I

Sowing Wind Science

No sooner did the Tacoma Narrows Bridge—the world's third longest suspension bridge, and the pride of Washington State—open in July 1940 than it earned its epitaphic nickname, "Galloping Gertie." The 4,000-foot structure, its main span reaching 2,800 feet, twisted and bucked in the wind. The pronounced heave, or more technically speaking the longitudinal undulation, caused some automobile passengers to complain of seasickness during crossings. Others observed oncoming cars disappearing from sight as if traveling a hilly country road. By November 7, amid 39-mile-an-hour winds, the $6,400,000 bridge wobbled and flailed, then rippled and rolled, then twisted like a roller coaster, until in its final throes it plunged, with a beastly roar, 190 feet into the waters of Puget Sound.

See Glossary for definitions

Speaking to a *New York Times* reporter the day after the collapse, Leon S. Moisseff, the bridge's designer and engineer, was at a loss to explain the cause, placing blame on "a peculiar wind condition."

Wind engineer Alan G. Davenport, founder of the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario, often summoned the memory of the Tacoma Narrows Bridge disaster as a cautionary tale. "Most features of this disaster are too familiar to bear repeating," he told his audiences, whether assembled at technical lectures or at popular talks. Both occasions always included screenings of grainy film footage capturing the bridge misbehaving as though fashioned from rubber—footage now preserved, owing to its cultural, historical, and aesthetic import, in the United States National Film Registry, as well as on YouTube, with numerous clips garnering more than six million cumulative views. Nonetheless, Davenport noted, as familiar as this disaster may be to the collective consciousness, the

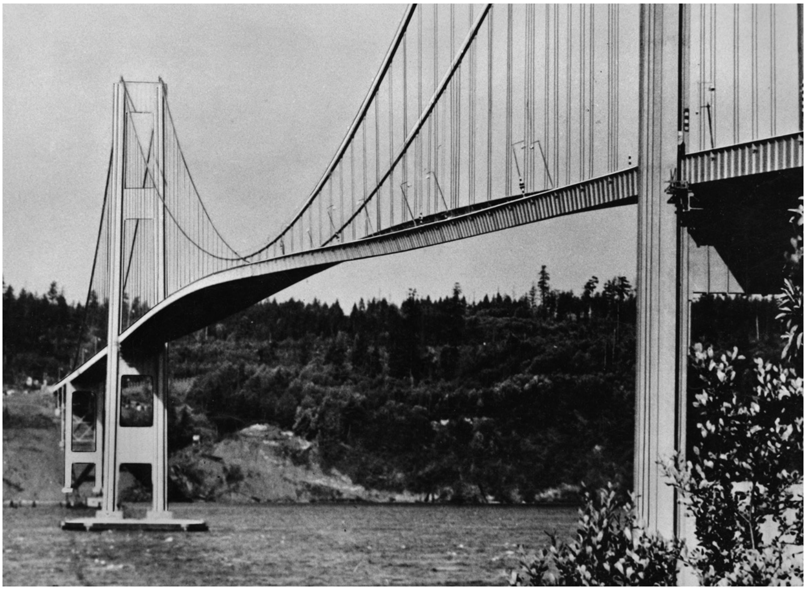

Figure 1A. The Tacoma Narrows Bridge displayed torsional oscillation and longitudinal undulation even before it opened on July 1, 1940. University of Washington Libraries, Special Collections, UW21413.

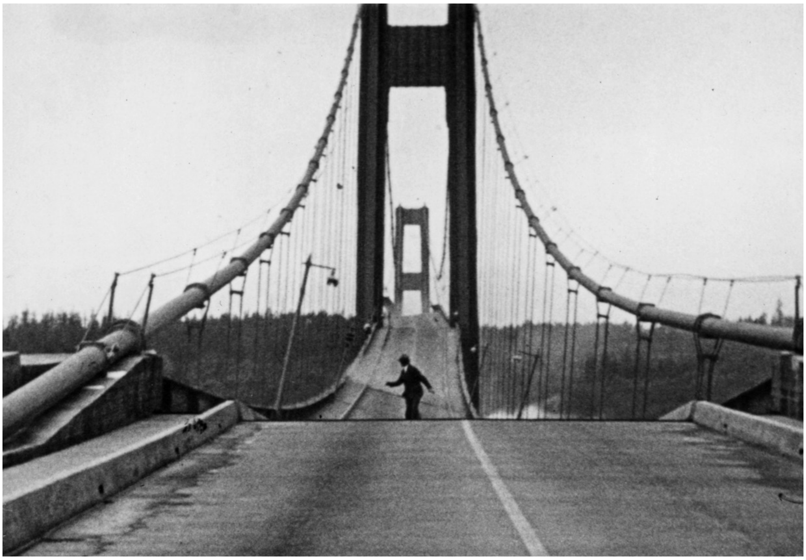

Figure 1B. Photographer Howard Clifford of the *Tacoma News Tribune* snapped a few shots and ran. University of Washington Libraries, Special Collections, UW20731.

Figure 1C. The bridge's main span collapsed into the waters of the Tacoma Narrows on November 7, 1940. University of Washington Libraries, Special Collections, UW21422.

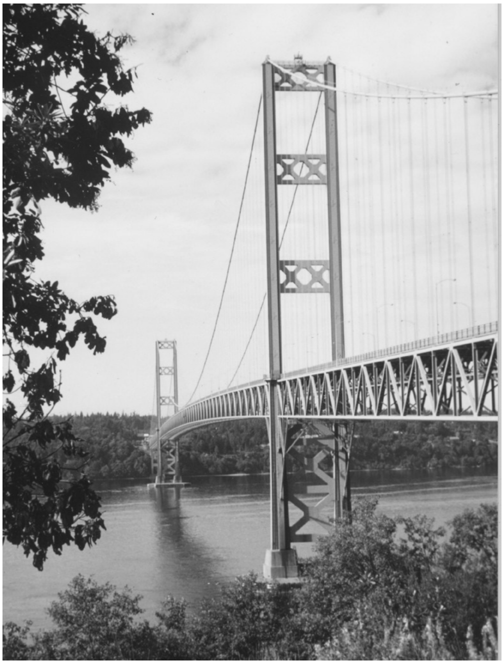

Figure 1D. The new and improved Tacoma Narrows Bridge, 1950. Courtesy of R. A. Dorton.

consequences bear continued consideration. "What's past is prologue," Shakespeare observes in *The Tempest* (and said the jester Trinculo, "Here's neither bush nor shrub to bear off any weather at all, and another storm brewing; I hear it sing i' th' wind"). In broadening the moral of the Tacoma disaster and applying it to the behavior of all structures—bridges, buildings, and beyond—Davenport made of this cautionary tale a professional credo that governed his lifelong fascination with the wind, and with balancing the wind's fickle forces.

It was in 1965 that Davenport established the world's first dedicated boundary layer wind tunnel designed to test civil engineering structures. The planetary boundary layer is the region of the atmosphere extending from the earth's surface upward about 3,000 feet, the wind churning the air into turbulent eddies, average velocity increasing with height. A boundary layer wind tunnel mimics these marbled striations of air—it mimics wind energy—in order to test designs for buildings and bridges that will face the wind when built. Making its debut in the 1960s, Davenport's wind tunnel arrived the same decade as the laser, the computer mouse and the Internet, handheld calculators and the ATM, Apollo 8, string theory, and Rachel Carson's *Silent Spring*. In the years to come, Davenport's revolutionary lab would investigate the windworthiness of some of the world's most innovative structures: many of the tallest buildings, including New York City's World Trade Center and Citicorp Tower, Chicago's Sears Tower, Boston's John Hancock Tower, Shanghai's World Financial Center, and Toronto's CN Tower (which, strictly speaking, is not a building but rather a freestanding structure), and many of the longest bridges, among them Florida's Sunshine Skyway, the proposed Straits of Messina span in Italy, France's Millau Viaduct and the Pont de Normandie, as well as the iconic Golden Gate Bridge and New York's Bronx-Whitestone Bridge. The Bronx-Whitestone Bridge, being very similar in design to the Tacoma Narrows crossing, has over the years required an extensive rehabilitation regime that continues to this day.

