Building Tomorrow's Society
Bâtir la Société de Demain

Fredericton, Canada
June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

NOMINATION OF BOUNDARY LAYER WIND TUNNEL LABORATORY AS A CSCE/ASCE INTERNATIONAL HISTORIC SITE

Zaitsoff, Sangie[1], King, J. Peter C.[2] and Bartlett, F. Michael[3,4]
[1] Centre for Study of Theory & Criticism, University of Western Ontario, Canada
[2] Boundary Layer Wind Tunnel Laboratory, University of Western Ontario, Canada
[3] Department of Civil and Environmental Engineering, University of Western Ontario, Canada
[4] corresponding_author_f.m.bartlett@uwo.ca

Abstract: At the time construction was completed in 1965, Boundary Layer Wind Tunnel I at the University of Western Ontario was the first boundary layer wind tunnel designed to test civil engineering structures. As a consequence, the Boundary Layer Wind Tunnel Laboratory has recently been nominated as a National Historic Site of the Canadian Society for Civil Engineering and an International Historic Landmark of the American Society of Civil Engineers. The paper briefly chronicles the historic significance and unique features of the laboratory, including some of the contributions to the science of wind engineering made there by Professor Alan G. Davenport and his colleagues.

1 INTRODUCTION

The Boundary Layer Wind Tunnel Laboratory (BLWTL) has experimental facilities that are comprised of two large wind tunnels that remain fully operational today. Construction on BLWT I commenced in the spring of 1965, with an opening ceremony on November 25, 1965. Construction on BLWT II began in the fall of 1982, with the official opening held on May 14, 1984. Together, these two facilities and the researchers and engineers employed at the BLWTL have made significant contributions to the science and practice of wind engineering.

Consequently, the BLWTL has recently been nominated as a National Historic Site of the Canadian Society for Civil Engineering and, concurrently, as an International Historic Landmark of the American Society of Civil Engineers. The paper briefly chronicles the historic significance and unique features of the laboratory, including some of the contributions to the science of wind engineering made there by Professor Alan G. Davenport and his colleagues.

2 HISTORIC SIGNIFICANCE

At the time construction was completed in 1965, BLWT I was the first boundary layer wind tunnel designed to test civil engineering structures. Its historic significance includes its physical construction as well as the contributions of its engineering team to research and education in this field. Conceived and founded by civil engineer Professor Alan G. Davenport, BLWT I was designed by Davenport and Jim W. Stewart, fellow engineer and professor at Western.

Prior to its inception, studies of wind effects on civil engineering structures focused on steady uniform air flow and did not account for the behaviour of the natural wind, including its dynamic and turbulent qualities. With an emphasis on these dynamic properties, Davenport identified an opportunity to expand the study of the dynamic nature of the wind as well as the dynamic wind-induced responses of structures. Designing BLWT I to test civil engineering structures in realistic wind conditions in a scaled simulation of the boundary layer (the section of the atmosphere where the velocity of the wind increases with height and the air is turbulent and variable, extending from the earth's surface upwards to a height of approximately 3,000 feet), Davenport sparked the development of wind engineering science as it is recognized, studied, and applied today.

Central to the historic significance of the BLWTL is the "Alan G. Davenport Wind Loading Chain" (shown in Figure 1), recognized as an official term in 2011 by the International Association of Wind Engineering (Isyumov 2012). Summarizing Davenport's insights regarding key considerations necessary to evaluate the effects of wind action on structures, the wind loading chain emphasizes the interconnecting concepts of wind climate, influence of terrain, aerodynamic data, dynamic effects, and criteria. Utilizing the framework of the wind loading chain as a foundation, emphasizing the significance of each component as well as its interconnectedness within the chain, the BLWTL engineering team pioneered early studies, fostered professional and academic curiosity, and led major advancements in the field of wind engineering. In fact, the historic significance of the BLWTL can be outlined using the components of the wind loading chain, demonstrating its influence on the research conducted at the lab.

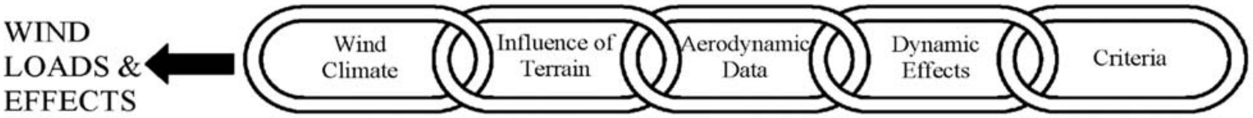

Figure 1: The Davenport Wind Loading Chain.

