

The Victoria University of Manchester's contributions to the development of aeronautics

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1.0 INTRODUCTION

This issue of the Aeronautical Journal celebrates the 50th anniversary of the foundation of the Honours Degree Course in Aeronautical Engineering at the Victoria University of Manchester. The following article therefore describes the aeronautical research and teaching activities of that university up to its recent amalgamation with the University of Manchester Institute of Science and Technology (UMIST) to form the present-day University of Manchester. This juncture provides a further justification for recording the Victoria University's achievements.

Both the Victoria University and UMIST had their roots in the nineteenth century although, apart from the relatively brief period of the First World War, neither of them was particularly involved in aeronautics until after the Second World War. However, as Sections 6.0-10.0 seek to demonstrate, thereafter the Victoria University's involvement became considerable. The preceding Sections describe the origins of the Victoria University and UMIST and, in the case of the former institution, the subsequent activities of its staff and graduates in engineering and mathematics which, although not always specifically aeronautical in content, nonetheless had a profound influence on the development of the aeronautical sciences.

2.0 THE ORIGINS OF THE VICTORIA UNIVERSITY AND UMIST

The Victoria University of Manchester had its origins in Owens College, established in 1851 with nonsectarian status – unusual for the time – as a result of the substantial bequest left for this purpose by the Manchester philanthropist and cotton merchant, John Owens (1790-1846). Originally the College became housed in Quay Street,

Manchester, in what was formerly the home of the Stockport MP, Richard Cobden (1804-1865). In 1873 the College moved to the present-day site on Oxford Road and in 1880 a Royal Charter established a federal institution, the Victoria University, which came to include Owens College and the University Colleges of Leeds and Liverpool. However, in 1903 the three institutions went their separate ways, a further Royal Charter granting the title of the Victoria University of Manchester to the former Owens College.

UMIST began its life as the Mechanics' Institute, established in 1824 for the training of artisans by a group of Manchester scientists, businessmen and industrialists including John Dalton (1766-1844), Robert Hyde Greg (1795-1875), Richard Roberts (1789-1864) and William Fairbairn (1789-1874). A new building was opened in 1902 on Sackville Street, where the Institute's successor, the Municipal School of Technology, was subsequently to expand. However, so as to award BSc and MSc degrees, from 1905 the School also became the Faculty of Technology of the Victoria University. In 1956 the School's successor, the Municipal College of Technology, achieved independent university status under the guidance of Bertram Vivian Bowden (1910-1989), well known for his wartime work on radar, who had become the College's Principal in 1953. Having moved its non-degree courses to what was shortly to become Manchester Polytechnic (since 1992, Manchester Metropolitan University), in 1966 the College adopted its final name and the better-known abbreviation UMIST. Nonetheless, UMIST retained close academic links with the Victoria University until achieving full autonomy in 1993.

The above two institutions merged in October 2004, thereby creating the largest non-collegiate university in the United Kingdom and taking as its name the University of Manchester.



Figure 1. Osborne Reynolds (1842-1912), born at Belfast.
[Courtesy of Professor J.D. Jackson, University of Manchester.]

3.0 OSBORNE REYNOLDS

A number of eminent Manchester engineers, including Fairbairn, Joseph Whitworth (1803-1887) and Charles Frederick Beyer (1814-1876), were keen to see a chair of engineering established at Owens College. Their intention was to provide the burgeoning local engineering industry with a source of young people trained to degree level in engineering science. As a result, at the early age of twenty-five, Osborne Reynolds (Fig. 1) became elected to the newly instituted Chair in 1868, remaining in this post and that at the subsequent Victoria University until his retirement in 1905. Details of his career can be found in Ref. 1.

It is worth pointing out here that with Reynolds's appointment Manchester joined Britain's leaders in degree-level engineering education, though Britain itself remained somewhat tardy by European standards. France's prestigious *École des Ponts et Chaussées* had been established as early as 1747, whereas the foundation of the *École Polytechnique* in 1795 is generally considered to mark the beginning of a more general high-level engineering education. In Germany the first of the many *Technische Hochschulen* was founded at Karlsruhe in 1825. In the same year University College London was established according to the utilitarian principles of its founder, Jeremy Bentham (1748-1832), and in 1827 John Millington (1779-1868) of Hammersmith, experienced in canal construction, was appointed to teach civil engineering there. Millington having left for Mexico City two years later, in 1847 University College appointed Eaton Hodgkinson (1789-1861), born near Northwich, Cheshire, and a former colleague of Fairbairn in Manchester, as Professor of Mechanical Engineering Principles. A further British professorial appointment in engineering went to William John MacQuorn Rankine (1820-1872) at Glasgow University in 1855. However, as far as this author is aware, Reynolds's appointment in 1868 resulted in Owens College becoming the first British higher education institution to establish a degree-level course specifically in the subject of engineering.

Reynolds made a number of highly important discoveries, four of which had considerable influence on the subsequent development of

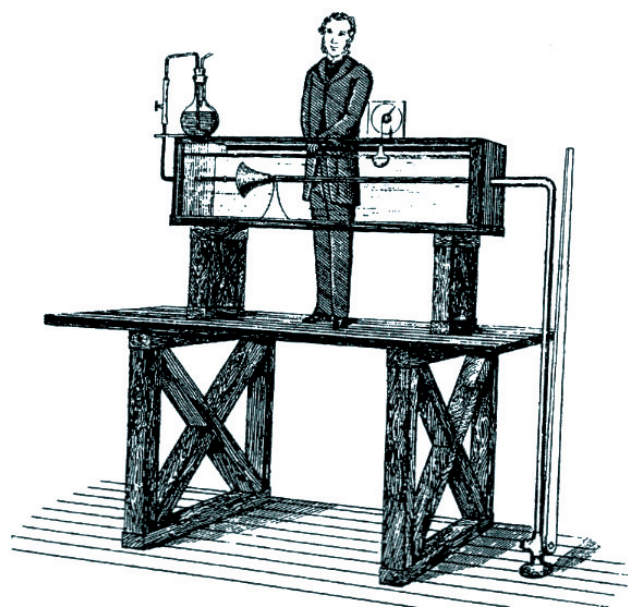


Figure 2. Reynolds's tank (1883).

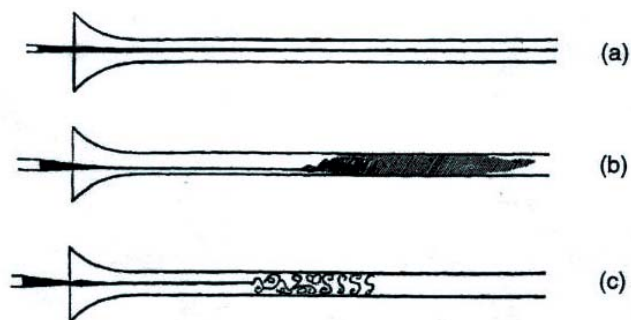


Figure 3. Reynolds's sketches of pipe flow (1883).

aeronautical science. The best known of these provided one of the earliest perceptions of viscosity's importance in all fluid flows and emerged in 1883 as a result of Reynolds's experimental work⁽²⁾ on the stability of water flow in pipes. His original apparatus (Fig. 2) still exists and is frequently demonstrated to students and visitors. His sketches, shown here as Fig. 3, illustrate the fate of the coloured flow filament introduced at the pipe's entry. Using three pipe diameters, different flow speeds and various water temperatures so as to change the viscosity, Reynolds found that the observed transition occurred naturally when the value of the non-dimensional quantity Vd/ν (V the mean flow velocity, d the pipe diameter, ν the kinematic viscosity) reached about 13,000. Nearly a century later, Reynolds's observations were repeated using his original apparatus; the photographic records of this shown in Fig. 4, reproduced in Van Dyke's collection⁽³⁾ of classic images of flow fields, can be compared with Reynolds's original sketches (Fig. 3).

The random eddies which Reynolds had observed in 1883 were named⁽⁴⁾ 'turbulence' four years later by William Thomson (1824-1907), later Lord Kelvin, and by 1908 Arnold Johannes Wilhelm Sommerfeld (1868-1951) was to suggest⁽⁵⁾ the name 'Reynolds number' for the non-dimensional quantity which had characterised transition in the pipe experiments. The use of such non-dimensional considerations had begun with George Gabriel Stokes (1819-1903)

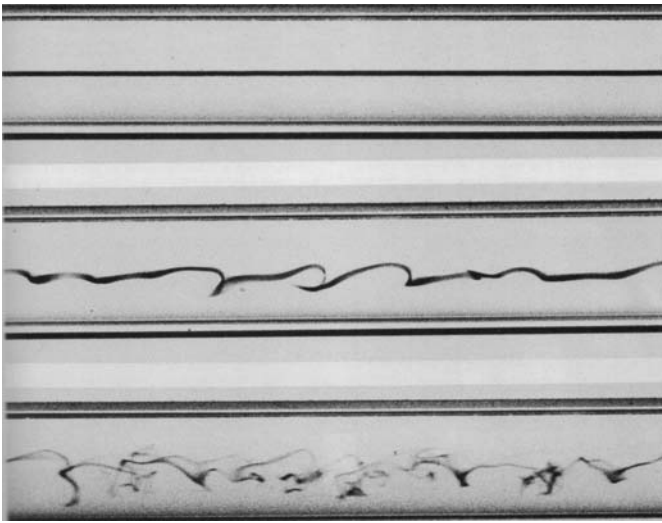


Figure 4. Photographs taken by N.H. Johannesen and C. Lowe using Reynolds's tank.
Top to bottom: laminar, transitional and turbulent flows.

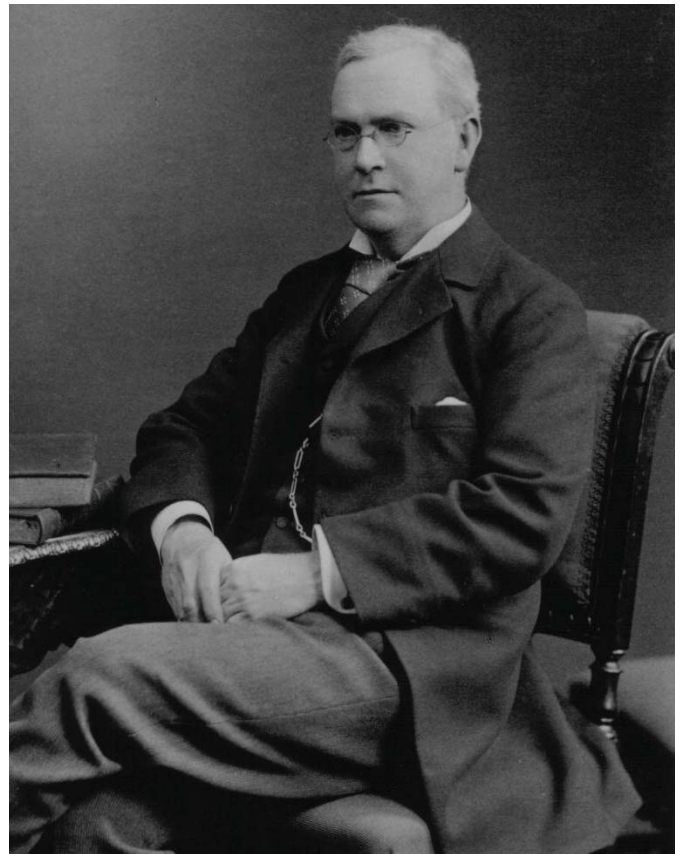


Figure 5. Horace Lamb (1849-1934), born at Stockport.
[Photograph © The Royal Society.]

in 1851⁽⁶⁾ and Hermann Ludwig Ferdinand von Helmholtz (1821-1894) in 1873⁽⁷⁾. By 1910, for the benefit of Britain's newly established Advisory Committee for Aeronautics (ACA), its president, Lord Rayleigh (1842-1919), was to demonstrate⁽⁸⁾ by such dimensional arguments that all aerodynamic forces can be expected to depend on the Reynolds number. Subsequently, the influence of Reynolds number has been recognised as being of crucial importance in all wind tunnel experiments, flight-test work and in a vast variety of theoretical investigations.

