chromium and nickel can be measured with great precision and reproducibility despite their low concentrations because this is a particularly favourable situation where heavy elements are being detected in a matrix of low atomic number.’

Although Graham continued to utilize electrochemical methods such as impedance, my recollection is that he greatly preferred observational methods such as analytical microscopy. As an example, it was then well-known that the top surface of porous anodic films had an open tubular morphology in a hexagonal near-close-packed array, but it was not possible to view the base of the film. There was some belief that the porous layer grew directly from the alloy, although impedance measurements implied the existence of a resistive barrier. Unfortunately, conventional preparation of electron-transparent sections by electropolishing removed the oxide film so it could not be imaged. However, Graham’s student, John O’Sullivan, developed an alternative method by cryogenic fracturing of anodized films, thus revealing the cross-section from which a carbon replica could be taken and imaged by TEM (13); see figure 3.
Figure 3. Electron micrograph cross-section of a carbon replica of a detached anodic film formed in phosphoric acid, showing the barrier film at the base of the porous film. (Image reproduced from (13) with permission.)

This paper proved beyond doubt that coherent barrier layers, with a thickness consistent with the applied DC voltage, existed under all circumstances of anodizing. To Graham, it was also a powerful illustration of the adage ‘a picture is worth a thousand words’. Thus, while electrochemistry might suggest the existence of barrier films, only a picture can prove the reality. The observational approach came to dominate Graham’s work and was the foundation for most of his future insights and achievements.

When he joined Ken Ross’s Corrosion Science Division in 1961, Graham did not have the field entirely to himself. Gradually, over the next few years, the ‘Corrosion Laboratories’ were further augmented by Ian Menzies (in 1962), Jack Postlethwaite (in 1965) and Tony Wragg (in 1967), all former students in the Chemical Engineering Department, plus David Miller (1968), recruited from the National Physical Laboratory to research microbial corrosion.

Menzies, like Graham, also worked on the performance of materials at high temperature and was a rival. However, Wragg was primarily an electrochemical engineer and Postlethwaite was more interested in corrosion in process plant, and neither was directly competitive. In 1970, Wragg left for Exeter and was replaced by John Dawson, from Magnesium Elektron and Chloride Research, who was the industrial supervisor of one of Wragg’s students and knew Ross well. In 1971 Postlethwaite emigrated to Canada to take up a position at the University of Regina and was replaced by Vic Ashworth from Nottingham, while the further appointment of Robin Procter, recruited from the Olin Mathieson corporation in New Haven (USA), to focus on mechanical influences on corrosion completed the set.

Over time, Graham’s personal research activity grew to become the largest in the division with a steady-state complement of around six and eight PhD students supported by one or two postdoctoral researchers. Graham maintained enduring collaborations with many of his early researchers, working particularly closely with Howard Stott and Tony Richardson, who become academic colleagues at Manchester, and with Dave Whittle (at UC Berkeley) and Ian Wright (at Battelle Institute), whom he visited regularly in the USA. A few years after promotion to reader, Graham started to look for a chair position outside Manchester. Thus, when a vacancy arose in 1970 to lead the metallurgy department at Loughborough University, both Menzies and Graham were in the frame. However, to his great disappointment, Ian Menzies was hired on the direct recommendation of Ross, but what Graham did not realize (and was not told) was that Ross had bigger plans in mind and did not want to lose him.
THE CORROSION AND PROTECTION CENTRE (1972–1982)

In 1966 the Manchester College of Science and Technology had become UMIST. In building its reputation as a major research-intensive university, UMIST was able to recognize, provide space for and encourage many unique activities. An early example of this was the establishment, in 1968, of the Control Systems Centre as an autonomous department that was able to focus entirely on the new technologies of, and applications in, process control and automation.

In 1968 Ken Ross was invited by Sam Hoar (its chair) to join the Committee on Corrosion and its Prevention established as an initiative by Tony Benn through the Department of Trade and Industry (DTI). In February 1971 the committee reported its conclusions (Hoar 1971, 1976) that the cost of materials degradation amounted to around 3% of the UK’s Gross National Product annually and that around one-quarter of this sum could be saved by the application of known technologies. Among the committee’s recommendations were the establishment of a national corrosion service to undertake forensic analysis of corrosion failures and provide supporting advice to industry and the expansion of research and teaching in the subject at university level.

