BIOGRAPHICAL
MEMOIRS

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Michael Burdekin and Bernard Crossland

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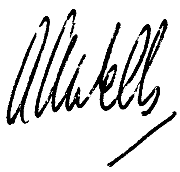

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Alan Wells was probably best known for his seminal contributions to studies of brittle fracture and fracture mechanics conducted during his period at the British Welding Research Association (BWRA) from 1951 to 1964. He was Professor of Structural Science at Queen's University Belfast from 1964 to 1977, when he returned to the Welding Institute (as the BWRA had then become) as Director General until his retirement in 1988. In his later years, he worked on wave energy devices and was responsible for the development of the innovative 'Wells' turbine, a device that continues to rotate in the same direction under oscillatory air flows.

EARLY YEARS AND EDUCATION

Alan Arthur Wells's family came of farming stock in the vicinity of Herne Bay on the Kentish coast north of Canterbury. His father, Arthur John Wells, left school in 1899 before he was 12 years old to work as an office boy in a livery stable in Herne Bay. However, like many young men at the beginning of the twentieth century, Arthur was enthused by the new-fangled cars appearing on the roads. Having gained experience with a motor and cycle agents and repairers in Canterbury, in 1911 he became chauffeur-mechanic to his Grace, Dr Davidson, Archbishop of Canterbury. By 1916 he realized that there were declining prospects for chauffeur-mechanics, and he joined the British Oxygen Company (BOC) as a production engineer, remaining with them until his retirement in 1948. So Alan grew up in a family steeped in the practice of mechanical engineering.

Alan Wells was born on 1 May 1924 in a rented farmhouse in Goffs Oak, Hertfordshire, where his family had moved when BOC relocated their works to Edmonton. He began his education in the small Goffs Oak Church of England Junior School. At the age of 10 years his father arranged for him to attend the City of London (day) School, although this meant a daily return journey of 22 miles. After two years he was awarded a Corporation of London Scholarship. Alan thought that travelling to and from London every day and exploring the city was a privilege, which contributed to his general knowledge as well as giving him a streetwise attitude to life. Like many young people of his day and age he found the bicycle a great liberating force. It allowed him to explore Cambridge, Ely and the Fens, as well as Suffolk, Essex and east Kent, where his paternal and maternal families lived.

In July 1939, at the early age of 15 years and 2 months, he obtained his School Certificate with all-round credits, which gave exemption from matriculation, then necessary for university entry. On the outbreak of war the City of London School was evacuated to Marlborough College in Wiltshire, where Alan continued on into the sixth form. However, he found the exclusive boarding school discipline an anathema. With his parents' agreement he left school in Easter 1940 to become an apprentice fitter and turner with Thomas de la Rue—a security printer and manufacturer of heavy intaglio printing machines. Despite very long hours and commuting daily from Goffs Oak he found joy in acquiring manual skills, while he studied for the intermediate external London BSc at Northampton Polytechnic by day release and weekend classes. However, his apprenticeship was brought to a sudden end during the night before New Year's Eve 1940, when the factory was reduced to rubble in a German air raid. Part-time study continued in undamaged premises near the Angel, Islington, leading to the award of the intermediate BSc in July 1941, when he was 17 years and 2 months old.

In 1941 the government of the day recognized a shortage of qualified engineers for both the armed forces and industry, so they introduced State Bursaries for suitably qualified apprentices to complete their studies full-time over a two-year period. Alan, encouraged by his mother, applied for a State Bursary but was rejected because he was too young or had insufficient experience. A second application was successful and he was directed to Nottingham University College, an external constituent college of London University. In Nottingham he joined a group of 27 students studying mechanical and electrical engineering—at the time, civil engineering had been discontinued. Most of the group had come up by the industrial route and had been given State Bursaries. They came from a wide range of industries with very varied experience and they formed a wonderful intellectual debating group, learning much from each other's experiences.

Although the lecturing staff was small, the students were fortunate to have lectures from Professor Charles Henry Bulleid, Professor Henry Cotton and Professor H. T. H. Piaggio. Bulleid was a shabbily dressed chain-smoker of Woodbines, and a beloved eccentric with a mercurial mind. He had been the 11th Wrangler in the Mathematics Tripos in Cambridge and a research assistant to the great engineer Sir Charles Parsons FRS. All his lectures were virtuoso performances and extempore, such that all students felt they were sharing in an adventure for the first time. Cotton, in contrast, was petite, dapper and arty; he wore a wide-brimmed 'Verdi' hat, not the dirty old trilby as worn by Bulleid. He was a prolific author, and his book *Electrical technology* sold in its many tens of thousands over the years. His lectures were dictated at speed from his notes and illustrated by beautiful drawings in coloured chalks. Piaggio was renowned for his book *An elementary treatise on differential equations and their application*, published in 1920, which few students found elementary. He never spoke in lectures but wrote furiously with a cloud of chalk dust enveloping him, but students found him stimulating in discussion after his lectures.

The two-year course was very intensive with a considerable load of designs and laboratory work required to be submitted to London University for assessment. This was made no easier by the absence of laboratory technician support so the students had to devise and organize their own laboratory programme, with a minimum of staff supervision, but probably as a result they learned much more. On top of the academic work was an increasing military training programme imposed by the Senior Training Corps, which all students had to join. This led to a student mutiny when they felt that their studies were being jeopardized by excessive parades and training exercises. As a consequence the Joint Services Board (JSB), under the chairmanship of Dr C. P. Snow, came to Nottingham and interviewed some of the students, including Alan. Instead of having the students court-martialled and shot at dawn, the JSB supported the student protest, and a reduction in military duties was agreed.