Even before embarking on his pipe flow experiments, Reynolds⁽⁹⁾ had suggested an analogy between heat and momentum transfer in fluid flows which proved valuable in relating surface heat transfer to skin friction, particularly so for turbulent flows. Moreover, by 1894 Reynolds⁽¹⁰⁾ had gone on to use the equations of viscous fluid motion to analyse the consequences of random flow fluctuations about a mean motion, thereby obtaining the forms of what became known as the Reynolds stresses of turbulent flow. He then derived equations for the kinetic energies of the mean and turbulent motions, noting that they contained terms, the turbulent energy production terms, which represent the total exchange of energy between the mean motion and the kinetic energy of the turbulence.

Reynolds should also be remembered for his work⁽¹¹⁾ on the flow of compressible gases through convergent nozzles. He showed that, provided a certain value of the ratio of the exit pressure to upstream stagnation pressure across the convergent nozzle is achieved (the now accepted value of 0.528 when the principal specific heats' ratio $\gamma = 1.4$), the maximum mass flux per unit area occurs at the nozzle exit. Moreover, at this point sonic conditions become established. Should the pressure downstream of that point be lower still, he argued that the nozzle's discharge rate is independent of that pressure since the emergent stream expands as a free supersonic jet and is therefore unable to influence conditions upstream of the nozzle's exit.

Students of Reynolds who later achieved distinction in areas other than engineering include the applied mathematician and geophysicist Sydney Chapman (1888-1970), born in Eccles, and the discoverer of the electron, Joseph John Thomson (1856-1940), who was born in Cheetham Hill, Manchester. Those more specifically involved in the development of aeronautical science we will come to presently.

4.0 SUBSEQUENT DEVELOPMENTS

Seventeen years after Reynolds's appointment, Horace Lamb (Fig. 5) joined Owens College's Mathematics Department. From 1876 until 1885 Lamb had been Professor of Mathematics at the University of Adelaide but had then accepted the Chair of Pure Mathematics at Manchester, in 1887 his title being changed to Professor of Mathematics (Pure and Applied). He remained in this post until retirement in 1920, one of his lecturing commitments being to teach the engineering students of Reynolds and his successors. From 1879 onwards there appeared the successive editions of his treatise on the mathematical analysis of fluid flow, significant parts of it, modestly unattributed, being his own work. Initially entitled *A Treatise on the Mathematical Theory of the Motion of Fluids*, by the third edition of 1895 the book had acquired its better known title, *Hydrodynamics*⁽¹²⁾. Each edition was brought up to date, the later ones including the work of Martin Wilhelm Kutta (1867-1944) and Nikolai Egorovich Zhukovskii (1847-1921) on what became known as the circulation theory of aerofoil lift^(13,14). By the final sixth edition of 1932, six pages dealt with the boundary-layer theory⁽¹⁵⁾ of Ludwig Prandtl (1875-1953) first announced in 1904; the latter date and that of the sixth edition give some idea of the time-span required for the boundary-layer concept to become thoroughly accepted in Britain.

Reynolds's effective successor was Joseph Petavel (Fig. 6). The descendant of a distinguished Swiss family, he had been educated largely in Switzerland and also in Germany before returning to Britain to study engineering at University College London. There and at the Royal Institution he established a considerable reputation



Figure 6. Joseph Ernest Petavel (1873-1936),
born at Streatham Hill, London.

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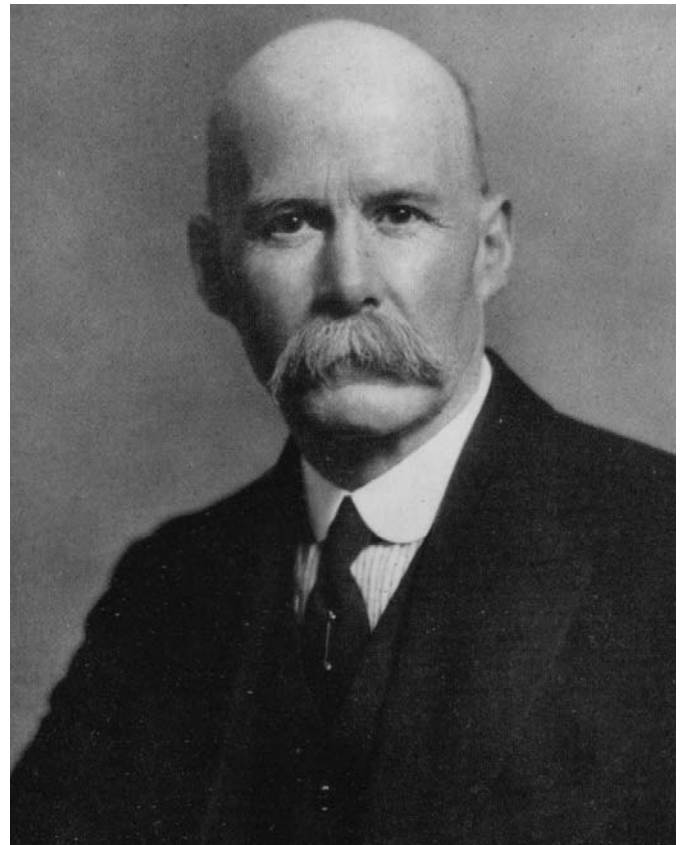


Figure 7. Thomas Edward Stanton (1865-1931),
born at Atherstone on Stour, Warwickshire.

[Every effort has been made to locate the copyright holder of this
photograph.]

for his investigations of electrical phenomena, the material properties of matter and the explosive pressures of gases, in all of which he displayed a notable ingenuity in devising appropriate apparatus. In 1901 he joined Manchester's Physics Department under Arthur Schuster (1851-1934), his research interests expanding to include such subjects as meteorology. The latter involved him in investigations of atmospheric variations up to altitudes of about 6,500ft (1,981m) using kites tethered at the University's outstation near Glossop. With his wide experience in the application of physical principles to engineering problems, Petavel was appointed Beyer Professor of Engineering in 1908 and remained in that post until 1919. Due to his widely respected knowledge of meteorology, he became a founder member of the ACA on its establishment in 1909. During the period of the First World War he and his staff at the University's Whitworth (Engineering) Laboratory became much involved in the design and testing of instrumentation needed for the ACA's research activities. In 1917 Petavel was appointed Chairman of the ACA's Aerodynamics Committee and, in 1919, succeeded Richard Tetley Glazebrook (1854-1935), Director of the National Physical Laboratory (NPL) and Chairman of the ACA, as Director of the NPL. It is largely due to Petavel's interest and professional involvement in Britain's then-emerging scientific work in aeronautics that the University's Library now possesses a comprehensive collection of early scientific and technical literature on this subject; Petavel's presentation of the earliest volumes of the ACA's reports has been particularly useful to this author. One of Petavel's better known research students was Ludwig Josef Johann

Wittgenstein (1889-1951), later famous as a philosopher, who spent the period 1908-11 investigating kites and developing a reaction jet propeller of his own design. Little appears to have come of these projects, however, and Wittgenstein subsequently departed for Cambridge to study mathematical logic⁽¹⁶⁾.

Meanwhile, a mile or so away from the Victoria University, two young men were receiving their technical education at the School of Technology. Both were later to make their marks in Britain's aeronautical endeavour. One of them, the Farnworth-born Roy Chadwick (1893-1947), later became Avro's Chief Designer responsible for the development of the ubiquitous Avro 504 through to the famed Lancaster bomber of World War Two and beyond to the early stages of the Vulcan's design. In 1911, as a young draughtsman at Westinghouse in Trafford Park, one evening a week he attended the Tech, as it was then popularly known, in order to improve his technical skills⁽¹⁷⁾. The second person, the Glasgow-born Arthur Whitten Brown (1886-1948), followed a similar route through the Tech before joining the Royal Flying Corps as aircrew during the First World War. In 1919 he, as navigator of a converted Vickers Vimy together with the Manchester-born John William Alcock (1892-1919) as pilot, achieved the first non-stop crossing of the Atlantic, flying from St John's, Newfoundland, to land 16½ hours later in a bog near Clifden, County Galway, in Ireland.

During the period of the First World War some of Owens College's engineering graduates began to achieve distinction in aeronautical research. The most notable of these was Thomas Stanton (Fig. 7). A former student of Reynolds, Stanton held various

academic posts at Owens College, at the then University College, Liverpool, and at the then Bristol University College (as Professor of Engineering). However, in 1901 he became Superintendent of the Engineering Department of the NPL, that Laboratory having been founded at Bushy Park, Teddington, in 1899. Within a year of the ACA's formation, Stanton was able to report⁽¹⁸⁾ on the NPL facilities now available for the aeronautical investigations proposed by the ACA. Whilst remaining in the post of Superintendent until a year before his death, briefly (1917-20) Stanton was also Head of the NPL's Aerodynamics Department. Before the close of the First World War he had already made a number of important contributions to the study of flow phenomena, one of which marked the origin of what became known as the Stanton number, the non-dimensional quantity useful in convective heat transfer work⁽¹⁹⁾. In 1921 Stanton became involved in the then secret work of Britain's Ordnance Committee on the aerodynamic testing of supersonic projectiles. By the following year he had successfully developed a small supersonic tunnel, the world's first, capable of producing a Mach number of 2.2. However, because of security restrictions his achievements here were not revealed until some years later⁽²⁰⁾. Further details of Stanton's career, particularly his supersonic flow investigations on behalf of the ACA's successor, the Aeronautical Research Committee (ARC), can be found in Ref. 21.

Another of Reynolds's former students, Arnold Hartley Gibson (Fig. 8), made significant contributions to early aircraft engine development. Having held various appointments between 1904 and 1909 in the Engineering Department of the Victoria University, he then moved to St Andrews University as Professor of Engineering, retaining that position until 1920. However, at the onset of the First World War he had joined the Royal Field Artillery but in 1915 transferred to the recently established Royal Aircraft Factory (RAF) (from 1918, the Royal Aircraft Establishment (RAE)) at Farnborough. There he became involved in engine research into the suppression of fuel detonation by the addition of benzole. Moreover, during the period 1915-16, in the company of Samuel Dalziel Heron (1891-1963), Gibson laid down the basic principles of the radial engine's cylinder head design. These principles were then applied to the RAF fourteen-cylinder, two-row radial engine being developed at Farnborough in 1916. In the following year Heron moved to the Siddeley Deasey (later Armstrong Siddeley) Company, taking with him the design of this engine. Subsequently, this became developed into the successful Armstrong Siddeley Jaguar engine. In 1920 Gibson returned to the Victoria University as Beyer Professor of Engineering and to his main interest, hydraulics, publishing a number of texts on this subject and hydro-electric engineering. However, he continued his engine researches at the University, jointly editing the early volumes of an influential text⁽²²⁾ on this subject, later editions appearing under the editorship of A.T.J. Kersey. Ref. 23 provides further details on an association with aeronautics, albeit relatively brief, which previously seems to have been lost in the mists of time. Thus it was the happiest of coincidences that, of all the University's Second Year Prizes awarded annually to engineering students, that allocated for award to the newly established Aeronautical Engineering Course's outstanding student was the Gibson Prize.