Wind studies performed at the BLWTL integrated historic wind climate data from local sources near the proposed structure, described in statistical terms (Davenport 1967). Davenport and his team pioneered probabilistic methods to quantify the wind climate at a particular site, including wind speed and direction, and introduced the use of the Monte Carlo method to reliably predict the winds associated with tropical storms.

Consideration of the topography, local wind exposure and roughness of the surrounding terrain of the proposed structure is summarized in the wind loading chain as the influence of terrain (Davenport 1967). To this end, the BLWTL pioneered the incorporation of topographical models into wind tunnel studies. Further, some of the first studies using numerical methods to profile wind behaviour over hills and ridges were completed at the laboratory.

Aerodynamic data are required to model the effects of the natural wind at a reduced geometric scale. New methodologies and instrumentation were developed at the BLWTL along with simplified models and testing techniques that became essential to the acquisition and analysis of such data, contributing to ever-expanding databases. Exemplary developments include the taut strip model, which contributed to studies of the three-dimensional response of long span bridges under turbulent wind; the high-frequency force-balance technique, first developed as the base-balance technique, a major contribution to the measurement of dynamic forces exerted on a structure; the pneumatic averaging technique, used to measure area-averaged fluctuating wind pressures on buildings; and high-speed pressure scanners, adapted from the aeronautical industry to facilitate the simultaneous measurement of pressures at high frequencies. Innovative approaches were also developed at the lab to relate the data acquired from wind tunnel experiments to design applications, increasing the value of including research findings in the process of structural design.

Additional studies were conducted to investigate dynamic effects, defined as wind-induced resonant vibrations that create a potential for load increases on a structure, or in the worst case, instabilities. In particular, loadings for wind-sensitive structures such as tall buildings and long-span bridges were quantified to distinguish between the low-frequency and resonant components of the dynamic wind load. Novel experimental techniques such as pneumatic averaging were adapted to capture these responses.

Finally, recognizing the importance of the consequences of the predicted wind action, the wind loading chain includes consideration of the integrity of the structure, the comfort of building occupants, and the usability of the area surrounding the structure, summarized as criteria. To this end, studies focusing on wind effects at pedestrian levels were designed and an index for determining occupant comfort levels was developed.

Also key to the historic significance of the BLWTL is its unique position at the intersection of three mutually beneficial areas within the science of wind engineering, as shown in Figure 2: (1) research and development, (2) education and training for future leaders of wind and structural engineering, and (3) commercial application to assist clients in finding solutions to design challenges. Closing the gap between engineering research and practice, this opportune position proved essential for Davenport and his team to create an environment at the BLWTL that attracted the most accomplished researchers, professionals, and students from around the world.

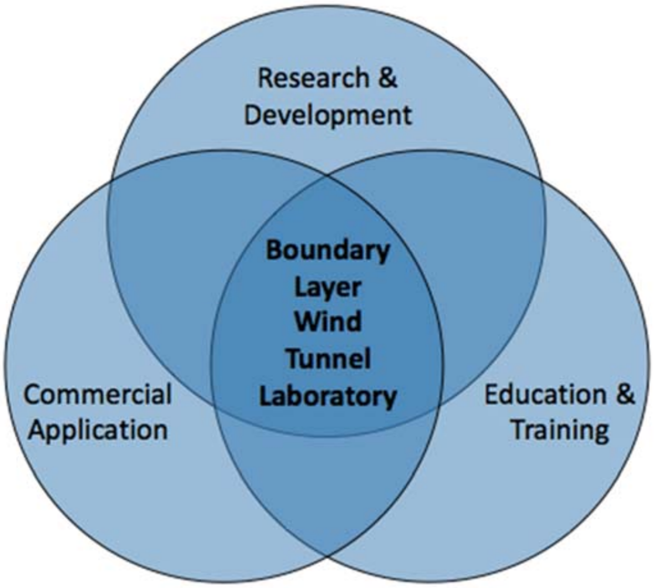

Figure 2: The location of BLWTL in the context of wind engineering

3 COMPARABLE FACILITIES ELSEWHERE

In the early 1960s, no comparable facilities existed when Davenport was recruited as a wind consultant by the structural engineering firm involved in the design of the World Trade Center Towers. Impressed by the insights and innovative approach to wind loading research that Davenport presented at a symposium in England in 1963, the firm's lead structural engineer Leslie Robertson sought Davenport's expertise for the design of these iconic structures.

