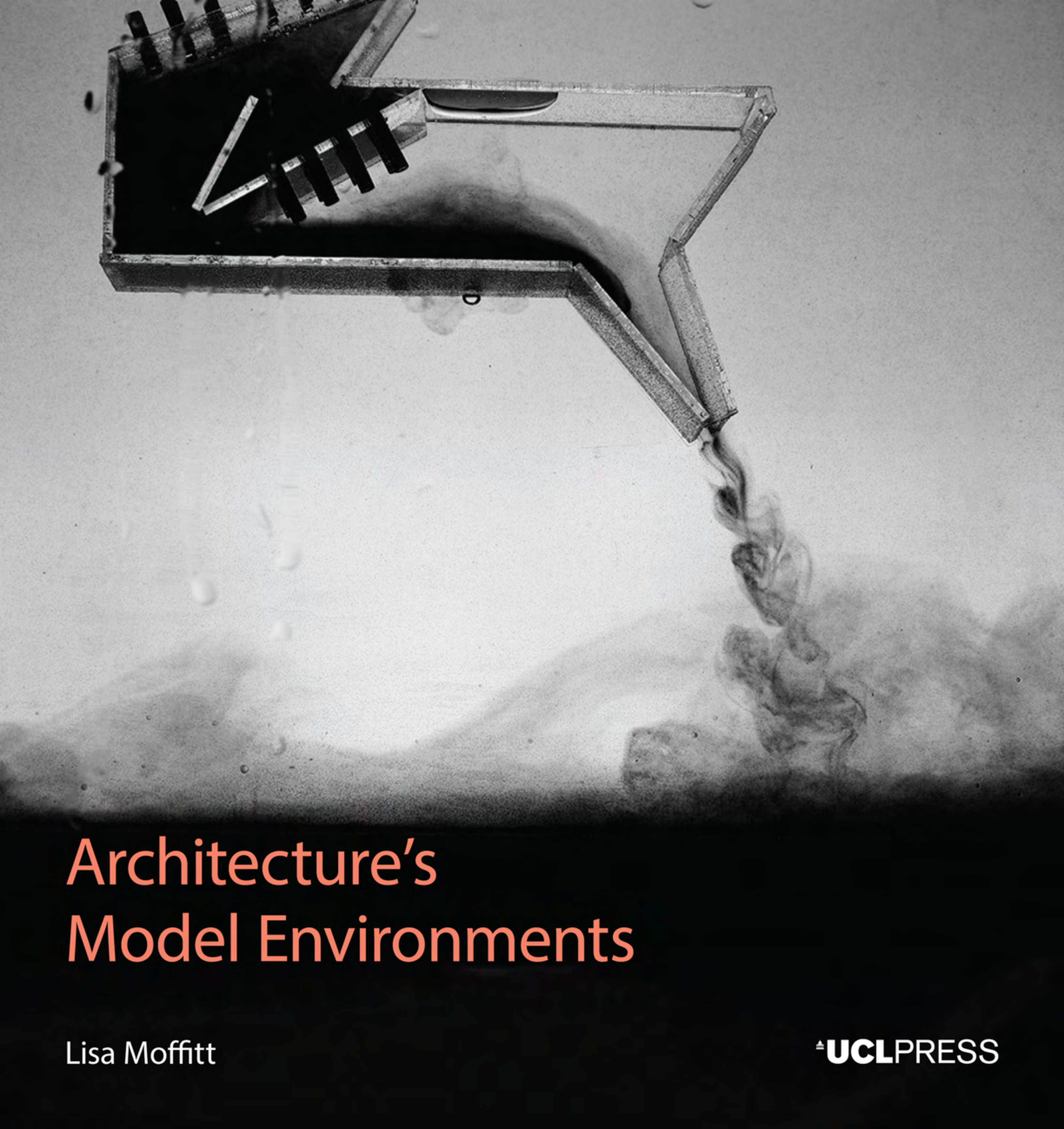

Architecture's Model Environments

Lisa Moffitt

UCL PRESS

Architecture’s Model Environments

DESIGN RESEARCH IN ARCHITECTURE

Since the Renaissance a number of architect-scholars have created methods of intellectual scrutiny of architectural design that rely upon the interplay of drawings, models, textual analysis, intellectual ideas and cultural insights. Yet there is still no cohesive framework or outlet for design research in architecture. This innovative book series – still the only one of its kind – showcases the very best proponents of architectural design research from around the globe, drawing on a range of exemplar positions between practice and academia.

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Architecture’s Model Environments

Lisa Moffitt

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For Charlie and Zachary

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Acknowledgements

All projects are shaped by the life trajectories of their authors, and this book is no exception. This project began in Huron County, Canada, on the first day that I visited 82251 Limekiln Line, in 2008. I am indebted to Nick Treanor and Zach Treanor for being willing collaborators in the installation of 100 steel poles on the 25-acre site. The questions that modest installation raised have sustained this project. I am grateful to Maggie Treanor, Nick Treanor, Zach Treanor, Tara Treanor, Pete Long, my parents Linda and Clyde Moffitt, and Ken and Judy Shortreed for their support and for all the work we did together building the house on Limekiln Line shortly thereafter.

The shift in my work from fieldwork to prototype coincided with my move from Ontario, Canada, to Edinburgh, Scotland. In 2010, I simultaneously began an academic position at the Edinburgh School of Architecture and Landscape Architecture (ESALA) at the University of Edinburgh and a part-time PhD architecture by design at the same institution. I am grateful to the University of Edinburgh for funding my PhD through a staff scholarship and to ESALA for annual research funding to defray material costs and to support student research assistance. Over several years, I read and wrote during the academic term. I also tested ideas pedagogically through teaching a series of undergraduate- and graduate-level design studios. Conversations with many Edinburgh colleagues and students helped shape the research. With special thanks to Liam Ross, Miguel Paredes, Remo Pedreschi, Tiago Torres-Campos, Suzanne Ewing, Simone Ferracina, Michele Bastian, Lisa MacKenzie and Victoria Claire Bernie, as well as my patient and supportive PhD supervisors John Brennan and Richard Anderson. Parts of chapters in this book were published in different formats in the journals *Technology | Architecture and Design* (2018), *Architectural Research Quarterly* (2019), *Architecture and Culture* (2019) and the *Journal of Landscape Architecture* (2022).

During the summers, I made. Some of my most visceral memories are amidst the busy hum of ESALA's wood and metal workshop. Thanks to Malcolm Cruickshank and the workshop technician team for being an ongoing fabrication sounding board. Many students in ESALA assisted in the summers with model construction and photography. With special thanks to Jamie Henry, Vsevolod Kondratiev-Popov, Emma Bennett, Bulat Gafurov, Laura Haylock and Calum Rennie in particular. My PhD exhibition and viva coincided with the Master of Architecture Degree Show for a one-year studio that I co-taught with Simone Ferracina. In the studio, titled *Streamlines, Vortices and Plumes: Bath and the Blue Lagoon*, students built their own environmental models. They taught me, among many other things, that vape smoke is the ideal wind tunnel visualisation medium, solving a mystery I had grappled with for several years.

The shift from thinking about environmental models within a historic context to understanding their implications today began with my PhD viva, which was examined by Susannah Hagan, Michael Hensel and Suzanne Ewing. This shift from a more technical to a more cultural focus also coincided with my move back to Ontario, Canada, in 2020, to start an academic job at Carleton University in Ottawa. I am grateful to the students at Carleton who enrolled in the *Tank Worlds* studios and seminar for expanding my understanding of environmental models as devices for telling stories. I am grateful to conversations and support from colleagues at the Azrieli School of Architecture and Urbanism at Carleton University. Thanks in particular to Dean Larry Kostiuk, Scott Bucking, Johan Voordouw, Suzy Harris-Brandts, Ozayr Saloojee, Paul Kariouk, Jerry Hacker and Piper Bernbaum. Many thanks to Carleton students Taylor Gauley and Saman Soltani for their assistance with organising drawings for the book and to Émélie Desrochers-Turgeon, especially, for being a solid sounding board and a fastidious editor. Thank you to wind engineers Kim Adamek and Dr Girma Bitsuamluk for helping me bridge between architecture and wind engineering.

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I can trace many milestones in this book around those of the lives of my sons, Charlie and Zachary, who were born in Edinburgh and to whom this book is dedicated. Balancing these two great projects simultaneously was both a challenge and an immense blessing. I would never have been able to juggle both without the ongoing dedication and encouragement of Nick – thank you.

Chapter 1 | Environmental models

Wind Grid

It was early autumn the first time I visited 82251 Limekiln Line, in rural Ontario, Canada. Tall, empty husks of cattle corn marched in rows up and down the gentle topography of the 25-acre agricultural lot. Gaps between rows invited occupation. Encountering this site of a future project that first time involved experiencing it as a series of walked lines bound by walls of papery husks rustling in the wind. In contrast to the dense, urban, wind-shadowed world of Toronto where I was living at the time, on Limekiln Line wind was vivid and experiential.

Wind was also instrumental on Limekiln Line. The site was off-grid and wind offered a viable renewable energy source, although it was abandoned later in favour of solar. Wind was a powerful mediator of wide Canadian seasonal swings, tempering the heat of harsh summer sun, or, when deflected, offering respite from the bite of a winter snowstorm.

More than anything, wind was capricious. While I experienced wind at certain moments as particular points along walked lines, wind at the scale of the site was ungraspable. I wanted to better see how the wind shifted across the landscape as a continuous, moving, shape-shifting phenomenon. I wanted to understand wind and its material properties. How does it behave? What does it *look* like?

In response, I completed a full-scale site installation, *Wind Grid*, to better understand global air movement across the undulating site. With the help of family and friends, I installed over one-hundred steel poles, slotted into conduit sleeves impacted into the ground, over a 25-metre grid across the entire site (Figure 1.1). A surveyor's level established parallel and perpendicular lines. When enough poles were installed with instrumental precision, the eye fine-tuned placement between previously installed poles. This visual acuity served us well later because we had to remove the poles and reinstall them several times over the course of the installation to permit harvesting. The poles were topped with freely rotating windsocks to register air movement through the site.

When the windsocks were outfitted for the first time, I stood back, watched and remained confused. Some windsocks flapped listlessly next to others that were fully activated. It was not clear whether this was because wind was not present at that point or due to constructional defects in either the windsocks or their receiving elements. But there was a bigger issue: dips in the topography occluded vast areas of the site. Despite the three-metre height

1.1

1.1 Photograph of *Wind Grid*, a site installation on a rural property in Huron County, Ontario. Over one-hundred steel poles, slotted into conduit sleeves impacted into the ground, were installed on a 25-metre grid across the entire site. A surveyor's level established parallel and perpendicular lines. When enough poles were installed, the remainder were placed through visual perspectival alignment with previously installed poles.

of the poles, it was impossible to attain a synoptic view of wind patterns.

To gain a synoptic view of the site in this pre-drone era, I attached a camera to a makeshift harness attached to a bundle of helium balloons. The balloons buoyed the mechanical eye of the camera to a vantage point I wanted to hold (Figure 1.2). It took photographs and videos of the site as activated by the wind, promising this synoptic, site-specific view of wind movement at that moment in time. This approach, too, failed, for when the wind activated the socks, it activated the balloons as well, tossing them about, creating blurred, incoherent photographs. Wind was captured in the photograph as a moving blur, not as the clear vectors of movement I had hoped for.

I changed vantage point again, moving to the ground. The grid of steel poles offered valuable insights about other related features of the site. They served as station points for multiple topographies: the rise and fall of the earth, the inconsistent growth of crops, and the banks and drifts of snow, which varied due to the vagaries of wind and the obstacles that shadowed it. I recorded these measures as a series of annotated grid drawings (Figure 1.3). They began as messy records but gained refinement over time. Drawings increasingly prioritised the quantitative over the material, spatial and experiential. Further drawings, reminiscent of Eva Hesse's *Circles and Grids*, integrated ink washes, using one fluid medium to represent another, attempting to regain material qualities lost to the quantitative (Figure 1.4). As a body of work, the drawings fixed air movement and its indices in the landscape at discrete moments in time. Static and fragmented, they failed to capture wind as a moving fluid condition.

I eventually designed and oversaw construction of a house on the site, and then moved from Canada to Scotland during construction (Figure 1.5). The site was no longer readily accessible, but questions raised by the installation and the survey drawings persisted. Bound on two sides by forests that sped up and channelled air movement, the site was analogous to a full-scale wind tunnel. Given my distance from the site, perhaps a real wind tunnel might make global airflow patterns through the site legible at scale (Figure 1.6)? The questions of how physical models in experimental environmental chambers might reveal insights about airflow and how these insights might inform the design process initiated this book.

1.2

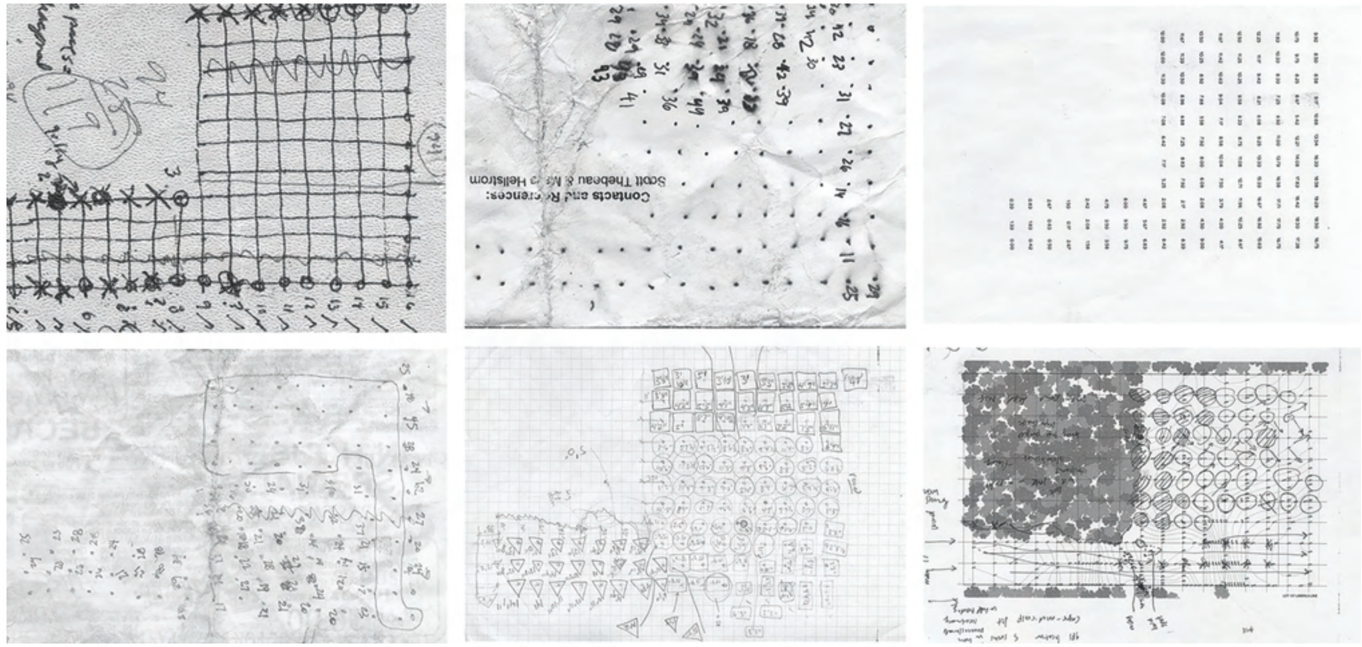
1.2 Photograph of *Wind Grid* taken from a makeshift helium balloon rig. The balloons buoyed the mechanical eye of a camera to a vantage point otherwise unattainable. When the wind activated the socks, it activated the balloons as well, tossing them about, creating blurred, shifty photographs. Wind was captured in most photographs as a blur – a reminder that recording that which is fluid and shifting requires a stable substrate.