In addition to the buildings and bridges that came through the lab, there were also a few exceptions and eccentricities. Legend has it that in the early days the lab conducted tests on portable toilets, and later on Arctic tents to be deployed by the Canadian military. NASA commissioned a study on the ground wind loads for the *Jupiter* launch vehicle (occasionally Davenport said he wished he'd been an astronaut). The 2,421-foot illuminated Glorious Cross of Dozulé had its day in the tunnel, though it has yet to grace the countryside of Normandy. *Sports Illustrated* splurged on an investigation of Augusta National's twelfth hole, the lynchpin of the Masters' famed Amen Corner, said to be among the toughest holes in golf, in part because of the seemingly indecipherable winds (see sidebar, "Driving into the Wind," below).

Driving into the Wind

Sports Illustrated turned to the lab to decipher the maddening winds at what's been called the "meanest hole" in golf, the 12th hole at Augusta National. "Augusta National is a one-of-a-kind golf course," the article reported, "but all it takes to reproduce it (albeit at a scale of 1 to 200) is high-density foam sculpted with drywall compound, more than 600 trees made of sponge and wire, an acrylic Rae's Creek (complete with tiny silicone waves) and, for good measure, foam golfers that are nearly as stiff as the real thing. . . . The shot's path was represented on the model by a fixed piece of copper tubing 5/16th of an inch in diameter. Meteorological data from 1949 through '99 (collected at Augusta Regional Airport, about 10 miles south of Augusta National) was then analyzed by computer to create a simulation of the typical April winds that blow through Amen Corner. Smoke was used to give these breezes visual paths. To illustrate the turbulence at higher elevations, a wire coated with oil was fixed upwind from the model. An electrical current was sent through the wire until the oil burned, producing yellowish smoke. To depict the wind's effects along the trajectory of the shot, 13 evenly spaced holes were drilled along the copper tubing. Inside, titanium tetrachloride was introduced, producing bright white smoke." Results showed that one wind took two directions: "On the tee the wind is in the golfer's face, quartering slightly to the left (east), in the direction of the 11th fairway. About 25 yards into its flight the ball encounters a crosswind blowing to the east. Another 40 yards toward the green, as the shot is approaching its apex, the ball is slammed by a wind shear, with gusts blowing to the west toward the 13th fairway. This wind dissolves into low-speed swirling 20 yards from the green, as the ball is passing over Rae's Creek." The lab's project leader, Greg Kopp, concluded, "The challenge used to be trying to figure out the wind. Now the players have all the information, but they may wish they didn't. It's still a frightening shot into a very difficult wind."

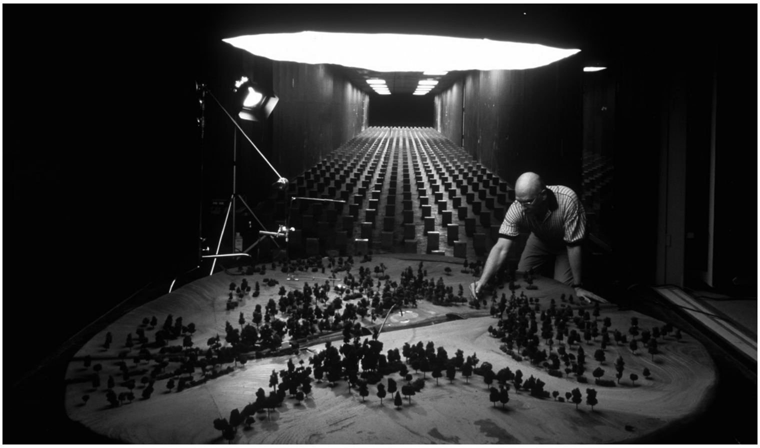

Figure 2. Wind tunnel tests on Amen Corner, Augusta National Golf Course. Courtesy of Robert Walker for *Sports Illustrated.*

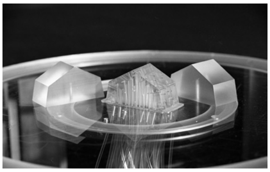

Figure 3. In the early days, the lab conducted tests on a design for portable toilets, and later on a ten-man Arctic tent to be deployed by the Canadian military. Courtesy of the Boundary Layer Wind Tunnel Laboratory.

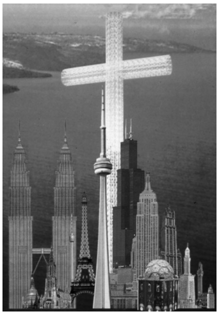

Figure 4. Stabilizing the Glorious Cross of Dozulé against the wind in Normandy, France, proved difficult to finance (the clients attempted to get papal recognition of the location as the site of a miracle, which would have made raising the necessary funds easier). Courtesy of the Boundary Layer Wind Tunnel Laboratory.

Figure 5. Davenport with a model of the *Jupiter* launch vehicle. In 1966, he presented two papers at NASA's Langley Research Center for the "Meeting on Ground Wind Load Problems in Relation to Launch Vehicles." Courtesy of Alan Noon.

Himself a great sailor, Davenport reveled in the testing of sails for an America's Cup vessel. There were also investigations into how better to spray fruit trees so that the mist would not be blown off course by the wind. The solution proposed by Davenport's colleague, the electrical engineer Ion Inculet, was to make the fluid electrostatically charged, so that it would be attracted to trees and repelled from the ground. There were inquiries into how to ensure a clean airflow over surgical patients during hip replacement procedures, which are particularly susceptible to infection. And after the construction in 1984 of a second-generation wind tunnel that doubled as a wave tank, Davenport tracked the wind-induced drift of icebergs and observed the battering of BP and Exxon oil rigs in the open seas.

With such a multidisciplinary portfolio, Davenport quickly accumulated unparalleled expertise in the nascent field of wind engineering—indeed, the field emerged and evolved largely because of his work. With one pioneering example after another, he set the agenda for investigating the effects of wind on the natural and built environments.

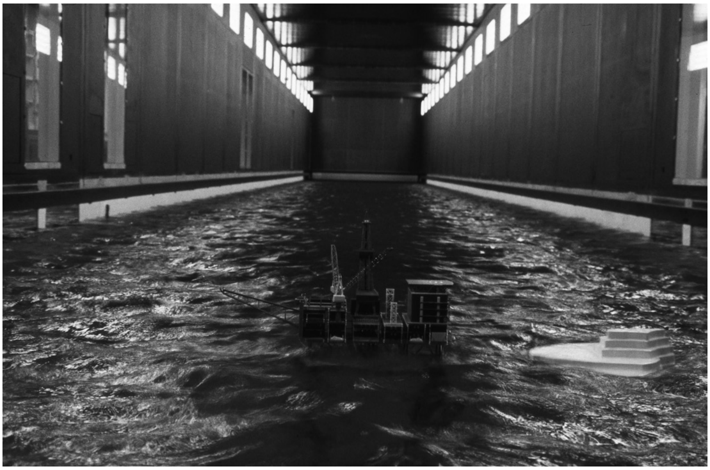

Figure 6. In 1984, with the construction of a second-generation wind tunnel facility that doubled as a wave tank, the lab began studying wind and waves—investigating the effects of wind on oil rigs and icebergs. Courtesy of the Boundary Layer Wind Tunnel Laboratory.

