BIOGRAPHICAL
MEMOIRS

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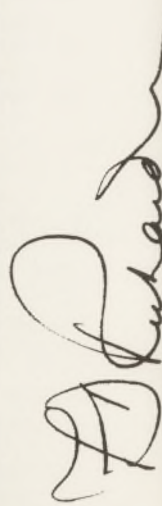

FREDERICK DENYS RICHARDSON

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Elected F.R.S. 1968

By J. H. E. Jeffes

Denys Richardson, as he was generally called by his friends, was born in September 1913 in Streatham, the third of a family of four. The Richardson family came from generations of farmers in Yorkshire. Denys's great-grandfather, John, broke this tradition and by setting up a brewery for black beer in Hull was the only known ancestor to have shown any technological bent. (The business was unsuccessful and John and later generations centred their lives on London and the southern counties.)

Both Denys's grandfather and father were involved in the clothing trade; his father's business was in Bombay but his wife could not tolerate the climate so that his immediate family lived in London at 19 Killieser Avenue, Streatham, where his father rejoined them during his annual leaves. When he was three years old Denys's father died suddenly of a cerebral stroke. A year later his mother rented a house at St Helens on the outskirts of Hastings, in rural surroundings and from which the sea could be seen, some three miles away.

He showed an early interest in observing the wild life of a pond in a nearby field and developed a love of nature, of birds, plants and particularly of horses and of riding, which lasted all his life. The family lived a settled life until 1919 when their mother was taken ill and taken to Hastings hospital, where she died on Christmas Day after failing to recover from anaesthesia. Her sister, Aunt Omie, who had come to help when Denys's mother was taken ill, took over the running of the house and of the family. She became the family's guardian and, in spite of being regarded by the children as unnecessarily strict and over-religious, she provided a happy, secure and efficiently run home. She was helped in this by Mrs Emily Parrott, a friend of hers, who acted as cook and nannie.

Denys went to his first school at the age of six, a local kindergarten, and when he was eight he went as a boarder to University School nearby. This was a school that taught a wide syllabus to children from 8 to about

17 years of age. It was here that his interest in chemistry was first aroused and where his ability to study and learn was given its opportunity. He rose to the top form at the age of 13 and obtained a first class in London Matriculation when he was 16. During this time he studied not only the set syllabus but he also studied mechanics and calculus far beyond it.

University College London

Denys planned to take the Honours Chemistry course at University College London. To start with he had to learn physics and mathematics in which his previous education had been inadequate. His energetic and logical approach to these subjects were such that they caused him no serious problems.

In his third year at University College he studied physical, organic and inorganic chemistry, and during this period he made one of the most fateful and fruitful acquaintances of his life, when he attended lectures given by the then Dr Charles Goodeve. Goodeve showed Denys the value of applying classical thermodynamics to the study of chemical reactions, and fired his imagination by his enthusiasm for the study of the kinetics and equilibrium conditions of reacting systems.

Denys had the opportunity of attending lectures by many distinguished scientists because the chemistry department of University College, under Professor F. G. Donnan, F.R.S., was a well-known centre of teaching and of research to which many celebrated visitors came. He became the secretary of the Chemical and Physical Society of the College, which enabled him to meet a number of famous scientists. During his undergraduate days he became much involved in the activities of the Artillery Unit of the Officers' Training Corps, where his horsemanship resulted in his becoming a sergeant of the University College subsection of the horsedrawn artillery.

After graduation Denys considered the possibility of taking an advanced course in chemical engineering, but after discussion with Dr Goodeve he decided to carry out research work with him for a Ph.D. degree. At that time Goodeve had a strong interest in establishing the properties of the oxides of chlorine. One of his students had developed a technique for making Cl_2O_6 from ClO_2 and O_3 and Denys took over this project.

Working with these unstable and explosive compounds required apparatus to be built entirely of glass, and Denys took a glass-blowing course and became adept at making his equipment out of soda glass, which had, of course, to be carefully annealed to avoid cracking. The apparatus was constructed with thin glass septa which could be broken by glass-encased magnets because lubricated taps could not be used. Closure of tubes was effected with a blow torch.

The safety precautions taken in laboratories in those days seem rather rudimentary to modern eyes but, happily, because of the obvious dangers

of the research in which Denys was engaged, the apparatus was mounted behind Triplex glass screens and, when these were drawn aside, a safety visor and gloves had to be worn. This is just as well because in the course of his work Denys presided over a number of explosions, fortunately without very serious injury to himself, although Dr Goodeve was heard to express concern at the number of occasions on which various parts of his anatomy were adorned with bandages. One explosion was a serious one which could have resulted in extensive injuries. Denys was vacuum redistilling about 100 ml of liquid Cl_2O_6 into a trap, cooled in a freezing mixture of alcohol and dry ice. An accidental breakage of a soda glass item caused the alcohol mixture to be sucked into the apparatus where it came into contact with the Cl_2O_6. There followed a tremendous explosion that broke the laboratory windows and destroyed the apparatus, but not the Triplex screens which protected him from the worst of the blast. His hands and left ear were extensively cut by flying glass and his hair caught fire. A woman cleaner in the next laboratory came in and with commendable resourcefulness put out the fire with a bucket of dirty water!

As a result of his work Denys established, by magnetic susceptibility measurements, that solid and liquid chlorine hexoxide consisted almost exclusively of Cl_2O_6 molecules. From the absorption spectra of the gas he established that this consisted entirely of ClO_3 molecules. Owing to the experimental difficulties of handling this material, his work has not been repeated.

Denys obtained his Ph.D in 1936 and published papers in the *Transactions of the Faraday Society* and the *Journal of the Chemical Society*, describing the results.

After this he worked with Dr Goodeve on a project supported by the Admiralty. This consisted of testing the use of phosphine gas to mark the position of torpedoes after they had been fired on practice runs. The phosphine was to be expelled from the torpedo, rise to the surface of the sea and ignite on contact with the air. In practice it was found necessary to add a catalyst such as nitric oxide, and further hazardous experiments were carried out. The problems of ignition were overcome but the method was never put into practice as other, less dangerous, markers were developed.

At the end of this work Goodeve drew Denys's attention to the Commonwealth Fund Fellowships (now Harkness Fellowships), which were awarded annually, and although he had some qualms in so doing, Denys applied for one. For his subject he thought he would try and combine his interests in chemistry and natural history by working in the field of agricultural chemistry. Professor Donnan suggested to Denys that he should contact a Dr B. A. Keen, F.R.S., of Rothamsted Research Station, and he learned from him that some Indian scientists had propounded the theory that nitrogen might be fixed in tropical soils by the interaction of strong sunlight and soil particles.

