Thermo-Fluids

By Bob Bilger

Early Days

W. H. Warren, the founding Professor of Engineering at Sydney, had peripheral interests in steam power engineering and served on the Royal Commission into the inadequacy of Baldwin steam locomotives (1892). The problem was with the wrought iron axles (see Materials chapter), but along the way Warren is recorded as having taken indicator diagrams to validate that the steam side was up to snuff.

Warren appointed Henry Barraclough, a former student, as a Lecturer in 1897. Barraclough had gained an MME degree at the Sibley School of Engineering at Cornell University, NY, USA and published frequently on steam power engineering, often in the *Journal and Proceedings of the Royal Society of NSW*. Explosions of steam boilers were a major problem at the turn of the century. As outlined earlier in this history, Barraclough subsequently became the first P. N. Russel Professor of Mechanical Engineering in 1915 and was knighted in 1920. He retired at the age of seventy in 1941 and died in 1958.

Sydney–Melbourne rivalry in the late 1930s over the establishment of an aeroplane manufacturing industry in Australia saw Sydney University win the establishment of an academic department of Aeronautical Engineering complete with a large wind tunnel. A crucial factor in this award was Barraclough's lobbying of the New South Wales government to fund the construction of a hydrodynamics laboratory with a towing tank for ship testing [Mann Hart, 1955]. It is worth noting that among the first recruits were a couple of applied mathematicians from Melbourne University named George K. Batchelor and Alan A. Townsend, who after a brief stay went off to Cambridge University to work with G. I. Taylor and establish the statistical theory of turbulence.

The winning of the towing tank led to the appointment of George G. McDonald as the second P. N. Russell Professor in 1940. He had:

> …served an apprenticeship to Marine Engineering with G. & J. Weir Ltd., Cathcart, Glasgow, between 1918 and 1924. He went to Glasgow University in 1924 with the Institution of Naval Architects "Weir" Scholarship in Marine Engineering, graduating in 1928 with first class honours in Mechanical Engineering. He was 1928 Prize man in the special class of Naval Architecture and Marine Engineering and is a Member of the Institution of Naval Architects, London.
>
> [McDonald, 1949].

McDonald stayed on at Glasgow University, gaining a PhD in 1939. At Sydney, McDonald's early efforts were focused on funding for the proper equipment for the towing tank. He acquired the Pelton Wheel and Francis turbines and a centrifugal pump for the Hydrodynamics laboratory, continued the development of the Engines Laboratory and was particularly interested in gas turbines. His interest in fluid mechanics led to the

appointment of Russell E. (Sam) Luxton who hailed from Adelaide and had completed his PhD at Queen Mary College, London on high speed laminar boundary layers. He also appointed Jean Bennett, our legendary departmental secretary. McDonald died before retirement in 1959.

Tom Fink and His Legacy

Tom Fink was appointed as the third P. N. Russell Professor in 1960. He left in 1968 to become full-time Dean at UNSW. In that short time he made a lasting impact on the Department.

Several of Tom Fink's eccentricities are recorded in the General Introduction to this history. With regard to that wrist-watch alarm, Bob Bilger found it particularly disconcerting when Tom would carefully set it in front of him at the beginning of their meeting! John Kent, on being interviewed by Tom for admission to the Research & Development Honours stream, was accused of being just 'a good-time boy'. Marvelling at the hospitality shown by Tom and Averill at one of the annual 'Tre Fontane' staff parties, Tom's response was 'just fill them up on carbohydrate'. One was often quite uncomfortable when Tom was 'on stage', for example when he lectured reporters about Helmholtz's theory of vorticity.

And yet, it was a very close and happy family in those days. By 1965 Civil Engineering had moved out and we had a large and convivial tea room, seldom attended by Tom, but always by most of the staff and the new flush of post-graduate students. Golf days and a camping excursion to the Warrumbungles are among fond memories.

Figure 1 Warrumbungles Excursion 1965
(Back row: Roger Tanner, Jill Bilger, Bob Bilger, Bob Feik (Aero), Bob Antonia. Front Row: Don Fraser, John Simmons).
Photo: Don Fraser

In Thermo-Fluids, Tom's legacy is more to do with the help and encouragement he gave to others rather than the furthering of his own research. He sent Bob Halliday off to the International Towing Tank Conference in London in 1962, followed by a visit to the Stevens Institute in Hoboken, New Jersey to learn the fine art of yacht testing. He invested large resources in support of Sam Luxton's plans to build a very low noise boundary-layer wind tunnel with a fully motorized traversing system to map 3D correlation patterns in turbulent boundary layers. He appointed L. F. (Roy) Henderson from the Aeronautical Research Laboratories and supervised his PhD on the gas-dynamics of shockwave refractions. Somehow, he found Roger Tanner at the University of Manchester and Bob Bilger in industry in Cambridge Massachusetts and persuaded them to come to Sydney, followed by Bryan Roberts and Peter Morgan. Thermo-fluids became the strongest lobe of the Department's research.