Figure 7. Davenport and his daughter Clare sailed windsurfers in the wave tank at the opening of the new wind tunnel facility. Courtesy of the Boundary Layer Wind Tunnel Laboratory.

When the interaction between wind and our environs is not properly factored into structural design, the consequences can be catastrophic. A powerful lashing of wind assaulted a family viewing Christmas lights during a walk around Toronto's City Hall in 1982. The wind lifted the plywood from the promenade, threw the family into the air, over a protective parapet, and then dropped them 20 feet onto Nathan Phillips Square below, with serious injuries resulting. Climate change is arguably exacerbating extreme weather events, such as the deadly tornado outbreak in the southern United States in 2011, Hurricane Katrina in 2005, and the North American ice storm in 1998. And our exposure and risk are only heightened in the more fringe and fragile edges of nature where people are living, in both developed and developing countries—whether those fringes are the Florida Gulf resort communities or the rural coastal villages of Sri Lanka, where Davenport attended a disaster relief conference after the Boxing Day tsunami of 2004. Wind engineering is vitally concerned with how to prevent wind-induced disasters, the most costly disasters in terms of property damage and casualties. And although most knew him as a wind expert, Davenport in his versatility was among the first to advocate that the same mindset of preparedness be applied to all shapes and forms of natural disaster, not just those powered by wind.

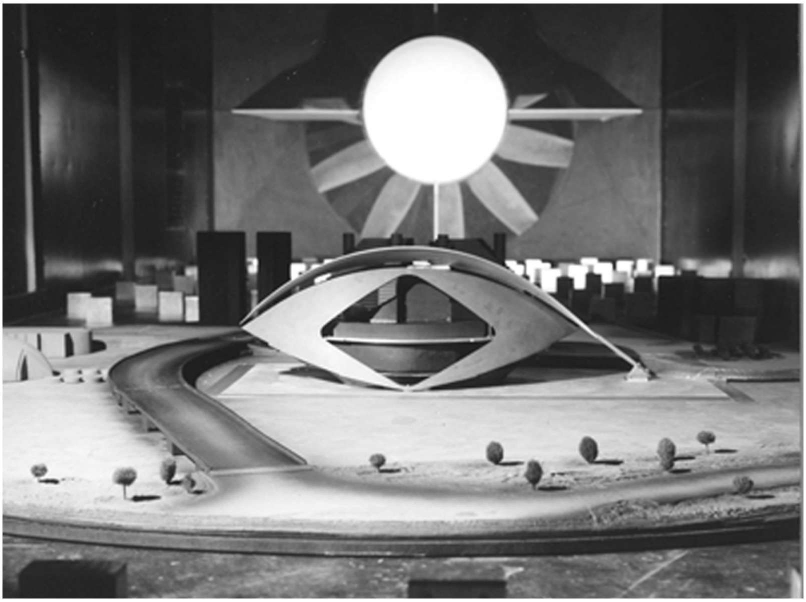

Figure 8A. The lab put to the test several structures by Spanish architect Santiago Calatrava, including the Valencia Opera House. Courtesy of the Boundary Layer Wind Tunnel Laboratory.

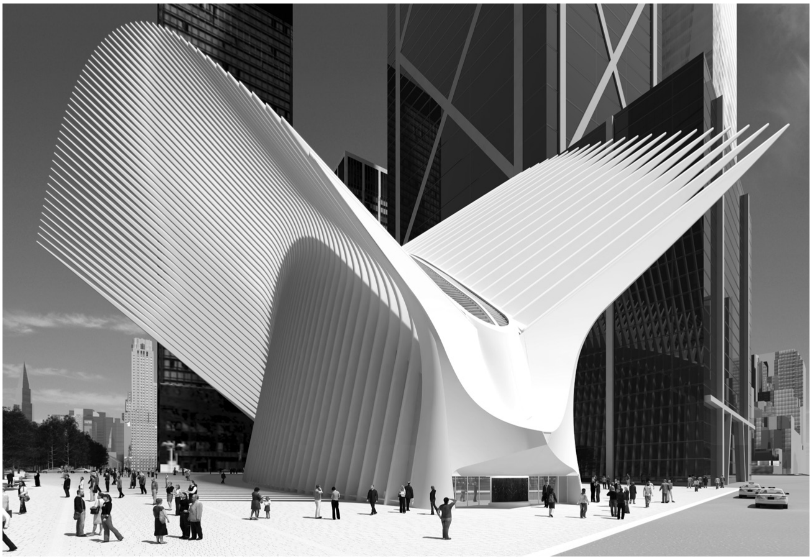

Figure 8B. Calatrava's World Trade Center PATH Terminal at Ground Zero. Courtesy of Santiago Calatrava.

Upstream, Downstream

Pollution control efforts to cut sulfur emissions from chimneys at old coal-burning power stations resulted in a busy time for the lab's Barry Vickery, an expert on towers, chimneys, and stacks. (Vickery is now retired and serving as a consulting director of the lab.) In 1979, the Canada-USA Sulphur Emissions Reduction Protocol mandated a 30 percent reduction in emissions by 1993. To meet this mandate, companies such as American Electric Power, in the Ohio Valley, faced constructing new chimneys at preexisting plants with no choice but to put them in proximity to both the generating unit and the old chimneys. "Companies often want to avoid the considerable cost of dismantling the old chimneys," explains Vickery. "But having a number of stacks clustered together results in nasty aerodynamic problems—the upstream and downstream structures strengthen the vortex shedding produced by each, creating interference effects and loads powerful enough to damage these tall stacks, sending their exterior brick walls flying, or knocking the interior linings and filters." Vickery developed the best method for predicting the response of chimneys in such scenarios, a method he subsequently applied to well over 100 chimneys. Problems resulting from interference effects can be solved in a variety of ways, but simply removing the top third of an old stack due for decommissioning usually solves the problem.

Figure 9. The close proximity of cooling towers and old and new chimneys precipitates aerodynamic problems. Mark William Richardson/Shutterstock .com

In a career spanning half a century, Alan Davenport published hundreds of technical papers and scientific reports on the wind. He also seized every opportunity to impart a more popular, cultural, even philosophical and romantic perspective. One staple talk in his repertoire, "Sowing the Wind," he delivered at the 1979 commencement ceremony at Belgium's University of Louvain upon receiving one of his numerous honorary degrees. He explained that the title was taken from the words of the Old Testament prophet Hosea, "For they have sown the wind, and they shall reap the whirlwind," suggesting that one must heed the action and power of the wind or deal with the consequences. "Our ancestors, and civilizations before us in the ancient world, respected the wind for both practical and spiritual reasons," he observed. The wind has the power to drive turbines and evoke emotions. It pushes ships, and sinks them. It winnows grain and turns windmills grinding grain to flour, but it also flattens crops and blows down barns. Spiritually, Davenport noted, "Primitive people were no doubt awed by wind" . . .

> What exactly they thought about this mysterious invisible force we cannot be sure. Did they believe, like the popular cartoon philosopher Charlie Brown, that the clouds pushed the wind along? Or, like Ogden Nash, that the wind is caused by the trees shaking their branches? We can only guess that the unseen hand causing the rippling of the water and the rustling of the leaves was a sign that the natural world was animated by life-giving forces; that when these ripples turned to storm tossed waves, those forces were angry.