Architectural theorist Christopher Hight refers to environmental conditions such as airflow and thermal exchange as 'non-visual phenomena object(s)' (2009, 26). As a 'non-visual phenomena object', wind is complex and resistant to representation because it is invisible, and it follows fluid dynamic principles that are not always intuitive. Solar trajectories for any given latitude are visible, legible over time and entirely predictable. Wind patterns, on the other hand, are invisible and often shift in intensity and direction erratically and rapidly.

The two predominant techniques architects use for describing air movement are static environmental diagrams, overlaying arrows of anticipated air movement, or more complex building performance simulations such as computational fluid dynamics (CFD). Many of the challenges and limitations associated with both techniques are explored throughout this book, particularly in Chapters 3 and 5. In brief, static diagrams are just that – static – representing a single moment in time and space. Moreover, they are hypothetical, failing to reveal substantive properties of air movement in the process of constructing the drawing. Building performance simulations such as CFD are unwieldy, particularly in the early design stages of a project. They are also easily misappropriated or misinterpreted by initiates. Fundamentally, neither technique captures wind as a graspable, experiential, moving material in the way that was so palpable when walking through the rows of papery stalks that first time on Limekiln Line.

This book presents a third technique, using physical models incorporating moving air and water, referred to as *environmental models*, for making the 'non-visual phenomena object' of airflow materially tangible. This approach is based neither on rules-of-thumb nor on complex digital simulations. It is based on observation, on tight-tolerance fabrication and on direct engagement with fluid materials, appealing to the architect's inherent spatial and material sensibilities.

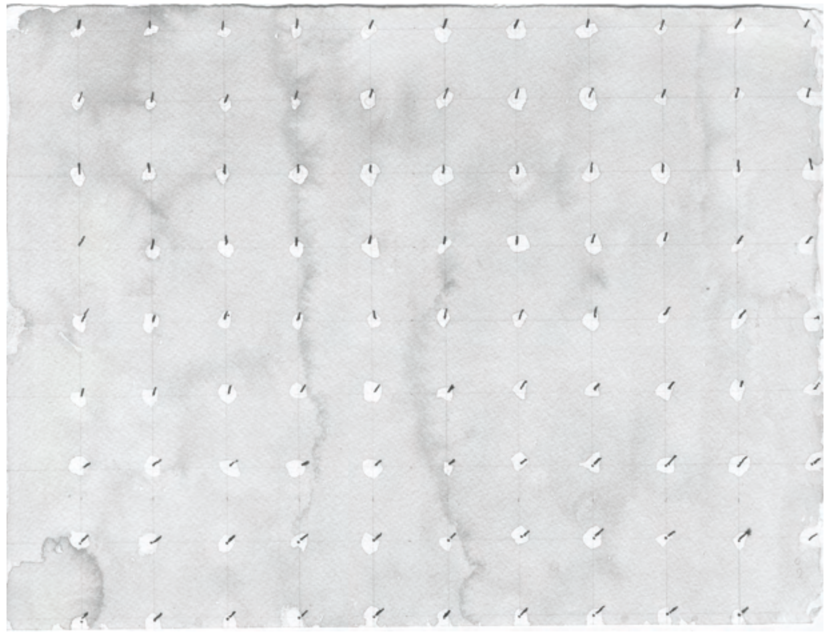
To design *with wind* is to work with a medium that has vast consequences across radically divergent spatial and temporal scales (Figure 1.7). Atmospheric phenomena such as turbulence occur at spatial scales as small as several millimetres, changing over the course of seconds or minutes, while global circulation patterns can operate at tens of thousands of



1.3

1.3 *Wind Grid* drawing surveys. The steel poles recorded other measures about the rise and fall of the earth, the inconsistent growth of crops, and the banks and drifts of snow. Air is, after all, one of many interrelated topographies, each a function in some way of the vagaries of wind and the obstacles that shadow it. While the site was not visible as a totality, the column of air surrounding each steel pole offered insights into subtler microclimatic conditions.

1.4 *Wind Grid* ink wash drawing. The drawing integrates moving water to represent moving air. Subtle pooling captures flow as a diffuse condition that contrasts the fixed vectors of air movement indicated at each grid point.



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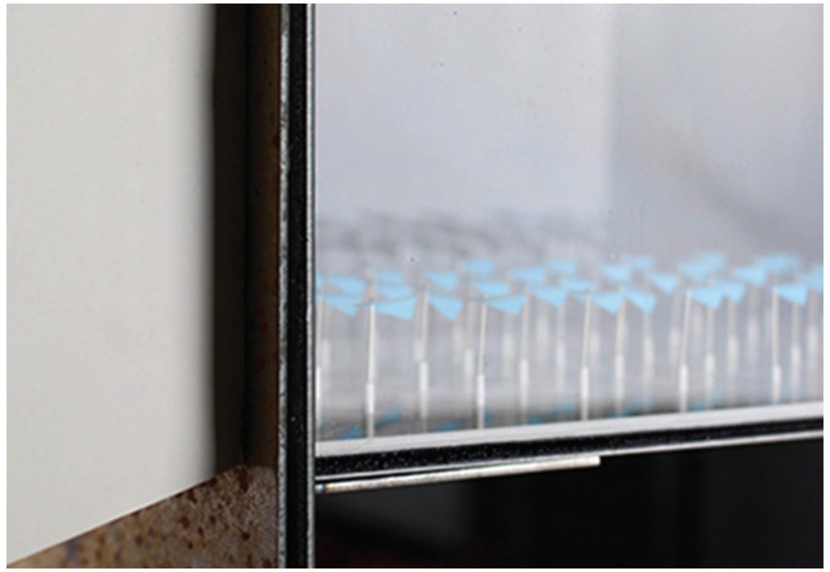
1.5 Photograph of the House on Limekiln Line. The *Wind Grid* installation was one of many studies that informed the design of the house. The saltbox roof pushes a heavy shoulder towards the prevailing westerly winter winds. The north and south façades are more porous, with operable windows that facilitate cooling effects of natural ventilation from southerly winds in the summer. A deck walk that extends into the landscape acts as a datum to the many shifting topographies beyond. Photograph: Shai Gil Photography.

1.5

1.6 Detail photograph of wind tunnel prototype 4. The Limekiln Line site acted as a notional wind tunnel, channelling and speeding up air movement through bounded forested edges. Subsequent questions raised by working with scale airflow models such as wind tunnels form the foundation for this book. What would a real wind tunnel reveal about air movement patterns, their tendencies and flow characteristics? What kind of architecture might an understanding of these principles reveal?



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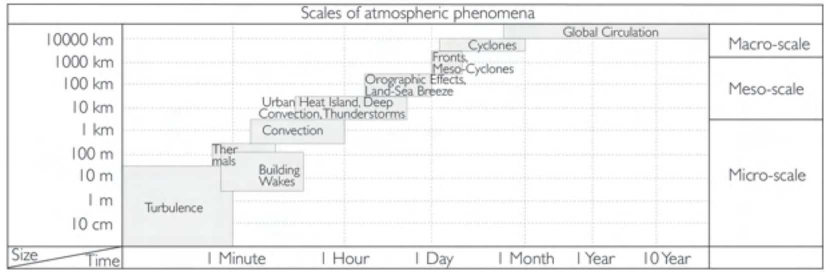


1.7

1.7 Diagram illustrating the spatial and temporal scales of atmospheric phenomena. Drawing by Saman Soltani based on a table by Blocken (2014).

kilometres over spans of several years (Blocken 2014). Within the built environment, air movement impacts thermal comfort; it constructs microclimates; it effects structural performance and material endurance; and it can either reduce or increase dependence on mechanical heating and cooling through natural ventilation. At meso- and macro-scales, the shifts and courses of wind determine the path and distribution of airborne particulates such as dust, sand and snow, as well as of airborne contaminants. As global weather patterns become more erratic, wind drives many catastrophic events such as the spread of wildfires, the intensity of hurricanes and floods, and the extent of erosion and desertification.

I refer to wind – the natural movement of air due to differences in pressure – as a moving material system throughout the book because it has distinct physical characteristics. However, it is not even clear whether wind is a material or a thing at all. Aesthetic scholar Tonino Griffero describes wind as a 'quasi-thing', with particularly ineffable material characteristics. Unlike more conventional architectural materials, 'The wind is not edged, discrete, cohesive, or solid … nor does it properly possess spatial sides' (2020, 34). The temporalities of wind are nebulous. Wind is intermittent and, as Griffero notes, wind does not age, degrade nor 'show any temporal patina' (2020, 34). Wind also shares characteristics of philosopher Timothy Morton's hyperobjects. Hyperobjects are ecological objects such as global warming, the biosphere or dust storms that operate at expansive temporal and spatial scales far beyond that of the individual human. Hyperobjects are not even really objectival because they lack distinct part–whole relations. Like many environmental systems, wind is immersive, omni-present, expansive and without clear centre or boundary. Fundamentally, wind drives and shares properties with many environmental processes that are complex, diffuse, expansive and unpredictable. Wind can therefore act as a proxy for many environmental processes across many timeframes and at many spatial scales.

The term 'environment' takes on many meanings depending on context and theoretical framing. The 'environment' of the 'built environment' is distinct from that of the 'environmental movement' which is distinct from an 'environmental factor'. They all, however, refer broadly to surroundings or things outside, beyond or in between us and other objects in the world. Even this tidy description is fraught because it calls to question many foundational concepts about human experience, what constitutes an object and how we might describe the 'stuff' in between the two. To fill in some of these gaps, British anthropologist Tim Ingold has carefully traced philosophical frameworks

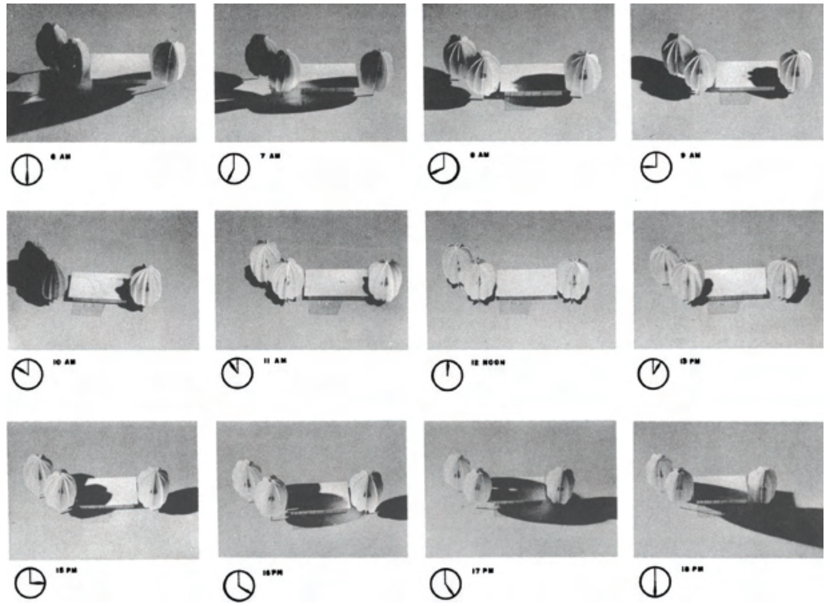
for making sense of what constitutes an environment and what makes that constitution unique to humans, exploring the contours of James Gibson's concept of affordance, Jakob von Uexküll's *Umwelt*, Gilles Deleuze's lines of becoming, to more recent understandings of environmental inhabitation as taking place within 'fluid space'. Ingold concludes with his own theory: 'In short, to perceive the environment is not to look back on the things to be found in it, or to discern their congealed shapes and layouts, but to join with them in the material flows and movements contributing to their – and our – ongoing formation' (2011, 88).

Hélène Frichot's definition of environment in *Creative Ecologies* is a useful starting point for understanding how the term is used throughout this book. Frichot notes that: 'Environment is what unfurls when the architect or creative practitioner turns her back to the built object – which is an environment of a special sort, contained, "well-tempered" (Banham 1984) and controlled – and witnesses another point of view' (2019, 21). She suggests that, on the one hand, the environment is something that is *out there*, that operates according to temporal and spatial logics often beyond immediate cognitive grasp. It is what we see when we turn our backs to buildings or squint our eyes and look past them. It is a source of wonder, awe and terror. It is beyond our grasp, yet within our control. On the other hand, the environment is something *in here*, also around us, but bound by the enclosures of our buildings. Here, environment is controllable through our technological systems, our airtight building envelopes, our energy-intensive HVAC systems and our high-tech clothing. Frichot acknowledges the duality of these two environments and all the contradictions that they entail. But she also invites us to witness the world from another point of view, to squint our eyes and see beyond the dominant figures of buildings in this case, for, in doing so, we invite other worlds and ways of thinking into our lives. We do this not to resolve complexity but to better understand it from another vantage point. It is in the spirit of Frichot's characterisation and the dualities of understanding environments as being both 'out there' and 'in here' that I use the term 'environment'.

Environmental models

What is an environmental model? The term is used throughout this book in the absence of an existing, more established term in architecture specifically. The term *environmental model* has currency in scientific disciplines such as ecology, hydrology and geology, where it refers to physical modelling or digital simulation of dynamic natural processes for analytic and predictive purposes. Some landscape architects build on these scientific methods, modelling environmental systems as a means of monitoring, analysing or designing in response to watershed management, urban heat-island effects, erosion and sedimentation patterns, and storm-surge effects, among other things.