A further contributor to Farnborough's engine development programme was James Edwin Ellor (1892-1951), born at Dukinfield, Cheshire, and a graduate of Petavel's Engineering Department. He joined the RAF, Farnborough, in 1915 and subsequently acquired considerable experience in the design of superchargers. In what must be one of the very earliest aircraft superchargers designed for the RAF 1A engine by Ellor in 1915, a disk was added to support the blades and enhance their effect. In later developments the whole impeller disk was cast as a single unit in which the blade roots were curved to guide the air-fuel mixture into the impeller's centre⁽²⁴⁾. In 1927 Ellor left Farnborough for Rolls-Royce, there to undertake the supercharger development required for the Kestrel and R engines, the latter being highly successful in the Schneider Trophy races (see

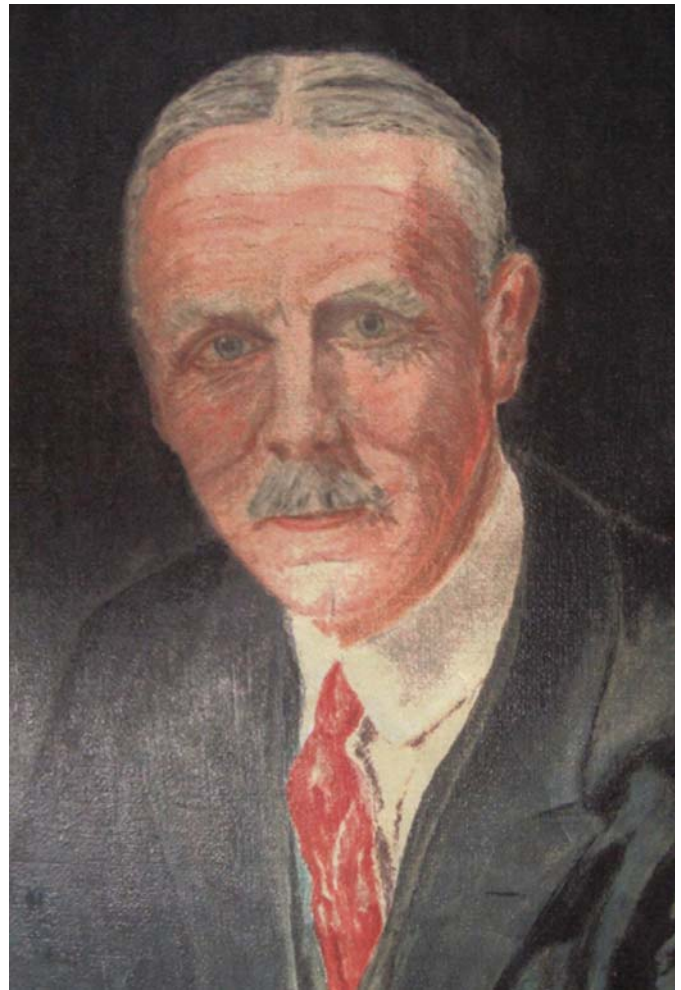


Figure 8. Arnold Hartley Gibson (1878-1959), born at Sowerby Bridge, Yorkshire.
[Portrait by Professor Jack Allen, Victoria University.]

Ref. 23). Ellor's subsequent career at Rolls-Royce progressed strongly. During the Second World War he played a key role as a Rolls-Royce representative at the Packard Company in the USA throughout the large-scale production there of Merlin engines.

Despite the sound foundations laid by Reynolds in engineering science and in the mathematical analysis of fluid flow by Lamb, apart from Petavel's activities during the First World War there were as yet few indications of a specific research interest in aeronautics itself at Manchester's two higher education institutions, and certainly no degree courses dedicated to that subject. All this was set to change, however, at the close of the Second World War.

5.0 THE GOLDSTEIN-LIGHTHILL ERA

The dramatic improvements brought about at the Victoria University from 1945 onwards were largely instigated by one man, the eminent neurologist and University Vice-Chancellor, John Sebastian Bach Stopford (1888-1961). In 1946 Frederic Calland Williams (1911-1977), born in Romiley near Stockport, was appointed Professor of Electro-technics (later, Electrical Engineering) and, in company with Tom Kilburn (1921-2001), born in Dewsbury, by 1948 had developed the world's first electronic stored-programme digital computer. Their subsequent work in producing the prototypes of succeeding generations of digital computers provided the foundation of Britain's computer industry. That, however, is another story, but



Figure 9. Sydney Goldstein (1903-1989), born at Hull.



Figure 10. Michael James Lighthill (1924-1998), born at Paris.

the point has to be made that their endeavour not only created the University's renowned Computer Science Department but also the massive computing facilities crucial to the later large-scale numerical work required in the analysis of fluid flows, including that required for aerodynamics.

During the war Williams had been deeply involved with the secret work on radar at the Telecommunications Research Establishment, Malvern. However, it was from the top-secret Bletchley Park, with its computational facilities so vital to the work on cryptography there, that in 1945 Stopford secured the appointment of Maxwell Herman Alexander Newman (1897-1984) as Fielden Professor of Pure Mathematics. In 1948 Alan Mathison Turing (1912-1954), a further veteran of Bletchley Park and famous for his work on the mathematical theory of the computing machine, joined the Mathematics Department as Reader. However, from an aeronautical viewpoint, Stopford's significant appointment of 1945 was that of Sydney Goldstein (Fig. 9) as Beyer Professor of Applied Mathematics. Not only did Goldstein and Newman organise a thoroughly integrated pure and applied mathematics curriculum – according to Ref. 25, a feature then sadly lacking at such prestigious universities as Cambridge – but Goldstein also founded a high profile research group specialising in both aerodynamic and more general fluid mechanic problems. His achievements can be judged from Ref. 26, more particularly from the glowing tributes^(25,27) paid to him by his colleague and successor in the Beyer Chair, James Lighthill (Fig. 10).

For a brief period from 1929 to 1931 Goldstein had been Lecturer in Mathematics at the Victoria University but had then returned to Cambridge, becoming in 1933 a teaching fellow at St John's College. However, earlier, during 1928-29, he had studied at Göttingen under Ludwig Prandtl and there produced a detailed mathematical analysis of the screw propeller⁽²⁸⁾ based on the

relatively new Göttingen theoretical work on the finite-span wing. Stimulated by Prandtl's work on the boundary layer, its link to vorticity and hence to wing lift, at Cambridge Goldstein continued working in these areas, and to considerable effect. Indeed, he became the natural successor to Lamb, after the latter's sudden death, as editor of what became at his hands the enormously influential compendium of much that was known on viscous flows, published in 1938 under the title *Modern Developments in Fluid Mechanics*⁽²⁹⁾. During the war years Goldstein was seconded to the NPL's Aerodynamics Division, there to work on the difficult inverse problem of designing aerofoil section shapes required to produce specific pressure distributions. Such methods were not only needed in the design of sections exhibiting extensive regions of laminar flow for drag reduction but also for those shapes producing the so-called 'roof-top' pressure distributions of interest in current investigations of flight near the speed of sound, the aim being to create sections possessing higher critical Mach numbers (see Ref. 21). The wartime successes of Goldstein and his co-workers at the NPL in these areas were reviewed by him in his 1947 Wilbur Wright Lecture to the American Institute of Aeronautical Sciences⁽³⁰⁾. By then Goldstein was Chairman of the ARC (renamed the Aeronautical Research Council in 1945), a position he occupied from 1946 to 1949.

Goldstein remained in the Beyer Chair until 1950 whilst producing a number of important papers, most notably his attack on the fearsome problem of laminar boundary-layer separation⁽³¹⁾, a highly original paper⁽³²⁾ on the decay of homogeneous, isotropic turbulence and his analysis of the aerodynamics of high speed wings and bodies⁽³³⁾. As mentioned earlier, he also gathered around him a small group of distinguished mathematicians interested in these areas of fluid flow analysis. The most notable of these, James Lighthill, a former colleague from the NPL's Aerodynamics Division, continued his work on supersonic flow⁽³⁴⁻³⁶⁾ whilst developing a powerful

hodograph method for dealing with problems of transonic flow⁽³⁷⁾. Producing a steady stream of papers covering a wide variety of problems associated with aeronautics, boundary-layer heat transfer⁽³⁸⁾ and the far field behaviour of shock waves⁽³⁹⁾ being obvious examples, he also provided as prelude to the latter the first example⁽⁴⁰⁾ of a singular perturbation method later to become known as the Method of Strained Co-ordinates. Indeed, as Pedley⁽⁴¹⁾ points out, on numerous occasions Lighthill developed virtually new mathematical methods to solve important practical problems, thereby opening up new branches of research. In view of matters arising in the next section, one must also mention his work on the dissociating gas^(42,43) and on sound waves of finite amplitude which also included a discussion of relaxation effects in such waves⁽⁴⁴⁾. Meanwhile, he made important contributions to the wider dissemination of scholarship, firstly with his article on the hodograph transformation contributed to Ref. 45. In this he was joined by other members of the Mathematics Department: R.E. Meyer (characteristics methods), C.R. Illingworth (shock waves) and G.N. Ward (approximate methods). Further contributions came from W.A. Mair of the Victoria University's Fluid Motion Laboratory, about which more in Section 6.0 below, and G.J. Kynch, Professor of Mathematics at the Manchester College of Technology, this on blast wave theory. Lighthill's second review article concerned higher approximations in high-speed aerodynamics⁽⁴⁶⁾, whilst a further contribution, published after his move from Manchester, formed the two introductory chapters to *Laminar Boundary Layers*⁽⁴⁷⁾. However, perhaps his greatest achievement was to provide, whilst still at Manchester, a firm theoretical basis for a new subject, that of aerodynamic noise⁽⁴⁸⁾, a subject to which he returned in his masterly review⁽⁴⁹⁾ in 1962. Meanwhile, during the Goldstein-Lighthill era a number of research students who were later to distinguish themselves cut their teeth on the aeronautically related problems of interest to the Department, W. Chester⁽⁵⁰⁾, S.N. Curle⁽⁵¹⁾, F.A. Goldsworthy⁽⁵²⁾, P.M. Stocker⁽⁵³⁾, G.B. Whitham⁽⁵⁴⁾, N.C. Freeman^(55,56), R.F. Chisnell⁽⁵⁷⁾ and N. Riley^(58,59) being examples. And although G.J. Hancock's doctoral work⁽⁶⁰⁾ concerned the very low Reynolds number swimming motion of micro-organisms, his subsequent career was notably in aeronautics.

During his earlier career at the NPL, Lighthill had produced an exact theory for the design of aerofoils of any required thickness and pressure distributions⁽⁶¹⁾. In this the pressure distribution is prescribed as a function of the angular co-ordinate around the circle into which the aerofoil shape is transformed. By 1947 the son of Muriel (née Barker) and Hermann Glauert, Michael Barker Glauert (1924-2004), then working in Goldstein's old group at the NPL, had applied and further extended the method⁽⁶²⁾. In 1950 Glauert joined Lighthill in the Mathematics Department and later co-operated in the analysis of laminar boundary-layer development along a slender cylinder⁽⁶³⁾. Glauert's continuing interest in boundary layers included an analysis of the unusual problem of the round jet ejected normal to a flat wall so that the efflux spreads radially outward over the wall (the wall-jet)⁽⁶⁴⁾. Both laminar and turbulent flows were considered, in the latter case the jet's inner and outer region eddy viscosities being given by then commonly accepted relations. Apparently the problem arose from the RAE's interest in the ground effect of jet lift. In 1964 Glauert moved to become Professor of Mathematics at the newly created University of East Anglia.