Because he was interested in photochemistry, Denys proposed to investigate possible reactions brought about by the effect of sunlight on light-absorbing oxides such as TiO_2 and ZnO, which were known to absorb radiation in the near ultraviolet spectrum.

Denys was interviewed by a selection panel chaired by Sir Walter Moberley, and three weeks later was delighted to be informed that he had been awarded a Commonwealth Fellowship to Princeton University for two years. Because Princeton was close to Rutgers University, where the famous Russian-born soil microbiologist Professor Silman Waksman was working, the arrangement was ideal.

The Royal Navy

When Denys returned from America in 1939 World War II was looming, and he found that Goodeve, whose naval connections had become even stronger, was involved with the development of methods of countering the serious threat to shipping posed by the German magnetic mine. This led to the development of the 'double L' sweep for detonating them. The protection of ships remained a vital problem and Denys joined Goodeve, who was by then a Commander R.N.V.R., with the rank of Sub-Lieutenant, also R.N.V.R.

The Admiralty department responsible for such things was H.M.S. *Vernon* at Portsmouth, and as with other service departments at the start of the war, it was slow to react to the urgency of the situation. The fitting of ships with 'degaussing' coils had been developed to a high degree of perfection, but the amount of insulated cable required to protect all allied shipping was so great that it was impracticable to consider the method for general application. Denys and Goodeve thought that the permanent magnetism of a ship could be altered by the passage of a heavy current through a cable rubbed along its steel plates, a technique that came to be known as 'wiping'. The initial tests by the established departments took so long to carry out that Goodeve got Denys to carry out some unofficial tests, and these were completed within hours by using a toy compass bought at a chain store as a detector

Agreement was then obtained to 'wipe' two destroyers to test the effect on their magnetism. Again, long delays threatened to develop and Goodeve took the unusual and now celebrated step of arranging for a signal to be sent from the Admiralty to himself at Portsmouth demanding to know why the tests had not yet been carried out. When he arrived at Portsmouth he found that Denys and he had been given the highest priority for their work. The eventual success of this development was proved during the Dunkirk evacuation when only two ships were lost from magnetic mine explosions.

Following the work at H.M.S. *Vernon*, Admiral Somerville, a man of vision and imagination, gave Goodeve 'a free hand' to try out some of his

ideas under the aegis of Somerville's cover title of Inspector of Anti-Aircraft Weapons and Devices (I.A.A.W. and D.). He secured the services of a strangely varied collection of energetic scientists and engineers, which included Denys, Commander John Dove, R.N. (a kite and balloon expert), Nevil Shute Norway (an airship engineer-cum-novelist) and others.

Many of the personnel in the department had had sea-going experience and could combine technical knowhow with a practical appreciation of the problems involved in developing weapons for use at sea. The Department of Miscellaneous Weapons Development (D.M.W.D.), as it came to be called, was organized to obtain rapid answers to problems, the 'Establishment' departments being already involved in other matters.

In addition to its headquarters in London, a trials establishment, H.M.S. *Birkbeck*, was set up on the pier at Weston-super-Mare, but work was also carried out all over Britain as well as at sea and, later in the war, at overseas locations.

Much of what happened in this department is well described in a book by Gerald Paule, entitled *The secret war 1939–1945* published by Harrap, from which some of the incidents described below are taken with kind permission of the publishers.

Denys remained with D.M.W.D. until the end of the war. This was where I first encountered him in 1943. It was fashionable at that time to be rather scornful of the intellectual powers of officers of the Royal Navy and when I presented myself for interview I was very much taken aback to find myself being interviewed by an R.N.V.R. Commander, who combined an obviously extensive knowledge of scientific matters with an energetic and incisive manner, which was ever the hallmark of Denys in action. He always demanded, and got, enthusiastic action from his subordinates and as Deputy Director of this highly effective Admiralty department, he was directly or indirectly responsible for many important developments that took place in the fields of anti-aircraft defences, methods of attacking submarines, radar countermeasures and a variety of truly miscellaneous devices.

All who served under Denys came to know that he expected them to get on with their work by any means and that if in doing this they ran foul of any of the numerous rules, regulations and protocols of the armed services, he would come to their rescue. I discovered this when I infuriated a Senior Naval Officer in charge of a harbour in the West Country by innocently arranging for a trawler to be put to sea without his prior permission. Visions of court martials were averted by appeal to Denys who pacified the S.N.O. by explaining that I was a naval tiro under his instructions. Later on, when I got back to the Admiralty, Denys invited me into the privacy of his office where he told me in very plain words what he thought of my ineptitude. It was well worth the telling off to know that my Commander would defend me in the face of all

comers even though I had acted foolishly, and that he would reserve a well merited 'ticking-off' for the privacy of his office.

This support that Denys gave to those who did their best for him was a lasting feature of his relationships with fellow workers in all fields throughout his life, and accounts, in part, for the strong personal loyalty that many of his colleagues felt for him and for the success of the several teams of experimentalists and theoreticians of which he became the director and who looked to him for inspiration.

The stories of Denys's activities in D.M.W.D. are legion and make interesting and often diverting reading. The following are some of the incidents that occurred during his time at the Admiralty.

Ships' camouflage had apparantly not been considered since World War I. An artist-turned-naval-officer named Currie was sent to observe ships at sea under varying conditions of light, as a result of which a standard shade of light grey paint was adopted for all shipping, and which has never been bettered.

A number of devices were developed that would lay a length of piano wire in the track of an oncoming aircraft and entangle it, to the discomfiture of its crew. One of these, the P.A.C. rocket, was mounted on many ships. It consisted of a cordite rocket that lifted a wire fitted with parachutes at either end and which, in service, not only scored a number of 'kills' but, perhaps even more importantly, caused German aircraft to make their attacks on our shipping with greater circumspection and with less lethal effect.

The greatest 'wirebound' anti-aircraft effort was the Free Balloon Barrage (F.B.B.) with which Denys was closely involved, and although it was not in the end successful it is worth describing, as it shows some of Denys's characteristics when confronted with a problem requiring energetic and unconventional action.