In 1943 Alan was awarded a second-class (undivided) honours degree, which was a great disappointment to him—he had expected better. He attributed his failure to achieve a first to his new-found freedom and greater financial independence and his indulgence in university life. However, it should be noted that he was awarded a degree when he was only 19 years 2 months old and the youngest of his year, which many might think was exceptional.

The record of this group of graduates who had mostly come up through industry might be considered as remarkable. Two of them, including Alan, were elected FRS and another FRSE (Fellow of the Royal Society of Edinburgh). Many of them reached positions of great responsibility, such as full-time Board Member of the Central Electricity Generating Board with responsibility for Technology, Chief Engineer of the Severn River Board, and Chief Engineer of Advanced Engines and New Projects, Rolls-Royce, to mention only a few.

The beginning of a career

Graduates at that period were not masters of their destiny, and the JSB interviewed them and directed them to where their services were most needed. For Alan that was the Admiralty Undex Works, Rosyth, with several months at the Road Research Laboratory (RRL) at Harmondsworth before moving to Scotland. The RRL was involved in military research, including the effect of small underwater explosive charges on samples of frozen pulp, in relation to the Habakkuk project to construct an aircraft carrier sited in mid-ocean. Alan always considered it an example of a useless concept being driven by politicians who were clueless.

At Rosyth Alan was responsible for setting up a photoelasticity and model stress analysis laboratory in support of the designs of warships based in Bath. Ultimately there were seven or eight assistants, including model makers, responsible to Alan. He was awarded the Institute of Civil Engineers Miller Award for a paper on modern photoelasticity methods in 1945/46 (1)*. With David Senior, a close friend, he studied stress wave propagation by combining spark photography with photoelasticity (2), which led to his lifelong interest in brittle fracture. In the mean while he became increasingly disenchanted with the condition of employment at Rosyth, and at the end of the war he accepted a post in the Research Department of Babcock and Wilcox, Renfrew, concerned with pressure vessel analysis. This led to an interest in the stress distribution in a plate with a rim reinforced elliptical opening (3), which with too little advice he unsuccessfully submitted for an external London PhD.

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

However, Professor J. F. (later Lord) Baker (FRS 1956), who was an Admiralty consultant, was aware of Alan's work at Rosyth and offered him a research assistantship at an attractive salary in the Engineering Laboratories of Cambridge University. This was a new venture involving jointly supervised research between the agricultural and engineering departments, and it examined the mechanics of the mole plough used to drain heavy, clayey land. Alan was responsible for devising the experimental equipment and the instrumentations needed (4) and for conducting tests on a range of soil types. He showed how the large shear forces developed on the flanks of the plough caused extensive fracturing in the surrounding soil, thereby greatly increasing drainage collection.

Professor Baker encouraged Alan to study for a PhD and organized his affiliation at Clare College. At that time there was a very active interest in soil mechanics in the Engineering Department, led by K. F. Roscoe, and an ideal topic emerging from the mechanics of mole drainage was a detailed study of the mechanical properties of surface soils in relation to agricultural ploughing. The unexpected results caused some problems with the external examiner from Oxford, which were only favourably resolved after Sir Geoffrey Taylor FRS was consulted as an arbiter. During this period Alan married Rosemary (*née* Mitchell) in June 1950.

British Welding Research Association—phase 1, 1951–64

Alan Wells joined the BWRA in 1951 through links with Professor Baker of Cambridge University Engineering Laboratories. The early engineering research activities into the plastic theory of design for welded steel structures were led by Professor Baker, who had had a positive influence on the acquisition of Abington Hall, some six miles southeast of Cambridge, as the new research centre for the BWRA in 1946. The site had been used by the Ministry of Defence during World War II and the BWRA obtained about 30 acres for £4000. This site still houses the main laboratories and headquarters of the Welding Institute (TWI), although with continued growth and development it now also houses a substantial Science Park (Granta Park) and the new TWI building.

Wells soon became Chief Research Engineer and then, when Richard Weck (FRS 1975) was appointed Director of Research, Wells became Assistant Director of Research. In the early 1960s he was appointed Deputy Director of Research. He had a brilliant mind for devising intricate experiments using carefully chosen and assembled available equipment and developing theoretical analyses to explain the results and predict general behaviour. Particular examples of some of his work will be described in the following sections.

Heat flow, cutting and resistance welding

In his initial work at the BWRA, Wells became involved in transient heat flow in fusion and resistance welding and in combustion studies for oxygen cutting (5, 9, 10 14). The basis for the theoretical studies of heat flow in welding was the classical solution for heat dissipation by conduction from a moving point source due to D. Rosenthal (Rosenthal 1946), but Wells had to allow for the efficiency of heat transfer from the welding arc or cutting flame. By careful calibration of experiments against the theory, he was able to predict the width of the melted bead for a given material and arc energy heat input. He showed a relationship between the appearance of the ripples on the weld surface and the heat input and weld travel speed used to deposit the bead (5). In studies with D. K. Roberts (9), Wells was able to establish theoretically the width of plates necessary in laboratory trials to represent large-scale structural behaviour in so far as cooling rates and heat flow conditions are concerned. Further studies with D. K. Roberts and J. E. Roberts (14) again combined theory and careful experimentation, using thermocouples introduced into the weld zone region, to predict thermal cycles, peak temperatures and cooling rates in resistance spot welding with a view to controlling post-weld heating cycles for tempering purposes.