Ross, in full knowledge of the impending recommendations in the Hoar report, had been pressing behind the scenes at UMIST to form a corrosion and protection centre along the lines of the existing Control Systems Centre. Publication of the report provided the impetus needed, and the project was approved. As part of the deal, a new chair was created for Graham. In April 1972, therefore, the Corrosion and Protection Centre came into being at UMIST, with Graham becoming, as the tabloid press had it, ‘Britain’s first Professor of Rust’ (Procter & Ashworth 1972).

The new centre inherited Miller, Ashworth and Procter, with Dawson joining a year later. However, this left significant gaps in subject coverage; so, in the period 1972–1973, Tony Richardson (plant corrosion and maintenance) was enticed back from Unilever, while Howard Stott (oxidation and wear) and Peter Elliott (hot corrosion and terotechnology), researchers for Wood and Ross respectively, were also recruited. In 1975, George Thompson (microscopy and anodizing) was seconded from Howson-Algraphy, joining the academic staff permanently in 1977. David Scantlebury (organic coatings) joined in 1976 from Cambridge via Portsmouth, while Tony Richardson returned to industry in 1977. The final academic appointment before Graham stepped down as head of centre in 1982 was Bob Cottis (aqueous corrosion), who joined from Cambridge via the Fulmar Research Institute.

Research in the Corrosion and Protection Centre increasingly relied on the use of high-resolution analytical tools, including electron microscopy, and Graham was always very mindful of the need to acquire the best equipment and to hire high-quality support staff. Bernie Lambert and Ben Vasko transferred from Ross’s group into the centre on its establishment. However, after Ben’s early death, Brian Bethune arrived from Nottingham in 1973, taking charge of electron microscopy. Later, Brian Johnson moved from Cranfield in 1975 as an experimental officer providing behind-the-scenes support for the research group while Graham became more involved in the operations and management of the centre.

At the start of his tenure as head of the Corrosion and Protection Centre, Graham’s earlier work had been recognized by the award of the ScD degree from Cambridge and the Beilby Medal and Prize from the Society of Chemical Industry. By the end of a decade in charge, Graham had cemented the reputation of the centre and expanded its scope while maintaining
Graham Wood

Figure 4. Graham receiving the U. R. Evans award (a sword to fight corrosion) from Professor Redvers Parkins, president of the then Institution of Corrosion Science and Technology (now the Institute of Corrosion) in 1983. (Photograph courtesy the Wood family.) (Online version in colour.)

a strong personal research group and more than doubling the number of his publications. He had been elected as the first chair outside North America of the Gordon Research Conference on corrosion and been awarded both the Carl Wagner Medal of the US Electrochemical Society and the U. R. Evans award of the UK Institution of Corrosion Science and Technology (figure 4).

The quality and impact of the Corrosion and Protection Centre was recognized in 1989 by it receiving the highest rating (category 5) in the Research Selectivity Exercise and in 1992 when it again received the highest rating (category 5A). UMIST also won the Queen’s Award for Export Achievement in 1992 for its large numbers of international students, particularly on taught postgraduate programmes, of which the MSc in corrosion science and engineering was pre-eminent. An additional accolade came in 1999 when Graham accepted the European Corrosion Medal, the highest honour of the European Federation of Corrosion, on behalf of himself and his colleagues in the Corrosion and Protection Centre.

Anodic oxides

The use of TEM to image anodized films was a significant step forward. However, obtaining electron-transparent sections by forming carbon replicas of fracture surfaces was not ideal. Artefacts from the replication process were often evident and, importantly, no analytical tools (such as electron diffraction) could be applied. Noting that ultramicrotomy (the technique of slicing materials into electron-transparent sections using glass or diamond ‘knives’) was
routinely used in the preparation of biological samples, Graham sought to apply the method to corrosion samples as a way of preserving the structure and composition of the oxide. The method was found to be more difficult than anticipated and required considerable skill to become proficient and to avoid damage to costly knives (ca1 carat flawless diamonds polished to near-atomic sharpness across a length of several millimetres). Nevertheless, after the method was perfected, most future insights into anodic oxide film growth, structure and composition were obtained in this way (19); see figure 5.

Anodic film formation requires charge transfer to take place at both the metal–oxide and the oxide–electrolyte interfaces. Cation and anion transport dominate charge transfer in oxides, which, at ambient temperature, is via the process of high-field ion conduction (Cabrera & Mott 1949). Since ultramicrotomy retains the anodic film intact, in principle it became possible to analyse its composition. Working with Thompson and using scanning transmission electron microscopy (STEM) with energy-dispersive analysis by X-rays (EDAX), phosphorus incorporation into barrier films was demonstrated, confirming for the first time their duplex chemical nature (26). Ion-implantation of xenon gas inert tracers permitted the original locus of the metal surface to be revealed by STEM imaging after anodizing (27). Thus, finally, a suite of tools was available to determine effectively anodic film growth mechanisms in different environments and to separate anionic from cationic transfer kinetics.