Initial wind studies on aeroelastic models of the structures were conducted at the Meteorological Wind Tunnel at Colorado State University in Fort Collins, CO, a facility led by another key figure in wind engineering, Jack Cermak. Though the facility was capable of generating representative models of boundary layer wind, as it was originally designed to test the diffusion and dispersion of gases and pollutants, adjustments to the CSU wind tunnel had to be made to decrease pressure gradients to appropriately test models of the proposed towers.

Comparison tests for the World Trade Center Towers were conducted at the National Physical Laboratory (NPL) in England. The wind tunnel at NPL, however, was also not ideal for conducting such studies: it had been designed to generate smooth uniform air flow required to perform aeronautical research, and as such was not equipped to represent conditions of the natural wind in the boundary layer.

Though these wind tunnel facilities were state-of-the-art, such studies exposed the deficiencies of both facilities to undertake pioneering structural wind engineering research. Building on what he had learned during these years of research and experimentation, and incorporating the work of pioneers in the field such as Martin Jensen and Kit Scruton, Davenport concluded that it was necessary to design a wind tunnel suited to examine the dynamic responses of structures to the turbulent qualities of the wind, allowing for important inclusions such as the meteorology of the wind in the environment of the proposed structure.

4 UNIQUE FEATURES AND CHARACTERISTICS

Boundary Layer Wind Tunnel I, shown in Figure 3, is 100 feet (30 m) long, 8 feet (2.4 m) wide and has an adjustable roof to achieve a height between 5.5 and 7.5 feet (1.7 and 2.3 m). A large fan, shown at the left of Figure 3, generates wind with a maximum speed of 30 mph (48 kmh). The adjustable roof height allows accurate simulation of pressure gradients, and the long test section allows turbulent boundary layer flow to naturally develop over roughness elements on the wind tunnel floor. The original facility began with a manometer board to measure pressures and expanded to include a data acquisition system with electronic instrumentation to measure pressures as well as wind speeds and outputs from strain gauges and other instruments. For example, Figure 4 shows statistics from the test instrumentation being printed during one of the laboratory's early studies of wind effects on cooling towers.

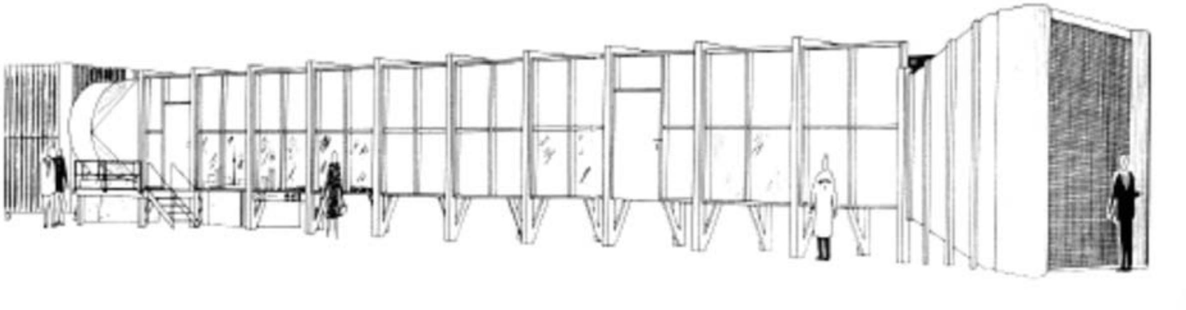

Figure 3: Boundary Layer Wind Tunnel I (1965)

Figure 4: Early data acquisition technology

By the early 1980s, as the field of wind engineering research was advancing rapidly with BLWT I continuing to play a leading role in new advancements, it was decided that a wind tunnel of increased capacity and versatility was needed. Boundary Layer Wind Tunnel II was therefore designed on the basis of experience with BLWT I. Working closely with Davenport and collaborating to design BLWT II, the Western wind engineering team included Nick Isyumov, David Surry, Barry Vickery, Milos Novak, Terry Base, Raouf Baddour, and Peter King – see Figure 5. The detailed design was conducted by the Western wind engineering team and the Toronto-based firm DSMA International Inc (now Aiolos Engineering Corporation),.

Figure 5: Members of the ‘80s wind engineering team. Left to right: Barry Vickery, Dave Surry, Nick Isyumov, Milos Novak, Alan Davenport, Peter King.