The studies by Wells on oxygen cutting were so innovative that his paper reporting the results (10) had a 'caveat' foreword by the chairman of the BWRA committee of industrialists to whom the work had been reported. This said that the committee was aware that there are important differences between the conditions of the experiments reported and practical cutting conditions that might render it unsafe to draw too general conclusions. Wells set up experiments that consisted of feeding a rotating circular bar of material into an oxygen jet directed perpendicularly to the axis of the bar, with combustion initiated by a carbon arc directed at the end of the bar. The combustion rate was determined from the rate of melting of the bar and limiting conditions were determined by increasing the axial feed rate until combustion was on the point of ceasing. The heat balance effects in the experiments were checked with a radiation pyrometer to measure the combustion face temperature. The velocity distribution of the oxygen flow from the flattened nozzles used was shown to be uniform by measurements with a Pitot tube traverse. Different compositions of steel were included in the experiments, as were different purities of oxygen. Wells concluded that the rate of heat generation by combustion for unit area of combustion face depended, for commercially pure materials, on the possible rate of diffusion of oxygen to the combustion face through a stagnant boundary layer of gaseous impurities. The implications of this conclusion on the importance of the purity of the gas for effective cutting were too much for the committee to swallow from a young research worker with relatively little experience in the field!

Seminal studies on brittle fracture in structural steels

After his early experience with the Admiralty at Rosyth, soon after joining the BWRA, Wells became fascinated with the problem of brittle fracture of the Liberty ships and T2 tankers made by welded construction from World War II onwards. He was stimulated by the theoretical work of Irwin at the US Naval Research Laboratory (NRL) in applying the Griffith hypothesis of a critical rate of strain energy release for fracture of brittle materials, and his work in this area will be discussed later. Wells recognized that if George Irwin (ForMemRS 1987) and Egon Orowan FRS were right and the Griffith theory of fracture had to be modified for the case of structural steels to allow for the consumption of strain energy released by the fracture in the form of local plasticity at the crack tip, then this plasticity would lead to a local but measurable transient temperature wave as a fracture passed by. To study this he used his experience in experimental stress analysis and heat flow to devise experiments with thermocouples to give an oscillograph trace of the temperature wave due to a passing brittle fracture (6). The theoretical predictions of the magnitude of the temperature fluctuation were based on the same equations due to Rosenthal that Wells had used for his studies of heat flow in welding described above. He showed that energy necessary to propagate the brittle fracture came entirely from the stored elastic energy in the plates and not from the external loads, and was able to demonstrate the ability of residual stresses to contribute to fracture propagation. This work so impressed George Irwin, who was leading research into fracture mechanics at the NRL, that it led to an invitation for Wells to spend a year's sabbatical period at the

NRL. A lifelong friendship and productive collaboration between the two resulted from this period.

Many researchers were trying to investigate the brittle fracture problem at this time, and several different tests were developed. Although these could show the transition from ductile tearing fracture to brittle cleavage fracture as the temperature was reduced, none of them could reproduce the service problem of failure at low applied stresses, below yield and within normal permissible design stresses. Wells quickly recognized the importance of welding on the brittle fracture problem, with respect to both the effects of residual stresses and metallurgical effects from the localized heating influence of welding. He started to try to quantify effects of material properties on safe working temperatures for welded construction, including initial considerations of limiting flaw sizes, in a paper in the *Journal of the West of Scotland Iron and Steel Institute* in 1953 (7). In this same paper, he recognized the importance of strain hardening in limiting the strains that could occur locally at crack tips under contained elasticity conditions such that, in notched bars in general, fracture would not occur until general yield of the full cross-section. However, he also noted the work of T. W. Greene (Greene 1949), which had shown spontaneous brittle fractures on cooling for large plates containing a butt weld into which artificial crack-like defects had been introduced before welding. Wells received the President's Gold Medal for his paper to the Society of Engineers on brittle fracture in Liberty ships in 1954 (8).

The failure of oil storage tanks during hydrostatic testing at Fawley was one of the factors that led Wells, on his return from the year at the NRL, to develop the notched and welded wide plate test (which became known as the Wells wide plate test) as a structural test for brittle fracture. He showed that this could be used to indicate the strength of welded plates containing artificial defects in tension to determine safe operating temperatures for different grades and thicknesses of steel. Effectively this involved testing similar specimens to those of Greene, approximately 3 ft (about 1 m) square with a butt weld along the middle of the plate width and artificial fine sawcut defects introduced into the weld preparation before welding, but with externally applied loading in tension. To demonstrate safe behaviour it would be necessary to find the temperature at which plates could withstand loading up to general yield. The cross-sectional area of the plates of 1 inch thickness (25 mm) was 36 in^2 (23 225 mm^2) and to raise such plates to general yield would require loads of 600 tonnes (6 MN). No conventional testing machines were available for the width of plate and load capacity required, so Wells designed his own (11). There was no question of using conventional design codes—the rig was designed to reach the yield strength of its own members at its maximum load to produce yield stress in the test specimen. To achieve the loads required, Wells designed four high-pressure hydraulic capsules, two on each side of the test plate. Recognizing that only limited displacement of the order of ± 0.2 inch (5 mm) was required, he designed a sealing system in which the space between the head and the body of the capsule was bridged by a flexible high-strength aluminium alloy ring of cross-section $\frac{3}{4}$ in $\times$ $\frac{3}{16}$ in (19 mm $\times$ 4.75 mm) that located on the outside rim of the head and inside annulus of the body and twisted as the two parts moved relative to each other. The system required care in alignment and setting up, but the dedicated technicians involved managed to make it work very effectively. With high loads and a large cross-sectional area, a considerable amount of strain energy was released by the brittle fracture of the test plates. The early work on the notched and welded wide plate test was conducted in one of the Nissen huts on the lawn of Abington Hall left by the Ministry of Defence after the war. After his retirement Wells recalled that no