A number of schemes for laying a wire entanglement in the path of enemy aircraft had been proposed and Mr Churchill was personally interested and urged their development. The scheme finally tested was in the form of the F.B.B. Each unit, of which there were hundreds, consisted of a large meteorological-type balloon, filled with hydrogen, suspended below which was a container fitted with a long reel of piano wire and a parachute. The balloon had a primitive device to cause it to rise to a given altitude and remain there. When it reached its operational height the piano wire reel was released and a contact bomb attached to its lower end was activated.

In theory, if an aircraft struck the wire, the parachute caused it to be pulled over the leading edge of the wing until the contact bomb struck it with suitably unpleasant results to the aircraft. The first major test of the weapon was on the night of a major German firebomb raid on London. Two thousand F.B.Bs were released and because of various faults, many came to ground in a highly dangerous condition. A special recovery team

was led by Midshipman J. R. D. Francis (later Professor of Hydraulics at Imperial College) who employed every available device, including patrols of Boy Scouts, to recover them.

A controlled test of 200 F.B.Bs was then organized by Denys in Bedfordshire. Recovery by men walking through fields proved very difficult and inefficient because the small bombs and the thin wires were very hard to locate. Denys, who always gained from previous experiences, realized that horses were the answer and he hired every horse from a local riding school for the afternoon. The result was the astonishing spectacle of a band of naval officers on horseback, some not very good at staying on, scouring the countryside with very much more success than the earlier foot parties. The resulting correspondence between Denys and the Admiralty accounts department concerning the hire of fourteen horses was a source of amusement to many of his colleagues.

In addition to his many tasks in assisting Goodeve, which included work on the ahead-thrown pattern of bombs for attacking submarines, code-named 'Hedgehog' and which accounted for the destruction of over 50 enemy submarines, Denys became particularly involved with some projects including the two-pounder starshell, of which he was the inventor.

There was an urgent requirement for a means of illuminating the scene of naval engagements, particularly attacks on convoys by surfaced enemy submarines. The Navy already had a very powerful flare called 'Snowflake' and Denys improved its tactical usefulness by adapting it to the P.A.C. rocket to increase its operating height and range of illumination. This was excellent for illuminating the immediate vicinity of the convoy but the need remained for illumination outside the convoy, to provide a background against which an enemy could be sighted without giving away the positions of the ships. The only means of providing such illumination at this stage was the standard naval starshell, a parachute store fired from a 4 inch gun. This had the disadvantage that the rate of firing was comparatively slow and, in any case, the 4 inch guns were urgently needed to attack the submarines.

Denys's invention gives an insight into the way his mind worked: logically and without fear of breaking new ground. The starshell he devised was revolutionary in that it was projected from a quick-firing two-pounder gun, and it had no parachute so that it fell fast and lasted only 5 seconds. The idea was to fire a pattern of these such that five flares were in the air at any one time, providing a curtain of light as a background. For this purpose Denys wanted magnesium flares of about one million candle power and the prototypes produced by the Navy Ordnance Board were very much less bright. He had some high speed films made and found that the magnesium was remaining jammed in the nose of these shells. A modification including a tinplate case was made,

which still was not satisfactory because bits of tinplate still stuck to the flare. At this point, Denys made one of his early contacts with Imperial College, where Dr Ronald Purcell devised and tested a method of packing the flares in cardboard cases. In the teeth of opposition from the Ordnance Board, I.C.I. technicians maintained that the design was perfectly sound and Denys's starshell was put into service. Although radar detection of surfaced submarines somewhat overshadowed the use of this pyrotechnic, over a million were produced. (It was later found by Coastal Forces that the two-pounder starshell was useful not only as an illuminant but could be used as a devastating incendiary device in combat with German E-boats.)

Among the other developments with which Denys was involved were 'Hajile', a means of decelerating heavy stores dropped from aircraft by means of retro-rockets and 'Panjandrum', a fearsome device consisting of two large wheels connected by a steel cylinder made to contain a very large charge of dynamite. This was propelled by rockets attached to the periphery of the wheels so that it behaved like twin Catherine Wheels resting on their edges and joined by an axle. The trials at Westward Ho! of this device were frustrated by difficulties in controlling the direction of travel of this machine. It was too late for either of these rocket-based devices to be developed before the invasion of Normandy, but they provided much interesting information and a memorable film of 'Panjandrum', made by the well-known racing cine photographer Louis Klementaski, exists and was shown some time ago on a B.B.C. television programme.

Several aspects of the construction of the artificial harbours towed to Normandy for operation 'Overlord' were the result of Denys's initiatives, particularly the 'Bombardon' breakwater units and their anchoring. He spent some time in Normandy measuring the attenuation of the waves by these devices. Floating roadways and airstrips also came into this category.

One of the stories about Denys that was quoted to the end of his life arose from his habit of playing with objects lying on his desk, particularly while he was talking on the telephone. On one occasion when he was waiting for a call, he tapped the end of the two-pounder starshell, which he was using as a paperweight. As it happened, it had not been defused and it exploded, ejecting the ignited magnesium flare so that the whole place was filled with dense smoke. So deep-rooted was his habit that some time later he set off a free barrage balloon detonator with a pen nib and after that his colleagues took care to remove any potentially dangerous objects from his desk.

One example of Denys's ability to get things done quickly and well was the testing of how susceptible to detonation from spigot bombs the German 'Teller' mine would be. Within the space of one week Denys located a supply of these mines in North Africa, had them air freighted to

the U.K., set them up as a minefield at Weston-super-Mare and determined the spacing of the spigot bombs necessary to clear the obstacle.

In February 1942 Denys married Irene M. Austin whom he had known as a fellow student at University College. She was a graduate in engineering and town planning and they had met through common social interests. She had also joined the Admiralty in the Department of Scientific Research. The marriage was a long and happy one in which they shared many interests. They had two sons: Hugh, born in December 1942, and Rodney, born in October 1947.

British Iron and Steel Research Association

At the end of the war Denys went to work once again with Goodeve (by then Sir Charles Goodeve, O.B.E.) who had left the Admiralty in order to establish the British Iron and Steel Research Association (BISRA). This was financed by the then independent steel industry and by the Department of Scientific and Industrial Research through the British Iron and Steel Federation. He was invited to build up the Chemistry Department of BISRA. The Association consisted of five applied divisions dealing respectively with ironmaking, steelmaking, mechanical working, plant engineering and physical metallurgy, together with three supporting departments: chemistry, physics and operational research. The departments were, in the main, intended to conduct basic investigations that would support the shorter term R&D programmes of the divisions.