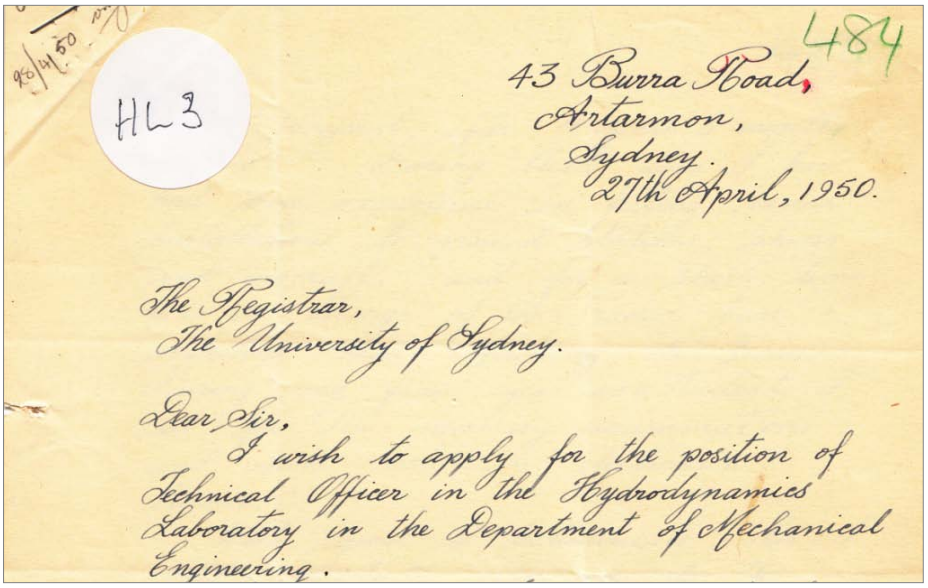
At Tom Fink's invitation, Professor Lloyd M. Trefethen of Tufts University, USA, spent a short sabbatical in Mechanical Engineering in 1964/65. Already famous for his work on surface tension phenomena, he led us into a repeat of the experiments on the bathtub vortex that had recently been conducted by Ascher Shapiro at MIT. After much careful design, a circular tank of some 2.4 m in diameter and 0.4 m depth was constructed and installed in one of the subterranean dungeons of the old Peter Nicol Russell building. Carefully designed procedures and their diligent execution resulted in absolutely conclusive results that were published in Nature [Trefethen, *et al*, 1965). A re-enactment for the local media was a disaster: Bilger and Tanner muffed the removal of the covering baffles creating a great vortex in the water that then went out the wrong way. 'Scientists baffled' cried the media. We even made Time magazine!

The Towing Tank and America's Cup Yacht Testing

Initial funding for equipment for the Hydrodynamics laboratory was squandered on the bad advice of an external member of the advisory committee who insisted on a level flume. Our Civil engineers wanted an inclined flume and the expense was wasted although it saw use as a 'Junior' towing tank. MacDonald spent much of his incumbency soliciting funds from industry to properly equip the towing tank [Mann Hart, 1955].

Keith Mann Hart was appointed by Barraclough in 1925 and became the Senior Lecturer in Charge of the Hydrodynamics Laboratory under McDonald. Progress was slow at first due to wartime shortages. In 1950 funding was made available for the appointment of a Technical Officer and two fitters. R. F. (Bob) Halliday, then a Teaching Fellow in Engineering Technology, was appointed to the Technical Officer position.

Figure 2 illustrates his beautiful copper-plate writing that we all have marvelled at over the years. In 1953 Bob was appointed as a Lecturer in Mechanical Engineering and Les Sarvas took over as the Technical Officer. Bob took over the towing tank development and, as noted above, gained much expertise after his visits to the International Towing Tank Conference in London and the Stevens Institute in Hoboken New Jersey in 1962.



43 Burra Road,
Artarmon,
Sydney.
27th April, 1950.

The Registrar,
The University of Sydney.

Dear Sir,
I wish to apply for the position of Technical Officer in the Hydrodynamics Laboratory in the Department of Mechanical Engineering.

Figure 2 Extract of letter of application from Bob Halliday [Halliday, 1950]

'Gretel', Australia's first yacht challenger for the America's Cup in 1962, was tank tested in America, but after she won one of the races the New York Yacht Club reintroduced the rule that tank testing had to be carried out in the country of the challenger. The Royal Sydney Yacht Squadron became the challenger for 1967, and suddenly in 1965 our towing tank had two syndicates vying for testing time. Alan Payne and Tryge Halvorsen, designers for a modified 'Gretel' (funded by Sir Frank Packer), had their testing done during the day shift and 'Dame Pattie' (funded by a syndicate from Melbourne) did their own testing at night. Don Fraser, a post-graduate student, worked with Bob Halliday on the 'Gretel' testing. He recalls:

> New models arrived about once a week. Each of the models was tested under several different conditions – speed, heel-angle, sideslip, etc. The towing balance, which was designed by Bob Halliday, included means of measuring drag and side force (rather like drag and lift for an aircraft). Things were comparatively primitive in those days, with small weights being added to the two balances until a pointer showed a null reading. No electronics was involved! …. Most of us will have noticed that racing yachts always seem to have very sharp bows. It is what one might expect of something required to cut cleanly through the water. However, one of the most critical times for a yacht is when it is beating against the wind. In such a case, the wind generates a strong side force on the sail and mast, and the yacht heels over and crabs sideways to oppose the side force. Thus, under these conditions, the yacht hull and keel behave like an aerofoil, developing lift and drag. So, what do most aerofoils look like? They usually have a traditional, tear drop shape with a rounded leading edge – quite unlike the traditional, sharp yacht bow. Bob Halliday felt that a rounded leading edge could be a winner. The yachtsmen were at first appalled but Alan Payne agreed to design a model yacht on this basis. Tests appeared to confirm that it behaved better in the heel-sideslip conditions than one with a sharply pointed bow. Probably against their intuition, the yachtsmen agreed to modify the existing, sharp-edged 'Gretel' to have a rounded leading edge to the hull and keel, which she presumably has to this day….
>
> [Fraser, 2011]

Figure 3 Don Fraser and Bob Halliday trimming a 'Gretel' model [Halliday Archive YM4].