In the context of the discipline-specific work featured in this book, I define environmental models as *instruments which create controlled environments that make the phenomena of airflow visible*

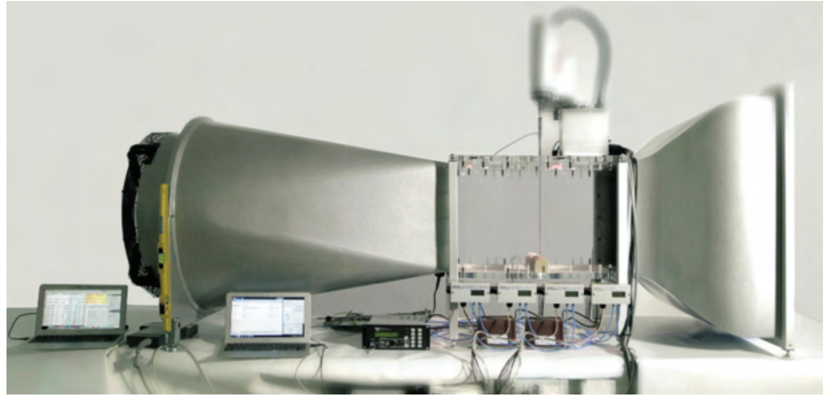


1.8

1.8 Victor Olgyay, *Summer Shading from Dawn to Dusk*, from *Design with Climate*, 2015 (2nd ed). **Olgyay incorporated a range of empirical model experiments, supplemented with diagrams and numeric analysis, to develop a bioclimatic design methodology in his canonical environmental design textbook.** Princeton University Press, reproduced with permission.

in relation to an architectural model. This is a working definition, and the broader contours, origins and significance of these terms – instrument, controlled environment, phenomena, architectural model – are explored throughout the book. Fundamentally, environmental models can be read at several scales: the one-to-one scale of the instrument as a tectonic artefact; the scale set by the architectural model on the testing bed; and the ambiguous scale of the controlled space of air and water flow. Each scale offers new vantage points for thinking about the dialogues between buildings, instruments, people, architectural models and the environments within which they are immersed.

Environmental models share a lineage with engineering experimentation devices. In the late nineteenth and early twentieth century, wind tunnels, water tables and flumes were devised to test hydrological and aeronautical principles primarily for vehicular movement – of boats and planes. Gustav Eiffel is credited as being the first to use wind tunnels to test wind loads on buildings, in 1908. In subsequent decades, understandings of turbulent flow and boundary layer characteristics, which are crucial for understanding airflow around and through buildings, were refined (Phillips and Soligo 2019). In the 1950s and 1960s, many schools of architecture developed dedicated environmental experimentation facilities. For example, Princeton, MIT and Columbia in the United States used heliodons (which simulate solar trajectories) and wind tunnels to design solar homes and to hone bioclimatic design principles (Figure 1.8). In the same period, in the United Kingdom, government-sponsored investigations by the Building Research Establishment (BRE) used wind tunnels to assess exterior pedestrian-level airflow patterns around mid- and high-rise buildings. Some schools of architecture have retained active environmental testing facilities, but research has generally shifted beyond basic design principles of form, aperture locations and orientation to more sophisticated and increasingly specialised concerns. For the most part, physical experiments focusing on urban airflow and building ventilation by architects have been eclipsed by digital simulation. The first engineering applications of computational fluid dynamics analysis of buildings took place in the 1970s, but CFD did not appear in the field of architecture specifically until the 1990s. Rapid increases in computer speeds and software refinements have led to an extensive array of CFD packages now available (Phillips and Soligo 2019). CFD is largely mainstream today with both commercial and open-source versions, but it presents challenges for non-specialists, explored in more detail in Chapter 3.



1.9

1.9 Photograph of Maider LLaguno-Munitxa's wind tunnel with integrated robotic arm. **Robotic integration enables iterative, real-time material studies, challenging the conventional linear 'model-measure-analyse' methodology that characterises conventional engineering experimentation.** Springer Nature, reproduced with permission.

While wind engineers rely on computational strategies, physical experiments are still commonplace for testing building ventilation and urban airflow patterns. Such experiments are often completed in tandem with CFD and on-site experiments, which are seen as complementary endeavours. Some engineers argue that CFD modelling is less accurate and reliable than wind tunnel tests due to challenges with solving equations associated with turbulent flow (Phillips and Soligo 2019). Regardless of method, engineers tend to focus on acquiring numeric results that can be scaled up to predict full-scale performance to a high degree of accuracy. Building models placed in wind tunnels, for example, are generally equipped with pressure sensors from which air speed is then calculated. This data is applied to scaling formulas to determine equivalent results at full scale.[1]

The engineering focus on numeric precision is incongruent with early architectural design speculation. For the architect studying airflow in the early stages of design, only a general understanding of basic flow patterns is necessary. Moreover, reconciling scale effects in small, low-tech models such as those featured in this book is not viable. Research conducted by Hitchins and Wilson (1967) using wind tunnels found that if architectural models are geometrically accurate, general airflow patterns in a wind tunnel were consistent enough to give a reliable indication of airflow patterns. This applies to bluff bodies, geometries with sharp edges, since flow separates at the edges similarly across scales.

For the architect, working with environmental models is a messier, 'designerly' variant of more conventional engineering experimentation. Engineering research tends to follow a model–measure–analyse methodology.[2] A physical model is placed in the testing bed, a series of tests are conducted that generate numeric results which can be used to assess effects at full scale, and then these results are analysed. Architectural design is distinct in that it is often non-linear, recursive, iterative and lacking rigidly defined controls and variables. Maider Llaguno-Munitxa's research at Princeton University, which integrates robotics with wind tunnels, critiques the conventional model–measure–analyse approach (Figure 1.9). In her research, a robotic arm alters elements of architectural models in the testing bed while the

1.10

1.10 Design Earth, *Pacific Aquarium Project*, installation at the Oslo Architecture Triennale. Each aquarium in the installation contains a speculative design proposal related to deep-sea resource extraction for a section of the Clarion-Clipperton Zone. The installation makes legible planetary-scale concerns within the objectified space of the fish aquarium, establishing a critical dialogue between the models and their co-constructed environments. Courtesy of Design Earth.

wind tunnel is in operation. This automation enables iterative, real-time testing of a range of spatial and material strategies for how building form and materiality impact airflow around and between buildings. The California-based research group Future Forms (previously Future Cities Lab) also conducts a designerly variant of experimental research using 'live models'. Their installations often translate real-time environmental data into dynamic physical artefacts that respond to this data. They conceive of these live models not as simulations or even as scale models, but instead as 'conceptual frameworks for architecture' (Kelly and Gattegno 2012, 141).[3]

While designing wind tunnels or water tables specifically is rarely the topic of architectural design scrutiny, there are contemporary designers whose work offers useful insights about working with air and water as constituent design materials across scales. For the architectural designer, environmental models enable speculation beyond simply examining the effects of airflow around the architectural model. This trait makes them particularly valuable as tools for design speculation about urgencies associated with the climate crisis. These concerns range from the pragmatic – the design of low-energy buildings reliant on natural ventilation – to the theoretical – speculation about what it means to design within diffuse, volatile environmental systems that operate all the way up to the planetary scales.

Design Earth's *Pacific Aquarium Project* highlights the role that environmental models can play as narrative devices that transcend radical scales of design speculation (Figure 1.10). In the *Pacific Aquarium Project*, nine scale models are submerged in individual fish aquariums. Each represents a design intervention within sections of the Clarion-Clipperton oceanic rift. Collectively, the projects make legible scales of environmental degradation otherwise beyond cognitive reach, while also reinforcing the historic role aquariums have played in the natural sciences as objects of reverie (Ghosn and Jazairy 2017). Operating at more conventional architectural scales, Lydia Kallipoliti's *Microclimates* project, included in the *Microcosms and Schisms* exhibition at the 2021 Venice Biennale, similarly uses physical models of notionally constructed environments to make a political statement (Figure 1.11). The project highlights some of the fantastically strange, yet unfortunately real, interior microclimatic constructions

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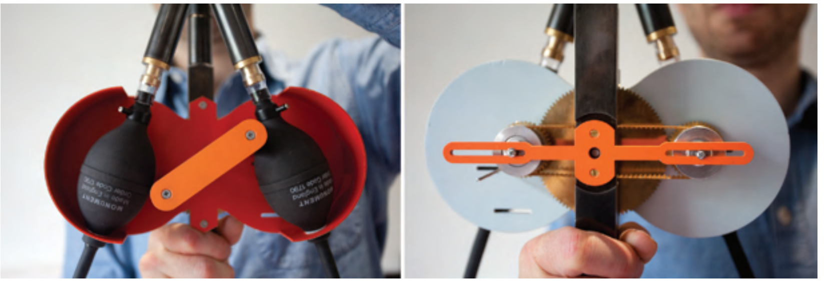

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1.11 Lydia Kallipoliti with Doosung Shin, *The Psychrometric Interior*. This model was part of the project *Microclimates*, exhibited at the Venice Architecture Biennale 2021. Courtesy of Lydia Kallipoliti.

1.12 Smout Allen, *Air Instrument*. The device integrates rubber pumps, referred to as 'twin glands' with painted and blued steel and machined brass components. Part of their *Envirographic Instruments* series, the air instrument offers a tectonic approach for working with air as a constituent design material. Courtesy of Smout Allen.

of late modern capitalism. Each microclimate model features an architectural space, such as a partitioned office or an enclosed atrium, built onto the carriage of a model train car and then encased in a plastic dome. The models critique the codifications of homogenizing thermal comfort standards and the ironies of constructing interior tropical gardens in standard office buildings, among other related concerns. Like the aquariums used in the *Pacific Aquarium Project*, *Microclimates* draws from aesthetic experiences associated with miniaturisation, in this case of model trains, which are objects of reverie.

Smout Allen's *Envirographic Instruments* shift focus to tectonic concerns raised by constructing environmental models (Figure 1.12). Designed as site-specific instruments for the Severn Estuary, one instrument registers air and the other water. Constructed of rubber hoses, air and water valves, manual air-pump 'glands', painted steel and machined bronze, the instruments sensitively respond to the pressure and movements of fluid materials. The instruments subsequently informed the framing of architectural design speculations on the site as technological interventions with the geomorphological, hydrological and atmospheric systems of the River Severn.

Finally, there are projects, such as Catty Dan Zhang's *Vents* installation at the University of North Carolina at Charlotte exhibition *SEE-ING: The Environmental Consciousness Project* which rely on techniques of flow visualisation to make interior meteorological conditions visible (Figure 1.13). Using smoke and strategic lighting, the project challenges conventional understanding of space as inert void. In *Vents*, a series of inverted umbrellas form an overhead canopy that puffs rings of fog which respond to datasets of wind speeds recorded over a seven-day period for Hurricane Florence. The installation translates an extreme meteorological event elsewhere into a constructed interior of atmospheric effects. Careful control of lighting through backlit screens and overhead, cool LED lights within an otherwise dark space further amplifies the

1.13

1.13 Catty Dan Zhang, *Vents*, installation at the *SEE-ING: The Environmental Consciousness Project* exhibition at UNC Charlotte. Through careful calibration of light and vapour, flow visualisation techniques are used to amplify the effect of constructed interior meteorologies. Vapour rings correspond to weather data associated with an extreme weather event elsewhere, translating the interior of the exhibition into a space of heightened atmospheric effects. Courtesy of Catty Dan Zhang. Photograph: Ben Premeaux, 2018.

visualisation of airflow patterns registered through the fog rings.

This sampling of architectural practices and approaches highlights the range of roles that environmental models can productively play in the design process: they are objects of speculation about building scientific processes; they are tectonic assemblies of environmental mediation; they are objects that tell stories about environmental degradation; and they are artefacts that make the construction of interior weather legible through flow visualisation.

Architectural models

Fundamentally, environmental models are *models* – distillations of complex conditions into artefacts that are legible at the scale of the hand and the body. As scale representations, models establish important dialogues with their referents. Much theorisation about architectural representation focuses on the nature of the correspondence between a representation (in this case a model) and its referent. Are they separate and distinct? Are they one and the same? What do models tell us about the world and what does the world tell us about models? Environmental models focus these questions specifically on environmental topics – about mediation, degradation, contamination and containment – and the sites (real or imagined) in which these processes play out.

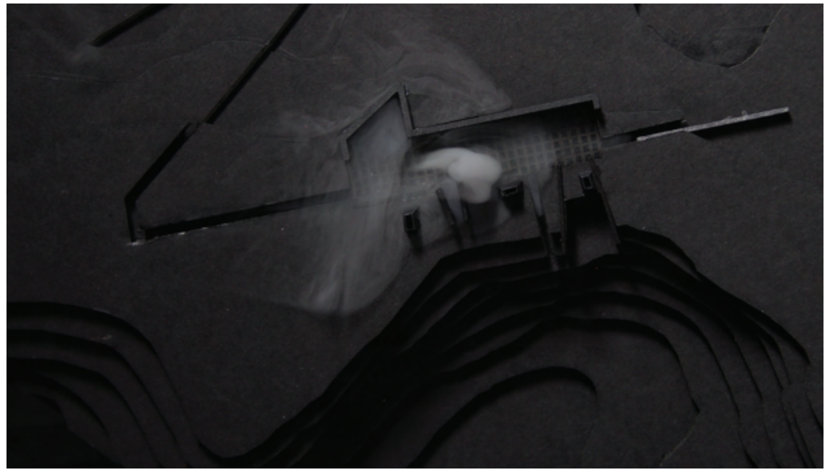
An interview between historian of science D. Graham Burnett and architect Daniel Solomon published in *Models: 306090* offers a useful framework for considering the dialogue between an environmental model and its *target system*, the term used in history and philosophy of science that is equivalent to the term 'referent' in architectural theory. The interview highlights some attributes of environmental models that both build on and disrupt conventions of models in architectural representation. In the interview, Burnett reflects on the historical use of physical scientific models within the context of contemporary architectural design, making a distinction between *analogical* models and *ontological* models. Analogical models, he suggests, are models whose central attributes apply by analogy to the physical traits or attributes of the scaled thing that is being modelled. In other words, the model is understood as distinct from, but analogous to, aspects of the world, or the target system, it represents. The connection between the model and its target system(s) are based on the juxtaposition of similarities in appearance or behaviour, and these similarities make the model analogous to the conditions in the world

that the model represents. Ontological models, on the other hand, start to blur distinctions between model and target; rather than operating by analogy, traits converge. Ontological models cause the physical traits of the world being modelled 'to be made manifest – and hence allow[s] for the revealing, touching, tweaking, or accessing of … the *actual forces and stuff* at issue' (Burnett and Solomon 2008, 44). In other words, ontological models start to make more direct material or causal alignments between model and world being modelled. They even have the capacity to inaugurate paradigm shifts in how we understand the workings of the world.