The principal god of the Aztecs, Davenport noted, was Quetzalcoatl, the plumed serpent and the god of wind. Quetzalcoatl's equivalent in ancient Egypt was Ammon, who shared the same godly status as Ra, the sun god. And the wind, in fact, derives its power not from the clouds or trees but from the sun—from the thermal shifts of the day-night cycle, as well as from the cooling effects of bodies of water and higher altitudes. Wind is defined by Environment Canada as the horizontal movement of air relative to the earth's surface caused by geographic variations in temperature and pressure. Solar radiation, beating down strongest at the equator and weakest at the poles, produces temperature and pressure differentials in the air. These pressure pockets are never stationary, always changing in their patterns, and altered by the earth's rotation. Air follows an eddying motion as it moves from areas of high pressure to low, rising as it warms, bringing cold air rushing in below to take its place. This mixing creates wind—the easterly trade winds of the Northern Hemisphere, which steer tropical storms across oceans and onto continents, and the violent prevailing westerlies of the Southern Hemisphere, known as the Roaring Forties, Furious Fifties, and Shrieking Sixties.

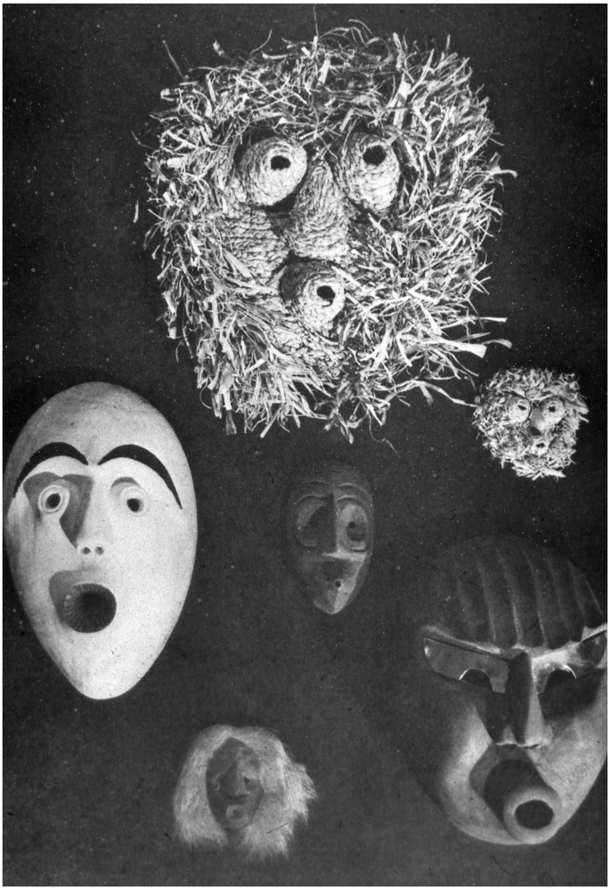

Figure 10. A few specimens from Davenport's collection of wind masks. Courtesy of the Boundary Layer Wind Tunnel Laboratory.

The wind was first treated as a subject of scientific inquiry in ancient Greece, and Aristotle's treatise on the elements, *Meteorologica*, written in 350 BC, endured as the standard reference in Europe for nearly two thousand years. Aristotle's pupil Theophrastus wrote two treatises on winds and weather, proposing that winds could be predicted according to the behavior of animals and the human body: "A dog rolling on the ground is a sign of a violent wind. . . . If the feet swell there will be a change to a south wind. This also sometimes indicates a hurricane." From Sir Isaac Newton, in his *Principia*, published in 1687, came the discovery that the wind force on a given shape is directly proportional to the shape's area, the air density, and the square of the wind's velocity. In 1759, another Englishman, John Smeaton, often called "the father of civil engineering," proposed a colloquial classification of the wind's force in a paper presented to the Royal Society. He listed eleven "common appellations," corresponding to the velocity of the wind by miles covered in one hour:

1	Hardly perceptible
2–3	Just perceptible
4–5	Gentle pleasant wind
10–15	Pleasant brisk gale
20–25	Very brisk
30–35	High winds
40–45	Very high
50	A storm or tempest
60	A great storm
80	A hurricane
100	A hurricane that tears up trees, carries buildings before it, etc.

In 1805, the Irish admiral Sir Francis Beaufort devised his eponymous Beaufort Wind Force Scale. It provided a standardized measure of wind speed based on sea conditions and is still used today (though now calculated with an empirical formula factoring in land conditions), ranging from zero, a calm and flat sea, to twelve, hurricane force with huge waves, foam, and spray.

By the end of the nineteenth century, fluid dynamics—the scientific domain with air and wind flow in its purview, as well as water flow—had advanced considerably. Equations developed in classical hydrodynamics produced beautiful solutions. The flow of air around a cylinder, for instance, produced a symmetrical pattern framed neatly by two stagnation points, the place where the air would come to a stop at the front and again at the back of the structure. But since classical hydrodynamics assumed ideal fluids—fluids with no viscosity, no resistance or friction—these beautiful solutions seemingly did not pertain to any real-life problems. As the British chemist and Nobel laureate Sir Cyril Hinshelwood reportedly lamented, "In the 19th century fluid dynamicists were divided into hydraulic engineers who observed things that could not be explained, and mathematicians who explained things that could not be observed."

In the early twentieth century, however, Ludwig Prandtl, a German scientist known for his seminal work applying mathematics to aeronautics, wedded these theoretical and practical solitudes. He proposed the concept of a boundary layer, and the notion that a viscous fluid actually possesses no velocity at the surface when it passes over an object. In dealing with ideal fluids mathematically and theoretically, as classical aerodynamicists did, fluids had been assumed to have no viscosity simply for the sake of simplicity, to make complex calculations easier. Now what Prandtl proposed was that this idealized theoretical assumption could be extended to practical applications as well. That the wind blowing over any surface doesn't have any velocity at the very interface with the surface is counterintuitive—a property of wind that even concrete-minded engineers describe as "magical," though it can be explained. If a viscous fluid such as air flows over a surface—say, the surface of a building, or the surface of the Arctic tundra—it is a fundamental property of the air that its particles have no motion when they meet the surface. Instead, on first contact a layer of air particles sticks to the surface. This is because at the microscopic level any surface is a craggy affair, and individual air particles can't help being trapped in the crags. Following this initial layer of air particles there is a second layer that viscously slides over the first. As a result, the second layer does have some velocity when it meets the surface; it shears past at a very slow velocity, dragged down by the particles that are locked into the crags. And so it goes, up and up and up. As the air moves away from the surface, its speed rapidly increases, and eventually the fluid reaches a speed more or less independent of viscosity, driven by a pressure field somewhere else, above or below. This stratification of the air and its variegated velocity make up the boundary layer.