As mentioned earlier, Lighthill succeeded Goldstein in the Beyer Chair when the latter departed for the Israel Institute of Technology in 1950. Lighthill was then 26 and remained at Manchester until 1959, when he moved to become the Director of the RAE, Farnborough. In 1964 he became a Royal Society Research Professor at Imperial College, London, and, in 1969, Lucasian Professor of Mathematics at Cambridge. His final move was to University College London as Provost, the position he held until his official retirement in 1989. Lighthill's successor in Manchester's Beyer Chair was Fritz Joseph Ursell (1923-), born in Düsseldorf, who had earlier co-operated with G.N. Ward in providing general



Figure 11. Charles Raymond Illingworth (1917-1992), born at Burnley.

theorems in linearised compressible flow theory⁽⁶⁵⁾ but whose abiding interest remained in water wave theory. Ursell was later to comment humorously, and with characteristic modesty, that "James Lighthill had retired in favour of an older man".

Gilford Norman Ward (1918-), a member of the Mathematics Department who had also worked with Goldstein⁽³³⁾, further extended Lighthill's earlier work on slender bodies in supersonic flow so as to produce the British basis of what became known as the 'area rule'^(66,67). This approach to the alleviation of wave drag at transonic and supersonic conditions was explored further at the RAE^(68,69); details of those contributions made in the United States and elsewhere can be found in Ref. 70. Ward subsequently became Professor of Mathematics at the College of Aeronautics, Cranfield, and later moved to a similar post at the University of Sussex.

Meanwhile, the laminar boundary layer, particularly that encountered in high-speed flow, was receiving the attention of the Mathematics Department's Charles Illingworth (Fig. 11). Having done wartime work at the Royal Armaments Research and Development Establishment, Fort Halstead, he had joined the Mathematics Department in 1945 and was later to become Professor there. By a scaling of the boundary-layer co-ordinates, and use of the von Mises transformation, Illingworth⁽⁷¹⁾ achieved a valuable simplification of the boundary-layer equations. Indeed, for the case of unit Prandtl number and constant total temperature within the layer (the zero surface heat transfer case), he showed that the compressible boundary-layer equations become transformed into those of a related low speed boundary layer which can then be solved by well-established methods. Almost simultaneously, Keith Stewartson (1925-1983), then in the Mathematics Department at Bristol University,

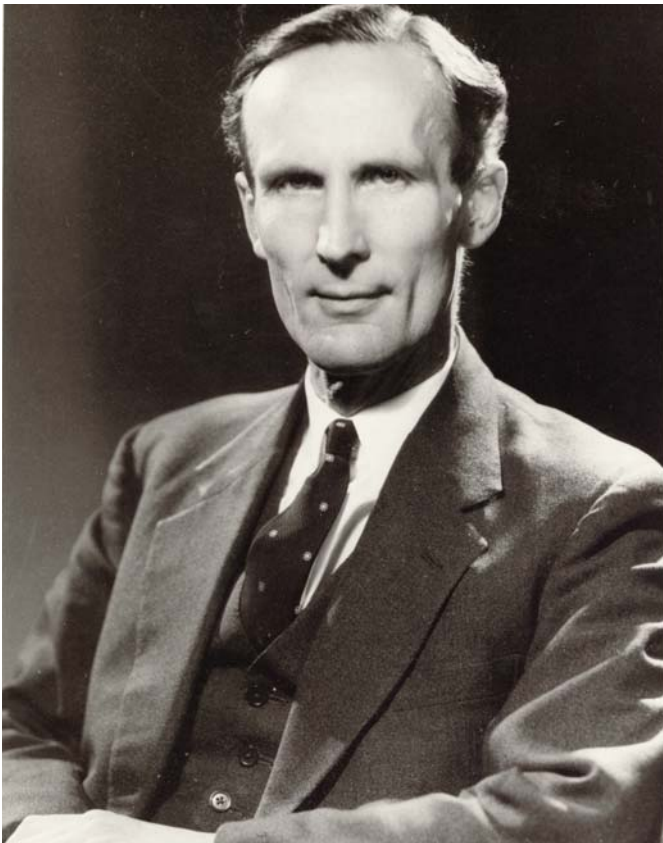


Figure 12. William Austyn Mair (1917-), born at Ewell, Surrey.



Figure 13. Niels Holm Johannesen (1921-1991), born at Lønne, Jutland.

arrived at a similar result⁽⁷²⁾ using the Dorodnitsyn-Howarth form of the equations so that the combined transformation became known as the Illingworth-Stewartson transformation, providing the basis for later advances in high-speed laminar boundary-layer theory.

Illingworth also contributed a chapter on low Reynolds number flows to Ref. 47, whilst Lighthill's former student, G.B. Whitham, provided a chapter on the Navier-Stokes equations and their exact solutions. A further two chapters on the two-dimensional boundary layer and approximate methods of solution came from C.W. Jones, G.E. Gadd and E.J. Watson. Eric John Watson (1924-), born in Canterbury, had joined the Mathematics Department in 1957, having already built a notable reputation for his contributions to laminar boundary-layer theory. His earliest work, on boundary-layer suction⁽⁷³⁾, had been done at the NPL, after which he returned to Cambridge for postgraduate study. This resulted in two later papers, one on the radial spread of a liquid jet over a horizontal surface⁽⁷⁴⁾, the earlier of the two on the unsteady boundary-layer flow about a cylinder impulsively started from rest⁽⁷⁵⁾. The latter was published during his stay in Rosenhead's Department of Applied Mathematics at Liverpool University. After his final move to Manchester his first research student, Robert Terrill, worked on boundary-layer separation and this resulted in a paper⁽⁷⁶⁾ which reinforced Stewartson's correction⁽⁷⁷⁾ to Goldstein's earlier treatment⁽³¹⁾ of this problem. Always partial to teasing the last nugget of mathematical gold out of a physical problem, Watson later began to apply this considerable analytical ability to matched asymptotic expansion methods in boundary-layer theory, his earliest case being that of strong blowing⁽⁷⁸⁾ which complemented his initial work on strong suction⁽⁷³⁾.

Eric Watson officially retired in 1982. Since then the Mathematics Department's strong tradition in fluid flow analysis allied to

aeronautics has continued in the capable hands of Peter Duck, Jitesh Gajjar and, since 1995, Anatoly Ruban, who prior to that date had been at the Central Aerohydrodynamic Institute (TsAGI), Zhukovskii, near Moscow.

6.0 THE FLUID MOTION LABORATORY, BARTON

Goldstein's experience of working with Prandtl at Göttingen had convinced him of the great benefits to be gained from linking mathematical analyses of fluid flows with appropriate experimental work. Consequently, as a further innovation at Manchester, he was instrumental in establishing in 1946 the Victoria University's Fluid Motion Laboratory. In the following year this took up residence in a World War Two aircraft hangar on the perimeter of Barton Airfield, near Eccles. The intention was that the Laboratory's activities would be closely linked to those within the Mathematics Department. Since the latter involved much work on supersonic flow, it was anticipated that the Laboratory's activities would be noisy and this consideration, together with a lack of space on the University campus, determined the Laboratory's location well away from populated areas. As we shall see, the Laboratory grew both in terms of facilities and reputation, went on to form the nucleus of a new university department and even established its own highly successful commercial arm. Consequently, in recognition of Goldstein's achievements the Laboratory was renamed the Goldstein Laboratory in 1988 and, in the same year, this Society agreed to the establishment of a named lecture, the Goldstein Lecture, to honour Goldstein's memory. Appropriately, the inaugural lecture⁽²⁵⁾ was delivered by James Lighthill.

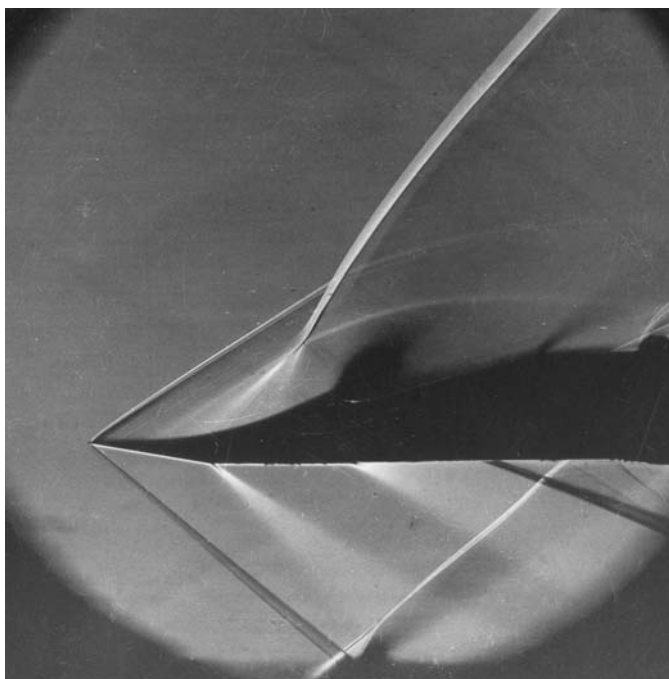


Figure 14. Compression waves from a concave surface focusing to become an oblique shock wave; Mach number 1.96, knife edge parallel to free stream (Johannesen⁽⁸⁵⁾).

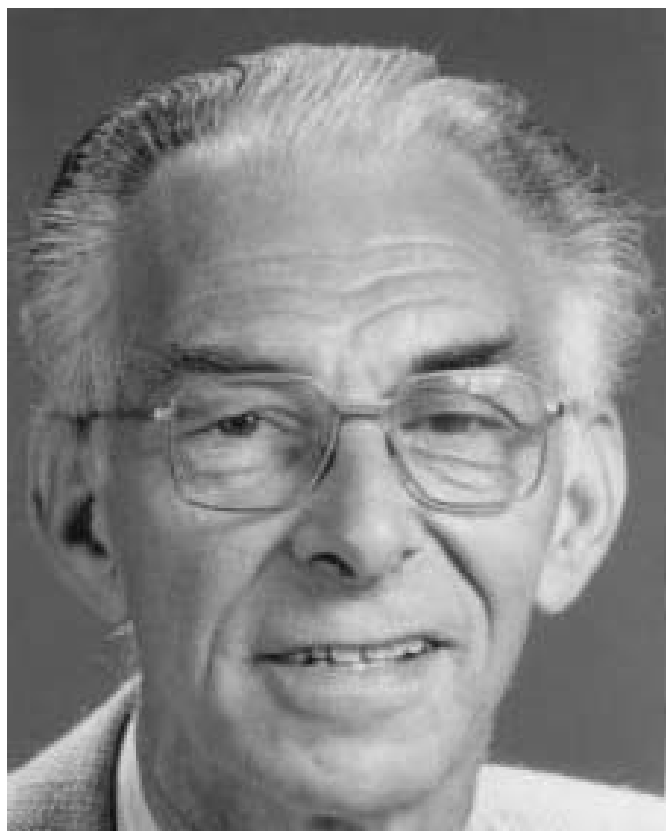


Figure 15. John (Jack) Higson Gerrard (1928-2005), born at Heaton Moor, Manchester.

The Laboratory's first Director, Austyn Mair (Fig. 12), was appointed in 1946 and already had extensive experience of the high-speed aerodynamic research undertaken at the RAE during the war years. On joining the RAE in 1940, he had become involved in the construction of the RAE's massive 10ft by 7ft (3.05m by 2.13m) closed return high subsonic tunnel (see Ref. 21) and, at the War's end, had edited the detailed review of the RAE's achievements in high-speed research⁽⁷⁹⁾. The latter report was much concerned with the development of instrumentation and its accurate calibration and this continued as a significant activity at the Fluid Motion Laboratory. Meanwhile, Mair, together with his former RAE colleague J.A. Beavan, brought up to date the earlier review⁽⁷⁹⁾ of high-speed flow over aerofoils and cylinders in their contribution to Ref. 45.