Burnett goes further to suggest that the distinctions between analogical and ontological models are less crucial than the dialogues between the two. He suggests that often a productive shift occurs when models move from being analogies to being *something more*, yielding insights to the workings of the world that one would not have access to otherwise. To illustrate this idea, Burnett uses the roughly four-hundred-year development of clock-making that eventually lead to a conception of a clockwork-universe as a prime example of the slippage between analogical and ontological modelling. Initially understood as a timekeeping device that modelled by analogy the orbiting of the Earth around the Sun, the clock eventually became a conception of how the world literally works: 'Somewhere in there a mess of thinking folks go from having built a clockwork model of the visible features of celestial dynamics to reasoning that the celestial dynamics themselves may well be a big clockwork' (Burnett and Solomon 2008, 45). The model, in this case a clock, which replicates the cosmic workings of the world in miniature, shifts from being a representation of the cosmic world to being understood as that world. This shift in understanding facilitated by the model instigated a paradigm shift in thinking about the actual workings of the world from one governed by the will of God to one governed by the mechanistic laws of science.

Burnett's analogical/ontological model distinction informs ways of thinking about environmental models within the broader context of architectural representation in three ways. First, it offers a framework for discussing how models converse with their targets, situating models within a broader context beyond the internal workings of the model itself. Models are, as visual artist Olafur Eliasson puts it, co-producers of reality.[4] The relationship between *good* models and targets is dialogic; it is one that *shifts*. The model informs conceptions of the world as much as the world informs conceptions of the model. Models are, after all, both physical artefacts and mental ideals. Working with environmental models prompts questions about how the models we make might inform ways of thinking about the ideals to which we aspire.

Second, the analogical/ontological model distinction highlights the material significance of environmental models. They allow for the 'revealing, touching and tweaking' of the 'actual forces and stuff' at work in the model, uncovering the world of fluid dynamics in a way that is material and intuitively legible (Burnett and



1.14

Solomon 2008, 44). Air pressure induced in wind tunnels replicates air pressure found at 1:1 in the world. Plumes of buoyant airflow in filling-box models follow the same natural laws as those at full scale within a building. These force-exchanges transcend being simply stand-ins for the actual forces they represent – *they are the same forces* – making them remarkable tools of material exploration.

The messy materiality of environmental models makes them productive as design tools, but this messiness challenges one trait conventionally valued in architectural models – their material muteness. The 'messiness' of models has historically been suppressed. Models have often been considered inferior to drawing in theories of architectural representation. The perceived inferiority can be traced to the Renaissance when a dissociation occurred between design and construction. Design took place in the clean, refined studio through the 'gentlemanly' act of drawing. Construction and material exploration such as model-making took place in the grubby, material world of the construction site or workshop (Starkey 2005). Moreover, models were often valued for their emphasis on form rather than materiality. In *On the Art of Building in Ten Books*, for example, Alberti warns against using unnecessary decoration in architectural models. He suggests that the materiality of the model and its means of construction should be subdued, noting: 'Better then that the models are not accurately finished, refined, and highly decorated, but plain and simple, so that they demonstrate the ingenuity of him who conceived the idea, and not the skill of the one who fabricated the model' (Alberti 1452 cited in Smith 2004, 28).

One consequence of the division of labour between model and drawing was that drawing gained a higher intellectual status than the model, a status that has largely persisted. However, as architectural theorist Robin Evans reminds us, some architectural conditions simply resist being drawn. Evans uses the palpable luminosities of James Turrell's light rooms as an example of one such condition. He notes that

> not all things architectural (and Turrell's rooms are surely architectural) can be arrived at through drawing … if judgement is that these qualities in and around the shadow line are more interesting than those laid forth clearly in drawing, then such drawing should be abandoned, and another way of working instituted.
> (Evans 1996, 159)

1.14 Model photograph of *GeoThermoHaptic*, a speculative project completed for a visitors' centre in northern Iceland. The project is designed as an experiential choreography, alternating between immersion within and hovering over the geological and thermal substrate upon which the Icelandic volcanic landscape rests. Inclusion of smoke as an analogue to steam in the model reinforces that pressure, heat and steam are constituent project materials. Project completed with Calum Rennie and Laura Haylock. Photograph: Calum Rennie.

1.15

1.15 Interior model photograph of *GeoThermoHaptic*. In the design, geothermal steam released from valves embedded in the excavated floor makes geological processes visible. The model, which incorporates wool, crushed rock and smoke, contrasts the conventional 'materially-mute' architectural model. Project completed with Calum Rennie and Laura Haylock. Photograph: Calum Rennie.

Atmospheric qualities, thermal exchange and air movement are similar architectural qualities that demand another way of working (Figs. 1.14, 1.15).

Finally, the analogical/ontological model distinction offers a way of describing working with architectural models as part of an iterative design process. Often, discoveries in the design process are made through accidental substitutions, by conceptual inversions and by shifting vantage point.[5] In these moments, sometimes profound reconceptualisations emerge. This book explores these dialogues between the constituent elements of environmental models – instrument, phenomena, architecture – and between models and their target systems. The book makes the case that conceptual connections between a model and its target system are strongest when the relationship between the two is not fixed or rigid, but instead oscillates through the process of design.

Overview

This book establishes insights learned through making and critical analysis. It moves in time between past and present. It works across many scales. Chapter 2 profiles 10 original prototypes, highlighting their role as mechanical artefacts that create controlled environments of legible flow. Chapters 3, 4 and 5 each tell the story of a single precedent model that has largely gone overlooked in the histories of architectural design and building science. The case studies range historically from the Industrial Revolution to the post-war period, a span of time in which the climate control of buildings emerged as a techno-scientific project. They establish some of the origins for contemporary design concerns related to flow visualisation, thermal comfort and building climate control. While they are organised non-chronologically, they are what architectural historian Daniel Barber refers to as 'epochal, recursive projects'; each is an 'object from the past that describes a relationship to climate with unanticipated relevance to the present and future' (Barber 2020, 9).

Chapter 2 is a visual catalogue of four wind-tunnel, four water-table and two filling-box prototypes. Each makes airflow associated with either pressure or buoyancy-induced differentials visible. This chapter focuses primarily on fabrication techniques for making environmental models and techniques for visualising flow. For those interested in building their own environmental models, this chapter offers relevant resources and techniques for doing so, often adapting material and fabrication techniques from engineering and DIY resources to those more readily available in architecture workshops.

Chapter 3 features French polymath Étienne-Jules Marey's wind tunnel and associated smoke-stream photographs. Marey was a prolific inventor best known for the photographic techniques he devised to capture incremental views of birds in flight. Towards the end of his career, Marey constructed wind tunnels that used smoke streams to visualise airflow around wing profiles, marking a shift in his research from the subject of flight to the medium of flight. The smooth, moving lines of smoke that erupt into trailing eddies and vortices around linear and cambered profiles have been celebrated as photographic achievements. While the curling vortex trails in Marey's photographs are beguiling, this chapter reveals that there is more to be learned about air movement by focusing instead on the steady, continuous streamlines of undisturbed smoke.

Chapter 3 examines Marey's wind tunnels through two frames: first, through the lens of the camera and, second, as a spectator in Marey's physiological research station. The initial frame focuses on the phenomena of airflow and its materialisation through smoke streams. Marey's work is situated within a broader context of early developments in flow visualisation, calling to question: what makes a good flow visualisation *good*? And what does a good flow visualisation tell us about the properties of air as a moving material system? The second frame of reference is as a spectator in Marey's physiological research station, observing the wind tunnel itself. While the wind tunnel appears a robust mechanical assemblage, it is in fact a delicate instrument that inadvertently registers external disturbance, revealing air's extreme material sensitivity. This chapter concludes with photographs of my water-table and wind-tunnel prototypes, highlighting the challenge of creating the steady lines of smoke that appear so effortless in Marey's photographs.

Chapter 4 features Victor and Aladár Olgyay's thermoheliodon, an incomplete experiment published in the appendix of Victor Olgyay's canonical *Design with Climate: A Bioclimatic Approach to Architecture*, published in 1963. The thermoheliodon was intended as an advancement of the heliodon, simulating wind flow and thermal conditions in addition to solar trajectories on physical models. The thermoheliodon highlights dialogues between models and their target systems, focusing on ideals of architectural environmental mediation that emerged in the US during the post-war era surrounding the climate control of buildings.

The thermoheliodon reflected two emerging post-war, data-driven conceptions of environment: variable exterior and controllable interior. It also reflected two conceptions of architecture that mediate these environments: one predicated on adaptation and the other on encapsulation. One is a filter; the other is a bubble. Through a deliberate misreading of the thermoheliodon as an architectural model, Olgyay's bioclimatic designs are contrasted with those predicated on creating a hermetically sealed interior. These two models of environmental design have persisted, largely informing discourse about the environmental management of buildings

today. This chapter concludes with photographic documentation of an exhibition of my prototypes, reflecting on the nested environments that environmental models – and by inference all objects, infrastructure and furnishing within buildings – are implicated in.

Chapter 5 examines Scottish physician David Boswell 'The Ventilator' Reid's convection experiments, published in 1844, in one of the first comprehensive textbooks of building ventilation: *Illustrations of the Theory and Practice of Ventilation*. The book, peppered with the kind of arrow-overlaid environmental diagrams ubiquitous in technology textbooks, incorporates two experiments that illustrate the principles of convection. Using a glass test tube and a glass 'tubular apparatus', coloured water and a naked flame, the experiments illustrate that air moves due to differentials in temperature, a principle he applied to many of his ventilation strategies. The utter simplicity of Reid's 'tubular apparatus' sits in contrast to the elaborate mechanics of Marey's wind tunnels and the Olgyays' thermoheliodon, lending itself to being read as an architectural model of interconnected spaces.

Reid's convection experiments prompt ready speculation about architectural models as vessels of atmospheric exchange in the early moments of the codification of building ventilation practice. They make visible principles underpinning a third model of environmental mediation present today: buildings as thermodynamic objects. This chapter explores the emergence of contemporary concepts such as thermal asymmetry, thermal imbalance and alliesthesia, all of which rely on thermal variability as drivers of spatial organisation. This chapter concludes with photographs of my filling-box models, highlighting an important distinction between models as physical artefacts and models as mental ideals. Physical models have material defects. They leak, unlike the ideals they represent. Filling-box models leak, and they leak somewhere, initiating a cascading series of exchanges that situate models within a much wider atmospheric context.

Chapter 6, the concluding chapter in this book, reinforces the significance of environmental models as tools for multiscalar architectural speculation about pressing environmental concerns. It asks: what is the target of our environmental models now and how can environmental models reflect these complexities? The chapter outlines three recurring terms of reference raised by case studies featured in the book – resistance, diminution and buoyancy. It explores what these terms offer for thinking about architecture's model environments today, especially given the challenges of climate breakdown and its associated injustices, as well as aerosol virus transmission associated with the COVID-19 pandemic.

Seen through the distilling lens of the architectural model, this book is an episodic and far-reaching exploration of dialogues buildings have with their environmental surroundings. The book covers topics including: how the material properties of airflow are revealed or concealed through flow visualisation strategies; how diverging building climate-control strategies are manifest architecturally through building enclosure; and how expanding models of thermal comfort drive the formation of architectural form. Each topic establishes some of the origins of architectural concerns associated with urgencies of designing today. The book reveals the potent ability for models to both reflect prevailing cultural views about the world and to even go reshape those views. It examines models as physical artefacts and models as mental ideals and reveals how environmental models open design insights across scales from the seam (that leaks) to the body (that feels) to the building (that mediates) to the world (that immerses).

Notes

1. Ventilation resources for architects also tend to stress that the value of working with physical experiments is that they yield quantitative results. As one example, in the comprehensive and informative book *Designing Spaces for Natural Ventilation: An Architect's Guide*, Francine Battaglia and Ulricke Passe describe some advantages of using wind tunnels, but lament that 'the drawback is that the dynamics of the air flow within the building is not measured' (2015, 281).
2. Bruce Archer offers a useful distinction between the disciplines of design and technology. He suggests that 'if technology is "knowing-how", then design is "envisaging-what"' (Archer, Baynes and Roberts 2007, 19). While their work focuses on structural concerns, the form-finding models by Antoni Gaudi, Heinz Isler and Frei Otto operate somewhere in this middle ground between technical invention and design speculation.
3. Several contemporary landscape architects use physical hydrological models to enable design speculation. Bradley Cantrell and Justine Holzman's book *Responsive Landscapes: Strategies for Responsive Technologies in Landscape Architecture* (2016) outlines a range of approaches of working with hybrid digital and physical models. See also Skylar Tibbits's wave-tank studies for the *Growing Islands* (Self Assembly Lab, n.d.) project in the Maldives and Catherine Seavitt-Nordenson. *On the Water: Palisade Bay* (2010), model studies featured in the next chapter.
4. Olafur Eliasson goes so far as to dissolve distinctions between model and world altogether, noting:

> Previously models were conceived as rationalized stations on the way to a perfect object. A model of a house, for instance, would be part of a temporal sequence, as the refinement of the image of the house, but the actual and real house was considered a static, final consequence of the model. Thus the model was merely an image, a representation of reality without being real itself. What we are witnessing is a shift in the traditional relationship between reality and representation. We no longer progress from model to reality, but from model to model while acknowledging that both models are, in fact, real.... Rather than seeing model and reality as polarized modes, they now function on the same level. Models have become co-producers of reality.
>
> (2008, 19)

Eliasson is describing a historic shift in the epistemological status of models. He suggests that models have moved from being conceived of as static representations of the world to being active agents in constructing understandings of it.

5. Peter Eisenman's 1976 *Idea as Model* exhibition at the Institute for Architecture and Urban Studies marked an important conceptual shift in the role and value of the architectural model. The exhibition catalogue notes that Eisenman was guided by

> a long-standing intuition ... that a model of a building could be something other than a narrative record of a project or building. It seemed the models, like architectural drawings, could well have an artistic or conceptual existence of their own, one which was relatively independent of the project that they represented.
>
> (Pommer cited in Frampton and Kolbowski 1981)

Many useful resources elaborate on the conceptual value of working with physical models. A few highlights include Karen Moon, *Modeling Messages: The Architect and the Model*, 2005; Marco Frascari, Jonathan Hale and Bradley Starkey (editors), *From Models to Drawings: Imagination and Representation in Architecture*, 2008; Mark Morris, *Models, Architecture and the Miniature*, 2006; Albert Smith, *Architectural Model as Machine: A New View of Models from Antiquity to the Present Day*, 2004; and Patrick Healy, *The Model and Its Architecture*, 2008.

