RONALD BULLOUGH
6 April 1931 — 20 November 2020
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Elected FRS 1985

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Ron Bullough spent most of his career at the Harwell Laboratory of the UK Atomic Energy Authority (AEA). He was a theorist with a special ability for collaboration with experimentalists. He is known for his research relating to the theory of dislocations and their role in setting the properties of metals, including their ductility and resistance to fracture and, in particular, the influence of dislocations on the development of damage during irradiation, an aspect upon which he was probably the world authority. During the latter part of his career he carried substantial administrative responsibility as Chief Scientist of the AEA while still maintaining a significant presence in fundamental research, including studies relating to the stability of strained-layer semiconductor devices.

Early years

Ron was the fourth son of Ronald Bullough, Company Secretary and Cashier of a bleaching company, and Edna, née Morrow, housewife. He was born and brought up in Farnworth, Lancashire. His eldest brother, Clifford, fourteen years his senior, became an art teacher and an accomplished pianist. His second brother, Roy, died in his teens. His third brother, Kenneth, four years older than Ron, became a Reader in Radio Astronomy at Sheffield University.

Ron’s father was also an accomplished artist and violinist, playing in the Northern Symphony Orchestra and other local orchestras for musical shows. Ron’s mother sadly died when he was six years old and he was cared for by several nannies until the outbreak in

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1939 of World War II. Nannies were no longer available, mostly through the demands of munitions factories, and Ron was left largely to fend for himself during the day. According to his own account, he interacted well with the local lads, playing such ‘games’ as dodging into cinemas through the back door between performances, to watch the next show for free, and experimenting with chemicals to make fireworks. On one occasion, he and his brother Ken lit fireworks in the fireplace, set the chimney on fire and were duly reprimanded by the local fire warden. Ron neglected his school work and failed his eleven-plus exam. His father paid for him to attend Farnworth Grammar School until fees were abolished under the 1942 Education Act.

By this time, a local cotton mill worker took pity on the family and offered to help them with meals. Clifford was serving in the Army so Ron and Ken were left unsupervised to do the shopping and housework. Some weeks they ran out of rations and survived on school meals and jam ‘butties’ for tea. Ron’s father had his mid-day meal in a local café and spent most evenings practising the violin or attending drawing classes. He tried, unsuccessfully, to teach Ron the violin: Ron was strong and full of energy and preferred to play football outside with his friends.

At school, he continued to enjoy himself at the expense of study and was frequently admonished and compared adversely with his more studious older brother: the phrase ‘could do better’ appeared regularly in his school reports. He nevertheless found an interest in mathematics in the sixth form (now, years 12 and 13), obtained excellent results in his A-level exams and was accepted at Sheffield University on the mathematics honours course.

In retrospect, Ron considered that his early life, mixing with less-privileged playmates and deprived of his mother’s care, taught him how to deal sympathetically with persons less fortunate or less able than himself, and how to survive in adversity.

Sheffield University

Ron thrived at Sheffield University and apparently shared digs with a number of interesting people, including the playwright Jack Rosenthal (1931–2004), who read English and enhanced Ron’s education by discussing with him the books he was required to read. Ron’s own formal studies went well and in due course he was awarded his BSc with first class honours. An encounter of still greater significance was meeting Ruth Corbett, a student of English, French and Latin at Sheffield, at a Saturday night hop in the Students’ Union, during his first year. They married on 31 July 1954. More detail of their family life will be given later.

Not all of his time at university was devoted to study. Ron continued to play football and tennis (and continued with the latter until he was 80). He also once told the writer that he was spurned by the University Rugby Club because he had played a few games of rugby league while at school. This has not been confirmed by Ruth, but Ron told the same story to Professor David Bacon. Ruth did, however, fill in the details of the story to follow. He had a motor bike for getting around Sheffield, including riding on occasions in evening dress, with Ruth riding pillion, with the result that both would arrive in a dishevelled state at their destination, usually a dance. Ruth was a keen dancer but Ron apparently could only manage a basic waltz and quickstep. An adventure related to the motor bike was a summer holiday tour of Europe with a university friend. An accident in Italy resulted in two broken fingers. Later, in France, the bike’s frame broke and was repaired by a kind local man. But it broke again when Ron was
close to the border between Germany and Belgium. Ron was broke too but luck was once more on his side. He met, by pure chance, another university friend, Hugh Young (later Professor of Mathematics at the University of East Anglia), who was also touring Europe. Hugh lent Ron the money to have his bike repaired.