As to the Fluid Motion Laboratory's experimental facilities, through the good offices of Sydney Goldstein as Chairman of the ARC the Laboratory acquired a supersonic tunnel of the vacuum-operated, atmospheric blowdown type from Göttingen, this fitted with liners to provide a working section area of 102mm by 127mm and a flow Mach number of 1.96. The indefatigable Goldstein then had to step in to obtain priority from the Ministry of Supply for the provision of the tunnel's essential pipework, together with adequate funding for the Laboratory's early research programmes. During this period, a low speed, closed-return tunnel was built to Mair's design, this having a 20:1 contraction ratio and numerous screens so as to ensure turbulence levels of less than 0.03% in its 0.5m square working section.

The earliest members of the Laboratory's staff were Niels Johannesen (Fig. 13), who joined Mair in 1951, and Vincent Attree, the latter concentrating on the development of the Laboratory's electronic equipment. Earlier, whilst working for his doctorate on ejectors at the Technical University of Denmark, Copenhagen, Johannesen had studied characteristics methods with Richard Meyer (see Ref. 45), the specialist on this subject in the Mathematics Department (later, the University of Wisconsin).

As mentioned above, one important area of the Laboratory's activities was in the development of instrumentation for its experimental

facilities. Thus, for example, Mair⁽⁸⁰⁾ became much involved in the provision of high quality schlieren images for high-speed work, whereas some of the Laboratory's earliest research students concentrated on the development of hot wire anemometry for low speed experiments^(81,82). Meanwhile, the small supersonic tunnel rapidly became highly productive, generating a considerable body of research results in current areas of aeronautical interest. These sprang from studies of two-dimensional interactions between shock waves and boundary layers together with associated phenomena⁽⁸³⁻⁸⁹⁾. Also included were investigations of blunt-nosed bodies at incidence^(90,91) and base pressure measurements on a blunt-based body⁽⁹²⁾. A number of the schlieren photographs presented in these papers (Fig. 14 is an example) were later selected for reproduction in Van Dyke's collection⁽³⁾ of classic images of flow fields.

During this period, one of the earliest uses of the new low-turbulence tunnel was to investigate Lighthill's theory of aerodynamic noise⁽⁴⁸⁾. The initial experiments centred on the wakes of circular cylinders and were conducted by a further research student, Jack Gerrard (Fig. 15), who was able to confirm⁽⁹³⁾ the presence of the dipole radiation field posited in Lighthill's theory. Later Gerrard went on to investigate the noise field of a subsonic jet⁽⁹⁴⁾.

By then Mair had left the Laboratory, in 1952 moving to Cambridge to succeed Bennett Melvill Jones (1887-1975) as Francis Mond Professor of Aeronautics. Mair's successor as Director of the Laboratory was Paul Owen (Fig. 16), appointed in 1953. In 1941 he had joined the Aerodynamics Department of the RAE, during the war years working on a variety of high-speed flight problems and later the aerodynamics of guided weapons. In 1948, as Nahum⁽⁹⁵⁾ points out, Owen, together with T.R.F. Nonweiler and C.H.E. Warren, produced

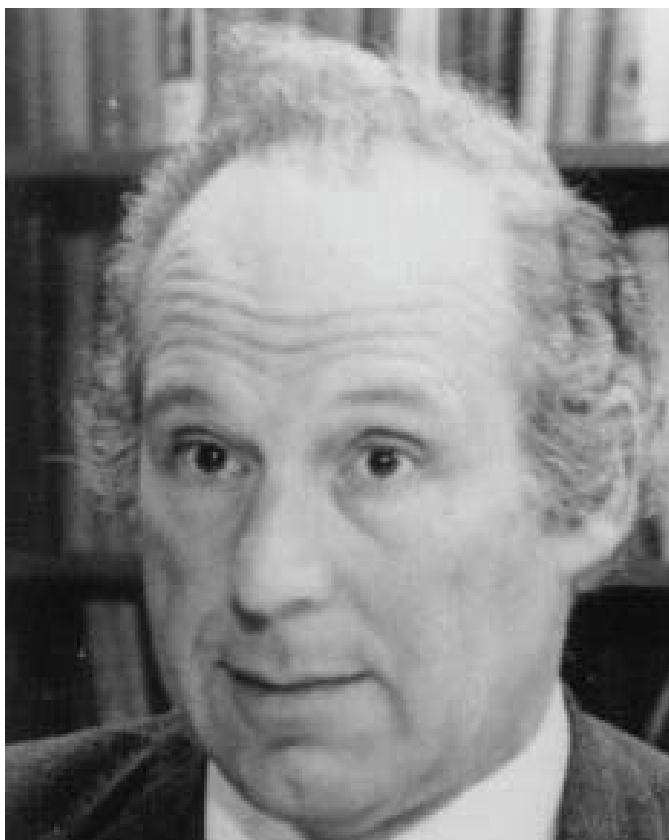


Figure 16. Paul Robert Owen (1920-1990), born at North London.



Figure 17. Ian Murray Hall (1931-), born at Cannock.

an RAE design for a supersonic research aircraft. A number of this design's features, particularly the staggered 'hip and waist' arrangement of its twin jet engines, were subsequently adopted for the English Electric P1/Lightning fighter. However, a little before his appointment at Manchester, Owen's interests had turned to low speed aerodynamic phenomena such as the separation bubble⁽⁹⁶⁾. These interests expanded at Manchester to include a wide variety of fluid mechanic problems, examples being his work on rough-surface heat transfer⁽⁹⁷⁾ and his contribution to Ref. 98 on saltation, the effects of air movement on dust particles, the latter being particularly important in areas such as mine safety. During this period, an experimental investigation⁽⁹⁹⁾ largely confirmed the structure and behaviour of Glauert's turbulent wall-jet⁽⁶⁴⁾ whilst supersonic jets in still air were investigated using schlieren and pressure traverses^(100,101). Moreover, the separation bubble problem was returned to, but now for the case of a blunt-nosed body in supersonic flow⁽¹⁰²⁾.

Meanwhile the Laboratory's staff increased. In 1955 Henryk Kazimierz Zienkiewicz (1925-), born in what was then Poland and one of the earliest graduates of the College of Aeronautics, Cranfield, arrived from English Electric's Guided Weapons Division at Luton. Together with Owen, he designed and tested a small wind tunnel producing a uniform shear flow created by a grid of parallel rods having varying spacing⁽¹⁰³⁾. One aim here was to provide an experimental facility for the testing of bodies exposed to a stream of uniform vorticity, a subject of interest to Lighthill in the Mathematics Department which had already stimulated Hall's analysis of this effect on a Pitot tube⁽¹⁰⁴⁾. At the same time Zienkiewicz undertook a theoretical analysis of the highly supersonic flow of air about cones having attached shock waves⁽¹⁰⁵⁾. The air's high temperature properties were assumed to be those for thermodynamic equilibrium, although relaxation effects aft of the shocks were briefly evaluated. A further staff addition occurred in 1956, the former research student, Jack Gerrard, returning after working

at the RAE. One of his early activities was to design and test piezo-electric pressure gauges of around $2\mu\text{s}$ rise time⁽¹⁰⁶⁾ for the Laboratory's small shock tube (the Mark I shock tube) constructed in 1954.

Under Owen the Laboratory's staff formed in 1956 the nucleus of a new department, the Department of the Mechanics of Fluids, with Owen occupying the newly founded Chair in that subject.

7.0 THE DEPARTMENT OF THE MECHANICS OF FLUIDS AND ITS SUCCESSORS

With an expansion of laboratory teaching facilities, in 1956 the new Department of the Mechanics of Fluids was able to offer an Honours Degree Course in Aeronautical Engineering, the first students being admitted in the following year; more details on this are given in Section 8.0 below.

As indicated in the preceding section, Owen fostered in the new Department the diversity of interests implicit in the Laboratory's original title so as to extend the massive advances achieved in aerodynamics to other branches of fluid mechanic technology. This policy had the active encouragement of James Lighthill⁽¹⁰⁷⁾ and became an ethos sustained for many years. Thus during the early years of the Department contributions from two Research Fellows, J.S. Turner and T.H. Ellison, centred on certain aspects of turbulent mixing, vortex pairs and associated phenomena; Refs 108-112 provide some examples of their work.

In 1960 another former research student, Ian Hall (Fig. 17), joined the staff of the Department, having previously worked in the Aerodynamics Division of the NPL. There, in company with Eric William Evan Rogers (1925-2004), he had conducted what is

considered to be one of the classic British experimental investigations of transonic swept wing aerodynamics^(113,114). One of his earliest activities after returning to Manchester was the analysis⁽¹¹⁵⁾ of the transonic flow in the throat region of nozzles, the highly accurate series method devised being included in his survey, in company with Cambridge's E.P. Sutton, of throat design published in Ref. 116. Later this work was extended⁽¹¹⁷⁾ and a further paper included the effect of a centre body at the throat⁽¹¹⁸⁾ whilst the original method was used as the starting point for the design of Mach 3 liners for the supersonic tunnel⁽¹¹⁹⁾. Both the original and the new liners were used in an experimental study of the three-dimensional interaction between a shock wave generated by a wedge and the turbulent boundary layer on the tunnel's side wall⁽¹²⁰⁾. This intermittent tunnel was used by another of Hall's research students, Peter Stow, later to achieve a distinguished position at Rolls-Royce, to investigate the interaction of an under-expanded jet with the tunnel's flow, the latter running at subsonic conditions⁽¹²¹⁾.

Meanwhile, stimulated by his work on the noise field generated by circular cylinder flow⁽⁹³⁾, Jack Gerrard had turned his attention to other effects created by such bluff bodies. Beginning in 1961, he concentrated initially on the oscillating lift and drag forces experienced by cylinders⁽¹²²⁻¹²⁴⁾. The last reference, together with his previous year's paper⁽¹²⁵⁾ with Susan Bloor on wake structure, are particularly notable, as is his much later paper⁽¹²⁶⁾ on this subject. Indeed, this interest in bluff body wakes continued throughout the rest of Jack's career, an endeavour sustained by a steady stream of research students and the provision of two towing tanks⁽¹²⁷⁾, one 2m long, the other double that length, together with an optical interferometer^(128,129), the latter to measure water surface dimples created by wake vortices. During 1973-74 the 4m tank was used by the visiting Japanese scientist, Hiroyuki Honji, born in 1938 and as yet in the earlier years of a distinguished career in fluid dynamics. His investigation centred on the starting flow past a downstream-facing step⁽¹³⁰⁾. However, by the late 1960s Jack Gerrard's interest in medical fluid dynamics, specifically arterial flows, had grown to the point where he began both experimental and numerical work, initially on flow in rigid cylindrical tubes but later extended to distensible tubes. In this he worked with the vascular surgeon David Charlesworth at Withington Hospital. References 131-137 provide a few examples of this work.