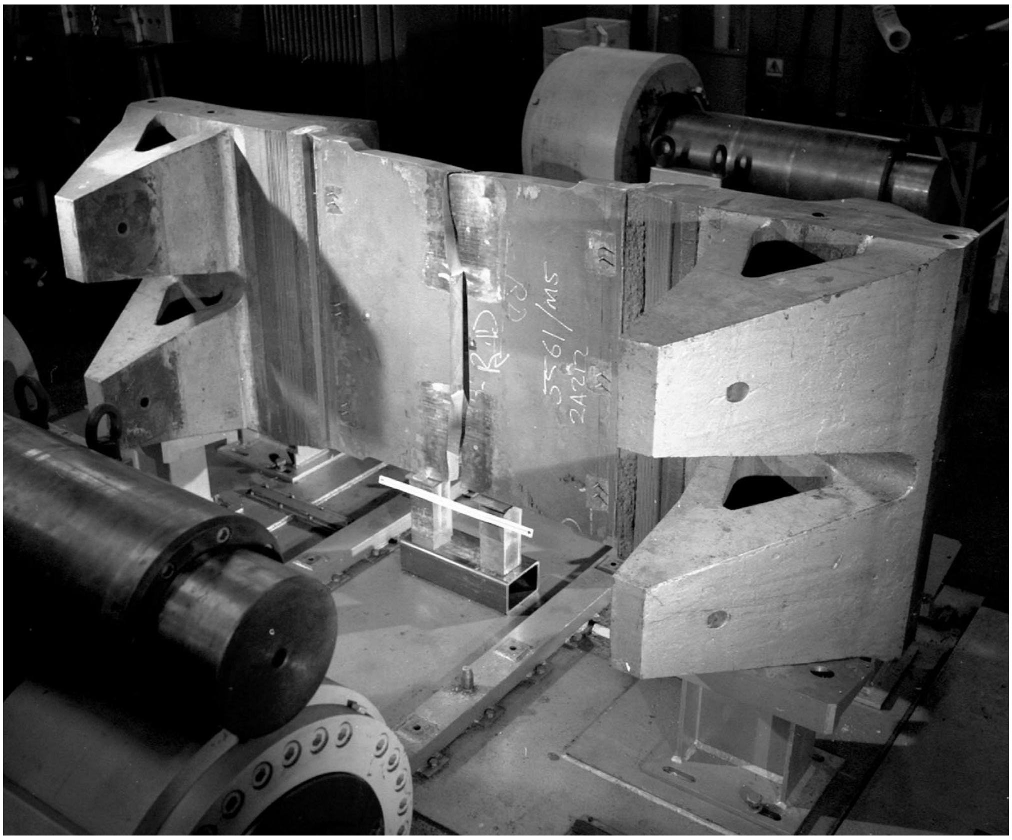

Figure 1. The 40 MN Wells wide plate testing rig. (Copyright © TWI; reproduced with permission.)

one involved would forget the first successful fracture test when the wire ropes provided to stop the ends flying apart proved quite inadequate and half a tonne of equipment flew out of the end of the hut. He then designed a neat method of absorbing this energy by connecting the two ends of the rig together with tie bars on which were mounted crushable steel tubes that collapsed in characteristic corrugated patterns. In due course, similar, larger machines were designed and built with load capacities of 2000 and 4000 tonnes (20 and 40 MN). A picture of the 4000-tonne rig is shown in figure 1.

The first results from a series of notched and welded wide plate tests attracted much attention and controversy. Wells's paper in *Transactions of the Royal Institution of Naval Architects* in 1956 (12) provided a step change in the understanding of the brittle fracture problem. It included the results of a series of notched and welded wide plate tests, some of which showed short arrested brittle fractures at low applied stresses and one of which showed complete fracture at a stress of about two-thirds of the yield strength. This led Wells to suggest that there was a 'calamity temperature' for steels at which propagation to failure would occur and below which only short arrested fractures would occur. Reloading of these specimens with arrested cracks always required the application of loads sufficient to cause general yield on the remaining cross-section. The tests included cases in which specimens had been preloaded to the yield strength above the ‘calamity’ temperature and then reloaded to failure at lower temperatures. In all cases the preloaded tests withstood higher stresses than the preload condition, despite being tested under conditions at which low-stress fractures would be expected without the preload. Wells was able to explain the effects of preloading in providing mechanical stress relief of the residual stresses. This paper also included the usual Wells sophisticated theoretical analysis of the results. The discussion session at the meeting at which the paper was presented showed a variety of levels of understanding, with some contributors describing the work as promising although limited in scope, lacking sufficient interpretation and praiseworthy. Several contributors doubted the evidence for a ‘calamity’ temperature and this was quickly acknowledged as not justified by Wells himself. However, the importance of this paper was recognized in a written discussion from G. R. Irwin, who concluded that he would treasure his copy of the paper for further study and reference.

There followed a series of investigations performing wide plate tests on different types and thicknesses of steels to determine safe minimum working temperatures, with some degree of calibration to Charpy V-notch impact test results for each steel. Variations were introduced with cross-welded wide plate tests in which the fracture was made to run in the weld metal or heat-affected zone of a transverse weld made before the specimen was then prepared with the longitudinal butt weld and sawcut defects located in the transverse weld. Tests were also conducted on specimens subjected to post-weld heat treatments at different temperatures to confer benefits from relief of residual stresses and removal of some types of metallurgical embrittlement. One of the major investigations in this series was sponsored by the pressure vessel industry to produce recommendations for minimum safe temperatures for as-welded and post-weld heat-treated pressure vessel steels (17). The results of these tests were used as the basis for the low-temperature appendixes of the British Standards for pressure vessels and vertical storage tanks and still form part of the background to these requirements. Although some wide plate tests are occasionally performed, developments in fracture mechanics methods from the 1970s have largely replaced the need for the full-scale tests.