Doubling BLWT I in many ways, BLWT II is a closed circuit wind tunnel with a maximum wind speed of 60 mph (96 kmh), as shown in Figure 6. It includes adjustable roughness elements that can be pre-programmed to create particular turbulent wind profile characteristics, and a wind/wave tank of 170 feet (52 m) in length that can be converted to a dry testing section. BLWT II includes two test sections: a high-speed section (at the right of Figure 6) to investigate problems involving the Reynolds number such as model tests of buildings, section models of bridges and other structures, and a low-speed test section (at the left of Figure 6) that is appropriate for investigations involving Froude number scaling, such as topographical models and full aeroelastic models of long-span bridges. In addition, further advancements were made regarding instrumentation and measuring capabilities of the lab, including laser displacement transducers, low mass accelerometers, high speed pressure scanners, and improved computer and data acquisition hardware.

5 CONTRIBUTIONS MADE TO THE CIVIL ENGINEERING PROFESSION

In addition to the historically significant contributions noted above, more than 2,000 reports since 1965 from wind studies conducted at the lab include a long list of remarkable buildings such as the Willis Tower in Chicago (formerly the Sears Tower), see Figure 7, the CN Tower in Toronto, see Figure 8, the Bank of China Tower in Hong Kong, the Shanghai World Financial Center Towers, the Walt Disney Concert Hall in Los Angeles, the Valencia Opera House in Spain, and the Canary Wharf Complex in London, England. Notable bridges include the Sunshine Skyway Bridge in Tampa, Florida, the Bronx-Whitestone Bridge in New York, see Figure 9, the Tsing Ma Bridge in Hong Kong, the Confederation Bridge joining New Brunswick and Prince Edward Island, the Paso del Alamillo Bridge in Seville, Spain, and the A. Murray

MacKay Bridge in Halifax, Nova Scotia - the first full model of a bridge ever tested in turbulent boundary layer flow, see Figure 10.

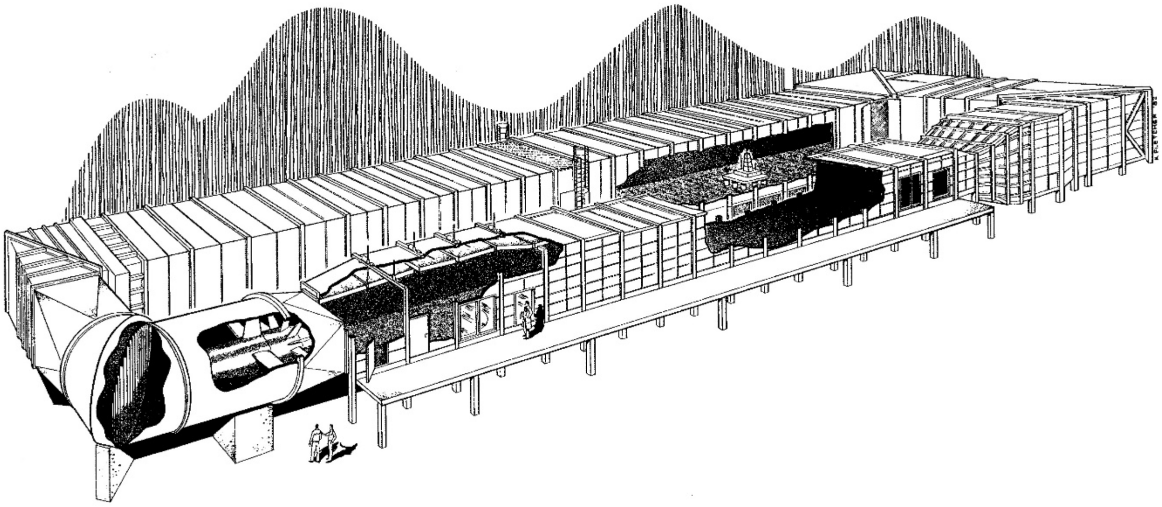

Figure 6: Boundary Layer Wind Tunnel II (1984)