'Dame Pattie' won the challenger series off Sydney Heads, unfortunately only to lose to 'Intrepid' off Newport, Rhode Island. Some testing was done for 'Gretel II' (the unsuccessful 1970 challenger) and for the early Alan Bond challengers designed by Ben Lexcen. The successful 1983 challenger 'Australia II' was tank tested in Holland. One of our graduates, Grant Simmer, was the navigator on the Australia II crew. Bob Halliday donated one of the 'Gretel' models to the Australian Maritime Museum in Darling Harbour. Later he wrote up a detailed account of the test equipment and procedures [Halliday, 1998] and had a copy lodged in the Museum's library.

Figure 4 The Towing Tank

Grant Simmer went on to a distinguished career in America's Cup racing and has recently been inducted into the America's Cup Hall of Fame. Another of our graduates, Ian ('Fresh') Burns of the same era is also making an outstanding career in sailing and design in this elite arm of yachting. It was great to be involved with them in the 1995 'OneAustralia' challenge. Conference papers on optimum sail coefficients and tacking theory resulted from these activities. These activities also generated several undergraduate projects, including a highly novel yacht which used dolphin thruster principles.

Boundary Layers and Shock Waves

Sam Luxton's major project was the design and construction of a large, low turbulence, low noise wind tunnel together with a stepper-motor controlled traversing mechanism that positioned hot-wire probes over a range of distances from each other in all three dimensions. Alex Georgescu was the Professional Officer who prepared the detailed design. Unfortunately the project was still unfinished when Sam left for the Chair in Adelaide in 1974. The wind tunnel is now at ADFA in Canberra.

Graeme Swenson, Bob Antonia and Phillip Mulhearn made do with much simpler rigs for their studies of turbulent boundary layers. Antonia did his post-doctoral studies at Imperial College London and came back to join the staff before taking up a Chair at Newcastle in 1977. Swenson went on to Queensland to research the cooling of meat carcasses and Mulhearn to the DSTO labs concerned with ocean turbulence and acoustics. Don Fraser completed his doctorate in the area of digital signal processing (particularly fast Fourier transforms) and went on to CSIRO before taking up his academic appointment at the Australian Defence Force Academy in Canberra. Michael Manton, after a Masters with Tom Fink, a doctorate at the University of British Columbia and a post-doc back in Sydney with Sam, went on to CSIRO Cloud Physics and later to head up Research at the Australian Bureau of Meteorology.

Roy Henderson's first PhD student, Alistair Macpherson, was self funded. With a family of four children he only paid his bills after getting solicitors' demands in writing! He finished in two years and went on to become a Professor at Lehigh University in Pennsylvania. Afo Bestman was a cheery Biafran who loved to open beer bottles with his teeth. He returned to Nigeria and took up an academic appointment. Andrei Lozzi designed novel techniques for enclosing argon and tri-atomic gases behind inclined membranes for the study of shockwave refraction. He joined the staff at Sydney and has for many years led our teaching of design.

Syndy Hall fired bullets in one of the old PNR dungeons to study methods of reducing the sonic boom from supersonic aircraft. She later became an academic at UTS. David Jenkins studied a kinetic theory model for the behaviour of crowds passing through passages with constrictions. He went on to an academic appointment at James Cook University.

Roy Henderson obtained substantial funding from Saudi Arabia to develop his idea for extinguishing oil-well fires by shooting at them with slugs of various types of glup from a modified Bofors gun. He delighted in wearing full Arab dress when travelling in business class to and from Saudi Arabia. He took early retirement in the early 1990s and has since had a series of visiting appointments in the USA, Japan and Europe.

Combustion Research

Bob Bilger

In the USA, Bilger had become challenged by the problems of predicting mixing and reaction rates in combustion systems of a non-premixed nature such as those of a fuel jet mixing and burning in air, the model problem for combustion in diesel engines, furnaces and fires. It was well known that reaction rates could not be predicted using calculations of mean temperature and composition - the correlations among fluctuating terms were hugely important. Hottel at MIT had shown that the length and other main aspects of a jet flame were determined by the rate of mixing – the 'fast-chemistry' model: 'when it's mixed it's burnt!' But what were the effects of heat release and the consequent drastic lowering of density on turbulent mixing rates? How about predicting the effects on soot formation, so important in the radiation from the flame? Soot formation rates were slow compared with mixing rates. Soot emission from flames was a serious pollution problem for diesel engines and many other industrial combustion systems. Carbon monoxide and nitric oxide emissions were also rising pollutant problems that were controlled by chemical reaction rates that were comparable with turbulent mixing rates.

John Kent, Bob's first PhD student, investigated turbulent jet diffusion flames of hydrogen mixing in a co-flowing air stream. Presented at the 1972 International Combustion Symposium at Penn State, it was claimed by Bob to be an attempt to keep the previous speaker - the great Professor Spalding of Imperial College - honest in his modelling! This created quite a sensation and perhaps put Sydney on the map in combustion science. Kent went on to post-doctoral studies with Forman Williams at UCSD prior to joining the staff at Sydney.

A laser-Doppler velocimetry system was developed by Monty Glass with measurements made in turbulent jet diffusion flames for his PhD. After a period as a hippie, Monty joined CSIRO and developed industrial instrumentation. Sten Stårner followed up with studies on turbulent mixing in jet diffusion flames with axial pressure gradients, confirming the finding that density-weighted (Favre) averaging clarified the effects of density variations and pressure gradients on turbulent mixing. After his PhD Stårner has stayed on and is a highly-valued research staff member.