It had long been surmised that occasional flaws in passive and anodically grown oxides caused, in some way, the development of pitting and other forms of localized corrosion on aluminium. While electrical impedance measurements were consistent with an interpretation of the existence of flaws (18), and carbon replicas had apparently imaged such flaws using TEM, their exact nature and form was disputed. The first detailed identification of such flaws, together with a meaningful mechanism for their formation, was obtained using
ultramicrotomed sections (24); see figure 6. The mechanism involved the initial accumulation of relatively noble elements (e.g. Cu, Fe) at the metal–oxide interface followed by disruption of the anodized film by oxygen evolution at these locations.

Metals at high temperature

Meanwhile, at the hotter end of the subject, efforts were underway to push the performance of alloys to ever higher temperatures to improve combustion efficiencies and lower fuel burn. In conventional high-temperature alloys, the addition of chromium to the base metal (generally nickel and/or iron) resulted in the formation of the ‘healing layer’ comprising the stable and slow-growing chromia scale Cr$_2$O$_3$. However, chromia is susceptible to further reaction with oxygen (forming CrO$_3$) and with steam and oxygen (forming CrO$_2$(OH)$_2$). These species being volatile, the protective scale is lost to evaporation as the temperature rises, becoming increasingly rapid above ca 950°C. This process can be sidestepped by promoting the formation of a different protective scale with controlled additions of aluminium forming a protective alumina (Al$_2$O$_3$). While this has greater thermodynamic stability, the scale growth process tends to form highly convoluted oxides with poor adhesion and a tendency to spall (i.e. delaminate from the metal) on thermal cycling.

It had long been known (Pfeil 1937) that additions of rare earth and reactive elements (e.g. cerium, yttrium) improved the performance of electrical heating elements by preventing scale spallation. The observation was not understood, with several mechanisms being proposed in explanation (Whittle & Stringer 1980), and John Stringer at Liverpool coining the phrase ‘reactive element effect’ to describe it. Marking the start of a highly fruitful partnership with Howard Stott, his former student and now academic colleague, Graham tackled the problem using a microscopy approach that revealed the early detachment of the oxide from the underlying alloy (21, 23). This led to the view that grain boundary diffusion supplied aluminium at a higher local rate, resulting in anomalous local oxide growth; see figure 7.
Work with Stott also continued to provide a comprehensive picture for the oxidation of binary alloys (20), with a general focus on the alumina-forming systems. Here, internal and intergranular oxidation plays an important role in the initial healing scale formation, by ‘gettering’ oxygen dissolved in the alloy, and also in the longevity of protective scales, by exhausting the supply of scale-forming element (25).

Something that Stott brought to the table was an interest in the tribological (i.e. friction and wear) properties of materials. It was observed that the friction coefficient between two metals at high temperatures reduced substantially after a short period of sliding wear. Careful examination revealed that oxide scales formed at 800°C appeared softened and melted by the frictional heating generated during sliding, which, of course, would cause the friction coefficient to drop as there was no longer any metal-to-metal contact (16). The formation of oxide glazes, and a reduced friction coefficient, were also observed during metal-to-metal sliding at room temperature, implying that, at contact asperities, the temperature must have reached a value sufficient to soften the oxide, i.e. at least 800–900°C (17).

**Atmospheric corrosion**

From studying the reaction of materials at high temperatures, Graham also became interested in similar metal–gas reactions under ambient conditions. This last form of environmental damage is termed ‘atmospheric corrosion’ and has the most variable corrosive environment, namely the weather! Graham’s first foray into this field characteristically was less interested in the kinetics of the reaction than, rather, the application of advanced tools (electron microscopy and XRD) to analyse the corrosion products formed (22).
From the early twentieth century, atmospheric pollutants, particularly gaseous sulfur dioxide and particulate soot from combustion of coal, had been assumed to contribute to the corrosion of metals (Vernon 1935). Graham applied analytical microscopy to understand the differing nature of atmospheric particulates: soot and fly-ash (from both coal- and oil-fired plant), chalk and sand; see figure 8. The major cause of atmospheric corrosion was found to be the presence of soluble sulfate and chloride ions within individual particulates, and not processes such as the creation of differential oxygen cells or the presence of sulfur dioxide itself.