In the late 1950s the Department had acquired an experimental facility which was to prove highly productive over a number of years. This was the 31ft (9.4m) long, 1ft (0.305m) diameter shock tube, named the Mark II shock tube by the Department, which had been built originally at the Atomic Energy Research Establishment, Harwell. The shock tube's low pressure section contained a convergent rectangular scoop leading to a 6.5ft (1.98m) long working section having a rectangular cross section of 2in by 8in (51mm by 203mm). The RAE had been instrumental in transferring this shock tube to the Department, the intention being that it would be used for hypersonic research, specifically to study gas relaxation phenomena behind shock waves. The re-assembled Mark II shock tube (Fig. 18) was commissioned in 1960 but, as a prelude to its use, Johannesen⁽¹³⁸⁾ showed how such relaxation regions can be analysed with great accuracy using an analogy with Rayleigh-line theory for compressible flow with heat transfer. Meanwhile, his research student, Phillip Blythe, demonstrated the inaccuracies of existing approximate methods⁽¹³⁹⁾ and later extended Freeman's work^(55,56) by including the effects of vibrational relaxation in hypersonic blunt body flow⁽¹⁴⁰⁾. By then the earliest Mark II shock tube investigations of relaxation regions in carbon dioxide had been reported^(141,142), showing agreement with the earlier Manchester theoretical work. A later paper⁽¹⁴³⁾ on shock wave reflection, including the effects of relaxation, provided a theoretical model based on the shock relations, characteristics methods and the Rayleigh-line equation, together with confirmation from shock tube experiments in carbon dioxide. The visiting Australian scientist Graham Bird contributed to this paper; during his stay in the Department in 1964, Bird also

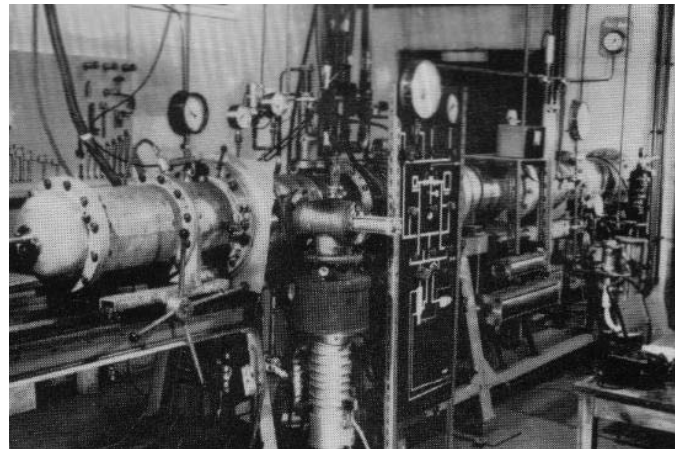


Figure 18. The Mark II Shock Tube.

contributed two papers^(144,145) on the effects of shock waves on rarefied gases.

A substantial number of publications on vibrational relaxation phenomena followed over the succeeding years, some of the earliest being the work of the research students Harry Bhangu and Terry Rees⁽¹⁴⁶⁻¹⁴⁸⁾. However, crucial to the associated experimental programme was the Mach-Zehnder interferometer system developed by Zienkiewicz, this being aided by his thorough analysis⁽¹⁴⁹⁾ of this type of instrument which not only removed a number of earlier misconceptions but also dealt with the effects of optical imperfections in the system. A further paper⁽¹⁵⁰⁾ produced a clearer understanding of the use of white-light fringes important for fringe tracing through discontinuous shock waves. In 1966 Zienkiewicz left Manchester for Exeter University, later to become Reader in Engineering Science there.

By then Owen had already left, moving in 1963 to become Zaharoff Professor of Aviation at Imperial College, London, his replacement at Manchester being Niels Johannesen. At that time the British universities were poised to experience major expansion as a result of the Robins Report and, under Johannesen's direction, the Department benefited considerably from this. Not only was the Barton Laboratory transformed from a bleak, half-empty hangar to become a well-equipped, comfortably appointed modern laboratory but staff numbers also increased substantially to cope with the increasing influx of undergraduate students. In 1964 the Manchester Mathematics graduate, Brian Stewart Hall Rarity (1938-), born in Airdrie, came from English Electric, Warton, producing two papers which built on earlier work in the Mathematics Department. The first of these considered Glauert's problem⁽⁶⁴⁾ of the laminar wall-jet, confined in this case to an incompressible fluid but which here impinges on a rotating surface⁽¹⁵¹⁾. The second paper⁽¹⁵²⁾ employed Lighthill's approach⁽³⁸⁾ so as to analyse hypersonic flow around blunt bodies. However, in 1966 Brian Rarity returned to the Mathematics Department. A further former employee of English Electric, Warton, Peter Laws (1935-), born at Bexleyheath, Kent, also arrived in 1964. A graduate of Imperial College, London, he had worked previously on the development of the Lightning at Warton. Later in that year, the Rochdale-born Thomas Neil Stevenson (1935-), a doctoral graduate of Queen Mary College, London, came from Cranfield. There he had already earned a reputation for his work on transpiration turbulent boundary layers⁽¹⁵³⁾, an interest which continued in his early years at Manchester⁽¹⁵⁴⁾. With this background he became involved, together with Johannesen, in the turbulent mixing layer experiments of Andrew Yule, later to become Professor of Mechanical Engineering at UMIST. Conducted in the low turbulence tunnel modified so as to produce two parallel streams of different velocities, the experiments demonstrated that both the turbulence intensity and the structure of the mixing layer between the streams depend on the streams' velocity ratio^(155,156).



Figure 19. White light interferogram of a fully dispersed shock wave in a carbon dioxide, nitrous oxide mixture (Hodgson⁽¹⁹⁵⁾).

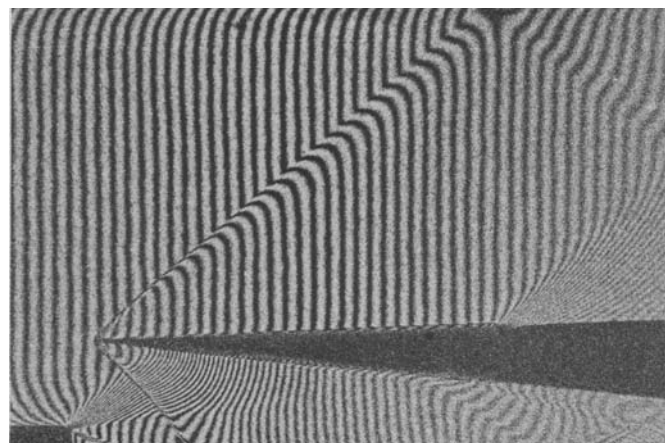


Figure 20. Relaxation regions behind oblique shocks in nitrous oxide (Hornby and Johannesen⁽²⁰⁰⁾).

Later, however, Stevenson's interests turned to internal waves in density-stratified fluids^(157,158). Work had begun earlier on this at the suggestion of Bruce Morton, then in the Mathematics Department (later, Monash University). An experimental programme on internal waves had been initiated by the research student David Mowbray⁽¹⁵⁹⁾, a programme in which Brian Rarity then became actively involved on the theoretical side, and to considerable effect^(160,161). At this time clear air turbulence was a problem for aircraft, internal waves together with the jet stream being one source of this. Under Stevenson's direction this research programme became highly productive and a steady stream of research students ensured its continuation for many years, sponsored by the RAE, the United States Office of Naval Research and finally by the Admiralty. Waves in the oceans⁽¹⁶²⁾ and the atmosphere⁽¹⁶³⁾ were considered, in the latter case Stevenson being joined by Peter Laws⁽¹⁶⁴⁾ who had also been involved in the development of a six-mirror interferometer for the experimental work on internal waves⁽¹⁶⁵⁾. Stratified numerical work was begun by the Research Associate Dimitrios Nicolaou⁽¹⁶⁶⁾ prior to his departure for Liverpool University. The most recent experiments of Huang⁽¹⁶⁷⁾ and the Research Assistant Andy Law⁽¹⁶⁸⁾ showed how the trailing vortices from a wing become internal waves downstream in a stratified fluid.

Meanwhile, Stevenson found time to design the Department's large low speed blowdown tunnel, commissioned in 1983 and fitted with an Elven six-component balance. Initially built with an open working section for ease of access, later the tunnel was provided with an optional closed working section and diffuser. In its open section guise, the tunnel's layout ensured rapid model interchange for student project work. Part of Stevenson's undergraduate teaching centred on aircraft design, an activity which produced insight into the interaction between the many important parameters in the design process⁽¹⁶⁹⁾.

In 1965 this author (John Anthony David Ackroyd), born in Bradford in 1938, joined the Department after having worked at Queen Mary College, London, on the testing times available in shock tubes⁽¹⁷⁰⁾. He continued this activity by concentrating on the shock-induced boundary-layer flows generated in such hypersonic testing facilities^(171,172). Subsequent research interests shifted to non-aeronautical subjects such as natural convection flows⁽¹⁷³⁻¹⁷⁵⁾, turbulent boundary layers along slender threads⁽¹⁷⁶⁾ and moving surface boundary layers⁽¹⁷⁷⁾, the series solutions for the latter being aided by the powerful summation method devised by Samuel and Hall⁽¹⁷⁸⁾. Nonetheless, he developed an obsession with aeronautical scientific and technical history which resulted in invitations to deliver this Society's Lanchester⁽¹⁷⁹⁾, Cayley⁽¹⁸⁰⁾ and Inaugural Cody Lectures, together with lengthy publications which have no doubt cured the insomnia of a number of this Society's members in recent years^(21,23,181-183).

Another Queen Mary doctoral graduate, Terry Hughes (1939-1987), joined the Department in 1967, thereby returning to his hometown after an interim period working for a NASA contractor in Washington, DC. Initially he prepared for publication his earlier work on numerical solutions for high-speed laminar boundary layers over surfaces of varying temperature⁽¹⁸⁴⁾ and heat transfer measurements on surfaces exposed to high-speed turbulent boundary layers⁽¹⁸⁵⁾. Meanwhile, he developed an interest in fluidics⁽¹⁸⁶⁾ and later became involved in the Department's programme of jet research^(187,188), of which more presently. Dogged by progressively debilitating ill health, however, his life was sadly all too short, his good judgement, fairness and dry Mancunian humour being greatly missed by all in the Department. His long and effective involvement with the teaching of flight dynamics resulted in his colleagues and former students establishing the Terry Hughes Prize awarded to the outstanding Second Year student in that subject.

A second person to join the Department's staff in 1967 was the former research student John Peter Hodgson (1943-2007), born in Selby. A Manchester Physics graduate, for his thesis work Hodgson brought this background to bear on a review of the available data on the infra-red properties of carbon dioxide^(189,190). Using the Mark II shock tube, he went on to measure the infra-red emission behind shocks in carbon dioxide, from which he was able to confirm the earlier belief of Johannesen *et al*⁽¹⁴¹⁾ that all the vibrational modes of this gas have similar relaxation frequencies⁽¹⁹¹⁾. In these experiments he was joined by Robert Hine, the Department's Experimental Officer, who later added to the Department's data on both carbon dioxide and nitrous oxide by calculating their equilibrium properties behind reflected shocks⁽¹⁹²⁾.

In 1971 Hodgson and Johannesen⁽¹⁹³⁾ turned aside from the original purpose of this research, namely relaxation phenomena in hypersonic flows, so as to apply their findings to the aircraft sonic bang problem. Their calculations indicated that the weak far field shock waves involved may well be fully dispersed due to the vibrational relaxation of oxygen; a later paper by Hodgson⁽¹⁹⁴⁾ produced the further indication that vibrational relaxation in nitrogen could aid this dispersion. In his survey paper⁽¹⁹⁵⁾ of the same year Hodgson showed a white-light interferogram (Fig. 19) of a fully dispersed shock wave in a carbon dioxide/nitrous oxide mixture. This had been obtained in the Mark II shock tube, the primary shock wave having been weakened sufficiently by transmission through a perforated plate; more details⁽¹⁹⁶⁾ on this technique were provided in the following year. The subject of weak waves was thoroughly reviewed in 1979⁽¹⁹⁷⁾ and in the same year shock tube results were presented for the passage of a weak shock through an aqueous fog⁽¹⁹⁸⁾. The latter had been generated in the driver section's moistened gas during the reflection of the primary expansion wave, the shock being

the primary shock's reflection from the closed end of the low pressure section. Results indicated a considerable dispersion of the shock by the fog. Meanwhile, analytical methods incorporating characteristics networks were developed for the calculation of flows possessing vibrational relaxation regions⁽¹⁹⁹⁻²⁰²⁾ (Fig. 20), the first of these by Kosh Mohammad⁽¹⁹⁹⁾ having been supervised by Ian Hall. Earlier, Brian Rarity had dealt with the difficulties encountered with characteristics methods employed in problems involving relaxing gases by considering the flow generated by an advancing piston and flow into a compressive corner⁽²⁰³⁾. Sadly, serious ill health forced Hodgson's early retirement in 1990, although it is good to report that, as a result of recent advances in medicine and surgery, his health was much improved for a number of years. Nonetheless, this no-nonsense yet humorous Yorkshireman is greatly missed by his colleagues, and not entirely for his extensive knowledge of sound physical principles.