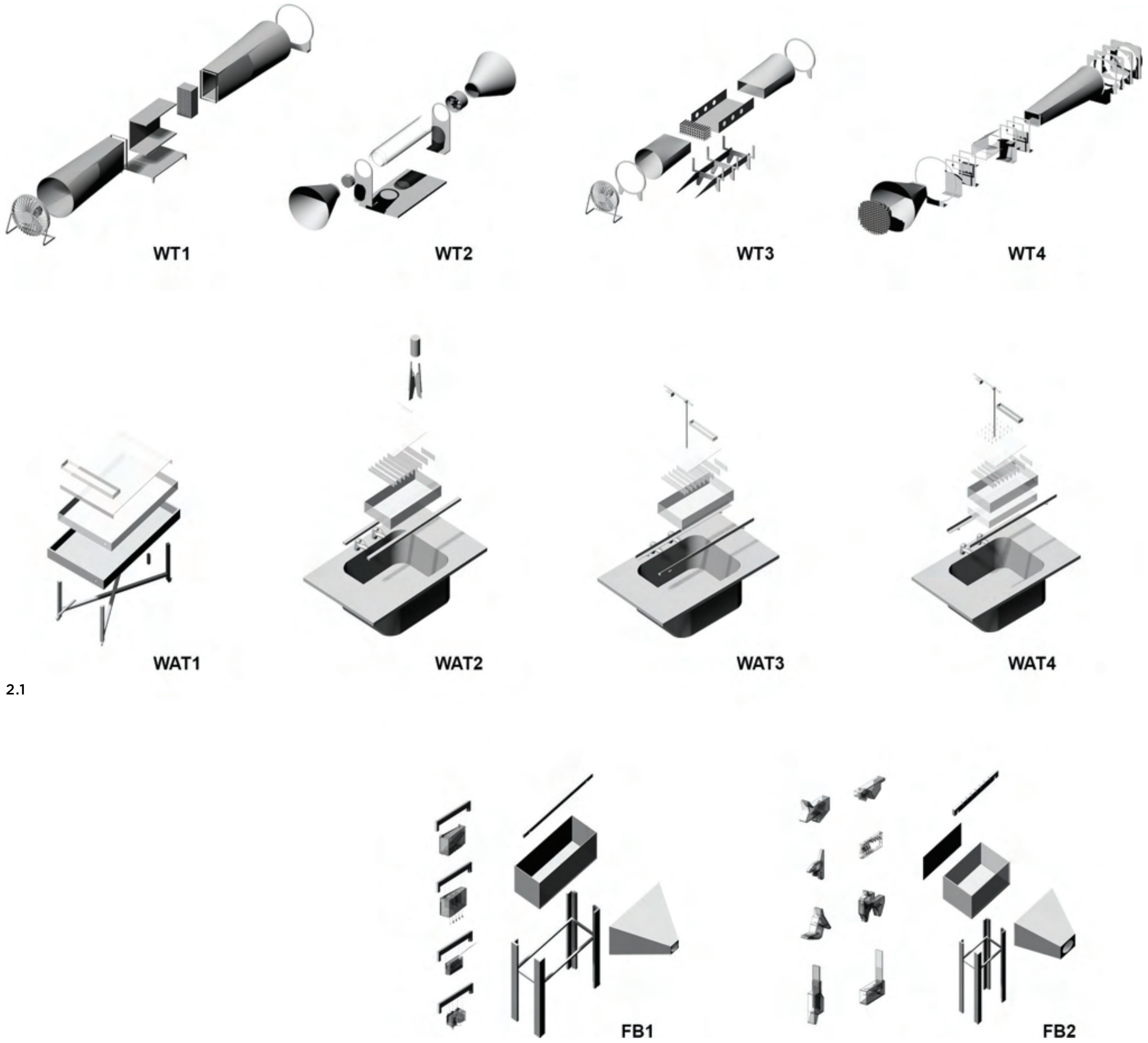
Chapter 2 | Prototypes

This chapter features 10 original prototypes: four wind tunnels, four water tables, and two filling boxes (Figure 2.1). All three model types make air movement visible. Wind tunnels and water tables reveal flow due to differences in pressure, which drives cross-ventilation and urban airflow patterns. Filling boxes reveal flow due to differences in density, which drives stack effect and displacement ventilation. All three have been used as tools of environmental verification in engineering and building science. They have also been used to teach architectural principles of building ventilation and urban airflow patterns around buildings. This chapter consolidates guidance about the design and construction of each model type from a range of technical and DIY resources and tailors them to the architectural designer.

Environmental models work in several capacities. They are mechanical devices, building on their origins as tools of engineering experimentation. They are also objects of design speculation, revealing architectural insights about environmental mediation across scales. These scales range from the tectonics of the full-scale artefact to the planetary scales of atmospheric exchange operating at scale in the model test section. This chapter focuses primarily on the former dimension of environmental models: their operation as mechanical devices that make steady, non-deviating flow legible. It touches on tectonic concerns raised by the process of designing, fabricating and assembling each prototype while also evaluating flow-visualisation strategies.

For each prototype, visual material illustrates two intertwined concerns: the development of a steady-state environment in the testing bed and the visualisation of high-contrast flow (Figures 2.2 and 2.3). Wind tunnels and water tables both rely on the creation of an environment of consistent, moving, non-deviating flow. This condition, known as steady state, is generated in the testing bed of the model. The steady-state environment establishes a baseline for observation. Models placed in the testing beds create deviations from this consistent flow, illustrating how the form of the model impacts flow patterns. While straightforward in principle, achieving this steady-state condition is extremely difficult, requiring precise methods of construction to ensure that any deviations, deflections, material gaps or internal obstructions do not disrupt flow patterns.

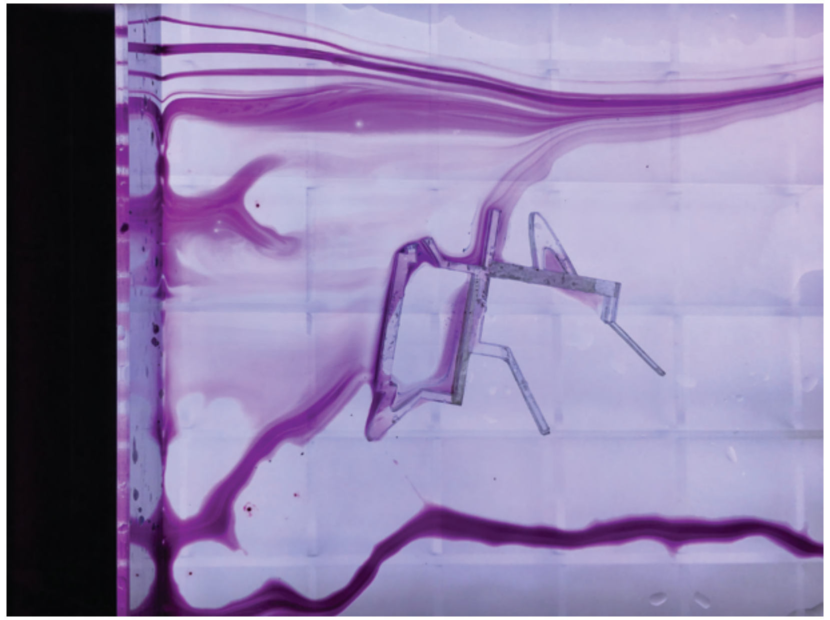
A twin concern to establishing a steady-state environment is that of making flow patterns visible. There are many strategies for visualising flow, including those that



2.1

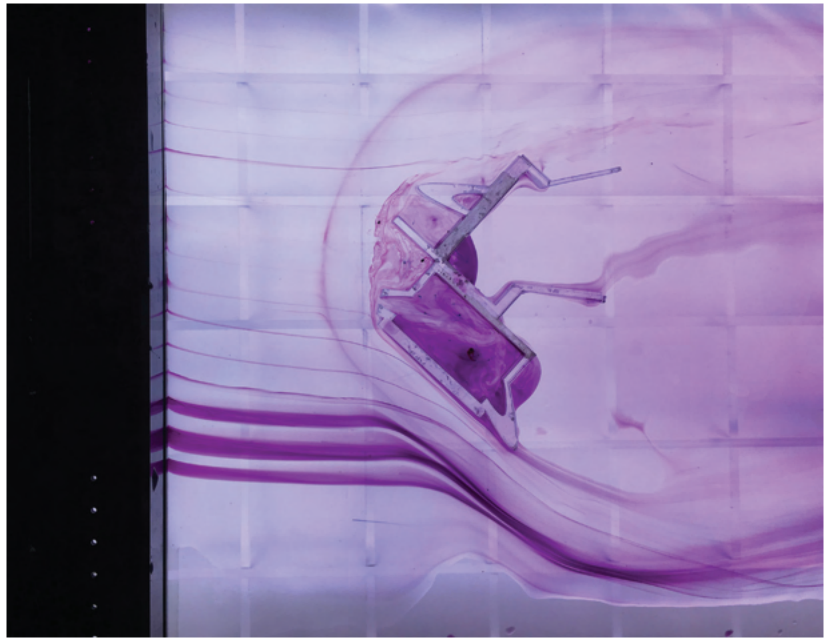
2.1 Axonometric drawings of 10 prototypes – four wind tunnels (WT), four water tables (WAT), and two filling boxes (FB) – profiled in this chapter.

2.2 Photograph of WAT2. Constructing an even surface of flow and steady lines of ink, reflecting a steady-state condition, requires elimination of any obstruction or surface deflection that unintentionally deviates flow.



2.2

2.3 Photograph of WAT2. Capturing a clear flow visualisation entails the careful control of light to eliminate surface reflections and the use of a high-contrast flow visualisation medium such as, in this case, plumbers' drain dye.



2.3

rely on complex optical techniques using light refraction. The prototypes featured here rely on the addition of a new material such as smoke or dye into the moving fluid. Good flow visualisations are those in which the flow patterns are highly discernible. They tend to be high contrast, in focus and free of external distractions. A good flow visualisation requires careful calibration of photographic settings; elimination of background light, which can create distracting reflections; and use of high-contrast materials in the model, the flow medium and the background of the testing bed. Focusing intensively on the interior of the testing bed, however, conceals the complexity of the relationship between the environmental model and its broader environmental surroundings in the spaces of its assembly and use: the dust, ducts, light and sounds surrounding and inputting into it. A reflection on these nested environments concludes Chapter 4.

Organised as a visual catalogue, each prototype is presented over two consecutive book spreads using identical modes of representation. The first spread focuses on prototype construction, and the second focuses on flow visualisation. Photographs and exploded axonometric drawings introduce model componentry and overall assembly of each prototype on one page. On the opposite page, a composite drawing consolidates all fabrication drawings used to build that prototype, using colour to distinguish between 3-D print files, laser-cut files and more conventional construction drawings. With each iteration, fabrication techniques gained precision to cope with the tight tolerances required to maintain air and water tightness. This was marked by increasing reliance on digital fabrication methods, which is evident when viewing the progression of composite drawings.

The second spread for each prototype illustrates the mechanics and effects of flow visualisation. The first page features a series of video stills illustrating flow patterns recorded over time for that prototype. The facing page includes a single representative flow visualisation photograph and an associated photographic setup diagram. Diagrams highlight the relationship between environmental model, architectural model, light source(s) and camera placement used to achieve the photograph above them.

Wind tunnels, water tables and filling boxes each presented challenges that guided the iterative development of that model type. Wind tunnels focused primarily on tectonic questions. Water tables highlighted challenges of constructing a steady-state condition. Filling tanks raised questions about photographic calibration. Each prototype can be read in isolation or as part of a trajectory of iterative development. As a body of work, the prototypes suggest approaches to developing materials systems that contain, resist, direct and channel air and water flow, suggesting architectural strategies that do the same.

To work with environmental models means to think through many disciplinary lenses: the plumber, the mechanic, the machinist, the photographer, the climatologist, the building scientist and

the environmental scientist. The process of creating a working mechanical object opens insights about working with air and water as material systems with particular characteristics. The process reveals strategies for designing the vessels that hold air and water and the componentry that directs, channels, straightens and speeds up this flow. Perhaps more important, the process highlights joints and seams that enable flow to continue unobstructed. Constructing environmental models reveals the need for stability, for precision and for a constructional logic attuned to material dimensions and fabrication tolerances. The process also prompts architectural speculation informed by these constructional approaches, raising questions like: what would an architecture of nozzles, baffles and hoods look like and how would it perform?

The term prototype is used throughout this chapter to focus on two features that distinguish the assembly as a totality from conventional architectural models. First, each prototype is understood as an artefact that operates at full scale, rather than as a scale model. Second, each prototype is part of an iterative process that is evaluated according to set performance criteria, in this case, the construction of a steady-state environment of highly visible airflow. While straightforward in principle, achieving this steady-state condition is extremely difficult, requiring precise methods of construction to ensure that any deviations, deflections, material gaps or internal obstructions do not disrupt flow patterns through the testing bed. Each prototype is a methodical refinement of the one before and could be considered what the pioneer of fabric-formed concrete, Mark West, refers to as a 'method prototype' (2008, 52).

The prototyping process is, of course, not purely a technical exercise. It is through the process of trying to satisfy technical concerns that new conceptual insights about environmental mediation are revealed. These design insights vary from prototype to prototype. Some are accrued steadily over time, while others are revealed in an instant during the misreadings and, to use Burnett's term introduced in Chapter 1, *oscillations* that take place during the design process. This chapter focuses primarily on the mechanics of each prototype, but it also serves as a point of departure for introducing some of the unexpected insights that emerged during the fabrication process. These insights – about the challenges of creating steady-state environments, ways of situating environmental models within many nested environments and the significance of unintentional model leaks – are presented in the concluding sections of the following three chapters.

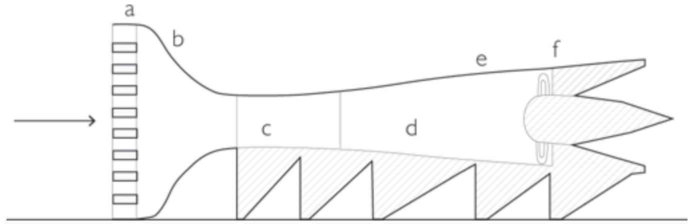
Wind tunnels

Wind tunnels come in many forms and have many uses. They are either high speed (supersonic), primarily used for aeronautical research, or low speed (subsonic), used, among other purposes, to study airflow around and through buildings. They are either open circuit or closed circuit, depending on whether air is recirculated within the tunnel or not. They are open or closed throat depending on whether the test section is open or enclosed. Engineering wind tunnels used to study airflow around buildings are referred to as boundary layer wind tunnels, and they incorporate spires of varying profiles on the windward side of the building model to simulate the roughness characteristics of ground depending on its open, suburban or urban characteristics. Prototypes in this chapter, however, neglect these boundary layer effects. Finally, wind tunnels are categorised as being either large or small. Even small wind tunnels are often substantial in size, measuring several metres in length. Prototypes in this chapter are all low-speed, open-circuit, closed-throat, small wind tunnels. This type of wind tunnel is often used as an educational or instructional tool. As the prototyping process revealed, wind tunnels of this type are prone to external disturbance.