The theoretical relationship between the rates of reaction in turbulent diffusion flames and the rates of microscale mixing - or scalar dissipation as it is known in the theory of turbulent mixing - was discovered in 1975. This finding has been the well-spring for much of the progress in this field ever since. It led to the development with Stårner of the now world-famous piloted jet diffusion flame burner that has provided bench-mark data

for the modeling of turbulence-chemistry interactions in turbulent combustion. Assaad Masri made comprehensive studies of these flames using probes at Sydney and then with laser-Raman/Rayleigh diagnostics at the Sandia Combustion Research Facility at Livermore, California, in association with Dr Robert Dibble, later a Professor at UC Berkeley. This work led to the award of the highly coveted Silver Medal of The Combustion Institute in 1988. After his PhD, Assaad stayed on at Sydney and now, as Professor, leads the combustion group.

Barrie Moss was a sabbatical visitor from Southampton University who later became a Professor at the University of Cranfield. He made the first laser measurements in turbulent premixed flames. Turbulent premixed flames are the model problem for combustion in spark-ignition engines and gas-mixture explosions. Frank O'Young, Yung-Cheng Chen and Peter Kalt followed this work with measurements of instantaneous flame-front structure and turbulent fluxes. O'Young later co-founded a family hi-tech company back in Taiwan after completion of his PhD, while Chen went on to become a professor at the University of Shanghai for Science and Technology, but unfortunately died at an early age in 2010. Kalt has an academic appointment at Adelaide University.

Interest in obtaining spatially and temporally resolved measurements in reacting turbulent flows led to the construction of a huge plastic bag in which mixing occurred between two air streams, one spiked with ozone and the other with nitric oxide. Hot-wire anemometry for measurement of two components of velocity together with a locally developed very fast chemiluminescent analyzer, provided time and space resolved measurements of mixing and turbulent fluxes. Salah Ibrahim and Richard Brown produced ground-breaking PhDs on this experiment together with post-doctoral researchers Neil Mudford, Lars Saetran and Jun-De Li. They (all-five) have tenured academic appointments at Loughborough, QUT, ADFA, Trondheim and VUT respectively. A television reporter dubbed the facility 'the world's largest condom'!

Ibrahim's colleague from Cairo, Mohy Mansour, studied combustion in a locally designed and developed reverse-flow reactor with laser Raman/Rayleigh measurements being made at Sandia with Dibble. After a Post Doctorate with Professor Norbert Peters in Aachen, he returned to Egypt, where he became Dean of the National Institute for Lasers in Engineering and Science (NILES) and then Vice President of Beni-Suef University. Mohy is now a key organizer of the successful series of Mediterranean Combustion Symposia.

The conditional moment closure (CMC) method for modeling non-premixed combustion was developed in the early 1990s. The main idea was that most of the fluctuations in temperature, composition and reaction rates were closely related, non-linearly, to the mixture fraction in non-premixed systems. The equations for species mass fractions and enthalpy, conditionally averaged on the mixture fraction, could then be closed by neglecting contributions from correlations among the fluctuations about these conditional averages. A forcing term associated with the scalar dissipation of the mixture fraction

fluctuations linked this work to the earlier ideas relating reaction rates to scalar dissipation in fast-chemistry flames.

Almost identical work was produced at the same time by Alexander Klimenko in Moscow. Klimenko came to Sydney as an ARC post-doctoral researcher and is now a Reader at The University of Queensland. Nigel Smith did a pioneering PhD on CMC studying nitric oxide formation in piloted jet diffusion flames and in incompletely stirred reactors. He is now the leader of advanced research on jet engine and rocket plumes at DSTO in Melbourne. Reza Roomina followed up Smith's work on nitric oxide formation in jet flames and Kamran Mobini continued that on incompletely stirred reactors. Roomina has not returned to Iran and now works in Sydney as a CFD software specialist. Mobini has an academic appointment back in Iran.

Andreas Kronenburg came from Germany and studied differential-diffusion effects in mixing and reacting flows with application to soot formation using direct numerical simulation (DNS) and the CMC approach. He now holds the Chair in Technical Heat Systems at the University of Stuttgart. Nedunchezi Swaminathan came to Sydney as a post-doctoral researcher and used DNS to study second-order closure in CMC and CMC in premixed turbulent flames. He is now a Professor in the Engineering Department at Cambridge University.

In association with Mikael Mortensen, the mixture-fraction approach has been extended to the evaporation and combustion of droplets and sprays. Applications of this in collaboration with Mastorakos at Cambridge University and Lakshmisha at IIS Bangalore are proving to be productive.

Bruce Lamb, seconded from CSR Ltd, studied the combustion of bagasse on sloping grates. A large applied research project on the formation and transport of photochemical oxidants in the Sydney air basin was carried out in the mid 1970s in association with Macquarie University and the NSW State Pollution Control Commission (SPCC). Keith Post headed up the field measurements and Greg Allen carried out our work on computer modelling. In association with John Kent, another large project on the pollutant emissions and fuel consumption of in-use motor vehicles was carried out in the early 1980s with funding from the National Energy Research and Development Corporation (NERDC). Another applied research project in the later 1980s involved the study of fire spread on conveyor belts in coal mines using the fire gallery built by the NSW government at Londonderry in Western Sydney. In the early 1990s a project was funded by DSTO on composite propellant combustion. It has led to greatly improved understanding of the near-surface flame structure.

John Kent

Born in Sydney in 1946, John completed his B.E. in Mechanical Engineering in 1967, his M. Eng. Sc in 1969 and PhD in 1972 all in the Department. After completing a post-doctorate at the University of California, San Diego and a short period with Esso in Sale, Victoria, John joined the staff as lecturer in 1974. John first studied pollution formation

in turbulent diffusion flames. Nitric oxide and soot were the pollutant species of major interest. He was an Alexander von Humboldt Fellow in Goettingen, Germany in 1979 and 1983.