One of Ian Hall's former doctoral students, the Norwich-born Peter George Bellamy-Knights (1941-), also joined the staff in 1969. For his earlier Masters degree under Jack Gerrard he had used inviscid potential flow theory to model the effect of the vortex pair present in the wake's starting flow about circular cylinders and hence calculate the drag-creating consequence of such vortices. This analysis he later expanded so as to establish the bounds on such drag forces produced by this type of model⁽²⁰⁴⁾. For his doctoral work, in contrast, he used the full Navier-Stokes equations to produce analyses of the cellular structures of unsteady viscous vortices^(205,206). With the natural phenomenon of the tornado in mind, he investigated the effect of such vortices meeting a plane surface, developing a solution for the boundary-layer flow on such a surface⁽²⁰⁷⁾. Later papers, including those by his research students, further developed this theme⁽²⁰⁸⁻²¹⁴⁾. However, by the late 1980s his attention turned to establishing exact analytical values of surface singularity distributions for potential flows about ellipses, thus providing bench-mark tests for the panel methods currently popular in aerodynamic calculations⁽²¹⁵⁻²²⁰⁾. In this he was joined initially by Jack Gerrard, the latter's research student Michael Benson, and Ian Gladwell of the Mathematics Department.

A change of staff also occurred in 1969, the Manchester-born David James Smith (1944-) replacing Robert Hine as Experimental Officer. Smith's background in electronics and computerised control processes had involved him by the mid-1970s in the Department's research programme on jets, an activity from which he gained both MSc and PhD degrees. This programme had arisen from Johannesen's collaboration with Rolls-Royce on Concorde noise problems, the latter having also stimulated the work of Hodgson and Johannesen on the weak wave sonic bang phenomenon mentioned above. The earliest experiments in the jet programme had been reported in 1972 by Pannu and Johannesen⁽²²¹⁾. In these they had explored the structure of a mildly supersonic jet issuing from a nozzle in which two V-shaped diametrically opposed cut-outs had been made at the nozzle exit, evidence from Concorde's Olympus 593 engine tests having suggested that such a configuration might create a side-line noise reduction. Schlieren images and pressure traverses from the Pannu and Johannesen notched nozzle experiments⁽²²¹⁾ indicated persistent trailing vortex pairs emanating from the notches, together with broad regions of low speed turbulent flow effectively shrouding the noise sources within the jets. Smith's involvement in this programme, initially with Hughes as mentioned above, began with experiments on sonic jets issuing into either still air or a co-flowing stream provided by the low turbulence tunnel⁽¹⁸⁷⁾. Later experiments, in which flow from a notched nozzle issued parallel to the low-turbulence tunnel's airstream⁽¹⁸⁸⁾, added further weight to the findings of Pannu and Johannesen⁽²²¹⁾. Subsequently, Smith joined with Johannesen and the latter's research student, Ian Hodge, to investigate the noise fields of short duration high subsonic jets⁽²²²⁾. These were produced by a nozzle fitted to the low-pressure end of the Mark II shock tube, the jets issuing into an anechoic chamber lined with polyurethane

foam wedges. The results indicated that this technique provided a relatively cheap method for the exploration of jet noise fields in a wide variety of gases. This technique was later employed in experiments using helium-argon mixtures, the results suggesting that jet noise fields are independent of the manner in which the jet densities are achieved, whether by heating or, in this ingeniously cheaper technique, by mixing cold light gases⁽²²³⁾.

A further early contribution to the jet programme came from Peter William Carpenter (1942-), born in Forfar, Scotland, a London graduate who had then obtained his doctorate at the University of Cincinnati. From 1970 to 1973 he was Rolls-Royce Research Fellow in the Department before moving to Engineering Science at Exeter University, finally to Warwick University as Professor of Mechanical Engineering. During his stay in the Department he published some of his earlier Cincinnati work⁽²²⁴⁾ and then a paper with Johannesen on inviscid swirling flow through choked nozzles⁽²²⁵⁾. Contrary to the then fairly common belief in the jet engine industry, this work indicated that swirl in jet exhausts need not lead to reductions in specific thrust. At this time, one of Ian Hall's research students, Roger Smith, used characteristics methods to analyse the flow within a swirling underexpanded supersonic jet⁽²²⁶⁾, showing that for swirl Mach numbers below 0.5 the swirl had little effect on the jet. This was accompanied by a largely confirmatory experimental study using schlieren, yawmeter, Pitot, static and temperature probes, the supersonic jet's swirl being produced by a jet-driven vortex chamber. A further paper analysed the effect of swirl on the hypersonic flow around blunt bodies⁽²²⁷⁾.

Albert William Bloy (1947-), born in Falkirk, joined the Department in 1974. After graduation from Glasgow University, he had worked in the Aerodynamic Design Department of British Aerospace (BAe), Hatfield, on Airbus stability and control and also on the initial project design of the BAe 146 aircraft. However, in 1969 he had moved to Imperial College, London, where he obtained his doctorate before joining the Von Kármán Institute (VKI), Belgium, to continue his doctoral work on hypersonic aerodynamics. Soon after his arrival in Manchester he published his results⁽²²⁸⁾ for heat transfer and surface pressures on a sharp wedge expansion flap tested at Mach 16 in the VKI's Longshot tunnel. Later he too joined the Department's jet programme, showing by characteristics calculations that temperature perturbations at a nozzle's inlet can cause significantly large pressure disturbances resulting in excess noise⁽²²⁹⁾. A second paper⁽²³⁰⁾ reported his jet noise measurements obtained by pulsing helium into a nozzle inlet, the results showing good agreement with existing theory. For this he designed the Department's first anechoic chamber. Later his interests turned to the stability and control problems of large receiver aircraft during air-to-air refuelling. Of importance to the Aeroplane and Armament Experimental Establishment, Boscombe Down, the Ministry of Defence and BAe, this resulted in a lengthy programme in which a number of research students became involved⁽²³¹⁻²³⁸⁾. He also began a programme of research on aerofoil performance related to wind turbines and the use of Gurney-type flaps⁽²³⁹⁻²⁴¹⁾.

In 1980 the Cambridge-born Peter James Lamont (1946-) joined the Department. After graduation he had worked on missile aerodynamics at BAe, Filton, before returning to Bristol University to obtain his doctorate. Following post-doctoral work there, in 1977 he was invited to join the NASA Ames Research Centre in California to continue his experimental work on high incidence aerodynamics. An international authority in this area when he arrived in Manchester, he brought his expertise to bear on the high incidence problems of an aircraft's forebody asymmetric separated flow and its influence on the overall flight dynamics of the complete aircraft. This work, supported by NASA, BAe and the SERC, resulted in a number of publications by himself and his research students⁽²⁴²⁻²⁴⁸⁾. The most notable of the latter, Andrew Kennaugh (1962-), born at Whitefield, North Manchester, became a temporary member of staff in 1988 and later was appointed Manager of the Laboratory's Large Closed Return Tunnel, mentioned below. Meanwhile, Peter Lamont had



Figure 21. David Ian Alistair Poll (1950-), born at Mirfield, West Yorkshire.



Figure 22. Norman Jeffrey Wood (1954-), born at London.

turned his attention to the aerodynamics of large-scale wind turbines and the problems of racing car cooling. Moreover, his wide experience of practical aerodynamics not only involved him in the activities of his colleagues^(231,249,250) but also, as described below, in the resolution of a troublesome problem encountered with the new Large Closed Return Tunnel.

In 1985 the University agreed to the Department changing its name to the Department of Aeronautical Engineering and in the following year Niels Johannesen retired. There followed an interim period during which Ian Hall became Acting Head of the Department. Nonetheless, around this time he also managed to complete his work, together with his research student Mike Suddho, on highly accurate solutions for potential flow about multi-element aerofoils based on successive applications of the von Kármán-Trefftz mapping function^(251,252), an activity which provided further benchmark tests for inviscid flow computer codes. During this interim period the Department amalgamated with the University's Engineering Department.

Ian Poll (Fig. 21) was appointed Professor of Aeronautical Engineering in 1987. Having graduated from Imperial College, London, he had joined Hawker-Siddeley Aviation, Kingston-upon-Thames, to work on military future projects before moving to the College of Aeronautics, Cranfield. There he gained his doctorate in swept wing aerodynamics centred on the topic of complex three-dimensional boundary-layer transition, his subsequent work expanding to include many current research areas in boundary-layer behaviour and its control⁽²⁵³⁻²⁵⁶⁾. His arrival in Manchester marked the beginning of a progressive revitalisation of the Aeronautical Group's activities, not least through his considerable experience of running successful sponsored research programmes. At Manchester these programmes expanded to include laminar flow technology⁽²⁵⁷⁻²⁵⁹⁾, hypersonic flow⁽²⁶⁰⁻²⁶³⁾ and computational fluid dynamics⁽²⁶⁴⁾, the

references quoted being a small sample of the many publications he produced, often in company with his large body of research students and a number of his colleagues. Moreover, he not only initiated a thorough review of the undergraduate teaching programme, this resulting in the revised and extended Aerospace degree courses described in the next Section, but he was also responsible for the creation of the Goldstein Laboratory's commercial arm, Flow Science (see Section 9.0), and for instituting this Society's Goldstein Lectures (see Section 10.0). During the period 1991-94 he was also Head of the Engineering Department. In 1994 the latter merged with the Electrical Engineering Department to form the Manchester School of Engineering, Aerospace becoming one of its four Divisions.

Through a serendipitous combination of timing, good luck and a notable Yorkshire audacity, in 1988 Ian Poll managed to arrange for the redundant BAe 9ft by 7ft (2.74m by 2.13m) Large Closed Return Tunnel to be transferred from its Woodford site to the Goldstein Laboratory. Commissioned at its new site in 1989, initially the Tunnel's working section turbulence level was found to be much higher than expected. The problem was quickly resolved, however, by Peter Lamont's recognition that the Tunnel's flow straighteners were incorrectly angled downstream of the five-bladed fan. Once corrected, turbulence levels dropped to expected levels.

In a further expansion of the Goldstein Laboratory's facilities, in 1991 National Power donated its 4.6m by 1.5m Environmental Tunnel, originally sited at its Leatherhead Laboratory. After a substantial building extension to accommodate this second large tunnel, the Goldstein Laboratory became one of the best-equipped university-operated aerodynamics laboratories in Britain, perhaps even in Europe. Much of the credit for the detailed arrangements needed to house and re-assemble these two large tunnels must go to David Smith, by then Laboratory Manager.

Earlier, in 1989, Jan Robert Wright (1947-), born in Southport, had joined the Engineering Department's Mechanical Group. However, his earlier career had centred largely in aeronautics and so he became involved, initially informally, with the Aerospace Group. Having graduated from Bristol University in Aeronautical Engineering, he had obtained his doctorate in flutter test analysis methods as an external candidate at that university⁽²⁶⁵⁾ whilst working at BAe, Filton, on dynamics problems associated with Concorde. Later, he became a member of staff in Aeronautical Engineering at Queen Mary College, London, where he concentrated on dynamic and aeroelastic phenomena⁽²⁶⁶⁾. Consequently, after his arrival in Manchester Jan Wright's work was predominantly in aircraft structural dynamics. Later in 1989 his former doctoral student at Queen Mary College⁽²⁶⁷⁾, Jonathan Edward Cooper (1962-), born at Portsmouth, joined the Aerospace Group after an interim period working at the RAE. Together they formed a team which not only became highly successful in both research output and in attracting a large number of doctoral candidates to their programme but also effectively complemented the largely aerodynamic/fluid mechanic research which had continued within the Aerospace Group since the days of Mair and Owen. Their team's researches covered such subjects as aeroelasticity^(268,269), flutter testing^(270,271), normal mode testing^(272,273), non-linear identification⁽²⁷⁴⁾, non-linear response calculation⁽²⁷⁵⁾ and blade tip timing⁽²⁷⁶⁾, the references quote being a small sample of their publications. Both Jan Wright and Jonathan Cooper became Professors of Engineering, Jan serving as Head of the Mechanical Division (1995-98) whereas Jonathan became the last Head of the Manchester School of Engineering before the Victoria University's amalgamation with UMIST.