While Prandtl applied his insights about the boundary layer mostly in the field of aeronautics, others, such as the French engineer Gustav Eiffel, played with structures of various shapes in wind tunnels. Eiffel

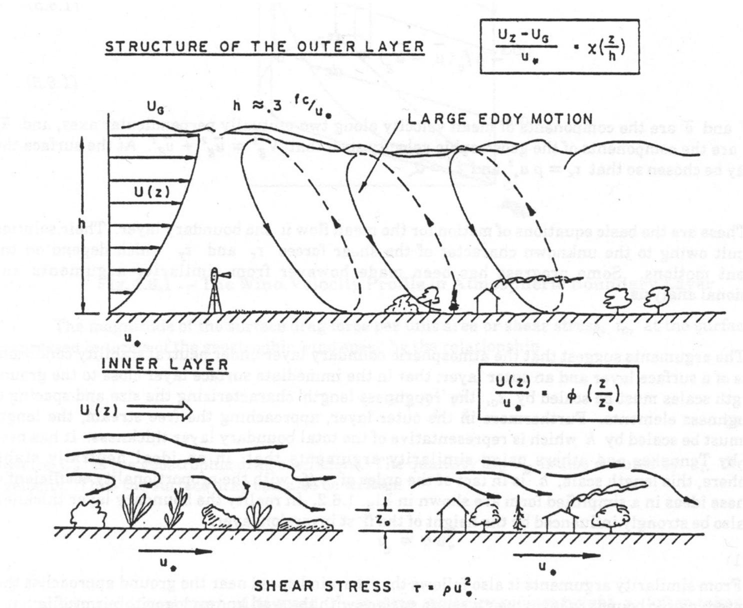

Figure 11. Davenport's illustration showing how large and small eddies make up the planetary boundary layer. Courtesy of the Boundary Layer Wind Tunnel Laboratory.

was one of the earliest engineers to factor in the important effects of wind on tall structures. When he designed his famous tower in 1887, he told the French newspaper *Le Temps* (defending himself against an artist's protest), "Now to what phenomenon did I give primary concern in designing the Tower? It was wind resistance. Well then! I hold that the curvature of the monument's four outer edges, which is as mathematical calculation dictated it should be . . . will give a great impression of strength and beauty, for it will reveal to the eyes of the observer the boldness of the design as a whole." By Eiffel's account to the Société des Ingenieurs in 1885, however, his wind calculations had been cautiously conservative: "With regard to the exposed surfaces, we have not hesitated in assuming, in spite of the apparent severity of the assumption, that on the upper half of the tower all the lattice work is replaced by solid surfaces; that in the intermediate section, where the openings become more important, the frontal area is taken as four times the actual area of iron; below this (the first stage gallery and the upper part of the arcs of the legs) we assume the frontal area is solid; finally at the base of the tower we count the legs as solid and struck twice by the wind (i.e. each leg separately exposed to the full force of the wind)." Completed to mark the occasion of the Paris Exhibition in 1889, the Eiffel Tower became the world's tallest structure. At 986 feet, it almost doubled the height of the Washington Monument, its predecessor as the world's tallest (and the Eiffel Tower retained the title until surpassed in 1930 by New York's 1,050-foot Chrysler Building).

Soon after the tower's completion, Eiffel installed himself in a laboratory at the top level and began experiments on subjects of meteorological and engineering interest. He hung a vertical cable from the second level of his tower, along which he dropped various objects to test their drag. He later built a wind tunnel facility at the tower's base. And he measured the effect of the wind on the Eiffel Tower itself, using a vertical telescope positioned at the base, aimed at a target on his laboratory's underside, and correlating the deflections with measurements of wind speed at the peak. Exposed to high winds approaching diagonally, the tower was found to sway in an elliptical path with a transverse diameter of three to four inches.

Experiment and experience are the best teachers. Too often, though, modern success is blinding, and history's lessons are forgotten. This is the mantra of Henry Petroski, a professor of civil engineering at Duke University with a special interest in bridges and the author of (among a long list of books on the subject) *To Engineer Is Human: The Role of Failure in Successful Design*. With a photograph of the collapsed Tacoma Narrows Bridge on the book's cover, Petroski therein points to this structural failure as an unfortunate example of engineering hubris and oversight. The Tacoma Narrows Bridge's collapse, in 1940, followed half a century of relative calm after a string of bridge failures—the Menai Suspension Bridge, over the Menai Strait, North Wales, completed in 1826, was severely damaged by wind in 1839; the deck of Ohio's Wheeling Suspension Bridge collapsed in a windstorm in 1854, five years after being built; the Tay Rail Bridge crossing the Firth of Tay in Scotland collapsed in 1879, after less than two years in service; and the Niagara Falls Suspension Bridge, built by Samuel

Keefer, stood from 1869 to 1889, when it was felled in the night by a violent storm. These failures should have advanced the understanding of wind loading considerably and taught engineers to take heed. But as Petroski observed, the nineteenth-century failures were forgotten with the great successes of the Brooklyn Bridge, in 1883, and its structural descendants. Then, as engineers strove for ever-longer and lighter bridges, wooed by new theories, technologies, and innovative materials, their confidence was again upended by the extraordinary failure at Tacoma Narrows. "Certainly no designer who remembers the ill-fated Tacoma Narrows Bridge will design another bridge like it," Petroski says.

Hence Davenport, in his lectures on the past, present, and future of wind engineering, repeated the familiar features of the Tacoma Narrows Bridge disaster that should hardly have borne repeating—and, known for speaking at a calm, contemplative tempo, Davenport was never one to waste words. He also had the habit of sharing his inclination for learning lessons about the wind in unexpected and unusual places. "It is interesting to consider the effects of wind in nature," he once noted of an unlikely role model: "Palm trees, for example, exhibit a remarkable adaptation to resisting strong winds such as hurricanes. Over the millennia they have developed a remarkably tough, fibrous trunk with excellent fatigue resistance. By furling their branches, they reduce wind resistance so that their drag coefficient reduces dramatically with an increase in wind speed. This is a strategy not yet perfected by engineers," he said ruefully, adding that, "In contrast, humans confront the wind by leaning forward and relying on gravity!" Clearly a more comprehensive scientific approach was necessary. On that front Davenport forged forward with characteristic persistence and focus.

The citation for his Canada Gold Medal in Science and Engineering noted, "It would be absurd to claim that Davenport's interest in airflow and wind behavior was innate. Yet it almost seems so." Herewith a brief recap of a wind wizard's formative years.

Alan Garnett Davenport was born in India's bustling city of Madras on September 19, 1932. His father, Thomas Davenport, of

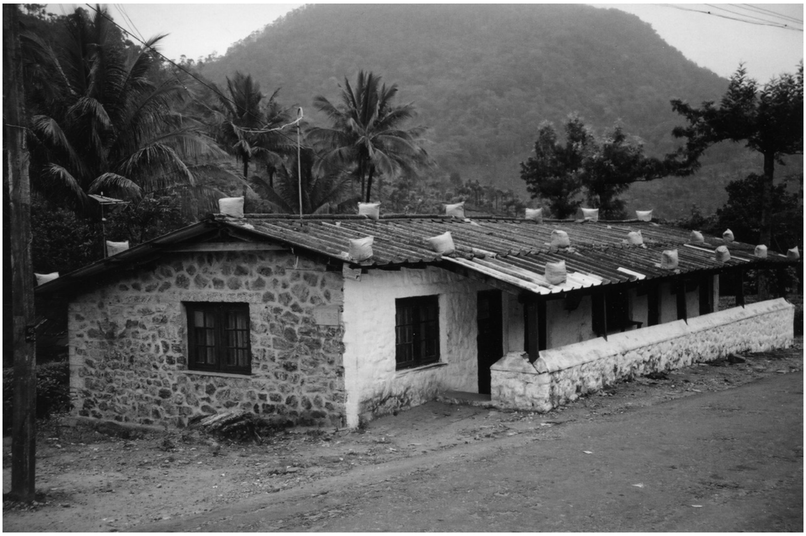

Figure 12. Sandbags on rooftops warded off the wind at Davenport's childhood family estate in the Anamalai Hills of southwestern India. Courtesy of Sheila Davenport.