John's research contributions have been in experimental measurements in combustion, soot formation and in Computational Fluid Dynamics (CFD) of a wide range of flows. He is a consultant to many industries; his boiler furnace modelling was used by the NSW Electricity Commission and by the Queensland sugar refinery industry resulting in the Babcock Award of the Institute of Energy in 1992. His CFD models were applied to many high-profile projects including the Sydney Harbour Tunnel, Sydney Airport terminals and facilities for the Sydney Olympics.

John served as the Director of the Centenary Celebrations for the Engineering Faculty in 1983. He was Head of Department for some nine years until 2000 during which time the Department expanded greatly with the development of Mechatronics, the beginning of Biomedical Engineering and finally the merger with Aeronautical Engineering to become the School of Aerospace, Mechanical and Mechatronic Engineering. He published over 100 papers and retired as Professor in 2006, but has continued his association with the School.

Ian Kennedy, John's first PhD student, used laser scattering measurements of fine particle concentrations to study mixture fraction statistics in turbulent jet diffusion flames. Ian went on to a post-doctoral position at Princeton and is now a Professor at UC Davis. Several studies of soot formation in laminar and turbulent jet diffusion flames have been carried out over the years, including experiments with Damon Honnery (who is now an Associate Professor at Monash University) and modelling computations in association with Professor D'Anna at the University of Naples.

The development of computational engineering codes for furnace modelling and fire engineering has been an active area over many years. With funding from the Electricity Commision of NSW (later Pacific Power) and the Australian Electrical Supply Industry Research Board, Rodney Boyd modelled pulverized coal fired boilers and Peter Benyon coal gasifiers. Boyd and Benyon are now with Connel Wagner, consulting engineers. With funding from the Sugar Research Institute, Anthony Mann and later Peter Woodfield and Jim Rogerson modelled combustion in bagasse fired boilers. They now have appointments at QUT, Griffith University and Doosan Babcock, respectively.

With David Fletcher in Chemical Engineering, post-doctoral students Vladimir Novozhilov, Behdad Moghtaderi and Dalton Harvie modelled fire extinguishment by water sprays. All three now have academic appointments at Belfast, Melbourne and Newcastle respectively. Mathew Cleary modelled carbon monoxide formation in fires and after appointments at Imperial College and The University of Queensland has joined the staff at Sydney. With Tony Green of the Workcover Authority of NSW, post-doctoral Vivek Apte modelled smoke flow in mine gallery fires. Apte is now a consulting fire engineer.

The fire model has also been used to model fire situations in the Sydney Harbour Tunnel as well as many commercial and industrial developments. The packages *FURNACE*, *AXIBURN* and *COALGAS* have over the years been licensed to Aeronautical Research Laboratories, Pacific Power, Royal Institute of Technology, Stockholm, CSIRO, Victoria University of Technology, Huazhong University China, Sugar Research Institute, University of Queensland, University of Newcastle, and University of Adelaide.

.Assaad Masri

Born in Lebanon in 1959, Assaad immigrated to Sydney with his family after surviving two years of civil war in his village. He graduated with First Class Honours and the University Medal in Mechanical Engineering in 1983 and a PhD in 1987. Assaad was awarded the coveted Silver Medal of the Combustion Institute in 1988. He joined the staff in 1989 and was promoted to Professor in 2002. He is now an ARC Professorial Fellow and leads the combustion group. His major interests include turbulent combustion of gaseous and liquid fuels as well as using advanced laser-diagnostic techniques to probe flames and develop an improved understanding of combustion and pollutant formation in turbulent reacting flows. Assaad served as Head of Department/School for four years and oversaw the amalgamation with Aeronautical Engineering.

Since 1989 Assaad has gradually broadened research activities in turbulent combustion to three areas (i) spray combustion, (ii) complex flames covering the range of fully premixed to non-premixed, (iii) advanced laser diagnostics.

(i) Spray combustion
The long term objective of this research is to study alternative biofuels and biodiesels but the initial focus was on understanding dilute spray jets and flames. Using a new piloted spray burner, James Gounder developed a comprehensive data base that later formed the computational platform for the international workshop series on the Turbulent Combustion of Sprays (TCS). James completed his PhD in 2009 and started a Post Doctorate at DLR-Stuttgart working with Dr Wolfgang Meier. Another PhD graduate who has later joined James at DLR is William O'loughlin who investigated the auto-ignition characteristics of dilute sprays using a jet in a hot coflow configuration. With the appointment of Dr Agisilaos Kourmatsis as a Post Doctoral Fellow late in 2011, the research activity has now shifted to studying dense sprays including biofuels and biodiesels.

(ii) Complex flames from premixed to non-premixed
With the aim of gradually reproducing the complexity of practical combustors, burners using bluff-body and then swirl stabilization were investigated in highly turbulent non-premixed modes. Bassam Dally and Yasir Al-Abdeli studied these burners, both of which became additional benchmarks for the successful Turbulent Non-premixed Flame Workshops (TNF) series. Bassam graduated in 1997 and has become an Associate Professor at the University of Adelaide and Head of the School of Mechanical

Engineering. Yasir graduated in 2004 and is a Senior Lecturer at Edith Cowan University in Western Australia.

The shift to premixed flames has the twin objectives of studying deflagrations as well as turbulent flames with distributed reaction zones. The project on deflagrations was a long standing collaboration with an ex-graduate from Sydney, Dr Salah Ibrahim, at Loughborough University. The objective is to study the interaction between premixed propagating flames and repeated solid obstacles. This is a continuing project with Ahmad Al-Harbi (a fully funded student from Saudi Arabia) in the process of completing his PhD on this topic. Distributed reaction zones were generated using a highly sheared, lean premixed flame situated in a wide hot coflow of combustion products.