After graduating in mathematics, Ron took the unusual step of pursuing research for a PhD in the Department of Metallurgy. His research was supervised, however, by a very unusual metallurgist, B. A. Bilby (FRS 1977), whose attributes included a serious talent for mathematics. Ron’s first research, in collaboration with Bilby, was the calculation of the stress generated near the tip of a moving crack and its influence on the formation of twins; the theory fitted well with observations for a cleavage crack in single-crystal zinc. His next work was to study a dislocation moving with uniform speed though an anisotropic crystal. This theoretical work was of a fairly conventional kind but it delivered results of practical relevance. It is perhaps worth noting at this point that dislocation theory had been gaining acceptance only over the previous few years and the existence of dislocations was only confirmed by transmission electron microscopy in December 1955. What followed next was a great conceptual advance. The paper (1)* by Bilby, Bullough and Smith considered the limiting case of a crystal containing many dislocations by regarding them as ‘smeared out’ into a continuous distribution, resulting in a description of the dislocated crystal that employed non-Riemannian geometry. The notion that curves in the deformed crystal could be mapped onto curves in a reference undislocated lattice could be applied only locally, to infinitesimally small segments: the lattice would otherwise be disjoint, or else it had to reside (conceptually) in a non-Riemannian space in which infinitesimal parallelograms would fail to close. The closure failure reflected the ‘torsion’ of the space and corresponded physically to the dislocation density tensor. Viewed in this way, the dislocated crystal could be regarded as a real-world realization of a non-Riemannian space. The third author, E. Smith (FRS 1996), was also Bilby’s student and an exact contemporary of Ron. What a start for both of them!

Ron produced one further paper with Bilby before leaving Sheffield. This was also on continuous distributions of dislocations but confined to an array on a surface, which could be treated with less sophisticated mathematics. The application was to a glissile array of dislocations whose lines and Burgers vectors were in the plane of slip and which, with suitable choice of directions, could model the spread of a martensitic transformation.

**ALDERMASTON**

After completion of his PhD, Ron’s first appointment was to a research post at the Associated Electric Industries Central Research Laboratories at Aldermaston Court, Berkshire. Ron Newman (FRS 1998) started on the same day. They became collaborators and lifelong friends.

Ron’s first research in his new post had some overlap with his work on surface dislocations at Sheffield, applying similar methodology to describe the development of deformation twins in crystals with diamond structure. Thereafter he branched out but remained within the general sphere of dislocation theory. It is not possible here to describe every one of his papers but the aspect of his time at Aldermaston Court that must be mentioned is his fruitful interaction with Ron Newman. This generated at least 15 journal publications, mostly treating the interaction

* Numbers in this form refer to the bibliography at the end of the text.
of point defects with dislocations. Representative examples include important works (2, 4, 5) on the precipitation of impurities on dislocations, allowing for self-diffusion, drift induced by the dislocation’s stress field and the saturation of impurities at the dislocation cores, and an associated study (6) of strain ageing. The paper (3) is somewhat different in developing and exploiting the much more complicated stress field of a prismatic dislocation loop to analyse the spacing of an array of such loops, regarded as having been generated from the surface of a misfitting impurity—in effect, the opposite of a pile-up of loops. Whereas Ron B. was always a theorist, Ron N. also performed experiments in support of some of their joint work. Both relished this sort of interaction and both repeated it with others in their subsequent careers.

**HARWELL: THEORETICAL PHYSICS DIVISION**

It is hardly surprising—given his already-established expertise in point defects and their interaction with dislocations—that he was attracted, in 1963, to join the Irradiation Damage and Theoretical Metallurgy Group within the Theoretical Physics Division of the Atomic Energy Research Establishment (AERE) Harwell Laboratory. Ron became Head of that group in 1966, when its first head, Alan Lidiard, moved up to become Head of the Theoretical Physics Division, replacing Walter Marshall (FRS 1971, Sir Walter from 1981, and Lord Marshall of Goring from 1985), who had been promoted to become Deputy Director of the entire Laboratory. Ron once told the writer that, during the interview process for his appointment, he asked Walter Marshall about prospects for advancement if he joined AERE. Walter’s response was to lean back in his chair, put his feet on the desk and reply ‘Look at me’. Ron was duly persuaded! Not very long after Ron’s arrival at Harwell, he was offered, unsolicited, a Chair at a prestigious university in the USA. Walter convinced him to stay by proposing that Ron take a year off, which Ron did, becoming a Visiting Professor at the University of Illinois for the year 1964–65; during subsequent years, Ron accepted visiting appointments for two or three months, at a variety of prestigious institutions, in the USA and elsewhere. Within Harwell, Ron quite rapidly received promotion to Special Merit Senior Staff status.