Denys started work by finding out about iron and steelmaking at first hand by visiting various works, mainly those of the United Steel Companies. They arranged a very instructive course that was attended by three new BISRA men and by the new Assistant Secretary of the Iron and Steel Institute, Mr A. J. Post. Denys was impressed by the harsh high temperature environment in which iron and steel were produced, and the great difficulties associated with controlling such processes to give the desired compositions and cleanliness of the metals produced. He was also surprised by the rather rudimentry chemistry in terms of which the processes were then interpreted.

At first he had no laboratories of his own, which restricted what he could do. He inherited responsibility for certain university researches sponsored and financed previously by the old Iron and Steel Industrial Research Council, now taken over by BISRA and financed through the chemistry department. There was a team at Cambridge working under the direction of Dr U. R. Evans on aqueous corrosion and a smaller one at the Royal Technical College, Glasgow, led by Professor R. Hay, working on iron blast furnace reactions and slag–metal equilibria. These groups had received grants-in-aid for many years past and it proved impossible to influence these programmes except by technical criticism.

Denys wanted to start other work more directly related to the basic chemistry of iron and steelmaking. The first thing that had struck him during his iron and steelmaking tour was the large number of reactions that occur and equilibria that are approached at the high temperatures during these processes. He had also been struck by the importance of oxygen potentials in influencing these reactions. One day he met Dr H. J. T. Ellingham who told him about the two free energy diagrams he had produced during the war, and which had been published in the *Journal of the Society of Chemical Industry*. In these he had plotted ΔG° for the formation of a substantial number of oxides and sulphides (per mole of O_2 or S_2) as a function of temperature from which could be seen at a glance the order of stability of compounds at any temperature, and how these varied with temperature. He saw at once the potential use of such diagrams for sorting out reactions and equilibria and separating the important from the unimportant.

I had rejoined Denys when I was demobilized from the Navy and I, and, later on G. Withers, worked with him to prepare a number of new diagrams based on the most accurate data then available, much of it coming from Dr K. K. Kelley's immensely valuable calorimetric studies and compilations. Eventually these diagrams covered oxides, sulphides, silicates and carbides. We devised special nomograms for reading off such useful data as the partial pressures of O_2 and S_2, carbon activities, equilibrium gas ratios (CO/CO_2, H_2/H_2O, H_2/H_2S, CH_4/H_2) and CO pressures in the presence of carbon in equilibrium with oxide systems at any temperature. Denys here demonstrated that a piece of fine string would be a valuable thermodynamic tool, especially useful in conjunction with the nomograms in discussion and lectures. The diagrams were later extended to equilibria involving carbon and sulphur dissolved in liquid iron in contact with appropriate carbides and sulphides.

A special series of such diagrams were prepared to demonstrate the equilibria approached at various temperature levels in the iron blast furnace. This was the first serious attempt to apply the principles of physical chemistry to the shaft and hearth reactions of such furnaces and many aspects were clarified. Among the new ideas were the conclusions that the alkali metals and silicon (as SiO) could be vaporized in the tuyere zone and swept up to cooler levels where they could be reoxidized and partly swept away as in the top gases, but also partly deposited on the solid burden so they recirculated within the furnaces. Alkali metals have since been found in blast furnace refractories and are a contributing cause of their failure. Other important points were made concerning cyanides and their production in blast furnaces.

Denys was anxious to get some basic experimental work started on the properties of liquid slags and on solutions in liquid iron. With the agreement of Sir Charles Goodeve he therefore initiated researches in the Chemistry Department at Imperial College under the supervision of Dr

J. A. Kitchener and Dr J. O'M. Bockris. One project was on the electrical and viscous properties of liquid silicates and the other on sulphur dissolved in liquid iron, and the influence of carbon at saturation on its chemical activity. He had frequent consultations on the progress of these researches and most friendly cooperation. The slag work revealed for the first time unequivocally that most silica melts are ionic conductors and that their viscosities are smooth functions of their compositions. The iron project was one of the first fully controlled gas–metal equilibrium studies conducted at 1200–1500°C, and showed clearly how greatly the activity coefficient of sulphur was raised by carbon, a factor important in understanding the slag–metal relations in the iron blast furnace. A third project was initiated with Dr A. J. E. Welch on the phosphorus–oxygen equilibrium in liquid iron held in contact with lime and solid calcium phosphate.

In due course BISRA acquired fundamental research laboratories in Battersea and he was able to set up an experimental chemical group led by the author, who was responsible for getting the laboratory equipped and working. We embarked on a variety of experimental investigations. I set up a heat-of-solution calorimeter for establishing the heat of formation of silicates for which only sketchy data then existed. Denys got Mr C. J. B. Fincham to start a careful study of sulphur in silicate melts by means of gas–slag equilibria, which had never been attempted before. Dr Welch's student, Mr J. B. Bookey, came across from Imperial College to complete his phosphorus work by using a more convenient technique with our newly installed induction furnace. Mr O. H. Gellner joined us and started a study of the way in which wustite grew on iron plates held under controlled oxygen potentials.

Towards the end of his time at BISRA Denys got Mr C. B. Alcock to join it from University College London, where he had learned to manipulate radioisotopes. It was intended he should study equilibria at high temperatures in which the use of isotopes could simplify the experimental procedures.

In 1948 Sir Charles persuaded the Faraday Society to arrange a discussion on the Physical Chemistry of Process Metallurgy. BISRA's Chemistry Department's work had not yet got very far, so Denys contributed a paper on the constitution and thermodynamics of liquid slags in which he endeavoured to put together what was then known about these systems, and what could be deduced concerning the stabilities of binary metal-oxide–silica mixtures on the basis of the known phase diagrams. It fell to him to organize the discussion, which was held at the British Iron and Steel Federation's country mansion at Ashorne Hill. He got most of the significant workers in the field to attend, most notably Professor John Chipman, who during the previous decade had led a group at M.I.T. working in this field. His experiments were of the highest standards and the ideas emanating from his school were most

important. Chipman's work differed from BISRA's in two main aspects. He tended to work with about a kilogram of melt whereas Denys's team preferred small drops of a gram or less. He also preferred to investigate slag–metal equilibria directly, whereas Denys preferred to study the metals or slags separately in equilibrium with gas mixtures in which the oxygen, sulphur or other potentials required could be precisely controlled.