**Corrosion and Protection Centre Industrial Service**

Following from the recommendations in the Hoar report, an advice service for industry, the National Corrosion Service, was created within the chemistry division of the National Physical Laboratory, but was not set up for commercial consultancy. Ross’s Corrosion Science Division at UMIST had historically offered such services and this continued after the Corrosion and Protection Centre was established. However, the number of enquiries rose significantly and began to compromise the academic mission. Consequently, Graham successfully lobbied the DTI for pump-priming funds to establish full-time support for a Corrosion and Protection Centre Industrial Service (CAPCIS). David Gearey, previously a postdoctoral researcher in Menzies’s group, took up the position of CAPCIS manager when it came into being in August 1973.

For many years CAPCIS was co-located with the Corrosion and Protection Centre and used the same laboratory facilities as the academic staff. Initially, consultancy advice was provided by the academic staff but gradually, as CAPCIS grew its business, it began to hire its own team, who often were former PhD students from the centre. This model was very much in the ‘three-pillar’ tradition of UMIST’s first principal, Bowden: teaching, research, and industrial service (which nowadays might be termed ‘impact’). The benefits for CAPCIS in having expert advisors close at hand was evident; but the work of CAPCIS also informed that of the centre.
by feeding real problems, and their solutions, into the MSc teaching programme. Conversely, materials failures in industry might prompt a fundamental evaluation of the problem at MSc project or PhD level, revealing more profound insights and leading to changes in industrial practice. CAPCIS also made a positive contribution to the finances of the centre, which helped to maintain facilities as near state-of-the-art.

Graham’s expertise in high-temperature corrosion and oxidation was often called upon and, although he knew his stuff, he was not necessarily confident with industry or industrial practice. In the early days of CAPCIS he was part of a team visiting a refinery to investigate an issue and provide advice. On reaching the gatehouse, and somewhat overwhelmed by the scale of the plant, he quietly asked David Gearey to ‘call me Mr Wood’. After that he was affectionately known within CAPCIS (although not in the centre, where he maintained a dignified presence) as ‘Mr Wood’.

Graham sat on the CAPCIS oversight board, in its various guises, until he retired. Over the next 30 years CAPCIS grew to become a major consulting organization with its own laboratories adjacent to the UMIST campus. It directly employed more than 60 staff, turning over >£3 million per annum in 1990. As such, it became the largest independent corrosion consultancy in the world, spawning a spin-off company (CAPCIS-March Ltd). In 2002, the corrosion activity in Manchester (i.e. the Corrosion and Protection Centre plus CAPCIS) won a second Queen’s Award for Technology Transfer. Later, when it became CAPCIS Ltd prior to final divestment by the university, Graham sat on the board as non-executive director. Although it has now lost its close links to the university, CAPCIS still exists as part of the Intertek group of companies and remains a major corrosion consultancy business some 50 years after it was founded by Graham.

**TEACHING AND SOCIAL LIFE**

The MSc in corrosion science offered by Manchester since 1961 went through several incarnations and name changes over the years, but it was always a core part of the centre’s mission. PhD and postdoctoral research were underpinned by the MSc programme, which, in turn, was supported by strong and industrially relevant research projects, many with involvement from CAPCIS. As many centre staff were metallurgists, they also contributed to service teaching in metallurgy and materials science to the engineering departments in UMIST. Regular ‘short courses’ for industrial employees were also provided on topics of interest. Graham thus propagated a corrosion education and training programme with a truly global reach. At one time around half the world’s graduate corrosion scientists or engineers had passed through Manchester.

After the Committee on Corrosion had reported, the DTI then established a Committee on Terotechnology (a subject concerned with maintenance, asset management and life-cycle costing’ Powley 1973). Picking up on this initiative, Graham devised and jointly organized a new MSc in terotechnology as a joint venture between the Corrosion and Protection Centre (contributing wear, corrosion monitoring, inspection and water treatment) and the Department of Mechanical Engineering at the Victoria University of Manchester (contributing condition-based maintenance). Tony Richardson, John Dawson and Peter Elliott made significant contributions to this course, a form of which still exists in Manchester as the MSc in reliability engineering and asset management. Later he developed and promoted, in conjunction with the
University of Salford and Manchester Metropolitan University, a unique PhD known as ‘Total Technology’ that provided the first flexible PhD training integrated to industrial needs and was the forerunner to the engineering doctorate (EngD) scheme. This led to Graham being invited to lead the joint UMIST/University of Manchester’s successful bid to run the UK pilot for the EngD scheme. Tony Richardson, his former student, colleague and by then a Royal Academy of Engineering visiting professor in the centre, served on its first steering committee.