Matthew Dunn took this burner to Sandia National Labs in Livermore, California where he performed excellent measurements before completing his PhD in 2009 and returning back to Sandia to a post-dotoral position with Robert Barlow. Matt has now joined staff at Sydney. Robert Gordon has studied auto-ignition using a simple jet issuing fuel in a wide, hot vitiated co-flow. After two Post Doctoral positions at Darmstadt (with Dreizler) and Cambridge (with Mastorakos, funded by the prestigious Newton Fellowship) Robert has joined Rolls Royce in Montreal, Canada, where he is battering his body learning ice hockey.

(iii) Advanced Laser Diagnostics

Advanced laser diagnostics, while expensive, has become an integral part of combustion research and it was painfully evident from the start that such capabilities must be developed at Sydney if an impact was to be made. Regular support from the University of Sydney through various large equipment internal funding schemes as well as repeated successes in obtaining ARC-LIEF grants has enabled Masri to continue to add sophisticated equipment to the laboratory to enable measurements of velocity, mixing and temperature fields as well as selected reactive scalar fields. Yachtie James Kelman was Assaad's first PhD student and the first to apply Planar Laser Induced Fluorescence in our laboratory, to image reactive scalars such as the hydroxyl radical (OH) in turbulent flames. After the PhD completion in 1995, James set sail for England and a Royal Society Fellowship at Cranfield. He is now an industry expert on fire risk assessment in London.

In 2008 a strategic move was made to acquire high-speed imaging diagnostics just as this laser and camera technology was starting to emerge. This was achieved through two consecutive ARC-LIEF grants and, at the time of writing (2012) our combustion laboratory was one of a handful of laboratories worldwide with capabilities to image time sequences of reactive scalar such as OH in turbulent flames. Mrinal Juddoo was the first PhD student in my laboratory to apply high-speed imaging to pilot-stabilized flames near blow-off. These measurements resolve an additional dimension (time) in turbulent flames and help unravel the nature of key transient processes such as extinction, re-ignition and flow instabilities. Mrinal graduated in 2010 and has continued as a Post Doctoral Fellow.

In parallel with this experimental program, Masri maintained a strong collaboration with Professor Pope at Cornell and made use of Pope's PDF code to compute the structure of turbulent flames. Farid Christo studied the use of artificial neural networks in modelling turbulent combustion: he is now with DSTO in Adelaide. More recently, Dr Nakul Prasad (who completed his PhD with Professor Bill Jones at Imperial College) has joined the group as a Post Doctoral Fellow in 2011. Nakul adds another dimension to the group with capabilities to use LES to compute turbulent flames. On laminar flames, Mr Jihad Badra has initiated a study of the interaction between homogeneous and surface reactions using a simple configuration of premixed flows over platinum. The project is highly relevant to micro-combustion. Jihad has completed his PhD in 2012 and joined KAUST in Saudi Arabia to 'Post Doc' with Dr Amir Farooq in their newly formed Centre for Clean Combustion.

International Combustion Symposium Sydney 1992

In 1992 we were hosts to the twenty-fourth International Combustion Symposium, the highly prestigious biennial meeting of The Combustion Institute. Some six hundred and fifty registrants attended, mostly from overseas. Chemical Engineering at Sydney managed registration and Macquarie University organized accommodation. Social activities organised by John Kent included attendance at the International Piano Competitions at the Opera House, a Harbour Cruise and a Banquet. Assaad looked after the lecture room facilities. Mrs Jill Bilger co-ordinated the accompanying visitors' program. The July weather was mild and sunny and a spectacular fire in an Ultimo woolstore was clearly visible from the Carslaw lecture room complex and so provided an unscheduled technical feature and entertainment.

The Halliday Lab

In 1965 the Mechanical Engineering laboratories in the old Peter Nicol Russell building were dominated by a great hall of engines of almost every conceivable kind. In an adjacent cavern, a Babcock and Wilcox water-tube boiler provided steam for the Parson's steam turbine and for steam engines of various sorts. Most of the workshop staff were engaged in maintaining this Jurassic Park. We were happy to collude with Professor Tom Fink in the extinction of what were now dinosaurs in our post-sputnik age. Workshop staff were then freed up to work on research projects and undergraduate laboratory teaching became focused on bench-scale experiments that eventually became the 'Pie-Carts' invented by Bob Halliday for the undergraduate laboratory now named in his honour. Test cells for a gas turbine, a variable compression ratio engine and commercial spark-ignition and diesel engines were provided in the new building on the Darlington site from 1974. Noise control, flexibility, and economic use of space were prime considerations. [Halliday, 1973].

The term 'Pie Cart' came from Bob's war-time days servicing radio equipment in aircraft in the RAAF:

> As substitutes for the (aircraft's) main engine driven alternators, technicians used small petrol engine driven alternators mounted on rubber tyred hand carts. These temperamental units were

> indispensible when ground testing the electronic equipment and became widely known as "pie-carts", a term sometimes of endearment but mostly of good humoured contempt.…
>
> [Halliday, 1973]

Figure 5 shows a pie cart for testing an air compressor. Notice the use of a swinging field motor for the measurement of input torque. Four or more units for each experiment were made. When deployed for use they need some 10 m^2 of floor space, but only a tenth of that when stored between periods of use. With two students per pie-cart and eight or more students per demonstrator, students had to be directly involved, rather than standing at the back a group of students watching the demonstrator do the tests. Some forty years on, they are still a key feature of our second and third year teaching.