The Faraday discussion of 1948 was a landmark and the papers reflect very well the state of both theory and experimental work at the time. There was clearly enormous scope for basic experimental work relating to the problems of metal production at high temperatures.

In 1949 Denys had concluded that the Chemistry Department of BISRA could not become a strong research group because of the way it was financed, and the lesser priorities attached to basic investigations compared with the *ad hoc* work organized by the various process divisions. He also found that the paper work involved with committees, for which he was responsible but whose work he could hardly influence, was an unwelcome deflection from his researches. He also felt that the steel industry was not as supportive of BISRA as it should have been. Despite the great attractions of working for such a dynamic person as Sir Charles Goodeve, he began to look around for other possibilities.

Imperial College, London

At the end of 1949 Denys found an out-of-date notice in the *Journal of the Society of Chemical Industry*, advertising a Fellowship at Imperial College to be financed for a five year period by the Nuffield Foundation and advertised by the Institution of Mining and Metallurgy. There was £5000 p.a. available, which included the Fellow's salary, and in those days it was considered sufficient for him to build up a research group in extractive metallurgy within the Metallurgy Department at Imperial College. He was attracted by the opportunity to work in an academic environment and to have scope to experiment on systems other than those of concern to the steel industry. This was a rather risky decision because he was by then superintending chemist of BISRA with a very secure post, whereas the Fellowship was only guaranteed for five years. He thought the opportunities were greater than with BISRA and that he could raise industrial money to supplement the Nuffield grant and ultimately to carry it on. He was encouraged by Professor C. W. Dannatt, then Head of Metallurgy at Imperial College and he agreed to take the Fellowship, on the basis of a five year budget proposed by himself, this to provide for two research assistants as well as his own salary and certain key apparatus that would have to be purchased specially for high-temperature research. One could do a lot with £5000 p.a. in 1949. The College was to provide the laboratory space, normal chemicals and glassware and other usual

laboratory equipment, workshop facilities, heat and light and some secretarial assistance.

When he arrived in February 1950 he found to his dismay that none of those arrangements had been put in train by the Department of Metallurgy. He was offered a small laboratory on the ground floor, quite unsuitable for the group that he envisaged. It was covered with dust and grime and filled with the interconnecting glassware of some bygone corrosion experiment. The creators of this experiment had departed with the experiment in full swing and it seemed they must have swept away with the suddenness of the Black Death. This place was impossible and unacceptable. He discovered a large laboratory in the basement with no benches but strewn with old packing cases and with mercury lying in small pools between the ridges of the floor tiles. There was a moderate-sized office next door. He could see that these could be conveniently converted to a small laboratory for isotope work, an office for the two research assistants and a main laboratory in which six research students could conveniently work.

The department could not apparently afford to put in new benches but luckily the Chemistry Department had discarded a lot of old benches that had been standing exposed to the weather for two years. The teak tops were still in good condition and the support benches were strong enough to be rebuilt. The laboratory and its services were designed around these salvaged benches. He decided to make a two-month trip to the U.S.A. and Canada to examine the researches in progress there, particularly at M.I.T. and the U.S.B.M. in Berkeley University. He knew nothing would happen in his absence unless he got a chaser so he engaged me as a consultant and to progress the conversion in his absence. It was an uphill task but I kept things moving and made some improvements to the original designs.

Denys's visit to the U.S.A. and Canada showed that there was a fair amount of research in progress scattered over a number of institutions, but by far the strongest high-temperature group doing the best experimental work was the one led by Professor John Chipman in the Department of Metallurgy at M.I.T. They tended to work with substantial inductively heated melts, usually involving quite complex equilibria. At that time Denys had no money for a high-frequency generator: he planned his programme of work with small drops of metal or slag, with resistance heating and gas mixtures to control precisely the chemical potentials of O_2, S_2, C, etc., they would require.

On his return from the U.S.A. he was able to start some four or five researches in the half-finished laboratory in the autumn of 1950. When his colleagues from BISRA heard what he was doing they started asking whether they could join him. Mr O. H. Gellner and Mr C. B. Alcock came and they were an enormous help. At the same time BISRA generously agreed to second Mr C. J. B. Fincham to complete the

slag–sulphur equilibrium work, which he had started at Battersea and which was then going very well indeed.

In 1952 Dr O. H. Gellner died suddenly of polio and the work was set back until the arrival of Dr J. W. Tomlinson, who had worked originally with Dr J. O'M. Bockris in the Chemistry Department at Imperial College during the classic work on slags that Denys had started there. He had then spent 2–3 years at M.I.T. in John Chipman's group and so was well equipped to help in establishing the group that was now named the Nuffield Group in Extraction Metallurgy.

The unusual nature of the research work being carried out in the Nuffield Research Group led to some peculiar situations in its early days. Because high-temperature experiments tend to take a long time (including the heating and cooling of furnaces) it was often necessary to start runs early in the morning and to continue until late at night. At that time only three keys to the Royal School of Mines were available to academic staff and these were held by the Heads of Metallurgy, Mining and Geology. Research workers in the Nuffield Group had to break in and out of the basement laboratory via the fire escape; they had numerous encounters with the police but were able to convince them of their innocence. It was over a year before the college authorities gave permission for keys to be issued to research workers and this illustrated the cause of some of Denys's early difficulties in dealing with the authorities. Professor Dannatt did not fully appreciate, at that time, the unusual requirements of the novel type of work that had taken root in his department.

The work progressed steadily and industrial and Science Research Council (S.R.C.) support was gradually obtained. They badly needed more workshop assistance than the Department could provide and when sufficient funds became available for a workshop technician, Mr Percy Worner was engaged and he was well able to cope with most of the work they needed. He was later joined by two assistants. The problem was to find tools they could afford; here Mr Alcock and Mr Worner became adept at hunting down machine-shop equipment thrown out by richer departments and that is how the Nuffield Group workshop was equipped; the lathe thrown out by the Physics Department, for example, served them well for a further ten years. The work of the Nuffield Group became known to the Rector of Imperial College, Sir Roderick Hill, and then to Lord Falmouth, the Chairman of the Governing Body, who took a personal interest in it. As the work gradually became more widely known, more students wanted to join the group particularly from overseas. In 1954 they had a visit from Dr P. Kozakevitch from the French IRSID (their version of BISRA). He was setting up the Chemistry Department of IRSID and sought advice. For the next seven years Denys was consultant to them making frequent visits to their laboratories in St Germain-en-Laye and the work of both groups was strengthened by this connection.