Social activities were focused on the MSc cohort of students and included all researchers, academics and CAPCIS staff. Their annual walk in the Peak District was eagerly anticipated and Graham, a keen hiker in his younger days, always joined in. He was even more interested in the annual staff–student cricket match, where he was a decent batsman (figure 9) and a handy fast bowler. One of Graham’s ambitions was to hit a six and smash the clock on the side of the pavilion, which he finally achieved when in a sufficiently senior administrative position that he could arrange for the clock to be repaired at no cost to the centre. In 1992 the centre ran a conference for its twentieth anniversary, which, with more than 500 delegates, was the largest corrosion conference in Europe to that date. Delegates had a half-day off on Wednesday afternoon at Chatsworth House, Derbyshire, where current staff played former students on the Duke of Devonshire’s private cricket ground. Unfortunately, history does not record who won!
EXTERNAL SERVICE

Following presidency of the scientific society the Corrosion and Protection Association in 1973, Graham became president of its successor body, the Institution of Corrosion Science and Technology (now the Institute of Corrosion) from 1978 to 1980, preparing and implementing its development plan. He served two spells as chair of the National Council for Corrosion Societies, which coordinated the corrosion-related interests of the Institute of Metals (now the Institute of Materials, Minerals and Mining), the Oil and Colour Chemists Association and the Institute of Metal Finishing. For many years he also represented the UK on the Science and Technology Advisory Committee of the European Federation of Corrosion.

For 15 years Graham was one of the two UK representatives on the International Corrosion Council. This body, with 120 nominated members, represents corrosion research and technology transfer interests of more than 70 countries and is essentially the only body that speaks authoritatively for corrosion interests worldwide. Graham was elected vice-chair and then became chair of the body for a three-year term, during which he increased the number of member countries by 50%.

ACADEMIC ADMINISTRATION IN UMIST (1982–1999)

In 1982 Graham was appointed vice-principal for academic development at UMIST and stepped down as head of the Corrosion and Protection Centre, handing over to Robin Procter but retaining his chair in corrosion science. From 1982 to 1984, in response to a significant reduction in funding from the University Grants Committee, he created UMIST’s first development plan that matched academic to financial needs. Between 1985 and 1986 he initiated, designed and supported major interdisciplinary and industry-linked research activities across UMIST and the Victoria University of Manchester, including the Centre for Electronic Materials, the Acid Rain programme, the Pollution Research Unit and the Marinetechnology NorthWest university consortium. From 1987 to 1989 he was appointed dean of UMIST, when he developed novel access initiatives and portfolios of undergraduate and postgraduate provision. In 1992, Graham was again dean, and a member of the Principal’s Advisory Group with a remit to establish a graduate school and aid planning for full independence from the Victoria University. From 1994 to 1996, with UMIST’s newly independent status, he became pro-vice chancellor, responsible for long-term strategic planning.

Throughout his spells in the academic administration of UMIST, Graham continued his research in close partnership with Howard Stott (materials at high temperature), George Thompson (anodic oxides), Brian Johnson (atmospheric corrosion) and other colleagues in the centre, publishing about 250 additional papers.

PERSONAL LIFE AND RETIREMENT

Graham was intensely private and worked long hours, often seven days a week. I remember a memo circulated to staff in early January where he insisted to his secretary that it be dated 25 December ‘because that’s when I wrote it’. He had few interests outside work and family, but relaxed by fellwalking in the Lake District (figure 10; the family owned a cottage near
Ambleside) and he particularly liked playing cricket on the beach with his son David during the annual summer family retreat to the Gower Peninsula in South Wales.

He had little time for hobbies, but played cricket for the UMIST staff team into his 60s and enjoyed gardening, keeping the family and neighbours supplied with fresh fruit and vegetables over the summer.

In 1997 Graham retired at the age of 63, but continued to contribute to research, particularly with his long-time collaborators Howard Stott and George Thompson, spending 2–3 days
per week at UMIST. Two of the last papers published in this period, concerning the growth mechanisms of anodic films (29) and the performance of protective oxide scales at high temperature (30), neatly summed up his enduring interests. In 2002 UMIST commissioned a commemorative portrait of Graham from local artist Stephen Ashurst (figure 11). It was unveiled in 2003 by Christopher Rose-Innes, chair of the Campus Improvement Committee.