Ron’s easy, approachable manner coupled with a reassuring air of confidence enabled him easily to fit in at Harwell and almost immediately led to collaborations with colleagues. One such early collaboration led to a paper (7) with A. J. E. Foreman that considered the orientation that would be adopted by a rhombus-shaped dislocation loop. Electron microscopy had revealed that small loops formed predominantly on \{012\} planes in a quenched aluminium alloy, rather than the \{110\} plane, which would minimize a loop’s perimeter and in fact is adopted if the loop is large enough. This was explained by calculating the energy of such a loop, with its edges constrained to the two relevant \{111\} planes but otherwise at arbitrary orientation. The observed orientations were explained by a careful analysis that took account of both the finite size of the loop and its core energy. The calculations assumed elastic isotropy; a corresponding calculation admitting elastic anisotropy was completed a few years later (9).

Ron’s collaboration with Brian Eyre (FRS 2001) was initiated soon after Ron’s arrival at Harwell and thrived until Brian departed to take a post at Liverpool University; their close friendship endured until Brian’s death in 2014. More will be written later about their subsequent professional interactions. Brian was a member of the Metallurgy Division. His experimental work was characterized by care and precision and ideally complemented Ron’s
Ronald Bullough

analytical skill. Their discussions over the years were a stimulus for each of them individually that extended far beyond the confines of their joint publications. The first of these (8) treated the formation of interstitial loops in irradiated body centred cubic (bcc) metals and still receives a modest stream of citations, 56 years after its publication. Interstitial loops had been observed to form under irradiation with Burgers vectors either \((a/2)(111)\) or \(a(100)\). The paper demonstrated how they could both be formed by crystallographic slip, from a common nucleus of a single platelet of interstitials on a \(\{110\}\) plane, with Burgers vector \((a/2)(110)\), perpendicular to the loop plane. The reasoning was again based on calculating the energy of the loop in a general orientation. The \(a(100)\) orientation had a higher energy barrier relative to the energy of the nucleus and was predicted to require higher temperature for its appearance. Several later publications were concerned with the interaction of point defects with dislocations, with motivation, either explicit or in the background, provided by the need to understand the effects of irradiation on critical components of nuclear power plant.

From the late 1960s to the mid 1970s the most promising long-term prospect for nuclear generating plant in the UK was considered to be the development of fast breeder reactors. In 1967 a paper was published showing some very interesting but ultimately disturbing observations of voids in stainless steel samples irradiated in the Dounreay Fast Reactor (Cawthorne & Fulton 1967). The possibility of such voids occurring in materials irradiated with energetic neutrons had been anticipated in the late 1950s (Greenwood et al. 1959) but had not been previously seen. These observations caused a lot of concern in the fast reactor community, as a new generation of prototype fast reactors (notably the prototype fast reactor at Dounreay, but also the Phénix reactor in France) were under construction. The volume changes associated with the voids would cause distortions in the cores of the reactors, as the phenomenon was sensitive to temperature and neutron dose, and it also was seen to be most significant in the operating regimes of the new reactors. An urgent request was made to Ron Bullough to provide an understanding of the new problem, which reflected a similar flurry of activity around the world and initiated a new interest in radiation damage, which had been until this time focused on irradiation hardening and embrittlement. The resulting research, initially with Roy Perrin using a lattice/cell model, and then with Alan Brailsford with the effective medium model, was important in understanding the experimental observations from Dounreay and the subsequent design and interpretation of simulations at Harwell using a 1 MeV electron microscope and various energetic charged particles (H, He, C, Fe) using accelerators. The main collaborators on the experimental side at Harwell, apart from Brian Eyre, were Stuart Nelson (a friend who also lived in the Goring area) and David Mazey on accelerators, and John Makin on the 1 MeV microscope, but there were many others. As well as Roy Perrin, a range of group members as well as visitors worked with Ron on the rate theory development—most notably in the mid 1970s Ron’s colleague Mike Hayns.