A wind tunnel is essentially a duct containing steady airflow that is either pushed or drawn by a fan. Components on both ends of the duct speed up, direct and straighten air movement (Figure 2.4). A contraction section on the end opposite the fan speeds air by compressing it from a larger to a smaller volume. Flow straighteners, composed of extruded grids or bundles of straws, are located at the mouth of the contraction section. The geometry of the section creates a smooth transition between circular and rectilinear geometries to minimise air turbulence as it moves towards the testing chamber. Once air has been straightened and turbulence reduced, air flows through the testing chamber in a steady-state condition. A diffuser connects the testing chamber to the fan, enabling a smooth transition between the two. The fan is typically oriented outward, drawing rather than pushing air through.

There are a range of DIY and engineering resources that offer a useful starting point for constructing wind tunnels. For example, DIY resources such as nasa.gov and instructables.com offer guidance on assembling simple wind tunnels using readily available materials. These assemblies are ad hoc and generally lack tectonic coherence, focusing instead on working with ready-at-hand materials and adhesives. Engineering resources such as Barlow, Rae and Pope's book *Low Speed Wind Tunnel Testing* (1999) provide more precise guidance on general layout and componentry, elaborating on technical concerns such as ideal size ratios between components. However, such resources are intended for more specialised use by engineers, and they are often constructed of large, folded sheet-steel and welded steel frames in sizes that are not practical to construct in most architecture workshops (Figure 2.5).

A successful wind tunnel has smooth transitions between geometries, stable connections between components and is free of interior obstructions, which generate turbulence within the testing bed. Prototypes in this chapter achieve these conditions by drawing from both technical and DIY resources. They exhibit an approach to detailing lacking from DIY guidance. Moreover, they rely on materials and fabrication methods familiar to the architect. As explored in more detail at the conclusion of Chapter 3, the process of wind tunnel refinement reflects a shift in focus from visualising streamlines to developing a detailing strategy of streamlining.



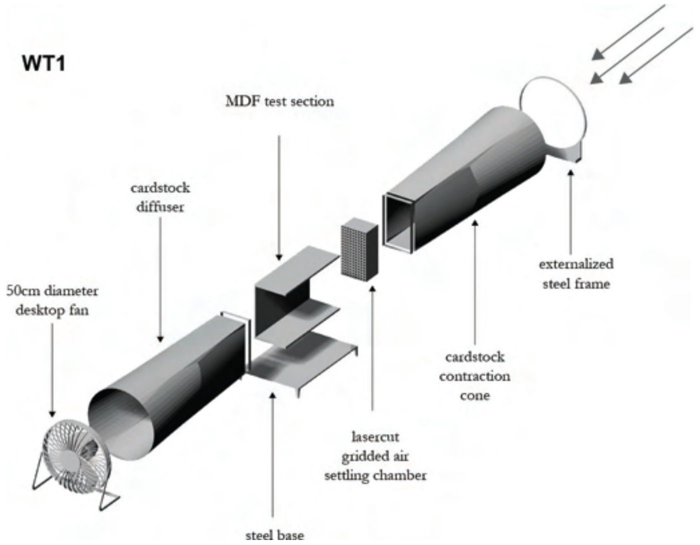
2.4

2.4 Diagrammatic cross section of an open-circuit wind tunnel indicating componentry as follows: (a) flow conditioners typically including flow straighteners and turbulence control screens; (b) contraction or nozzle; (c) test section; (d) diffuser of at least three or four test section lengths; (e) transition from rectangular to circular cross section; (f) fan and straightener section. Drawing by Saman Soltani based on diagram in Barlow, Pope and Rae (1999).

2.5

2.5 Photograph of three open-circuit wind tunnels at an engineering testing facility. Most resources for constructing wind tunnels are intended for engineers, and the resultant wind tunnels are often too large and unwieldy for qualitative architectural design purposes. Courtesy of Wacker Ingenieure Wind Engineering.

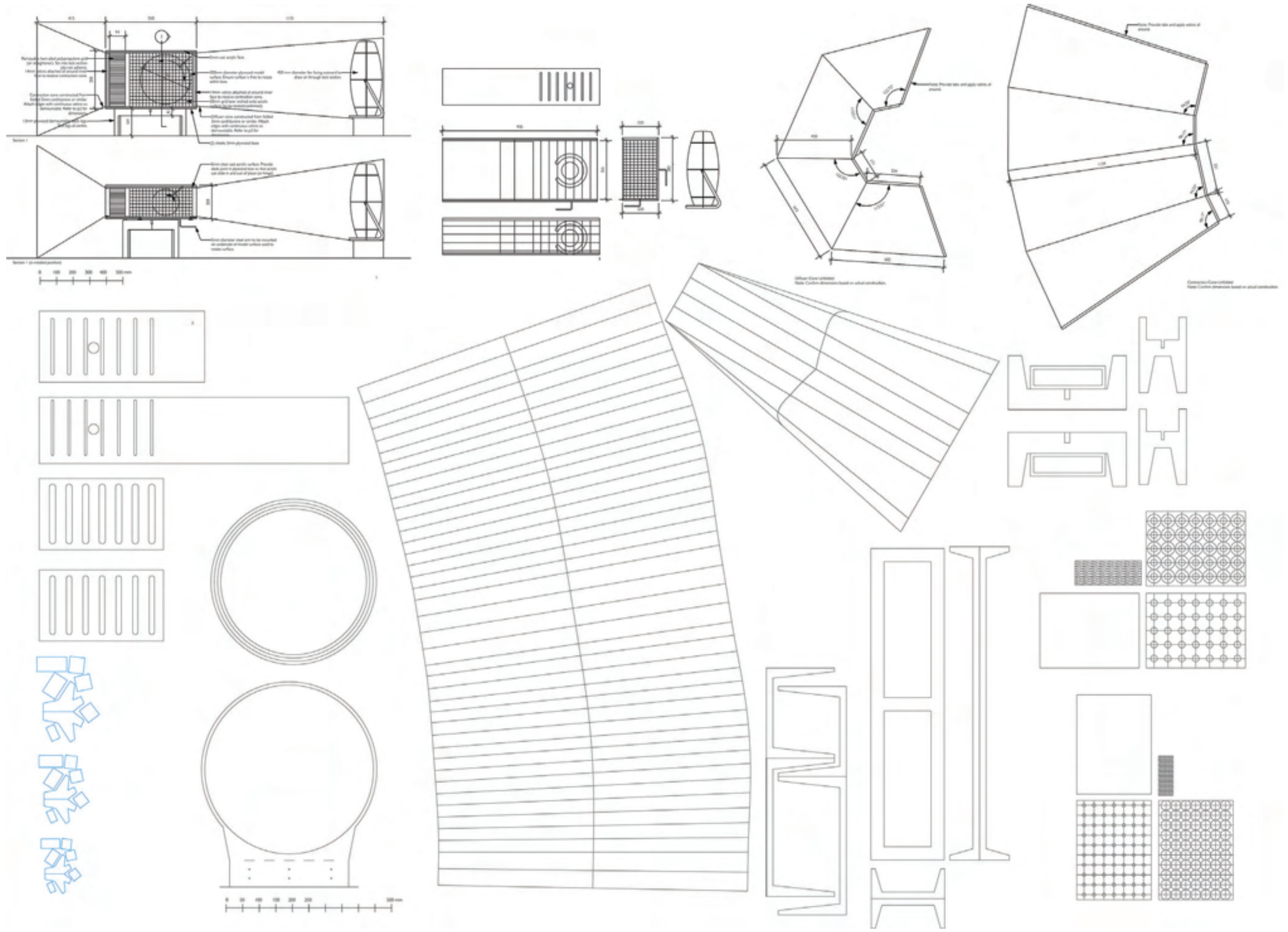
2.6 Exploded axonometric assembly drawing of the first wind tunnel prototype (WT1). A 50 cm diameter desktop fan draws air through the 20×50×35 cm test section. The diffuser and contraction cones were constructed out of large sheets of thin cardstock.



2.6

2.7 Photograph of WT1. The first prototype was ad hoc, lacking a clear assembly or connection strategy. It was unstable and difficult to assemble, and gaps between materials created turbulence in the testing bed. The contraction and diffuser sections deflected under their own weight and intersected awkwardly with the testing bed. Internal frames, designed to create more stable connections between components, created internal turbulence. Construction assistance by James Ness and Malcolm Cruickshank.

2.7

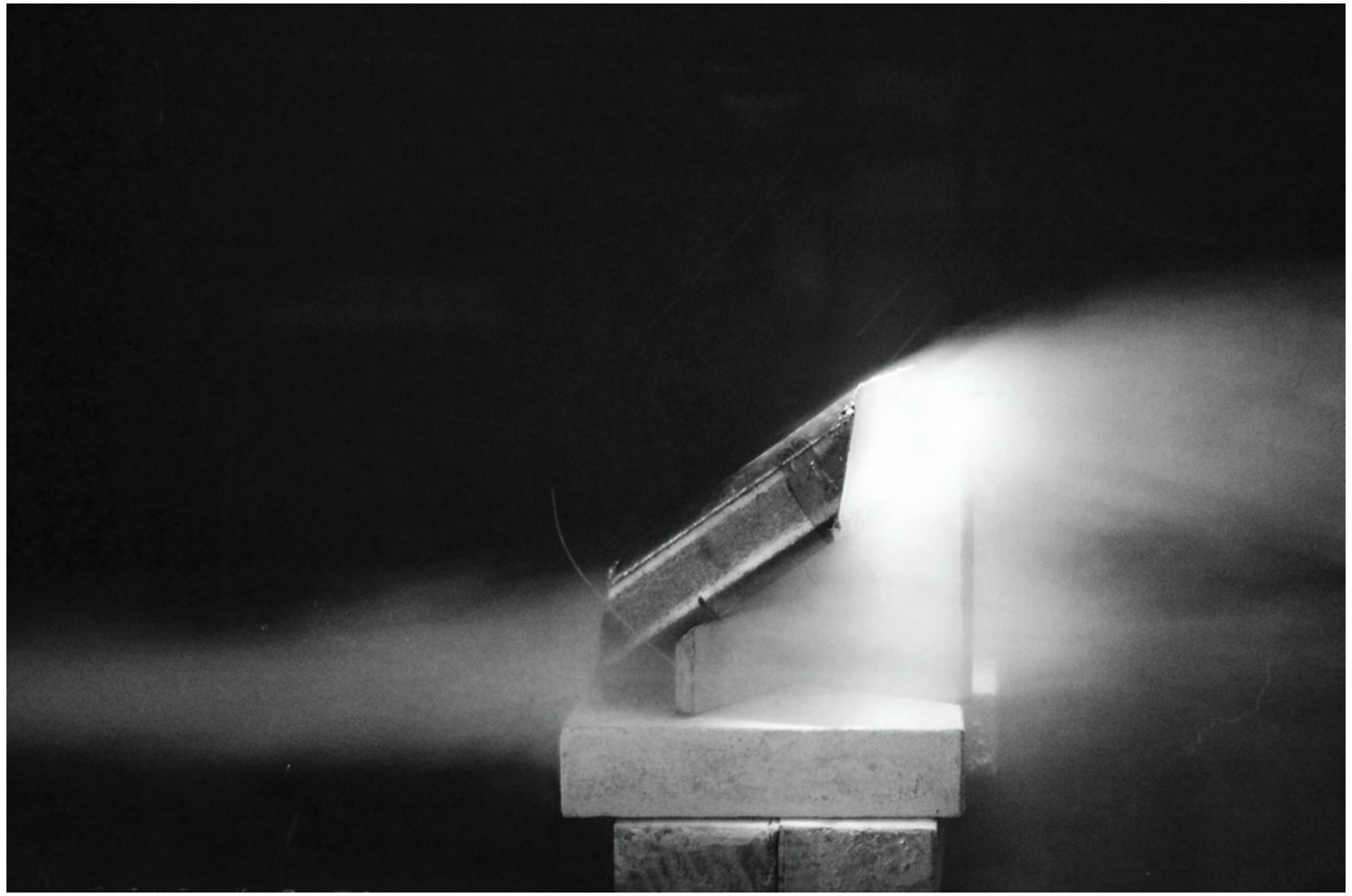


2.8

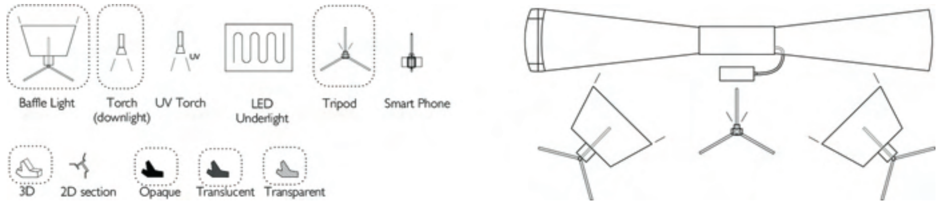
2.8 Composite fabrication drawing of WT1. Colour designations distinguish between drawing type and fabrication method. WT1 was developed primarily using conventional two-dimensional construction drawings, which provided a loose template for construction. Subsequent prototypes were developed as three-dimensional models and utilised digital fabrication methods.

2.9 Video stills illustrating flow patterns through opaque and transparent architectural models in WT1. Vapour from an off-the-shelf smoke machine generated visible flow patterns through the testing bed. This technique lacked the clarity and density of the smoke streams in Marey's wind tunnel featured in Chapter 3. The fan speed caused the vapour to dissipate too quickly to yield highly legible results. Video and photography assistance by Emma Bennett.

2.9



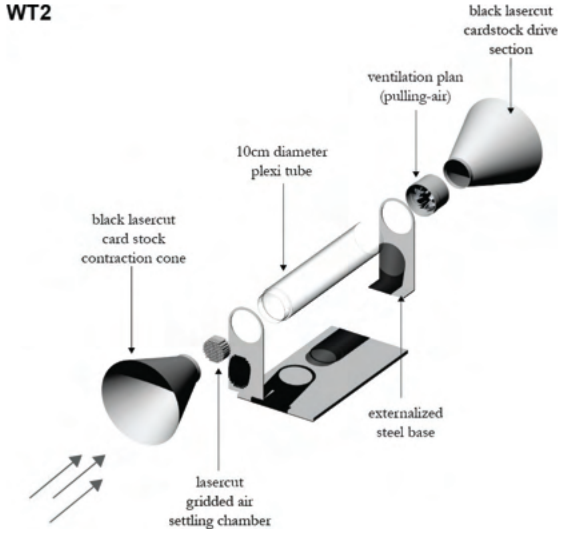
2.10 Photograph of WT1 flow visualisation study testing lighting and camera settings. The model was spot lit from above to establish contrast between vapour and the model. Photographic lights were placed at an angle to the test section, ensuring sufficient light for photography while also eliminating reflections on the plexiglass surface covering the test section. Shutter speeds taken at 1/100 appeared a blur; those at 1/200 and 1/320 captured movement more clearly. Photographs by Jamie Henry.