In 1955 increased laboratory space was, with some difficulty, obtained and work on molten salt chemistry was put in hand. Professor P. M. S. Blackett, F.R.S., was instrumental in arranging a large grant from the Science Research Council for a 5 year programme of research on high-temperature techniques. This led to an important development in the laboratory in the form of the purchase of the first high-frequency induction generator. This was used for studies of reactions involving drops of metal of $\frac{1}{2}$–$1\frac{1}{2}$g, levitated and heated simultaneously in flowing gases. Dr Alex Jenkins was invited for a session from the University of New South Wales to develop the technique that he had started to use in Australia. In the ensuing years many investigations on equilibria and kinetics were made by this method.

By 1955, when the original Nuffield Foundation grant was coming to an end, the success of Denys and his co-workers measured by completed and published researches had resulted in growing industrial and government support. The Foundation extended its grant to aid the transition to support from other sources. In the same year Denys submitted his publications in high-temperature metallurgy and was awarded the D.Sc. degree of London University.

In 1957 Professor Dannatt retired and Denys was appointed to the new Chair of Extraction Metallurgy. He was disappointed to discover that J. G. Ball, Professor of Physical Metallurgy, was to be Head of Department. Because in those days headships of departments were of indefinite duration Denys seriously considered moving to another University, but the disruption of the work of his research team and the problems it would have entailed dissuaded him from this course.

The Nuffield Research Group was absorbed into the structure of the Metallurgy Department and the funds it had accumulated made possible the appointment of Dr J. W. Tomlinson as the new Nuffield Fellow. Dr Alcock became a lecturer in Chemical Metallurgy and Dr P. S. Rogers joined the Department from BISRA as did Mr L. E. Leake.

The relationship between Denys and the new Head of Department was to prove an uneasy one and this was perhaps predictable as his interests were centred on the fields of extraction and chemical metallurgy whereas the Head's interests lay in the direction of physical metallurgy and materials science.

To begin with they were united in their resolve to modernize the undergraduate syllabus, which was very much out of date. They were opposed in this endeavour by Professor Dannatt, who, in spite of having retired, remained on the board of Studies of the Royal School of Mines. This delayed the syllabus revision which was, however, eventually carried through. The diversity of the interests of the two professors led to continuing friction about the relative emphasis of the subjects taught. The Nuffield Research Group has, however, remained for many years the world major academic research group in this subject, recognized by industry and government agencies alike.

By 1962 Denys began to see that the major equilibrium studies made by the group and in other centres had provided a fair understanding of the nature of metal, slag and salt melts, and of quite complex mixtures. The speeds of processes were, however, poorly understood. Despite the tendency by previous workers to explain these in terms of chemical kinetics, it became obvious to him that at high temperatures they were most likely to be controlled by the rates of mass transfer of reactants and products to and from the interfaces to which the most important chemical reactions were restricted. Denys managed to have established a Readership in Process Engineering and got Mr A. V. Bradshaw to come from Consolidated Goldfields initially as a lecturer, to develop the fields of fluid flow and of heat and mass transfer in relation to metallurgical processing. This he did most successfully and was later appointed Reader. Denys then applied to the Nuffield Foundation yet again for a grant to start a special research group in this area. They generously provided a five year grant totalling £35 000 and the way was open for a major research effort in this new field. The group was called 'The John Percy Research Group' after the famous Dr John Percy who had been the first Professor of Metallurgy in Britain.

The first John Percy Research Fellow was Mr A. W. D. Hills, an able young metallurgist with a penchant for mathematics and computers, who had come from Cambridge to do a Ph.D. research in chemical metallurgy. He abandoned this and proved an excellent research leader in the process field. Under the overall direction of A. V. Bradshaw the group grew and developed well.

After three years of the Nuffield Grant for the Percy Group Denys decided they must find sufficient finance to be able to carry on beyond the five years. He made personal appeals to Sir Harry Oppenheimer and to Sir Monty Finniston, the Chairman of the British Steel Corporation. He raised sufficient funds to ensure another five years' work. They had hoped to get Dr Hills a position with tenure on the staff but this they were unable to achieve and he soon left to take the Headship of the Department of Metallurgy at Sheffield Polytechnic. Denys transferred the administration of the Group to the Wolfson Research Fellow, Dr R. G. Tait, who looked after it most ably until 1975 when he left to join Johnson Matthey. An outstanding young Indian, Dr V. Rajakumar, carried on until he left to take up a position in Australia.

In about 1962 Imperial College began to take a less restrictive view about the appointment of Readers to Personal Chairs and Dr P. L. Pratt was awarded a Chair and Dr C. B. Alcock became Professor of Chemical Metallurgy. A new Chair in Process Metallurgy was created and A. V. Bradshaw was appointed to it, covering both the work currently in progress in the Percy Group and also in solid metal processing. I rejoined Denys as a lecturer in 1962 and eventually succeeded him as Professor of Extraction Metallurgy.

Both Professor Alcock and Professor Bradshaw eventually left the Department, to become Head of the Department of Metallurgy at the University of Toronto and of the C.S.I.R.O. Minerals Processing Research Laboratory in Australia respectively. The increasing financial stringency facing the College prevented their replacement at the time.

In 1970 Denys was granted a B.S.C. Fellowship for two years to write a book incorporating the knowledge then available on melts in metallurgy. This took longer than expected and was finally published in 1974 as a two-volume textbook entitled *The physical chemistry of melts in metallurgy*, which is accepted as the standard work on the subject. He ultimately retired from Imperial College in 1976 because of his health, but remained a very active Senior Research Fellow until his death in 1983.

During his career, Denys was a strong supporter of the Iron and Steel Institute (later the Metals Society and now the Institution of Metals) and of the Institution of Mining and Metallurgy, on whose committees he served diligently and became President of the I.M.M. in 1975. He received many honorary degrees and awards from learned societies:

1956	Sir George Beilby Memorial Award
1962	Charter Fellow of the American Institute of Mining and Metallurgical Engineers
1968	Bessemer Gold Medal of the Iron and Steel Institute
	Fellow of the Royal Society
1971	Honorary Doctorate of Technische Hochschule, Aachen
1973	Honorary Doctorate of the University of Liège
	Honorary Member of the Association des Ingénieurs de l'Université de Liège
	Honorary Member of the Japanese Iron and Steel Institute
	Gold Medal of the Institution of Mining and Metallurgy
1975	Gold Medal of the American Society of Metals
	President of the Institution of Mining and Metallurgy
1976	Foreign Associate of the National Academy of Engineers of the U.S.A.
	Fellowship of Engineering
	Peter Tunner Medal of the Eisenhutte Osterreich
1978	Grande Medaille de la Societé Française de la Métallurgie
1980	Carl Lueg Medal of the Verein Deutsche Eisenhuttenheute
1983	Kelvin Medal of the Institute of Civil Engineers

His premature death has left an empty space in the leadership of his chosen subject and is much regretted by many colleagues in the United Kingdom and abroad.