The outstanding technical problem (of course there were others as well) was that key components received massive doses of irradiation by neutrons, which generated damage in the form of cascades of vacancy–interstitial pairs (around 30 displacements per atom per year). This provided a major driver for the research of the Radiation Damage Group (figure 1) and for Ron especially, and contributed greatly towards his growing reputation as the world expert on irradiation damage. His collaboration with Alan Brailsford, who spent a small number of years as a senior researcher attached to Ron’s group, was of particular significance. Together, Ron and Alan developed an important methodology for assessing the effect of irradiation
that had similarities with the rate theory of chemical reactions. Their paper (10) was a major milestone. It considered local spatial variations to have been averaged out, leaving a set of nonlinear ordinary differential equations governing the evolution of the densities of interstitials and vacancies, in the presence of sinks due to sessile dislocations, grain boundaries and voids, all described by their densities or, in the case of voids, volume fraction. The sink strengths were estimated by solving a set of steady-state problems in which one chosen sink was placed in an environment whose properties were chosen so as to mimic the influence of the surrounding sinks. There were three stages in the development (explained in (13))—lattice or cell models where the sink strengths were just calculated on the basis of a sink-free zone around the sink, an effective medium approach with a sink-free zone surrounded by the effective medium whose sink strength was to be determined self-consistently, and a simpler effective medium approach for random distributions, with no sink-free zone and the effective medium extending to the sink being evaluated. Subject to solving this set of problems, the sink strengths were defined by a set of nonlinear algebraic equations and the rate equation formulation was complete. This formulation was widely adopted and was exploited to great effect by Ron and his associates in ensuing years. An important example is the paper (12) by Bullough, Eyre and K. Krishan (a visiting scientist from India), which admitted the possibility of reduction of the availability of vacancies due to the formation of vacancy loops in a damage cascade and their subsequent temperature-dependent shrinkage. The study explained the very dramatic differences in swelling, associated with the different damage rates due to irradiation by neutrons, carbon ions or high-voltage electrons. Paper (13) gives Brailsford and Bullough’s definitive account of the theory of sink strengths.

One issue with the basic rate theory model was that it relied on knowing the densities of the sinks, which could depend on quite complicated void nucleation processes depending on vacancy clusters in collision cascades, helium bubbles (from transmutation helium) or heterogeneous nucleation (e.g. on carbide precipitates). This problem was tackled by using hierarchical sets of rate equations—requiring a lot of computing power. This work was done mainly by Mike Hayns and Mel Wood (e.g. Hayns & Wood 1979); they do not appear in the group photograph (figure 1) because they had moved to senior positions in the AEA by 1985.

While the rate theory absorbed much of Ron’s attention during this period, he still continued with further studies on the interaction of point defects and dislocations, including clarification of a mode of irradiation creep due to a bias caused by applied stress in the way that dislocations attract vacancies and interstitial atoms—the stress-induced preferential attraction (SIPA) mechanism (11). The model of an interstitial atom as a hard misfitting inclusion was too simplistic to exhibit this mechanism. A more refined model, hard in compression but soft in shear, motivated from atomistic simulation, was required instead. There was a further foray into irradiation creep with a visit to the group by Frank Nabarro FRS in 1981, which resulted in a further mechanism being identified, also associated with the softness in shear of the interstitial atom (14).

There was also an interest in fracture mechanics, and Jim Sinclair was recruited to the group to reinforce expertise in this area. Later the issue of reactor pressure vessel embrittlement started to receive attention, with plans to build the first pressurized water reactor in the UK—Sizewell B. A particular problem Ron was proud of resolving was the loss of upper shelf ductility in low alloy steels, owing to sulfur (S) impurities. Some experimental observations of segregation of S to crack tips was explained by diffusion of S under the stress field from the crack tips (15).
The rate theory methods were applied by members of the group to a wider range of problems, such as fission gas swelling in nuclear fuels, and thermal creep and microstructural evolution in metals. This was in parallel with computer models of fission and fusion reactor structures, including detailed models of radiation damage and creep as well as thermal processes. This reflected a gradual change in the role of the Theoretical Physics Division to becoming a centre for computational modelling of complex systems—thermohydraulic finite element modelling, modelling of geological radioactive waste stores, structural integrity modelling of reactor components, performance and safety modelling of nuclear fuels. As a result, there was a tension in the group between the original role of developing theory in challenging areas and applying existing theory to develop computer models that could be used by third parties for design calculations or interpreting experimental results. This required a very different set of skills and attention to detail, including application of new quality assurance standards. Ron’s move to become Head of the Materials Development Division was at least in part prompted by these changes.