Cheshire, England, was a tea estate manager for the Scottish-owned London firm the Bombay Burmah Trading Company, situated in the Anamalai Hills of southwestern India. Traveling to the tea plantation involved a steep climb along a ghat, or pass, with forty-two hairpin bends. At the top, a 4,000-foot Shangri-La of bright green tea bushes emerged into view. Local denizens included elephants, tigers, black panthers, scorpions, cobras, porcupines, and monkeys. Ants were uninvited guests at the family home, a sprawling teak-paneled bungalow tended by his mother, Clara May Davenport (née Hope), along with her Indian staff.

The Davenport estate was called "Thoni Mudi," meaning boat-shaped hill. Perched at the top of the range, it caught exotic winds, winds from the cyclones and monsoons that swirled through the region seasonally. In 1935, a tropical cyclone hit India, killing sixty thousand people—one of the worst natural disasters in recorded history. To keep houses secured against the gusty winds, the general practice was to place large rocks and sandbags on the corrugated iron rooftops. Visiting Thoni Mudi with his brother Rodney and their wives fifty years later (after delivering the keynote address at the Indian National Structural Conference at Madras in 1993), Davenport was amazed to see how little had changed. Even the crude engineering precaution of rocks on roofs had endured.

Alan had two older brothers, Rodney, born in 1926, a historian living in Cape Town, and Tony, who was born in 1927 and knocked over and mortally injured by a truck in 1935. In October 1940, after the outbreak of World War II and their return with their parents to India from leave in England, Alan and Rodney were sent for safety's sake to live with relatives in South Africa. They traveled by ship, the fear of U-boats warranting a destroyer escort and a zigzag course to deceive the enemy. Alan found himself entertained in the evenings by the other children mounting dramatizations of dogfights using model airplanes and flashlights.

For the duration of the war and its aftermath, Alan was buffeted from school to school, guardian to guardian. He and Rodney lived with his mother's older brother, Arthur Hope, and his family for a time in Johannesburg. When Alan contracted tuberculosis he was sent to convalesce with his mother's younger brother, Ronald, who farmed in the Transvaal. The one constant he carried with him from place to place was his growing passion for aircraft. He not only made model airplanes, he designed them, carving the smaller craft from solid wood. He equipped the larger ones, as large as several feet in wingspan, with miniature gasoline engines not much bigger than spools of thread. Some put-putted around within a modest radius until they crashed, while others flew too far to recover (over half a mile). He acquired a love of aerodynamics and aeronautics at the tender age of fourteen, which comments on his report cards confirmed, noting he was, "A keen photographer and a brilliant aero-modeller." Comments also remarked on his capacity to lead. "He made a good prefect, reliable, conscientious and not afraid of responsibility. His handling of boys under his control was characterized by a quiet firmness which won him the respect of all. He is a thoughtful as well as an intelligent boy with an unusually developed sense of proportion and values . . . A very able and promising boy in every way."

Alan returned to England as a teenager, and since he was yet too young to attend university he spent a further year at the Repton School after having matriculated in South Africa. While studying for

Figure 13 (left). Alan Davenport as a youngster. Courtesy of Sheila Davenport. **Figure 14 (right).** Alan Davenport with his elder brother, Rodney. Courtesy of Sheila Davenport.

his entrance exams to Cambridge University he worked briefly for an actuarial firm, taking a cue from an aptitude test suggesting that statistics and numbers matched his inclinations. But then, inspired after hearing astronomer Fred Hoyle speak on the subject of the expanding universe, he took up mathematics in his first year at Cambridge, though he devoted more time to bridge, golf, and a cricket club that aimed to tie rather than win matches. In his second year he switched to the more practical mechanical sciences. Still, his extracurricular activities predominated, launching him onto his lifelong trajectory. Recruited as a cadet in the Royal Air Force, he flew between morning and afternoon lectures and made weekend jaunts in propeller planes over the English countryside, taxiing grassy airfields from Cornwall to Yorkshire. He also devoted considerable amounts of time as a writer and editor for *Light Blue*, the Cambridge sports magazine. During a reportorial visit to Oxford in 1954, he witnessed the first sub-four-minute mile, run by Roger Bannister. High winds on race

Figure 15. As a student at Cambridge's Emmanuel College, Davenport (in the plaid waistcoat) joined the Pagans' Cricket Club, whose mission was to play every match to a draw. Courtesy of Sheila Davenport.

day, at times reaching 25 miles per hour, had nearly convinced Bannister not to run. But the blustery conditions subsided as race time approached, and he ran the mile in 3:59.4 before a roaring crowd (with thousands more cheering in front of their television sets).

England's World War II rationing had only just ended when Davenport graduated with a bachelor's degree in engineering in 1954, so he set out for Canada to seek his fortune in a burgeoning economy. After botching an interview for a journalism job (confusing St. John's, Newfoundland, with Saint John, New Brunswick), he took a position as a lecturer teaching surveying at the University of Toronto. He again found himself flying, getting his wings with the Canadian Navy, and charged with the unlikely task of deterring enemy submarines from Lake Ontario. From there, however, he redirected his interest: instead of *making things fly*, he focused his energies on *preventing things from flying*.

Davenport's zeal for wind engineering coalesced when Carson Morrison, head of civil engineering at the University of Toronto, of-

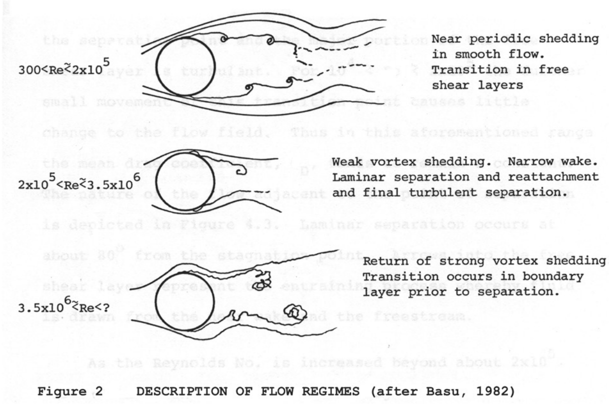

Figure 16. An illustration of vortex shedding, or the formation of eddies in the wake of any bluff object situated in a steady flow of wind. Courtesy of the Boundary Layer Wind Tunnel Laboratory.

fered him a summer job. A television transmission tower was giving rise to some alarming vibrations, wobbling and swaying on a hill in Rimouski, a small town in Quebec overlooking the St. Lawrence River. The tower vibrated so violently it caused fatigue cracks in the foundation. It was also disturbing to onlookers and disrupting to Quebecers' cherished TV-viewing habits, causing ghosting, a doubling or tripling of images transmitted to the screen. Davenport went on a mission with his professor to investigate. "It was a puzzle why something purely circular should oscillate so violently," he recalled. When they arrived at the scene to conduct their investigations, the more immediate problem was that there was no wind. The duo thus contrived to mimic the wind and "excite" the structure themselves. Professor Morrison, being the weightier man, climbed to the top of the tower and lunged back and forth to induce vibrations, while Davenport measured the motion from below. The trouble, it turned out, was a dynamic form of excitation known as vortex shedding, or the formation of eddies in the wake of any structure subjected to a steady flow of wind. This was Davenport's first professional experience of the wind's destructive forces.