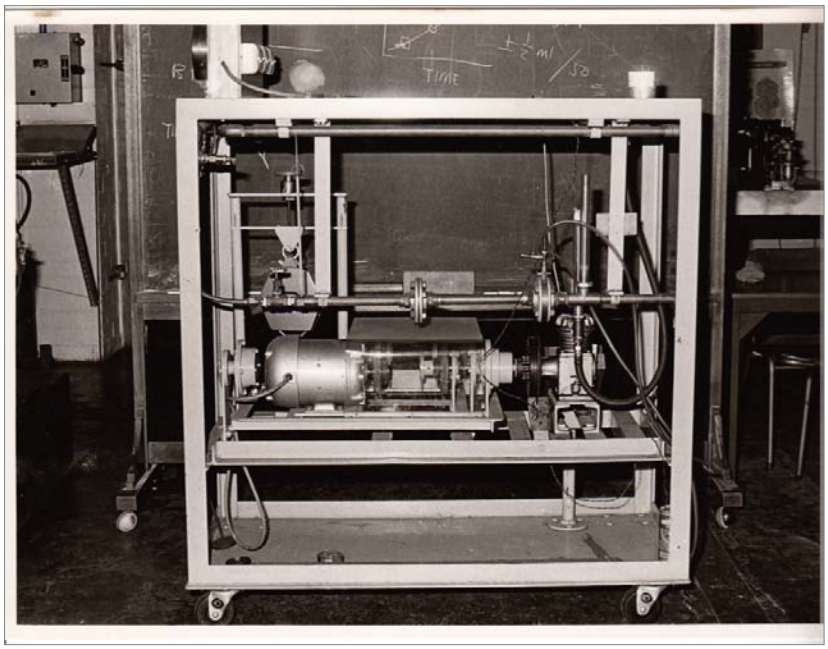


Figure 5 Pie cart for air compressor test experiments

Computational Fluid Dynamics and Buoyant Flows

Computational Fluid Dynamics (CFD) models were developed by John Kent to serve the building industry. During the 1980's and early 1990's the commercial CFD codes were not so widespread as they are today and industry turned to the University for predictions of flow, temperature and humidity in complex buildings. An early project in 1992 was the development of an air-conditioning strategy to cool patrons, but not the pool surface, in the Sydney International Aquatic Centre which would house the 2000 Olympics. During the 1990's there followed air-conditioning CFD modeling of Qantas air terminals, Australia Post letter-sorting facilities, Perth Concert Hall and other buildings. Fire and smoke dispersal was modeled for the M2 road tunnel, Sydney Harbour tunnel, Waverly Library, RAS Pavilion and Darling Harbour venues for the Sydney Olympics. Stack effluent dispersal was modeled for industrial parks and cooling-tower emission dispersal was modeled for high-rise buildings.

Clive (C. A. J.) Fletcher joined us in the early 1980s after his doctorate at the University of California, Berkeley on the computation of flow about a cone in supersonic flow. Here his research focused on the numerics of fluid computations for laminar flows and his resulting two-volume text '*Computational Techniques for Fluid Dynamics'* has been widely adopted for teaching. His most notable doctoral student is Steven Armfield who returned to Sydney after post-doctoral appointments at the University of Western Australia and is now Professor and Head of School. Clive moved to a chair at the University of New South Wales in the late 1990s. Steven Armfield was appointed as a Senior Lecturer in Computational Fluid Dynamics in January 1996, in the (then) School of Mechanical and Mechatronic Engineering, taking the position previously held by David Fletcher, and before that Clive Fletcher.

Prior to his appointment at the University of Sydney, Steven Armfield held positions as a National Research Fellow, and then Lecturer, in Civil Engineering at the University of Western Australia, and Senior Lecturer in Mechanical and Civil Engineering at the University of New South Wales. He has a BSc in Applied Mathematics from Flinders University, and a PhD in Mechanical Engineering from the University of Sydney. He was the UPS Visiting Professor in Civil and Environmental Engineering at Stanford University in 1997, and since then has held an ongoing visiting appointment at Stanford. He was promoted to Professor in 2006, and appointed Head of School in 2008. His interests have been in the development of efficient numerical algorithms for laminar and turbulent flows and applications to buoyant flows.

At the time of Steven's appointment, computational work in the school was carried out on a number of UNIX workstations and mini-computers, including a Stardent vector computer. Shortly thereafter staff moved into large scale parallel computing by setting up the SYDCOM switched cluster of thirty-two Dec Alpha workstations, used by the rheology and computational fluids groups. Nhan Phan-Thien, Ka Yan Lee and David Tullock won the Gordon Bell prize on this facility in 1997, with price performance of 10.8 Gflops/ $ 1 M on twenty-eight DEC Alpha machines. Over the next several years this facility was augmented by smaller clusters of more recent machines, including the Xfarm, of eight DEC DS10s. From about 2000 the price performance of standard Intel based computers exceeded that of the scientific workstations such as the DEC and SUN machines, and the computational fluids group set up the BORG, a switched cluster of thirty-two INTEL based machines. This facility has been the mainstay of computational fluids work in the school since that time, with machines typically upgraded on a four year cycle with, most recently, Intel X79 Quad memory channel machines added, providing 10 Gflop/sec performance.

The fluids group was augmented by the appointment of Michael Kirkpatrick in 2006 as a Senior Lecturer, with promotion to Associate Professor in 2013. Michael is a graduate of the School, both at BE and PhD level. He has also spent time as a Research Fellow at Stanford University, and as a Lecturer in the School of Engineering at the University of Tasmania. Michael has a background in both computational and experimental fluid dynamics, and has taken the primary role in driving the experimental fluids laboratory

since his appointment. His interests lie in the areas of environmental and buoyancy dominated flows, as well as renewable energy and sustainability.

In 2008 Masud Behnia stepped down from his position as Sydney University Dean of Graduate Studies, and was given a Professorial appointment in the School. Prior to his appointment at Sydney University in 2003, Masud held an academic position at the University of NSW for sixteen years. He has a strong research record in Heating Ventilation and Cooling, and in Power Station Design and cycle analysis, and he has continued work in that area at AMME.