**The Materials Development Division**

By the mid 1980s, Ron had thoroughly consolidated his status as a scientist of international repute, working from the somewhat protected environment of the Theoretical Physics Division.
Division, but times had changed for the UKAEA and his talents were required elsewhere. He became Head of the Materials Development Division in 1985. The UKAEA had recently been put on a Trading Fund basis, facilitating its pursuit of commercial work, through its AEA Technology brand. In early 1985, the Sizewell B Inquiry into the case for Britain switching from advanced gas-cooled reactors to pressurized water reactors had been completed and it was expected that, once the industry had decided its preferred option, several of the chosen plants would be commissioned. The anticipated rise in the cost of uranium favoured the continued development of fast breeder technology for the longer term. The Chernobyl disaster of 1986 changed completely the public perception of nuclear power and by 1987 the only immediate prospect for civil nuclear power in the UK was the decommissioning of existing reactors as they reached end of life, and the building of the Sizewell B pressurized water reactor as a one-off project. Technical difficulties with the Dounreay prototype fast reactor in 1987 ensured the announcement of its planned shut-down in 1994. All that really remained for the long term was the maintenance of fusion research through the Joint European Torus (JET) project at the Culham Laboratory. Against this background the Harwell Laboratory had to become increasingly commercial and the Materials Development Division was an important participant in its transformation (figure 2). The Division comprised more than 300 staff distributed over ten Groups and four major Business Centres. Ron inevitably became an almost full-time manager, with much-reduced time for research.
In June 1988 Ron took up a new, elevated, position. The changes within UKAEA were continuing apace. It had been decreed that as part of the forthcoming electricity privatization, there was no longer a need for such a large public nuclear research organization. The part of the UKAEA concerned with longer-term fusion research, plus the liabilities for old research facilities that needed decommissioning and associated waste, would remain in public ownership but the rest was to have a commercial orientation with a view towards privatization and would henceforth operate under the name AEA Technology. It was structured as a group of nine high-technology businesses totalling about 9000 staff straddled across the nation. Ron was appointed Chief Scientist and Director of Corporate Research of AEA Technology. Ron shared the misgivings of the many AEA personnel who questioned the wisdom of the privatization and associated dismantling of the nuclear expertise at Harwell but he accepted the policy and worked hard and effectively to ensure its success. According to an account given in volume 1, issue 11 of R&D Efficiency, published in September 1992, his task was to ‘provide technical leadership in defining the corporate research programme and seeing that it meets the highest standards of technical excellence; ensuring that it contributes effectively to the sustained development of the businesses and laboratories; stimulating new research; overseeing quality and efficiency of technology transfer; providing technical advice to its chairman and chief executive’.

An early task was to characterize the AEA’s science, decide which of its activities would remain relevant in the new climate, and which should be merged or abandoned, to realize the aspirations of the nine newly formed companies, four concerned with nuclear and five with industrial businesses. Whereas the AEA had traditionally maintained a large underlying research programme, centred on the Harwell Laboratory, this had to change, to underpin the R&D services sold commercially by the businesses. Ron characterized this as ‘corporate investment in research and exploitation’ (CIRE) and was concerned to emphasize that this was investment for the businesses; research for its own sake could not be supported. The funding for CIRE came from the AEA’s business margin and was in competition with other investment demands. CIRE was not concentrated on Harwell but was spread across all sites. Clearly this was a big cultural shift and its implementation required all of Ron’s skills of persuasion supported by his personal charm and a degree of toughness. It is appropriate here to mention that Ron’s close associate Brian Eyre had returned to the AEA in 1984 as Director of Fuel and Engineering and he became CEO of AEA Technology in 1990. They shared the same vision for the future of the AEA and supported each other in accomplishing its transformation.

While most of the CIRE budget went into research of immediate relevance to the business activities, a relatively small amount remained available to support basic science, so long as this retained the prospect of future commercial exploitation. Perhaps the most high-profile (and most speculative) of these was Ron’s deployment of about £250,000 to check out the claim that cold fusion had been achieved in a laboratory. This followed a visit to Ron from the originators, Martin Fleischmann FRS and Stanley Pons, and a telephone call from the Prime Minister, Margaret Thatcher FRS. The conclusion of the study commissioned by Ron was that cold fusion had not been achieved.