Ask engineers to explain how a slender structure moves in the wind—whether a vertical or a horizontal structure—and they are apt to invoke an analogy with a musical instrument, likening the phenomenon to the movement of a violin string when plucked or bowed. All linelike structures—towers and bridges, stacks, masts, power lines—will lean or bend under the influence of a steady wind. "There are two principal differences between the response of 'line' and 'point' structures to a natural wind and both are related to the effects of gusts," noted Davenport. "First, a point structure is likely to have only one mode of vibration, whereas a line structure may have many modes, each of which may be excited by the wind. Second, a point structure is only affected by the temporal velocity fluctuations of the wind at a point, while for a line structure the spatial variations of the wind velocity across the span are also important."

In addition to this static bending in response to a steady wind, structures have a dynamic response to the turbulent gustiness of the wind. Faced with such winds, built structures, like violin strings, have natural frequencies at which they vibrate. When incited by a quick gust of wind, a tower's response—like a string's when played—is not only to vibrate but also to resonate, reinforcing, prolonging, and amplifying the oscillation beyond the initial response. Another informative analogy is a child swinging on a swing. This is a simple "first mode vibration," going back and forth, back and forth, as a building or a bridge does in a turbulent gusty wind. To sustain the swing's desired motion and generate momentum, the child must pump or be pushed in sync with the swing's cycle. Just a little bit of input, a small tap at the top of each cycle to offset the energy lost by friction, makes the oscillation bigger and bigger and the swing climb higher and higher.

The wind acts much the same way on built structures. Imagine the wind's gustiness as a stormy sea with lots of choppy wavelengths, short and long. More likely than not, there will always be some wind wavelength hitting the building at just the right frequency to excite motion at the structure's natural frequency. This is called the "resonant wind frequency." If this particular wind wavelength rhythmically hits, say, the Rimouski TV tower in Quebec, the tower will sway alarmingly, traveling on an excursion even greater than that caused by steady wind. Gusting up against a building, like ocean waves against a breakwater, and hitting in sync with the structure's natural

Figure 17. Davenport with his wife, Sheila, in Bristol, 1959. Courtesy of Sheila Davenport.

frequency, the wind causes the structure's oscillations to grow and take on a life of their own.

The structural engineer's concern is to mitigate this motion. The Rimouski tower, Davenport and Morrison found, vibrated with a period of 7.5 seconds per cycle. The prescribed remedy was to stiffen the tower by installing guy wires, tensioned cables that work like ropes stabilizing a tent. This raised the tower's natural oscillating frequency, which in turn raised the wind speeds that would excite the structure to values that were not likely to occur, or at least not very often, given the local climate.

This little project in Rimouski proved seminal for Davenport. It inspired his master's thesis at the University of Toronto and later a paper often cited by colleagues, right down to the specifics of its series number—*Wind Loads on Structures*, Technical Paper No. 88 of the Division of Building Research of the National Research Council of Canada. It was published in 1960 following a stint at the NRC, where Davenport shared an office with two others, though he alone required an extra desk for all his books and papers on wind loads. The paper's preface states simply that wind forces on structures depend on two factors, on the velocity of the air (meteorological information) and on the shape of the structure itself (aerodynamic information). Grounded in an extensive survey of the existing literature on wind loading requirements in Canada's national building code, this epistle of sorts was assertive and full of recommendations. Davenport could see a long list of problems that needed solving.

In search of answers, he embarked on his doctorate in 1959 at the University of Bristol. This was a fortuitous locale, home to the Clifton Suspension Bridge, which became a much-loved loafing spot in high winds. The newly married Davenport was even successful in persuading his Canadian wife, Sheila Rand Smith, to accompany him there for informal investigations during storms. For the more formal research, Davenport's adviser and colleague was Sir Alfred Pugsley. Pugsley had been knighted for his leadership in structural and aeronautical engineering during World War II, and Davenport had selected Bristol chiefly because of Pugsley's reputation. He was a pioneer of research on safety. His ideas reflected a clarity and elegance of thought. He once wrote a treatise about wind in trees. And he was the author of a thin volume titled *The Theory of Suspension Bridges*. This latter solidified Davenport's own interest in the subject, an interest that quickly became an enthusiasm.

In particular, Davenport took note of Pugsley's work on the problem of aircraft flutter, a problem that increased as aircraft speeds accelerated. Prior to World War II, Pugsley had worked in the Airworthiness Department of the Royal Aircraft Establishment, where he conducted rigorous investigations into the dangers of flutter in aircraft structures. He studied how turbulence excited aircraft wings, causing them to resonate and twist. He derived new design criteria for wing stiffness and "aeroelasticity," a term he coined to describe the combination of aerodynamic effects and the elasticity of a structure. In the run-up to World War II, Pugsley was given the special responsibility of determining the aeroelastic properties necessary for new military planes, including the wing positioning and stiffness of the *Spitfire* and the *Hurricane*. Davenport, standing on Pugsley's shoulders, hypothesized that wind turbulence would also act on tall buildings and long bridges, and that there might be a parallel aeroelastic solution.

"One of the things that was very perplexing was how to deal with the ever-present problems due to turbulence," Davenport recalled. "Turbulence was an aspect of the wind which hadn't been dealt with in a very satisfactory way. Turbulence was muddled. It was chaotic. It fluctuated and you couldn't predict it. It was very indefinite, you didn't know how big it was, or what the frequencies were. This was turbulence. And how to summarize it neatly and compactly in such a way that engineers could use it, and design for this kind of flow, was not readily apparent. This constituted at least half the questions on my long list."

Pugsley gave Davenport free reign to explore. And so, in his PhD thesis, he sought to address a slew of questions on his list about turbulence that had hitherto gone unanswered:

> *What were the strengths and sizes of gusts and eddies in the atmosphere?*
> *How did the nature and texture of the ground affect the wind?*
> *What was the wind like in cities?*
> *How did the wind vary with height above the ground?*
> *How did slender structures, tall towers, and long span bridges, pummeled by gusty winds, respond statically and dynamically?*
> *What were the risks of extreme winds, the chance of catastrophic hurricane-force winds with return periods of several hundred years?*

Davenport contends that much of his success was due to luck. He was in the right place at the right time. For starters, rudimentary aeronautic theories about turbulence had been developed in the1930s. With the increasing availability of computers in the 1950s and 1960s, it became possible to compute statistical properties of turbulence. "Suddenly what burst in on the scene was a way to capture these chaotic qualities of turbulence into a rather neat and tidy statistical framework," he said. That was the essential thing—that there was a framework provided by aeronautics research for organizing the problems pertaining to turbulence. Davenport saw the way, as he recalled, "to apply these theories to more mundane structures, like chimneys and buildings and bridges. It was not so much inventing new knowledge as transferring knowledge just coming to light in another field and applying it to the civil engineering field." Nonetheless, he admitted with characteristic modesty, that it was "a very satisfactory step forward—that suddenly these terribly untidy problems became extremely tidy and manageable."

Anticipating his world-renowned boundary layer wind tunnel even in his Bristol days, Davenport attempted to bolster the statistical analyses with some crafty experimental technology. He commissioned the construction of a gust tunnel from a company specializing in the manufacture of church pews. His fellow grad students teased him about this contraption, and rightly so, because it never really worked. It was a basic wooden box, eight feet wide, with slats on either side that, when exposed to a jet of air, generated two independent flows amounting to a gust, if not a terribly realistic one. Davenport, nonplussed with the end product, soon gave up on his wooden wind tunnel. Still, he was onto something.