Achievements at Imperial College

Denys's work during his time at Imperial College covered many topics and it is impossible to describe them all in detail. The following are some comments on the outcome of his researches and are grouped in the same order as that of his list of publications given below.

1. *Free energy diagrams: analyses of metallurgical processes*

The origins of the free energy diagrams belong to the period when Denys was at BISRA as described above. They turned out to be of long lasting value and they were revised at intervals in the light of new data arising from the work of Denys's research and that elsewhere.

In addition to earlier analyses of the iron blast furnace, deoxidation and desuphurization of steel, a wide ranging survey of the chemistry and process engineering aspects of the vacuum degassing of steel was well received.

2. *Metal solutions*

Revelation of the way Cr lowers the activity coefficients of C in liquid iron and explanation of the difficulty of removing C to low levels from stainless steels. The equations indicated that low CO pressures in the emergent gases would help. Processes subsequently developed by Creusot-Loire, and A.O.D. (Union Carbide) exploited this either by use of low pressures or lowering the partial pressure of CO by added neutral gas.

First data for solubility of oxygen in liquid lead (oxygen was hitherto thought by 'old timers' to be insoluble).

First measurements of the activity of a non-metal solutes (such as S or O) at high dilutions in binary alloys across the field of compositions from one metal to another.

Observations that in the Fe + Cu + S system, the addition of both Cu to Fe and of Fe to Cu lowered the activity coefficient of dissolved sulphur. This led to the development of models for such mixtures: the first was a regular solution model which worked quite well for metal solutions and hydrogen, then came a quasi-chemical model that was quite good for Si in Cu + Fe but failed for oxygen in Cu + Sn and in other cases where there are large differences in the activity coefficients of solutes in the separate metals. The observation of this discrepancy later led Alcock and Jacob to develop their two-bond number model which is the most practically useful of all models proposed so far.

The work on the activity of silicon in iron and other metals and alloys was the first example of establishing Si activities via SiO in the gas phase and provided important new data on these solutions.

The electrochemical measurements of oxygen in silver and copper were novel and led to his development of the commercial Oxycell probe for continuous measurement and control of oxygen in flowing copper at 1051–1200°C before its being cast into slabs and, more importantly, into wire rod. This Oxycell is now used in five countries in Europe and in Japan. The life of each probe is about 70 hours in 7 dips but depends greatly on slag conditions and care in use; it is used most successfully in Japan.

3. *Thermodynamics and structures of slag solutions*

The first important result of the work on slags was the elucidation of the equilibria controlling the sulphur content of slags. Hitherto this had not been understood because all experiments had been made on slag–iron equilibria so that, when the oxygen potential was raised, iron oxide entered the slag. His work employed the novel slag–gas technique, the oxygen and sulphur potentials in the gas being controlled by the ingoing composition of a $CO_2+H_2+SO_2$ mixture and calculated for high temperatures by the thermodynamic data on these gases and of CO, COS, H_2O, H_2S and SO.

$$\tfrac{1}{2}S_2+(O'')=\tfrac{1}{2}O_2+(S''), \quad (1)$$

$$\tfrac{1}{2}S_2+(2Si\text{–}O')=\tfrac{1}{2}O_2+(S'')+(Si\text{–}O\text{–}Si), \quad (2)$$

$$\tfrac{1}{2}S_2+(O'')+1\tfrac{1}{2}O_2=(SO_4''). \quad (3)$$

At low oxygen potentials (S″) is important and at high oxygen potentials (SO_4''). The minimum slag sulphur for a fixed sulphur potential is achieved at particular p_{O_2} values.

Equation (1) was established for a number of binary $XO+SiO_2$, $XO+Al_2O_3$ and ternary slags $XO+SiO_2+YO$, $YO+SiO_2+Al_2O_3$.

A function C_S, called the sulphide capacity, was developed for comparing the sulphur-holding properties of slags, defined by the equation

$$C_S = \text{wt\% S in slag} \times p^{\frac{1}{2}}_{O_2}/p^{\frac{1}{2}}_{S_2}.$$

It was shown that the higher the metal oxide content or activity in a slag, the higher the sulphur capacity, and from the way C_S varied with composition in binaries such as $MO+SiO_2$ it was concluded that only equations (1) and (2) could account for sulphur pick-up, the reaction

$$\tfrac{1}{2}S_2+(Si\text{–}O\text{–}Si)=(Si\text{–}S\text{–}Si)+\tfrac{1}{2}O_2$$

being impossible or at least of negligible significance.

It thus became clear why desulphurization of iron in the blast furnace was effective with only weakly basic slags, (p_{O_2} being so low), whereas in steelmaking at much higher oxygen potentials highly basic slags were needed.

The results also explained why the addition of FeO under steelmaking conditions had little influence on the desulphurization of steel. There are two opposing effects: as FeO is added the oxygen potential is raised so tending to lower the slag sulphur, but at the same time C_S is raised, thus tending to raise the slag sulphur. Under process conditions the effects nearly cancel each other out.

The work on activities in the ternaries $XO+YO+SiO_2$ showed that the pattern established by Chipman and co-workers in the system $CaO+FeO+SiO_2$ was broadly followed in other systems; the extent

to which the activity coefficient of the metal oxide more weakly interacting with silica was raised depended on the difference in $\Delta G^{\circ}(MO+SiO_2)-\Delta G^{\circ}(YO+SiO_2)$. These observations led to the calculation of XO and YO activities in the ternary $XO+YO+SiO_2$ on the assumption that binary silicates of equal silica mole fraction mix ideally, i.e. $\Delta H_M = 0$, ΔS_M = configurational entropy of mixing the cations X and Y. These calculations showed that such ideal mixing would lead to markedly raised activity coefficients of oxides reacting more weakly with silica and in extreme cases to miscibility gaps. The actual systems showed ideal silicate mixing in the metasilicate region but more negative free energies of mixing in the orthosilicate region. Although more sophisticated mixing models of silicates have since been proposed, the concept of ideal mixing has provided a valuable yardstick with which to compare actual behaviour, and still provides a useful insight into silicate behaviour.