Remarkably, Ron also found some limited time for personal research. In particular, Suresh Jain, a brilliant Indian scientist who had a long association with Harwell, approached Ron
about a basic question concerning the stability of strained-layer semiconductor devices. The question was when it would become energetically favourable for the relaxation of stress in the layer by the introduction of dislocations, and this required an accurate and unambiguous solution for the stresses and associated energies of a single dislocation as well as arrays of dislocations, in the proximity of a free boundary. Several papers resulted, of which (16), (17) and (18) are representative.

Also in 1988, concern for providing continuing support for the nuclear industry resulted in the setting up of a new group, the Technical Advisory Group on Structural Integrity (TAGSI), which was funded essentially by subscription from various parts of the nuclear industry. It was, in a sense, a successor to the Marshall Committee, whose main purpose had been achieved when its second report on the safety of pressurized water reactors, published in 1982, was accepted and resulted in the go-ahead for the Sizewell B pressurized water reactor. Ron was a member of TAGSI from its inception and chaired the Risk Sub-Group. His membership continued until long after his retirement and led to technical publications including (19) and (20).

**Retirement**

Ron retired in March 1993 (figure 3) and maintained contact with many close friends from his life in AEA throughout his retirement (figure 4). In addition to his membership of TAGSI, he held a position as Scientific Advisor to the National Physical Laboratory (for three years from October 1995), acted as a consultant for Atomic Energy of Canada (Chalk River and White Shell), General Atomics (San Diego) and Rolls Royce Marine Power. He also held Visiting Professorships at the University of Liverpool, University College London, and the University of California San Diego. He continued to publish research papers, with a variety of co-authors, on his special interest of the interaction of point defects with dislocations or other sources of
stress, including the edge of a crack, and on other topics including modelling a dislocation in a discrete lattice and more work on strained epitaxial layers. He was particularly pleased with one of his last papers (21) and its successor (22). Paper (21) explained the predominance at high temperatures of $a\langle 001 \rangle$ type dislocation loops over the $(a/2)\langle 111 \rangle$ type in irradiated bcc iron by allowing for the dramatic decrease with increase in temperature of the shear stiffness constant $c' = (c_{11} - c_{12})/2$, performing calculations of energy based on anisotropic elasticity as in (9). The value of the constant $c'$ approaches zero as the temperature approaches the temperature $T_c = 912^\circ$ C of the $\alpha \to \gamma$ phase transition. This softening towards the transition was attributed to thermal magnetic fluctuations in (22).

Ron was elected a Foreign Member of the US National Academy of Engineering in 2011, ‘For contributions to understanding radiation effects in solids and leadership in nuclear technology’.

**Family Life**

Ron married his fiancée Ruth Corbett while still a research student. They rented rooms in Sheffield while Ruth continued teaching and Ron completed the research for his PhD. They also rented rooms for two years when Ron moved to Aldermaston. Then they purchased a comfortable house in Earley, Reading, and had four sons: David, Timothy, Mark and Neil—by which time the house must have felt pretty crowded! Ron and Ruth were a charming and sociable couple and entertained many of Ron’s associates when they visited Harwell. Equally, Ron and Ruth were reciprocally welcomed during Ron’s many travels abroad. After some years, they moved to a larger house in Goring and (as the writer can testify) continued to
entertain many visitors. These facts are relevant to Ron’s career, because he and Ruth were held in universal affection, and collaboration with Ron was correspondingly a true pleasure.

In their youth, Ron and Ruth both displayed considerable prowess in sport, and after Ron’s retirement they took up golf, to quite a serious level. They enjoyed many golfing holidays with friends, especially in Florida during winter. Later, when Ron became less fit, they enjoyed holidays on cruise ships; whether or not Ruth managed to persuade Ron to share her pleasure in dancing is not known to the writer . . . .

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The author’s grateful thanks are due to Mrs Ruth Bullough and Professor Juan Matthews for invaluable input. The frontispiece photograph is used with permission from the UK Atomic Energy Authority. Permission to reproduce all other photographs was kindly granted by the copyright holder, the Nuclear Decommissioning Authority.

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