Contributions to fracture mechanics

Almost from his first involvement in fracture research, Wells recognized the importance of fracture mechanics methods and used them to guide many of his studies, both theoretical and experimental. The work on the temperature wave produced by a propagating fracture attracted the interest of Irwin; as a result, Wells made many exchange visits to the NRL in Washington, and Irwin made several visits to the BWRA at Abington. Whereas Irwin was mainly concerned with high-strength steels for use in rocket motor casings and for which linear elastic fracture mechanics provided a satisfactory basis, Wells was primarily concerned with welded structural and pressure vessel steels that normally showed yielding and plastic behaviour but could also fail by brittle fracture. The recognition that fast unstable fracture was not confined to the brittle fracture problem of structural steels was shown by Wells in his assessment of the Comet aircraft failures. Although attributed by the official inquiries to fatigue, Wells demonstrated that the high-strength aluminium alloys used in the aircraft fuselage could fail by unstable fast fracture from relatively small initial fatigue cracks and that the real problem was the inherent fracture toughness of the material. At that time, the concept of fracture toughness in aircraft alloys was not understood by the industry, although fairly rapidly it became a major consideration, as it is today.

The major contribution that Alan Wells made to the application of fracture mechanics to low-strength structural steels was his introduction of the concept of 'crack opening displacement' (or crack opening dislocation (COD), as he originally called it) in his paper to the Cranfield Crack Propagation Symposium in 1961 (16). He argued that the occurrence of plasticity at the tip of a crack allowed the surfaces of the crack to move apart physically at the crack tip as the plastic zone spread ahead of the tip. He proposed that the COD would be uniquely related to the plastic zone size, crack extension force and stress intensity factor. He also proposed that the COD in a Charpy test specimen would be determined by the angle of bend and the position of the axis of the plastic hinge in the specimen. He took account of the effects of triaxiality or constraint, by distinguishing between plastic zone sizes under plane stress and plane strain conditions. He used this approach to derive a requirement for energy absorption in the Charpy test to tolerate a defect of length equal to the plate thickness at an applied stress of yield as follows:

$$U = \sigma_Y{}^2 T/40,$$

where U is the energy absorption in the Charpy test in foot-pounds, σ_Y is the yield strength in tons per square inch and T is the thickness in inches. It should be noted that this equation is not non-dimensional and the number '40' is specific to the geometry of the Charpy specimen and to the units stated. Although Wells tried to demonstrate that this analysis gave results consistent with those from notched and welded wide plate tests for the transition temperature to low-stress fracture, the resulting Charpy energy levels were regarded as very low by several other experts and were not widely adopted. The main concerns were about the theoretical nature of the link between COD and the Charpy test, about the application of plastic zone size analyses on the basis of small-scale yielding to large plastic zones and about the need to consider local metallurgical effects of welding. However, the COD approach (which later became crack tip opening displacement, or CTOD) was widely adopted and developed as a fracture criterion and as a basis for fracture mechanics treatments in the PD6493 and BS7910 approaches used extensively in the offshore and structural industries.

The development of the J-contour integral approach, based on the original work of J. R. Rice (ForMemRS 1996), took place in parallel with the CTOD methods. The two are broadly equivalent, but the J-integral approach has the advantage that it is more amenable to calculation by finite-element analysis methods. It should be noted that virtually all of the contributions made by Alan Wells were made without the benefit of finite-element methods, and most of his theoretical solutions were based on closed analytical methods.

Although Wells published several papers developing his ideas further in the use of COD methods to define transition temperatures for safe operation, including one in *Proceedings of the Royal Society* (18), the International Institute of Welding Houdremont Lecture (19) and the Welding Institute Larke Medal Award paper (20), they did not have the practical impact of the fracture mechanics treatment built into the PD6493 and BS7910 methods. The latter methods provided a basis for the assessment of the significance of defects, allowing for the effects of residual stresses and different standards of workmanship, whereas the thrust of Wells's recommendations was on the selection of materials.

The Houdremont Lecture (19) included an analysis of crack arrest conditions in wide plate tests, demonstrating that the combined effect of applied and residual stress conditions led to a region in which the combined stress intensity factor went through a minimum and this corresponded to the crack lengths at which crack arrest occurred. It developed the concept of COD as a fracture criterion on the basis of work conducted by Burdekin & Stone (1966) and attempted to define fracture transitional behaviour on the basis of the ratio of the notional plastic zone size to the plate thickness. Further attempts were made to develop a correlation between the Charpy V-notch impact energy absorption at the ductility transition from plane strain to plane stress conditions, and the thickness and yield strength of the steel. This was extended to produce results for the ratio of available Charpy energy to energy at the ductility transition versus ratios of half defect length to plate thickness for different ratios of fracture strain to yield strain. Although the work showed impressive correlations between theoretical analysis and experimental results, there were reservations by some experts about the need to consider residual stress and local weld properties in more detail and about the interpretation of defect sizes in wide plate tests.

Other contributions

Other significant contributions were made by Wells in the field of design of nozzles and manholes for pressure vessels and storage tanks. Of particular significance was the paper with P. H. R. Lane and R. T. Rose (15), which demonstrated that the design of nozzles in pressure vessels could be based on providing sufficient strengthening by thickening the nozzle itself rather than providing a reinforcing 'doubler' flange attached to the shell around the nozzle. Up to this time, conventional design had been by the area replacement method, in which the area cut out from the shell to form the hole for the nozzle was replaced as a reinforcing pad around the outside of the nozzle. The nozzle thickening approach was shown to be more economical and became an established alternative in the design codes.

He also used his experimental stress analysis skills during one of his early visits to the NRL to perform work with D. Post (13) on the dynamic stress patterns associated with a propagating brittle crack through photoelastic methods.