Subsequent to Armfield's appointment in 1996, and the more recent appointment of Kirkpatrick, the fluids group has established an experimental fluid dynamics laboratory for investigating transition and mixing in density varying flows. Initial facilities consisted of a horizontal buoyant jet rig and a small fountain rig. These were followed by a two layer mixing flow rig, curved channel rig, and most recently a convectively unstable double sheared boundary layer rig. Data acquisition has been by standard photographic and shadowgraph methods, Acoustic Doppler Velocimetry and, most recently, Particle Image Velocimetry, Laser Doppler Velocimetry and Laser Induced Fluorescence.

Since 1996 the fluids group has supervised twenty-two research students, with many moving on to academic positions after completion of their degrees. As well as Michael Kirkpatrick, now an Associate Professor in AMME, Stuart Norris completed his PhD on parallel and moving boundary solvers for the Navier-Stokes equations in 2000 and is currently a Senior Lecturer in Mechanical Engineering at the University of Auckland. Wenxian Lin, who completed his PhD on the scaling and simulation of fountain and natural convection flows in 2000 is currently an Associate Professor at James Cook University. Sujin Jiracheewanun, who completed his PhD on conjugate natural convection boundary layers in 2008, is a lecturer at King Mongkut’s University of Technology Thailand and Vivian Djanali, who completed in 2013, is a lecturer at the Institut Teknologi Sepuluh Nopember (ITS), Indonesia.

Other research students during this time include: Pat Morgan, who took a position in DSTO; Yoel Tenne who went on to a position as a research fellow at Kyoto University; Nick Williamson, currently an Australian Post-Doctoral Research Fellow in AMME; Srinarayana Nagarathinam who remained in the group after completion as an Australian Post-Doctoral Research Fellow (now working at Tata Industries, India); Tae Hattori, currently a Research Associate in Civil Engineering at Sydney University; Tilek Aberra, working as a consulting engineer in refrigeration design; Luthfi, working as a casual tutor; Karl Dittko, now training to become a Patent Attorney; Natalia Gillam, working in water policy; Jenny Rollo, currently a Research Associate in the Charles Perkins Centre at Sydney University; as well as Hamid Maghaddassi-Naini; Morteza Nateghi; Ramin Mousavi; Xu Dong Liao; Jack Ling and Nick Bartos (all of whom are working in industry); and Peter Rollo, who is retired.

In addition, Geordie McBain joined the group as a University of Sydney Research fellow in 2003, working on the stability of conjugate natural convection boundary layers. He remained until 2007, leaving to take up a position with Silverbrook Research. He is now a Research Fellow at the Institut Jean Le Rond d'Alembert in France.

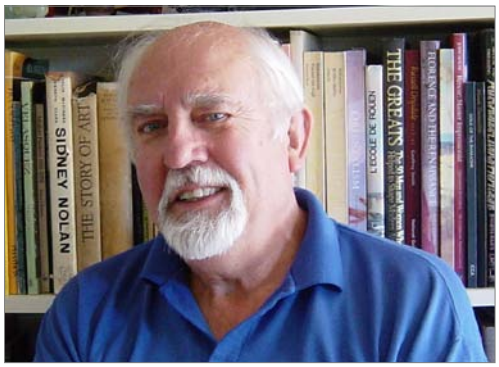
Other Research

Roger Tanner supervised a range of projects in the thermo-fluids area. Of particular note was the development and use of a solar panel test facility in association with Professor Collins in Physics, and of diffusion bonded compact heat exchangers using printed circuit technology. Tony Johnson, the PhD student on this latter project, went on to found Heatric Ltd, a highly successful company in the UK He has since funded a large research program in Chemical Engineering at Sydney.

Bryan Roberts was appointed by Tom Fink in 1964, after a cadetship with CSR Ltd and a PhD on airfoil flutter at Cambridge. He carried out extensive R&D on disposable plastic parachutes and tethered rotor craft for energy capture. His most notable student on the tethered rotorcraft project, David Rye, is now a leading member of the centre for Field Robotics. Bryan moved to a chair at The University of Western Sydney in the 1990s.

Robert W. Bilger

Born in Rustenburg, South Africa in 1935, Bob grew up in New Zealand. He graduated with First Class Honours and the Fowlds Prize in Mechanical Engineering in 1957 together with a BSc and the Senior Scholarship in Mathematics at the University of Auckland. As a Rhodes Scholar he completed his DPhil at Oxford in 1961 before spending four years with Northern Research and Engineering Corporation in London, England and Cambridge, Massachusetts. He came to a Senior Lectureship at Sydney at the end of 1964 and was appointed to the advertised second Chair in Mechanical Engineering in 1975.



He has achieved world-wide recognition for his research into the structure and modelling of turbulent flames and other reacting flows. He has been awarded the prestigious Silver Medal and also the Zel'dovich Gold Medal of the Combustion Institute and has served as

its Vice President (International). He was elected a Fellow of the Australian Academy of Technological Sciences and Engineering in 1987 and as a Fellow of the Australian Academy of Science in 2003. As the University's representative on the NSW Clean Air Advisory Committee in the 1970s he played a leading role in the introduction of stringent industry controls on sulphur, hydrocarbon, oxides of nitrogen, fluoride, lead and asbestos emissions and also contributed to the successful adoption of advanced emission controls for motor vehicles. At Sydney University, he is a founder of the Warren Centre for Advanced Engineering and served as its first Executive Director. His efforts to maintain contact with graduates led to the founding of USMEA. He served as the President of the University of SydneyAssociation of Professors and as a founder of the Chancellor's Scholarships in Engineering. He has also served as Head of Department for some seven years in all. Since 2006 he has become an Emeritus Professor.

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