In 1961, continuing to refine his PhD thesis, honing it with a litany of big formulas pressed into the pages littering every room of his house, Davenport was offered a faculty position at the University of Western Ontario in London. The job brought the engineer and his wife back to Canada, along with their first son, Tom. Spending time in a bar on the ocean liner during the trip home, he wrote up his thesis, which contained seeds for much of his future work. The 237-page document demonstrated that the natural wind was turbulent, and that the mean velocity increased with height. These characteristics of the wind were well understood in meteorological circles of the day, yet were largely ignored in the investigation of wind forces on buildings. "Transference was the key to my success," he always said. He transferred knowledge from the fields of meteorology, structural engineering, and aeronautics to what would become known as the field of wind engineering.

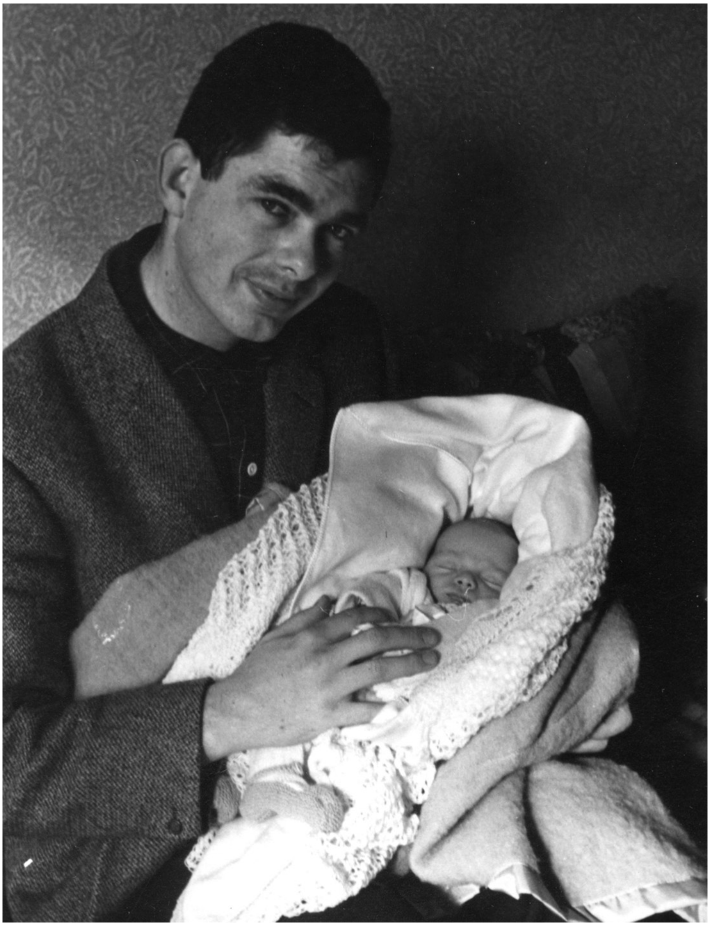

Figure 18. Davenport with his firstborn son, Tom, 1960. Courtesy of Sheila Davenport.

Davenport's success also hinged on simplicity of his professional style. His guiding philosophy was to keep things simple. His inattention to detail at times meant that hot-off-the-press handwritten lecture notes, and sometimes even published papers, skipped over seemingly important steps in his argument—often to the bafflement of students, researchers, and established engineers alike, who tried to retrace his path. (He was known as a gifted teacher on every level, even of practicing engineers in specialty courses for which he was in demand to teach internationally.) Details were lost, at the mercy of typos, since Davenport had no time or patience for proofreading. Nevertheless, in the big picture the answers and the insights were always right. He saw the forest without getting distracted by the trees (and he felt that leaving students to fill in the trees was good motivation; and to good effect, since at the end of a course he was known to proudly and drolly announce that his students had "Passed wind!").

Pulling out the essential information, not worrying about what was missing—that was quintessential Davenport. He was happy to capture 90 percent of a problem, sacrificing some specifics for the sake of simplicity. In this fashion, the initial formula he put down caused his mentor Pugsley some consternation—the elder statesman wondered what he'd unleashed on the world. Davenport's theory on the statistical analysis of wind forces on structures was impressively innovative and elegant, if a bit vague. His formulation rested on a naïve yet crucial guess about how winds accelerate as they go around the body of a structure. But then again, without this crucial approximation the phenomenon of wind turbulence would have remained mired in minutiae. And Davenport wasn't a fluid dynamicist; it fell to fluid dynamicists to improve on the fundamentals he set down. Sir Julian Hunt subsequently showed with his own method that the wind acceleration term in Davenport's formula was incorrect. Davenport's acolytes, however, are quick to come to his defense. "Alan's success was his ability to concentrate on primary issues, those that mattered, and pay less or no attention to secondary ones," says Nick Isyumov, one of Davenport's early PhD students, who made his entire career at the lab (where he is now a consulting director). "This I believe is a mark of a genius and not an attribute of a careless person or a bon vivant," says Isyumov. "The key to his success was his separation of the wind load into a mean or static component and a time-varying or dynamic component due to turbulence. The concerns about the stretching of the wind eddies, as the flow accelerated around the building, are a secondary consideration and one which has little influence on the end product." And in the end, the indefatigable Davenport, with the perfect combination of subtle diplomacy and relentless

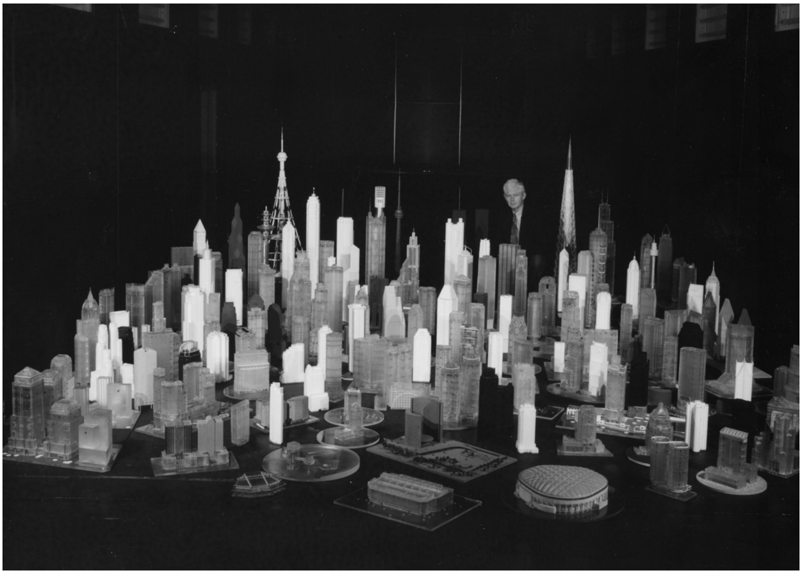

Figure 19. Davenport amid a "Gotham City" of international buildings tested at the lab. Courtesy of the Boundary Layer Wind Tunnel Laboratory.

determination—proposing slews of new ideas and proselytizing their importance with inimitable panache—thereby started nothing short of a revolution in how civil engineering dealt with wind.

Seed by seed, Davenport's influence fostered the modern science of wind engineering. Boundary layer wind tunnels sprouted in Australia, Brazil, China, Denmark, France, Germany, Hong Kong, Italy, Japan, Korea, Norway, Thailand, Singapore, Spain, and Switzerland, as well as in the United Kingdom, the United States, and even at home in Canada. The leading practitioners all sought advice from Davenport, the internationalist and the inspiration. It is fitting, then, that for the logo of his lab Davenport chose the maple key, the tree's fruit that spins in the wind, floating great and small distances before reaching the ground and seeding another tree.