Ian Poll left Manchester in 1995 to become Head of the College of Aeronautics, Cranfield. After a further interim period in which Ian Hall once again became Acting Head of the Aerospace Division, Norman Wood (Fig. 22) was appointed Professor of Aerospace Engineering in 1996. Having obtained his doctorate at the University of Bath, he had spent the period 1980-88 as Research Associate at Stanford University, thereafter returning to Bath. During his stay in Manchester until 2005, Norman Wood's research interests included unsteady aerodynamics, aerodynamics modelling, active and passive flow control and vortex flows. From 1997 to 2003 he served as Head of the Manchester School of Engineering. In 1997 he was joined by his former doctoral student at Bath, William James Crowther (1968-), born in Weybridge. He, together with the other more recent arrivals in Aerospace, will be describing current research activities in later papers in this issue of the Journal.

8.0 THE HONOURS SCHOOL OF AERONAUTICAL/AEROSPACE ENGINEERING

At its foundation in 1956 the Victoria University's Honours Degree Course in Aeronautical Engineering, the fiftieth anniversary of which is celebrated here, became the ninth within the British university system to offer this discipline at undergraduate level. Its course structure followed closely the precedent set by the other eight institutions, emphasising the four main subject areas of aerodynamics, aircraft structures, propulsion systems and flight dynamics, all of which had been foreseen by George Cayley (1771-1857) as early as 1809⁽²⁷⁷⁾ as crucial to both the understanding and the future development of his brainchild, the aeroplane.

Responsibility for the course rested with the University's relatively new Department of the Mechanics of Fluids and in 1963 Ian Hall provided an informative description⁽²⁷⁸⁾ of this Department and its activities in the teaching of aeronautical engineering. In this he stressed the Department's origins, not in Engineering, but in Mathematics. Consequently, although developing a comprehensive curriculum covering the aeronautical sciences, an emphasis on mathematical rigour continued to be a hallmark of the Department's teaching.

Initially, in keeping with many engineering courses at the time, the First Year of the course followed a programme common to those other degree courses offered by the University. Thus all the engineering students studied such subjects as mathematics, thermodynamics, structures, electrical engineering and engineering materials whilst obtaining practical experience, in-house, of drawing office methods, machining and other processes in workshop technology. However, by the early 1970s the First Year began to incorporate a more distinctive aeronautical flavour by introducing the basic elements of such subjects as flight dynamics and orbital mechanics related to space technology. In this the idea was to show the students how their knowledge of A Level mathematical physics could be immediately applied to such problems as the minimum drag and power conditions of aircraft and the orbital periods of satellites. These themes were further developed in the Second Year by introducing rocketry and the basic elements of aircraft stability and control, the latter being greatly extended in the Third Year. Whilst such subjects as mathematics and electronics continued in the Second Year, taught by the Mathematics and Electrical Engineering Departments, later the Department's staff with backgrounds in mathematics took over the teaching of that subject.

The subject of aircraft structures was introduced in the Second Year and extended in the Third Year. Initially this was taught by staff in Civil Engineering at both the University and UMIST who had had prior experience in the aircraft industry, but subsequently the Department's staff with backgrounds in aeronautical engineering took over the teaching of this subject. A similar transfer of teaching responsibilities occurred with the subject of propulsion also taught throughout the Second and Third Years, this spurred on by the Department's increasing involvement in the Concorde engine programme.

Inviscid and viscous flow theories were introduced in the Second Year, the former as prelude to the aerofoil theory also taught in that Year, whereas viscous theory provided a deeper understanding of the applicability of aerofoil theory. Unusually at the time of the degree course's inception, compressible flow theory was also included in that Year, this reflecting the early staff's research involvement with this subject. All of these Second Year courses then provided the basis for the Third Year's teaching of both low and high-speed aerodynamics, this including significant contributions on boundary-layer theory and convective heat transfer. Both aerodynamics and aircraft structures teaching also provided the foundation for the subject of aeroelasticity introduced during the Third Year. As a further indication of staff research interests, the Third Year also included a course on real gas behaviour, this introduced from basic elements of quantum theory and statistical thermodynamics so as to provide an understanding of the properties of high-temperature gases and their application to hypersonic re-entry problems.

Formal laboratory sessions accompanied many of the courses from the First Year onward and a course on experimental methods was introduced in the Second Year; later, however, its material was absorbed into other main courses. During the late 1970s the subject of aircraft design was introduced into the Third Year. To some extent as a prelude to this, the study of the scientific and technical history of aviation was included in the preceding Years; in the case of the First Year, this had the further benefit of boosting the aeronautical content of that Year.

During the Second Year the students attended the Cranfield Flight Testing Course. Although for many years the students resided at Cranfield itself for this, latterly the Course was run from the University with Cranfield's Jetstream aircraft being based at Woodford aerodrome. In the Third Year members of staff from the BAe Woodford, Warton and Rolls-Royce Derby sites gave generously of their time and expertise to lecture on their specialist subjects, student visits to these sites also being provided.

Each of the students undertook an individual research project during the Third Year and produced a short thesis and presentation on the work, this providing an important consideration in degree assessment. Whilst the latter was otherwise determined mainly on

the results of the traditional written examinations held at the end of each Year, most of the core courses included coursework elements which also contributed significantly to a student's final degree classification. The degree initially awarded was the BSc but in the early 1980s this changed to the BEng, as recommended by the Engineering Council. From the latter's inception of its accreditation process, conducted in this case by this Society, the Department's degree course continued to enjoy a clean bill of health.

As mentioned in Section 7.0 above, in 1986 the Department of Aeronautical Engineering (formerly the Department of the Mechanics of Fluids) amalgamated with the Engineering Department. Ian Poll's appointment as Professor of Aeronautical Engineering in the following year resulted in the later decision to offer both BEng and MEng Degree Courses in Aerospace Engineering. The further decision was taken to offer these courses in collaboration with UMIST's Department of Mechanical Engineering, the latter's staff contributing further diversity and expertise in such areas as management, manufacture, design and certain of the thermo-fluids disciplines. Apart from providing some of the high level material required for the Fourth Year of the MEng course, this collaboration resulted in the further benefit of having nearly the whole of the First Year being presented from an aerospace viewpoint. In the planning for these changes, staff benefited considerably from the advice and practical help provided by the retired BAe Director, John Beaumont Scott-Wilson (1927-2001), born in Bromley, Kent. John Scott-Wilson had taken an interest in the Department's activities over a number of years and was appointed Visiting Professor in Aerospace Engineering at the Victoria University in 1992. In addition to his help in areas such as design and management, he established a highly successful First Year course on the aircraft industry given by himself and a number of his high-level contacts within the industry.

The new Victoria University/UMIST BEng and MEng Courses in Aerospace Engineering began in 1992 and did much to boost student numbers, these rising to about 220 students during any one academic year and thus producing one of the largest aerospace schools in Britain. In 1957 the Victoria University's first entry had been six students; by the time of the amalgamation of the University and UMIST in 2004 some 1600 students had graduated from the Victoria University in Aeronautical/Aerospace Engineering, approximately a third of whom had been foreign nationals. However, in 2001 UMIST withdrew from the joint Aerospace Course so as to establish its own degree courses in this discipline, a move which has since been reversed by the amalgamation of the two institutions.

From the early years of the Department of the Mechanics of Fluids onward, that Department and its successors were jointly responsible with the Mathematics Department in providing an MSc Course in Fluid Mechanics. This combined lecture courses with individual research projects from which each student produced a short thesis. To date, the Department's staff have successfully supervised some 70 students attending this course. A further forty or so students have obtained the MSc degree entirely by research, whilst about 150 have been awarded the degree of PhD.

9.0 FLOW SCIENCE

With the acquisition of Large Closed Return and Environmental Tunnels, it was decided to make the facilities of the Goldstein Laboratory available on a commercial basis. Thus in 1990 Flow Science Ltd was established as a wholly owned subsidiary of Vuman Ltd, itself a company owned by the Victoria University. With Ian Poll as Managing Director and John Scott-Wilson as a non-executive Director, David Smith, by then the Goldstein Laboratory Manager, became the Operations Director who carefully nurtured the company's activities over the succeeding years. Thus a portfolio of clients, of the order of 70 companies, was rapidly estab-

lished so that the considerable loans covering the costs of moving the two large tunnels were quickly repaid. One client generously donated not only a new working section for the Large Closed Return Tunnel but also provided a rolling road with a top speed of 60ms⁻¹.

In 1993 Ian Ryall was appointed Manager of the Large Closed Return Tunnel, having previously obtained wide experience of aerodynamics, including wind tunnel testing, at BAe Warton. Ian returned to Warton in 1997 and was replaced by Andrew Kennaugh (see Section 7.0). When the Goldstein Laboratory acquired the Environmental Tunnel it also obtained the services of Ian Lunnon as Tunnel Manager, he having had considerable experience with the Tunnel at its Leatherhead site.

10.0 THE GOLDSTEIN LECTURE

With the support of this Society, the Goldstein Lecture was established as a biennial event to celebrate the achievements of Sydney Goldstein. As mentioned in Section 6.0 above, the inaugural lecture was delivered by James Lighthill⁽²⁴⁾. The subsequent lectures were as follows: October 1991; Fluid Dynamics in Aircraft Design, Dr John Green, Aircraft Research Association. October 1993; The Work of the Russian Central Aerohydrodynamic Institute (TsAGI), Professor German Zagainov, TsAGI. November 1995; Aerodynamics Past, Present and Future, Professor John Stollery, College of Aeronautics, Cranfield. October 1997; AW52 Laminar Flow Technology, Professor Ian Poll, College of Aeronautics, Cranfield. October 1999; With Science Alongside, Professor John Scott-Wilson, Victoria University of Manchester.

11.0 CONCLUDING REMARKS

The foregoing has attempted a description of the Victoria University's activities in aeronautics and, in the case of the Department of the Mechanics of Fluids and its successors, provided a portrait of the evolution in both the research and teaching involved. How well this has fulfilled the ambitions of Sydney Goldstein, readers must judge for themselves. Nonetheless, the article suggests the important point that, even in the current era of fabulous computing capability, the inter-relationship between well-defined mathematical modelling and careful experimentation continues to be a vital part of aerospace design capability. And for the foreseeable future it is inevitable that there should be experimentation to provide confirmation for designers before committing themselves to future designs. A further point illustrated here is that the activities of independently-minded people have often fostered further advances in subjects unrelated to aeronautics, the reverse, of course, also being true. Any country which fails to support this freedom within its university system does so at its peril. As to Britain itself, aerospace remains a vital part of its economy. Many examples spring to mind, one of the more obvious being that Chester's Airbus Division ships out (literally) on average one set of Airbus wings each day of the year, and to these Derby's engines are often added. Thus despite questions concerning the future ownership of Chester's Airbus Division, the training of this country's future aerospace engineers remains an important contribution to its economy.

Regrettably there has been no room to mention the contributions made by the Victoria University's technical, administrative and secretarial staff also involved, but these have been considerable. Many of the people mentioned above have now retired but undoubtedly they would join this author in offering their best wishes to those younger people remaining and who now face so many challenges ahead.

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