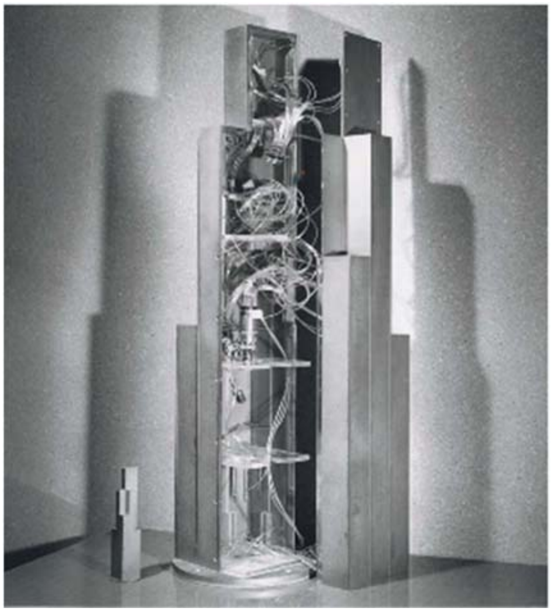

Figure 7: Pressure transducers on a pressure model of the Sears Tower

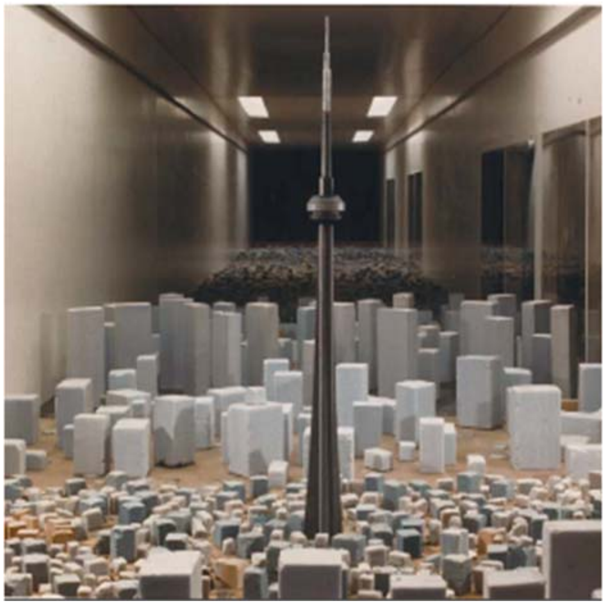

Figure 8: CN Tower Model in BLWT I

Other major contributions by Davenport and his team at the BLWTL include wind loading specifications, specifically wind force and wind pressure coefficients, as well as research focusing on wind effects on low buildings. These research accomplishments have had a major influence on building codes and standards around the world, particularly in Canada, the US, Europe, Southeast Asia, and the Caribbean. Additionally, Davenport's gust factor approach, the spectrum of gustiness of strong winds and the categorization of terrain roughness continue to be used in the National Building Code of Canada and many other international standards. Further, the team at the BLWTL conducted some of the earliest studies of wind effects on communications towers and transmission lines as well as pioneering studies on cooling towers, tall chimneys, guyed towers, and cranes. Overall, research conducted at the BLWTL has contributed to an improvement in the safety of structural design and overall reliability of buildings, bridges, and other structures, as well as a reduction in the cost of both design and construction of such structures.

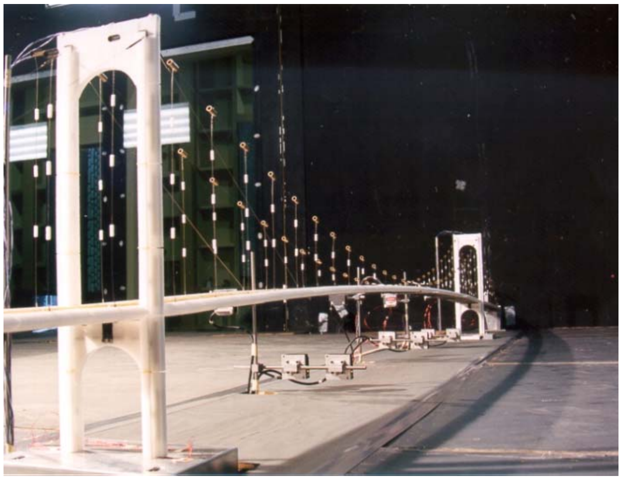

Figure 9: Aeroelastic model of Bronx-Whitestone Bridge

Figure 10: Aeroelastic model of MacKay Bridge

Despite the variety of achievements of the engineering team working at the BLWTL, the contribution that remains most significant is its role as a catalyst for innovation and collaboration, each facilitating the success of the other. Advantageously situated within the university community at Western, nearly 200 students have completed graduate work at the lab. The opportunity for these students to conduct research under the mentorship of accomplished professionals and researchers at a cutting edge facility, along with the value added to this research environment by a constant stream of new thinkers, resulted in a ripple effect within the field of wind engineering. Many students stayed on at the BLWTL in a professional, research, or academic capacity well after their graduation. Others have become leaders in the field, developing and improving the state of the art in university and private sector facilities throughout the world.