Academic life at Queen's University Belfast

In 1964 a Chair of Structural Science was created within the Department of Civil Engineering in the Queen's University of Belfast, and Alan accepted an invitation to fill it. Interestingly, the Head of Department, Professor Thomas Malcolm Charlton, was a fellow graduate of the year of 1943 in Nottingham University College. Also another fellow graduate, Professor Bernard (now Sir Bernard) Crossland (FRS 1979), was the Head of the Department of Mechanical Engineering. In 1970, when Professor Charlton left to take up the Chair of Civil Engineering in the University of Aberdeen, Alan became Head of Department, and from 1973 to 1976 he was also Dean of the Faculty of Applied Science and Technology.

He found the post a liberating experience, freeing him to indulge his natural innovative spirit. Almost as soon as he arrived in Belfast he became interested in the possibility of a tunnel between Northern Ireland and the Stranraer peninsula in Scotland. To drill such a tunnel under the deep waters of the North Channel would be enormously expensive, and Alan conceived of a tunnel to be built onshore, floated out and submerged. To back his proposal he organized research, including the erosion tests on the seabed in the vicinity of a model tunnel, which were carried out in Dundrum Bay. The proposal, together with what seemed to be a modest estimate of cost, attracted wide public and political interest. Under pressure the

Northern Ireland administration made a technical and economic assessment, which showed that the cost was greater than claimed and that this made it unviable.

In the early 1970s he recognized the potential for stabilizing light steel structures against local buckling by using bonded polyurethane foam, and this attracted a generous Wolfson Foundation grant. The high energy-absorbing capabilities of this composite form of construction, which he had expected, were demonstrated experimentally—a concept now widely used in the production of energy-absorbing components for cars. However, the oil crisis of 1974 led to a quadrupling of the cost of polymers, which made the idea unviable. As a consequence he approached the Foundation with a proposal to deflect the remaining funds to wave power, which was agreed.

By far the greatest contribution Alan made to wave-power technology was the invention of a novel turbine, which was named after him and patented by the university. It is fascinating to note that the Wells turbine was invented 130 years after the second Professor of Civil Engineering at Queen's, Professor James Thompson FRS, invented a turbine very similar to the Francis turbine. The Wells turbine rotates in one direction irrespective of the direction of axial fluid flow driving it. It works by the principle of lift in a similar manner to the keel of a high-performance yacht or feathered helicopter blades. In fact it was his earlier work on helicopter blades that gave him the idea. However, the clever step was to place several symmetrical aerofoil section blades set at zero angle of incidence around a hub, forming a turbine which is placed in a duct. The turbine is best suited to devices containing an oscillating water column in which waves force the piston-like motion of a column of water in a chamber with the air above blown and sucked through a Wells turbine. Thus low-speed reciprocating movement is efficiently transformed into high-speed rotational motion of the turbine shaft, which is used to drive an electrical generator.

In 1976, to demonstrate that his invention worked, he employed a graduate to undertake the initial research and build a quarter-scale wave-power device based on an oscillating water column for testing in a local sea lough. Although the structure was damaged during a winter storm in 1977, the operation of the turbine had been demonstrated and it became the most commonly adopted machine in prototype wave-power devices throughout the world during the next 30 years.

Although Alan left Queen's in 1977, his legacy of wave-power research was continued and expanded by his research assistant Trevor J. T. Whittaker, now Professor, under the supervision of the new head of department, Professor Adrian E. Long.

In the late 1960s Alan was approached by the Gas Council (subsequently renamed British Gas), which had experienced a long-running crack in a pipeline under test at one-third of the test pressure. As a consequence he addressed the brittle fracture of pipelines and argued that once a crack started it would travel at an axial velocity that exceeded the decompression velocity of the pressurizing gas. This led him to postulate that the energy driving the crack derived from the strain energy released, which allowed him to predict the level of fracture toughness required to prevent crack propagation.

In 1970 Dr R. W. E. (Ernest) Shannon had completed his PhD in the Department of Mechanical Engineering at Queen's; this was devoted to the fracture of thick-walled vessels under high internal pressure. He wished to continue work in the field of fracture mechanics, and during some literature research he happened across the problem of long running fractures in older gas pipelines, including one that had run for 16 km. When he happened to mention his interest to Alan, his response was to arrange a joint visit to the Gas Council Research Station near Newcastle upon Tyne, and to give him a copy of the report he had written on brittle fracture in pipelines.

It occurred to Ernest that it might be possible to model the brittle cracking phenomenon in small-diameter pipes if the material properties and gas dynamics were right. On their visit they sold the idea to the Gas Council team, which led to a research programme in the Department of Civil Engineering in Queen's under Alan's supervision. The results of extensive model fracture tests on pipelines enabled them to provide guidelines for design against brittle fracture in pipelines. They also undertook work on the ductile fracture problem and produced proposals that enabled the phenomena to be eliminated.

At that stage Ernest joined the Gas Council Research Station to continue his study of pipeline fracture, culminating in the production of new specifications for the inspection and repair of defective pipelines. This established the need for online monitoring of gas pipelines, and ultimately to his appointment as Project Leader of the British Gas intelligent pig project. In the meanwhile Alan, who had been a consultant to British Gas on pipeline matters, was appointed to the Company Research Committee chaired by the Chairman, Sir Denis Rooke FRS, as an external adviser. In that capacity he retained an advisory interest in the intelligent pig, which Ernest brought to a successful conclusion and which has been widely exploited worldwide.

In 1977 Richard Weck, the Director General of the Welding Institute, retired on the grounds of ill health, and Alan accepted the invitation to replace him.