Graham was unfortunately diagnosed with Alzheimer’s disease in his mid 70s, which prompted him to start attending conferences again so that ‘I can learn something new before I forget everything’. In 2014, as the disease was beginning to severely impact his life, he and Freda moved near his son’s family in Bury St Edmunds. He eventually moved into a

Figure 11. Graham and his portrait by Stephen Ashurst in 2002. (Photograph by the author.) (Online version in colour.)
nursing home, where he died on 4 November 2016. He is survived by Freda, his son David (an optometrist) and daughter Louise (a physiologist turned senior civil servant).

**EDUCATION AND CAREER ACHIEVEMENTS**

1945–1953  Bromley Grammar School  
1953–1961  Undergraduate (Christ’s College), PhD student and postdoctoral researcher at the Department of Metallurgy, University of Cambridge  
1961–1972  lecturer, senior lecturer then reader in corrosion science at the Manchester College of Science and Technology, latterly the University of Manchester Institute of Science and Technology (UMIST)  
1972  ScD (Cambridge)  
1972–  professor of corrosion science (the first such position in the UK); subsequently professor of corrosion science and engineering; personal chair from 1992 (all at UMIST)  
1972–1982  established and led the Corrosion and Protection Centre at UMIST  
1973  established the Corrosion and Protection Centre Industrial Service at UMIST  
1982–1984  vice-principal for academic development, UMIST  
1983  deputy principal of UMIST  
1987–1989  dean of UMIST, Victoria University of Manchester  
1992–1994  dean of UMIST  
1994–1996  pro-vice chancellor of UMIST

**HONOURS AND AWARDS**

1973  Beilby Medal and Prize: an award administered jointly by the Institute of Metals, the Society of Chemical Industry and the Royal Society of Chemistry  
1981  Chair, Gordon Research Conference on corrosion  
1983  U. R. Evans Award and Honorary Life Membership: the premier award of the Institute of Corrosion (UK)  
1983  Carl Wagner Memorial Award and Life Membership: a premier award of the Electrochemical Society (USA)  
1986  T. P. Hoar Prize, Institute of Corrosion (UK) for the best paper in the journal *Corrosion Science* (with B. D. Bastow & D. P. Whittle)  
1987  Cavallaro Medal, European Federation of Corrosion  
1989  Hothersall Medal and Prize: a premier award of the Institute of Metal Finishing (UK)  
1993  Elected Fellow of the National Association of Corrosion Engineers (USA)  
1990  Elected Fellow of the Fellowship of Engineering (now the Royal Academy of Engineering)  
1997  Elected Fellow of the Royal Society  
1999  European Corrosion Medal: the premier award of the European Federation of Corrosion
SERVICE TO PROFESSIONAL BODIES

1973 President of the Corrosion and Protection Association
1978–1980 President of the Institution of Corrosion Science and Technology
1994–1996 Chair of the International Corrosion Council

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The portrait photograph was taken in 1997 by Prudence Cuming Associates and is © the Royal Society.

AUTHOR PROFILE

Professor Stuart Lyon FREng

Stuart Lyon was educated in the west of Scotland and University of Cambridge, taking materials science and metallurgy in Part II of the Natural Science Tripos. He stayed at Cambridge to undertake a PhD with Derek Fray (FRS 2008) on detection of hydrogen generated by corrosion using a solid-state proton conductor. After a short spell in industry, he moved to Manchester in 1983, joining the Corrosion and Protection Centre at UMIST as a postdoctoral researcher under George Thompson and Graham Wood. Three years later Stuart was elevated to the academic staff, subsequently developing industry-relevant research with a focus on atmospheric corrosion, corrosion inhibition, localized corrosion and corrosion protective organic coatings. In 2008 he was appointed as AkzoNobel Professor of Corrosion Control in the Department of Materials at Manchester to lead an academic–industry strategic research partnership on behalf of the company’s global corrosion protective coatings businesses. Stuart is a former president of the UK Institute of Corrosion (ICorr) and, as (pro-bono) CEO of their trading body Correx Ltd, he led a team that persuaded industry to embrace the UK’s first nationally accredited training programme for industrial painters. Some 21 years after Graham, Stuart and colleagues in the Corrosion@Manchester research group were awarded the European Corrosion Medal for a second time in recognition of their continued and outstanding contributions to the subject.

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