The pioneering work of Davenport and his peers at the lab became an inspiration for the design of many boundary layer wind tunnels in Canada and around the world. Notably, two researchers at the BLWTL have initiated research projects with Western University to study the effects of extreme wind and weather on structures: the Insurance Research Lab for Better Homes (IRLBH), a laboratory that generates hurricane-force wind pressures at full scale (Kopp 2010), and the Wind Engineering, Energy and Environment (WindEEE) Research Institute, the world's first hexagonal wind tunnel, able to generate a variety of naturally occurring wind flows, including tornado-flow winds (Hangan 2010). As Canada has the second highest rate of tornado occurrence in the world, the collaborative research performed at these facilities, inspired by the BLWTL, demonstrates the continued value of research contributions to both the region of Southern Ontario and communities across Canada.

By founding the Boundary Layer Wind Tunnel Laboratory, Alan G. Davenport nurtured a rare culture of remarkable collaboration. Structured much like the Davenport Wind Loading Chain, the BLWTL links innovative minds with a one of a kind facility, making invaluable contributions to a once-budding and now-flourishing discipline. With no shortage of challenges in the future of designing civil engineering structures, including new environmental and energy considerations, the historic significance and continued relevance of the BLWTL remain a constant source of inspiration for future innovators.

6 DRAFT CITATION

The CSCE Board of Directors has approved the designation of the Boundary Layer Wind Tunnel Laboratory as a National Historic Site. More recently, the nomination has also been approved as an International Historic Civil Engineering Landmark by the Engineering History and Heritage Committee of ASCE, the ASCE Committee on Advancing the Profession (CAP) and the ASCE Board. It is envisaged that a joint ASCE/CSCE plaque be erected on site with text along the lines of the following:

> *The Boundary Layer Wind Tunnel Laboratory*
>
> *This facility, founded by Professor Alan G. Davenport (1932-2009) and constructed at the University of Western Ontario in 1965, is the world's first wind tunnel designed to test wind-sensitive structures in turbulent boundary layer flow. Its staff of engineers, researchers, and students conduct ground-breaking studies that quantify the effects of dynamic wind action on structures, accounting for wind climate data and the influence of terrain. The Boundary Layer Wind Tunnel Laboratory developed the science of wind engineering, contributing to the overall reliability and economy of civil engineering structures across Canada and around the world.*

7 CONCLUSIONS

At the time construction was completed in 1965, Boundary Layer Wind Tunnel I at the University of Western Ontario was the first boundary layer wind tunnel designed to test civil engineering structures. As a consequence, the Boundary Layer Wind Tunnel Laboratory has recently been nominated as a National Historic Site of the Canadian Society for Civil Engineering and an International Historic Landmark of the American Society of Civil Engineers in recognition of the historic significance and unique features of the laboratory, including the contributions to the science of wind engineering made there by Professor Alan G. Davenport and his colleagues.

Acknowledgements

Financial support from Western's Faculty of Engineering is gratefully acknowledged. The cheerful assistance of Ms. Karen Norman, who retrieved photographs from the Wind Tunnel Archives, is also gratefully acknowledged.

References

Davenport, A.G. 1967. The Treatment of Wind Loading on Tall Buildings. *Proceedings of a Symposium on Tall Buildings, University of Southampton, April 1966*. Eds A. Coull & B. Stafford Smith, Pergamon Press, U.K. 3-44.

Hangan, H. 2010. Current and Future Directions for Wind Research at Western: A New Quantum Leap in Wind Research through the Wind Engineering, Energy and Environment (WindEEE) Dome. *Japan Architectural Wind Engineering Journal.* **35**(4): 277-281.

Kopp, G. 2010. Current and Future Directions for Wind Research at Western: Disaster Mitigation and the 'Three Little Pigs' Project. *Japan Architectural Wind Engineering Journal.* **35**(4): 282-286.

Isyumov, N. 2012. Alan G. Davenport's mark on wind engineering. *Journal of Wind Engineering & Industrial Aerodynamics*. **104-106**: 12-24.