The Welding Institute, 1977–88

Alan Wells returned to what had then become the Welding Institute (formerly the BWRA) as Director General in 1977. The previous Director General, Richard Weck, had been an organizational innovator with a very strong character who had driven the BWRA/Welding Institute to become a world-class research organization with a sound business basis. Wells considered himself to be an opportunistic researcher, but despite 13 happy years in Belfast, universities were beginning to experience more difficult times and with the political instabilities in Northern Ireland the opportunity to return to Abington was welcomed. The Welding Institute Council was looking for a period of consolidation after the years of Richard Weck, particularly in the development of courses, teaching and the professional side of the Institute. Wells had an able team of senior managers and received appropriate support on the commercial aspects of management such that the business remained sound. Of course, he could no longer be involved in detailed scientific research. Nevertheless there were still opportunities for innovative contributions.

When the Welding Institute decided to develop its electron-beam welding capability to a large scale, it required a vacuum chamber with a volume of several cubic metres. Wells designed a chamber using folded petal plates that was significantly cheaper than the commercial alternative from external consultants. Wells also designed the striking Members' Building (figure 2), also used as the main reception building for some years, which has now been converted to the library and bears his name as the Alan Wells Building.

Figure 2. The Alan Wells Building at the Welding Institute, Abington, Cambridge.
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The International Institute of Welding

The International Institute of Welding (IIW) is an organization involving most of the leading industrial countries throughout the world. It operates through a series of 16 'Commissions', each tasked with considering one particular topic related to welding. Each year there is an IIW Annual Assembly held in one of the member countries and attended by delegates, experts and observers from each country. Alan Wells became a regular attender at the IIW Annual Assembly soon after he joined the staff of the BWRA. He became the UK delegate to Commission X, concerned with residual stresses and stress relieving, although this Commission was also the centre of discussions on the brittle fracture problem. He rapidly earned the respect of all the other delegates from other countries, and his contributions were always regarded as incisive and authoritative. Every year he would set out by car to drive to any of the locations for the Annual Assembly in Europe, often with the vehicle laden with his latest reports and documents to be distributed to the other delegates at the Assembly. He retained his involvement with the IIW throughout his time at Queen's University Belfast and on his return to the Welding Institute as Director General. He was the chairman of Commission X from 1978 to 1988.

The respect in which he was held throughout the IIW was demonstrated when he was invited to deliver the prestigious Houdremont Lecture in 1964 at the age of 40 years. Through the contacts made at the IIW, Wells became one of the joint authors of an authoritative textbook on wide plate testing in 1967 (21). Subsequently he was awarded the Edstrom Medal in 1987 and he was the first recipient of the new Yoshio Arata award in 1994.

Innovative ingenuity

Alan maintained his interest in wave power after leaving Queen's, and when he retired in 1989 he turned his attention back to it. In the meantime the group at Queen's under Professor Whittaker had flourished, developing wave-powered navigation aids. In the late 1980s the team from Queen's built a small prototype wave-power plant based on an oscillating water column on the shoreline of Islay off the west coast of Scotland. An engineering company located at the Welding Institute won the contract to design and build a 75 kW Wells turbine generator set for the plant, shown in figure 3, and Alan, as a consultant to the company, was responsible for the conceptual design and analysis work. He was actively involved in bench testing, installing and commissioning of the unit on site. He was on site with the Queen's team when the plant was switched on and he joined in the excitement of witnessing the first kilowatt-hour of wave-power-generated electricity being transmitted to the national grid in the UK. In 1994 Professor Trevor Whittaker FREng, Professor Raghu Raghunathan and Professor Adrian Long FREng of Queen's University Belfast, and Professor Alan Wells OBE FREng FRS, Engineering Consultant, were awarded the Royal Society Esso Energy Award for their work on the design and development of shoreline wave-power stations.

At the start-up of the Islay plant Alan met a Scottish entrepreneur, Allan Thomson, who was interested in wave-power technology. Later that year a new company, ART Ltd, was formed with Allan Thomson as managing director and Alan as technical director, a position he held for 10 years. Thus began a very productive period when Alan spent much of his time developing novel wave-power concepts, pushing the laws of physics to their limit. The essence of each concept was a deep physical, theoretical insight combined with the elegant efficiency of pure geometric shell structure and the absolute simplicity of power take-off. Alan always maintained that in the harsh marine environment it was these three principles that would ultimately combine to produce commercial success. He also contributed to two further prototypes, the OSPREY device in 1995 and LIMPET in 2000. LIMPET, which again was a joint venture with Queen's, is still operational today and is one of the most successful wave-power plants in the world so far. It has produced an output of 200 kW delivered to the grid and is capable of 500 kW if located in a deeper site.

However, this is not the end of the story because during Alan's last five years he worked closely with his son Nick on yet another novel wave-power device concept, which is currently under development. Professor Whittaker has teamed up with Allan Thomson and a new wave-power device is to be launched in due course. Although Alan did not live to see the full-scale commercial development of wave power, his immense contribution has shaped the future and his legacy lives on.

Alan Wells was full of ingenious ideas outside the world of professional scientific research. In 1958 Alan and Rosemary bought the beautiful sixteenth-century Guild Hall in Linton and he put in his own design of central heating in which steam rose through pipes to the top of the house and then condensed and ran back down the same pipes to the boiler at the bottom. He said that the children rapidly learnt not to sit on the pipes! He built a welded aluminium boat, and scared the life out of the local community when he wanted an aluminium oil-storage tank for his heating system and built it out of flat petals before inflating it with air pressure in an open field on a Saturday morning to blow it out into a sphere.