The work on structural and thermodynamic aspects of phosphate glasses paved the way for the application of polymer theory to polyanionic melts and a better understanding of the nature of silicate slags.

4. *Equilibria and kinetics involving solids*

Detailed studies of reactions such as the reduction of wustite by hydrogen, the oxidation of cobalt metal and the transfer of silicon via gaseous SiO showed the importance of understanding both the chemical driving force of reactions and the mechanisms whereby they take place.

Thermodynamic measurements made to elucidate these processes included the study of the sulphur potentials of the iron sulphide system as a function of its non-stoichiometry, by using a radioactive sulphur isotope; measurements of the heats of formation of manganese orthosilicate and sulphide; and the determination of the thermodynamics of silicon monoxide and of other systems.

Kinetic studies on solid–gas systems included the development of techniques to measure self-diffusion coefficients.

5. *Kinetics of reactions involving levitated metal drops*

The technique of holding a levitated liquid metal drop in contact with a stream of gas containing a reactive component, without the metal's being in contact with any solid container material, was seized upon with energy and used to study reactions such as the oxidation of copper by oxygen, of copper and nickel by carbon dioxide and the oxidation of carbon–iron alloys.

Careful analysis of the results of the copper–oxygen reaction indicated that oxygen pick-up was very much slower than that predicted from mass transfer correlations. It was found that although very pure copper was used for these experiments the small amount of silicon present caused the

formation of a film of silica on the metal surface. If this was removed by prior oxidation, freezing while levitated and removing the silica film by treatment with hydrofluoric acid, an oxygen pick-up rate was attained that was compatible with a model in which the rate-determining step was transport of oxygen in the gas phase.

The oxidation of carbon from solution in liquid iron, an important industrial process, showed that the formation of carbon monoxide by homogeneous nucleation of the gas in the liquid iron was a very difficult process requiring large excess pressures. The formation of a nucleating point such as a film of iron oxide caused violent nucleation to take place. The surface evolution of carbon monoxide was found to be governed by gas mass transfer except at very high reaction rates.

The formation of fumes of ferric oxide during oxygen steelmaking was found to be due at least in part to the complete oxidation of small spherules of iron ejected from drops of reacting metal by carbon monoxide bubbles bursting through the metal surface.

6. *Bubbles, drops and interfacial phenomena*

Because of the corrosive nature of slags and liquid metals, relatively crude methods of slag–metal–gas contacting have to be used in smelting and refining processes. The realization that reactions occur mainly at interphase boundaries and that their rates are usually controlled by mass transfer led to a series of important investigations into the rates of heterogeneous reactions.

The understanding of the importance of phase dispersion was a key factor in the design of small reactors in which intensive and thermally efficient processes could be carried out. Studies were made of the behaviour of gas bubbles in liquid metals and because these are difficult experiments to perform quantitatively at high temperatures, models using mercury and aqueous solutions at room temperature were also used. It was observed that gas bubbles rising through a mercury–aqueous interface became completely covered by a film of metal, which then peeled off and fell back into the pool in the form of tiny droplets, thereby significantly increasing mass transfer between the phases.

Experiments on the transfer of oxygen from large bubbles in a column of liquid silver showed that the cold model could be useful to predict the behaviour of hot systems.

Corresponding studies on mass and heat transfer from droplets of metal to flowing gases were performed with a levitation melting technique, and from metal to liquids by allowing the metal droplets to fall through columns of reacting liquids.

The factors affecting the shapes and rates of rise of gas bubbles were established and the importance of interfacial turbulence in enhancing rates was made apparent.

The complex effects of stirring liquid–liquid interfaces by passing gas bubbles upwards through them were quantitatively determined and mathematical models set up, which enabled laboratory investigations to be satisfactorily correlated with industrial reactors.

The great developments in the application of process engineering principles to metallurgical processes since 1960 have been mainly due to the work carried out in the field by the John Percy Research Group during this period.

7. *Other contributions*

In addition to the 'mainstream' research publications, many additional contributions came from the development of new experimental techniques such as the use of solid electrolyte probes to measure the oxygen contents of molten metals.

A notably complete biographical memoir of Sir Charles Goodeve, F.R.S., was published in 1981, and an extensive series of reviews and published lectures was produced from 1950 to 1978. These included notable contributions on the structure and teaching of metallurgy and the texts of a whole series of important lectures. These included memorial lectures to most of the major societies and other organizations concerned with extractive metallurgy.

Personality

From the above list of Denys's achievements in war and in peace it could be supposed that he was so much a dedicated scientist that there was no room in his life for other pursuits or human relationships. Such an idea is totally wrong and anyone who worked with him could be astonished at the range of the outside interests for which he found time, in addition to the enormous amount of work he gave to his scientific pursuits.

He lived with his happy and united family in a fine house surrounded by a beautiful garden, which was Denys's pride and joy and to which he gave a great deal of time and energy. He was an accomplished painter in water colours, a connoisseur of fine art and a gifted conversationalist. His personality was vivid and although he was rather slight in build, his presence was always noticeable. He was intolerant of what he considered to be sloppy thinking and his brusque treatment of some of his contemporaries earned some resentment. To his friends Denys was a charming and amusing companion; his care for the welfare of those who worked under him was unending and through the worldwide network of his ex-students and colleagues his influence remains clearly to be felt and will continue for years to come.

I have been asked to write this memoir because I probably worked with Denys over a longer period of time than any other living person. I deliberately chose to rejoin him twice at work and, like his family and his many friends, I am glad to have known a great man.

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I wish to convey my gratitude to those who have provided information and ancedotes about Denys Richardson. I particularly wish to thank Mrs Irene Richardson who has provided much help and information. Denys's sons, Hugh and Rodney, ex-colleagues, James Close and Wally Voice, and his friends at Imperial College and all over the world have contributed most helpfully.

It is unusual but characteristic of the man that the most important contribution to the present memoir was made by Denys himself, who in the last months of his life wrote an extensive series of biographical notes; these have been used by kind permission of Mrs Irene Richardson.

'He was a man, take him for all in all,
I shall not look upon his like again.'

William Shakespeare
Hamlet

The photographs reproduced were taken in about 1939 and 1968 respectively. The latter was taken by Godfrey Argent.

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