2.10

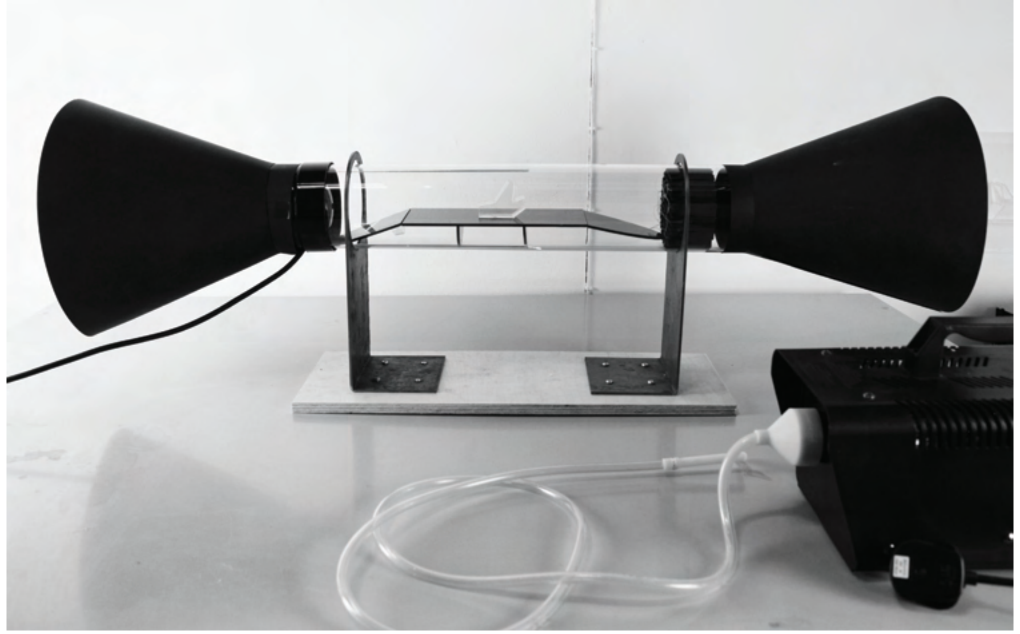
2.11 Exploded axonometric assembly drawing of the second wind tunnel prototype (WT2). The test section was constructed out of a 10 cm diameter × 50 cm long plexiglass tube. A 10 cm diameter exhaust fan, friction fit on one end of the tube, drew air through the test section. The contraction and diffuser sections were constructed from laser-cut black matte paper. Laser-cut externalised steel frames stabilised the assembly. This assembly relied primarily on lapped and friction-fit joints.

WT2



2.11

2.12 Photograph of WT2. The second prototype diminished in size to increase overall stability and precision fit between components. A cylindrical testing bed eliminated the transition between rectilinear and curvilinear components. Reduced material spans enabled the conical sections to retain rigidity without additional support. Construction assistance by James Ness.



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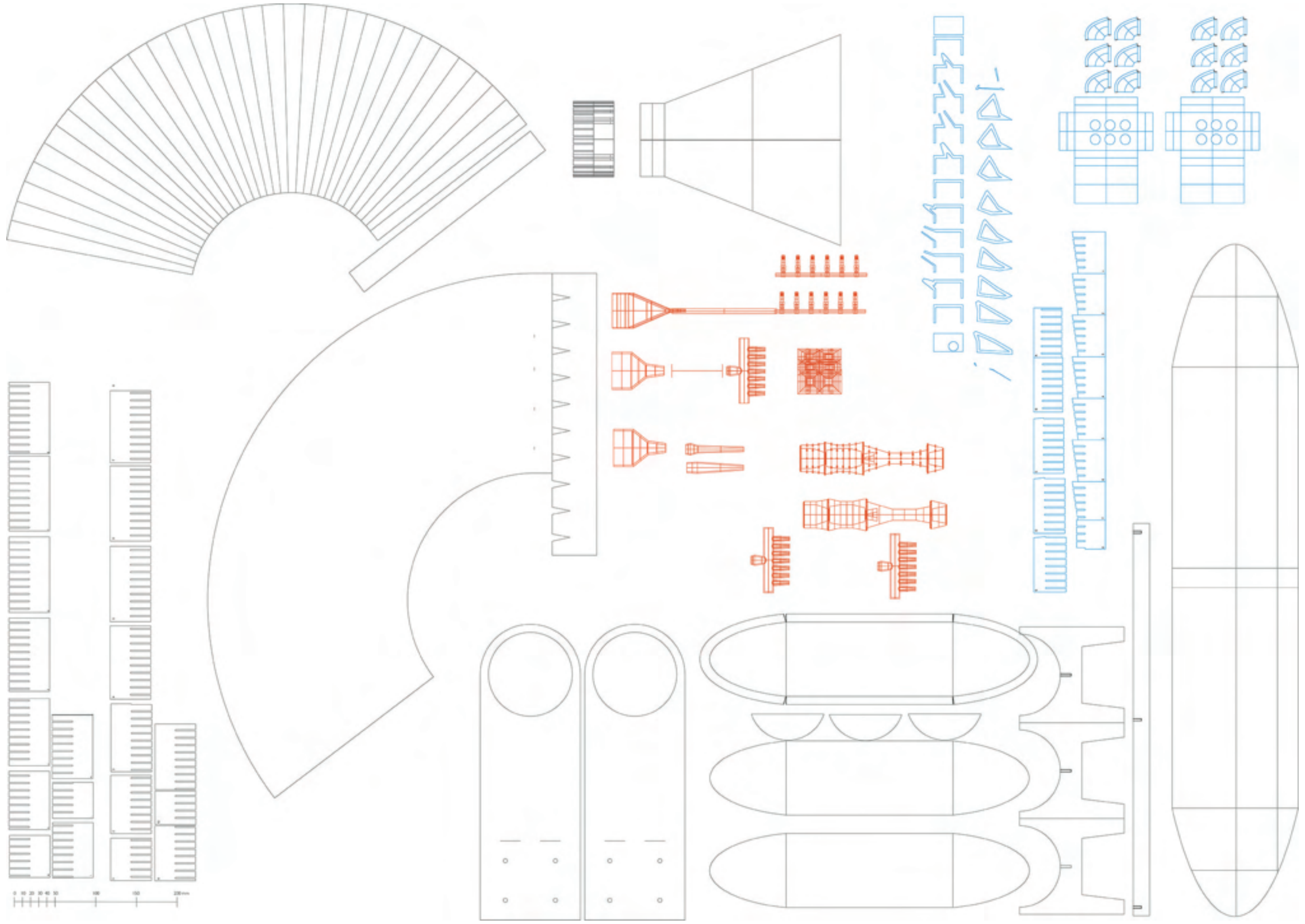
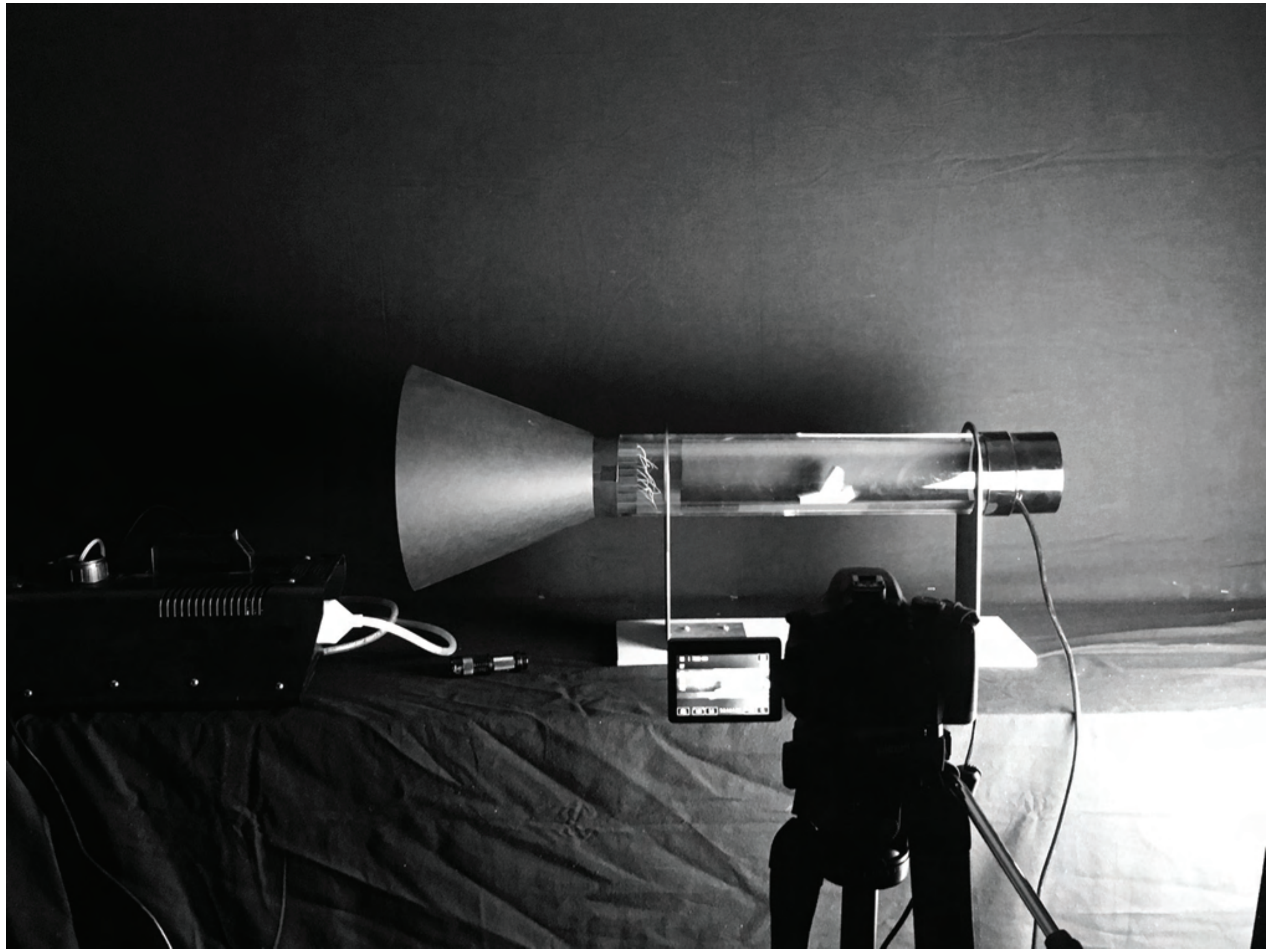


2.13

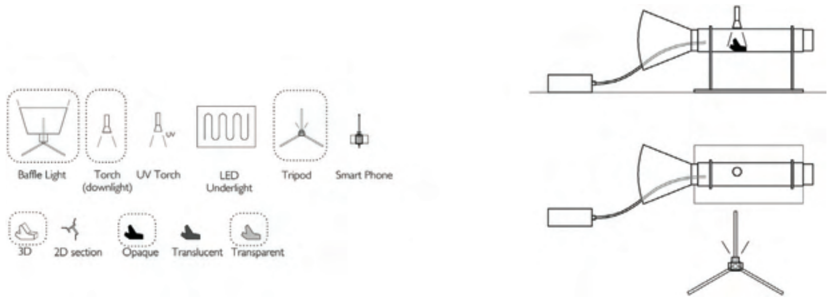
2.13 Composite fabrication drawing of WT2. Colour designations distinguish between drawing type and fabrication method. To increase model precision and to reduce construction tolerances, WT2 was designed as a digital model and then fabricated primarily using digital fabrication methods such as 3-D printing and laser cutting. Designing within the digital modelling environment streamlined fabrication, and the resultant assembly creates a smooth, continuous interior free of obstructions.

2.14 Video stills illustrating flow patterns through opaque and transparent architectural models in WT2. Vapour from an off-the-shelf smoke machine visualised flow patterns through the testing bed. Overall, the flow visualisations in WT2 were poorer than for WT1, likely a function of higher fan speed and erratic smoke machine vapour output.

2.14

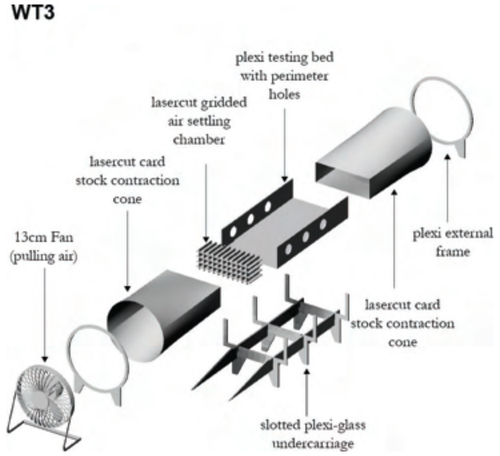


2.15 Photograph of WT2 photography set up. Photographic lights were placed at an angle to the test section, ensuring sufficient light for photography while also eliminating reflections on the plexiglass surface of the test section.