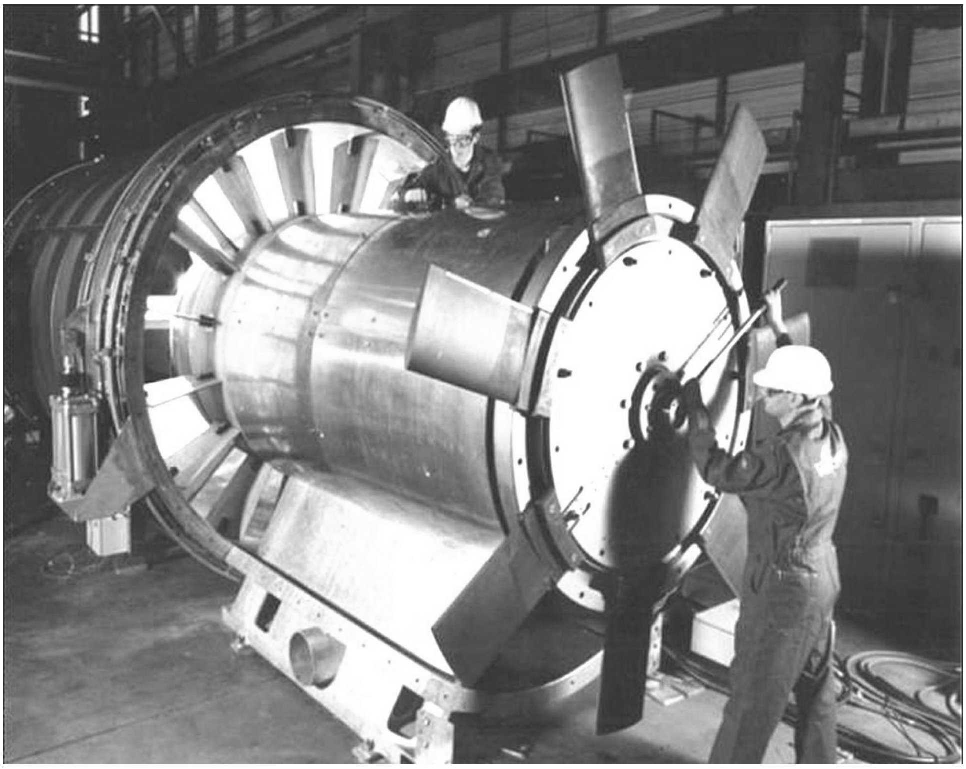

Figure 3. A Wells turbine under assembly. (Copyright © Queen's University Belfast; reproduced with permission.)

Personal reflections

Reflections by B.C. on A.A.W. as a person

From a young age Alan was a quiet contemplative thinker, even as an undergraduate, but still waters run deep. Many will remember him, pipe in mouth, listening and contemplating the debate going on around him, and occasionally making a very perceptive comment. He was a master at the end of a long and sometimes tendentious meeting in delivering a résumé of the discussion, and not infrequently reaching a conclusion that, one suspects, was probably his objective from the beginning. He was a most innovative thinker who stimulated great loyalty from those who worked for him or with him. He was generous with his time and a valuable source of good advice to all who sought his views, and he will be sorely missed.

Reflections by F.M.B. on A.A.W. as a person

Alan Wells was one of the most able and original engineers it has been my privilege to know. He was quiet and modest, and was a kindly man but with a determination to carry through whatever needed to be done. He was never confrontational and always listened patiently to others, but his capacity for lateral thought and problem solving was such that he nearly always persuaded meetings to adopt his solutions. He sometimes gave the impression of being absent-minded or rather of being preoccupied with higher thoughts. You were never sure that he had put his pipe out before he put it in his coat pocket. When travelling with him by car, it was wise to carry additional cash to ensure that the petrol tank could be refilled.

Brittle fracture failures were relatively common during his early years at the BWRA; he was in high demand to conduct investigations, and I was privileged to be involved with several of these. Among those in which he was involved were the failures of the Fawley oil tanks, King's Bridge in Melbourne, a hydroelectric scheme spiral turbine casing at Ffestiniog, and a boiler at Sizewell nuclear power station, the latter two during initial hydrotesting. Later he became an expert witness in the legal case after the fracture of an oil tank in Qatar, which was particularly difficult because much of the evidence had been damaged by the ensuing fire, and several of his friends and colleagues were also involved on the other side. After his retirement he was involved as an expert adviser in the inquiry into the Clapham rail disaster.

The importance of the collaboration and friendship between Wells and George Irwin is reflected in the Royal Society Biographical Memoir of George Irwin written by Alan Wells in 2000 (22).

Honours and awards

1942	Bayliss Prize, Institution of Civil Engineers
1946	Miller Prize, Institution of Civil Engineers
1955	President's Gold Medal, Society of Engineers
1956	Premium Award, Royal Institution of Naval Architects
1964	Houdremont Lecture, International Institute of Welding
1966	Hadfield Medal, Iron and Steel Institute
1968	Larke Medal, Institute of Welding
1969	Honorary Fellow, Institute of Welding
1973	Honorary Doctorate, University of Ghent
1975	Member, Royal Irish Academy
1977	Fellow, Royal Society of London
1979	Fellow, Royal Academy of Engineering
1982	Rupert H. Myers Award, University of New South Wales
	Officer, Order of the British Empire
	DSc (*honoris causa*), University of Glasgow
1983	Ludwig Tetmajer Award, Technical University of Vienna
1984	Freedom of the City of London
1986	DSc (*honoris causa*), Queen's University Belfast
	Platinum Medal, Institute of Metals
1987	Edstrom Medal, International Institute of Welding
1994	The Esso Medal, Royal Society
	Yoshiaki Arata Award, International Institute of Welding
1999	Honorary Fellowship, Institution of Mechanical Engineers
2003	Named for Professional Members Building and Library at the TWI, Abington

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The frontispiece photograph was taken in 1994 by Prudence Cuming Associates.

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