2.15

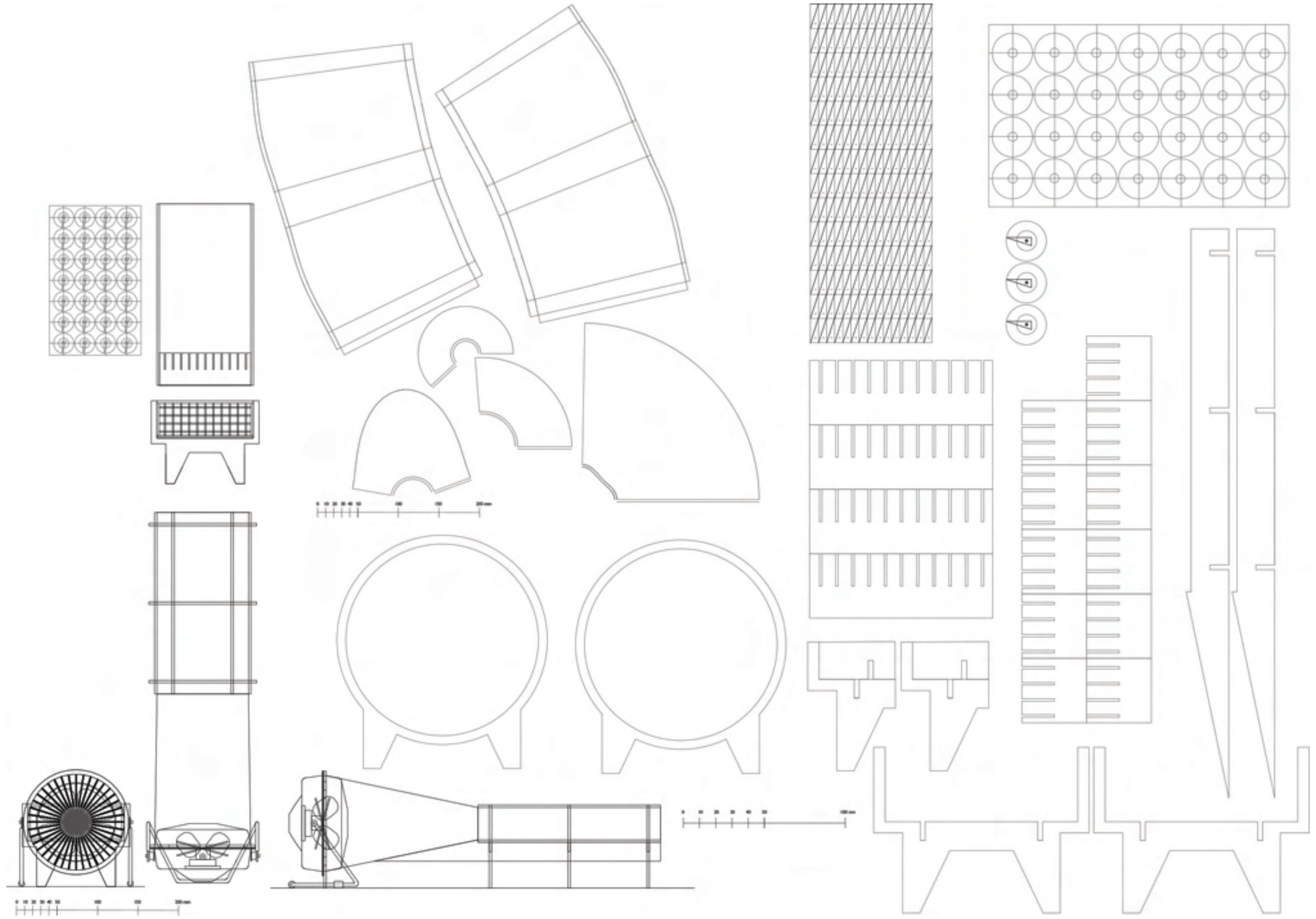
2.16 Exploded axonometric assembly drawing of the third wind tunnel prototype (WT3). This prototype tests the limits of diminution, reducing the wind tunnel to a 'desktop' size. The 13 cm diameter desktop fan draws air through the 22×11×4 cm testing bed. The assembly is bookended by laser-cut black cardstock contraction and diffuser sections, held in place by laser-cut acrylic frames.



2.16

2.17 Photograph of WT3. A series of holes in the side of the testing bed remain covered to create a continuous sealed test section of steady-state flow. Componentry can also be 'plugged' into these holes, disrupting the steady-state interior. In these cases, the wind tunnel turns into an architectural model with cones and baffles mediating between interior and exterior environmental conditions.

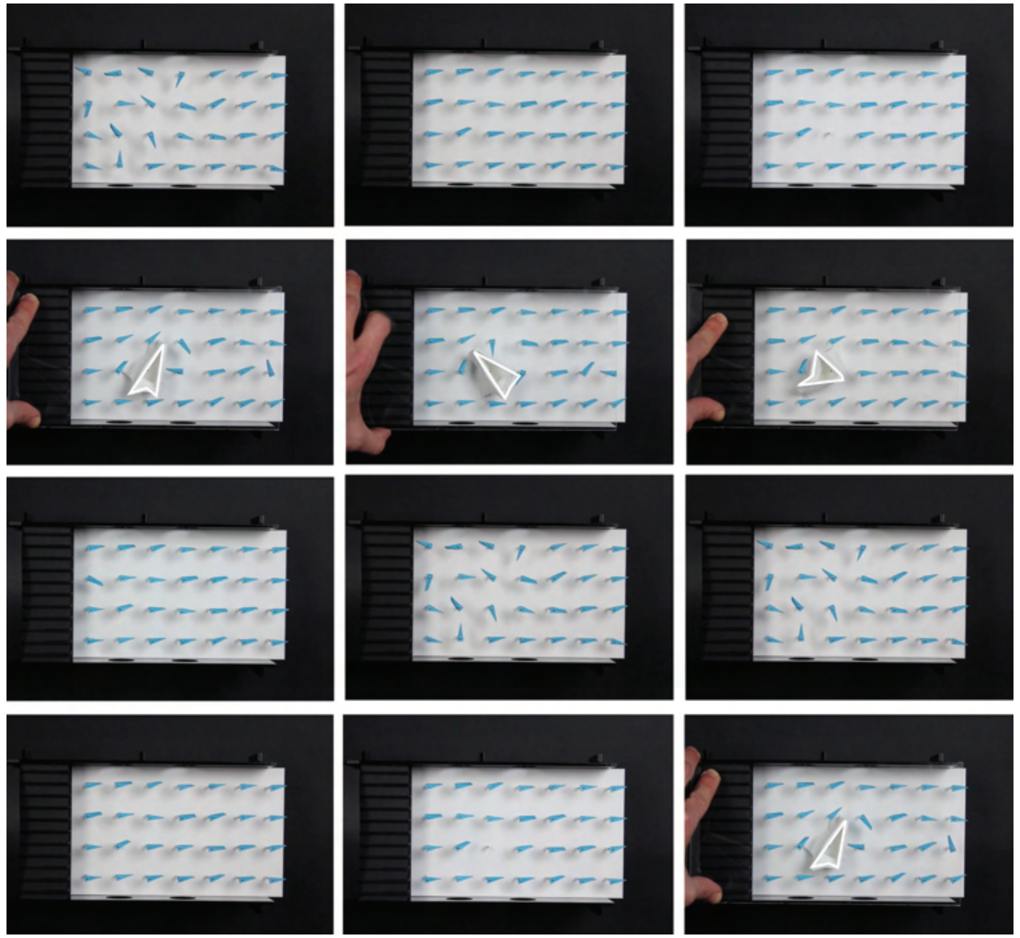
2.17



2.18

2.18 Composite fabrication drawing of WT3. Colour designations distinguish between drawing type and fabrication method. WT3 draws from its predecessors, working between conventional working drawings and three-dimensional model and digital fabrication methods.

2.19 Video stills illustrating flow patterns in WT3. WT3 incorporates an alternative strategy of flow visualisation. Laser-cut cardstock 'rudders' attached to straight pins freely rotate within hollow plastic tubes installed in a plexiglass grid base. In areas of smooth flow, rudders remained largely immobilised. In areas of turbulence, rudders spin continuously. The rudders become vectors indicating flow direction, operating as a model analogue to drawings that incorporate wind barbs to indicate airflow intensity and direction. Unlike static drawings that fix position, turbulent rudders remain agitated and spin continuously.



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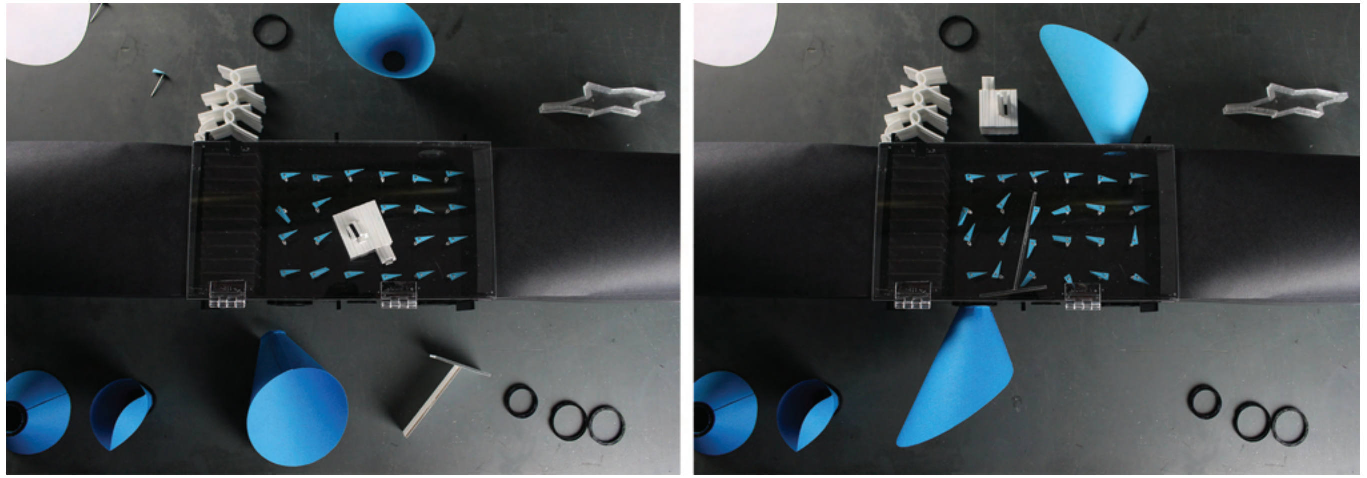
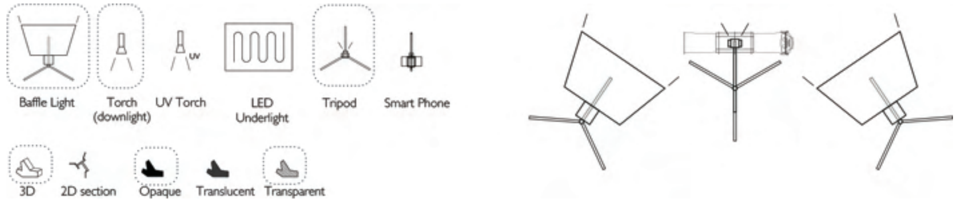
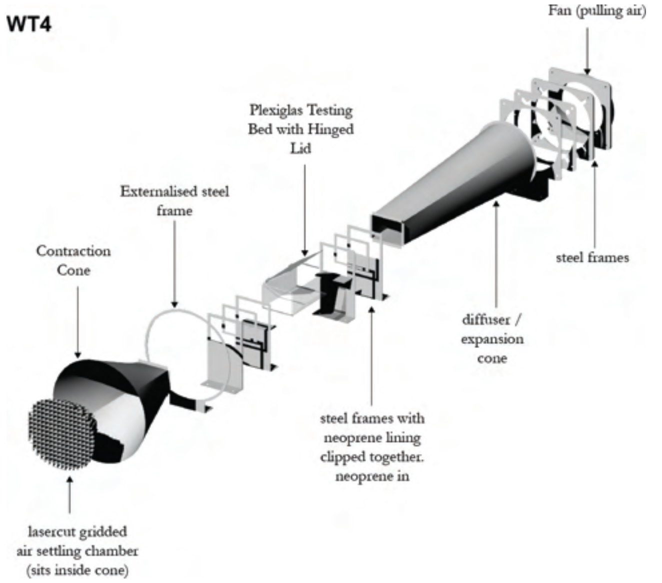


2.20 Photograph of WT3 illustrating a double reading of the wind tunnel. The image on the left presents the conventional view of an architectural model within the test section. The image on the right incorporates a series of model components on the exterior of the testing bed, turning the test section into a building interior that is mediated by exterior componentry. This model prompts the questions: how might an environmental model be read as an architectural model? What might an architecture of nozzles, baffles and hoods look like and how would it perform?



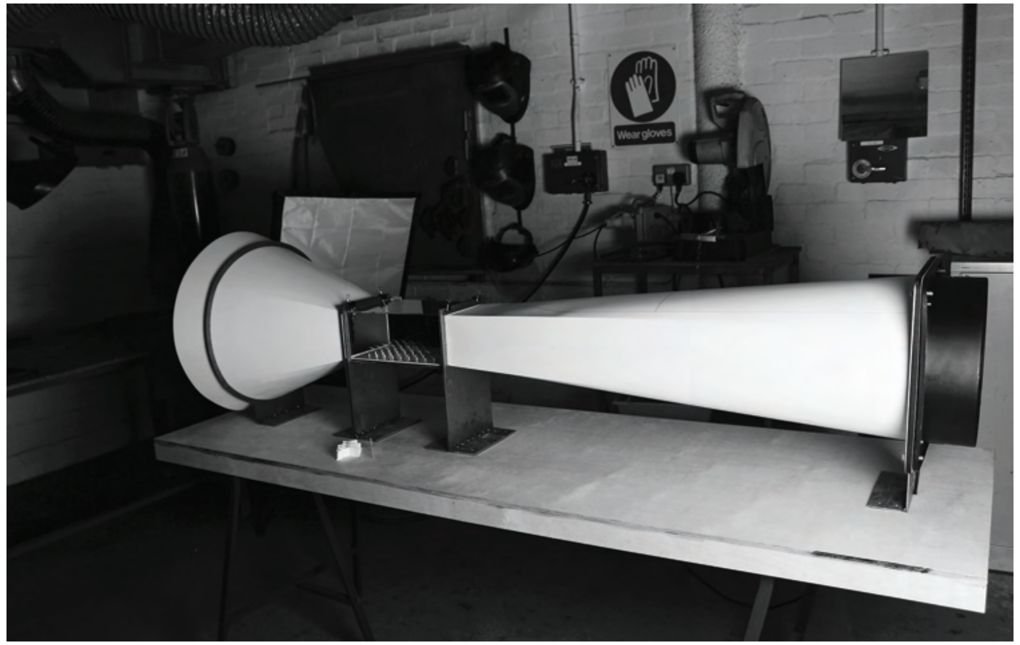
2.20

2.21 Exploded axonometric assembly drawing of the fourth wind tunnel prototype (WT4). WT4 regains stature and component precision lost in the previous prototypes. A 30 cm diameter radius ventilation fan anchors one end of the tunnel, drawing air through the 30×20×12.5 cm rectilinear test section. White cardstock diffuser and contraction sections are supported on either end by exterior steel frames. The frames double up at component intersections, ensuring tight, stable connections. Neoprene layers dampen vibrations and reduce air infiltration at seams.



2.21

2.22 Photograph of WT4. WT4 merges insights accrued through the prototyping process and resolves challenges posed by working with the larger material spans of WT1 by applying fabrication insights from WT2 and WT3. This prototype more closely follows guidance from engineering literature about component proportions. As a result, the contraction section diameter increased, and the diffuser section extended. Construction assistance by Malcolm Cruickshank.



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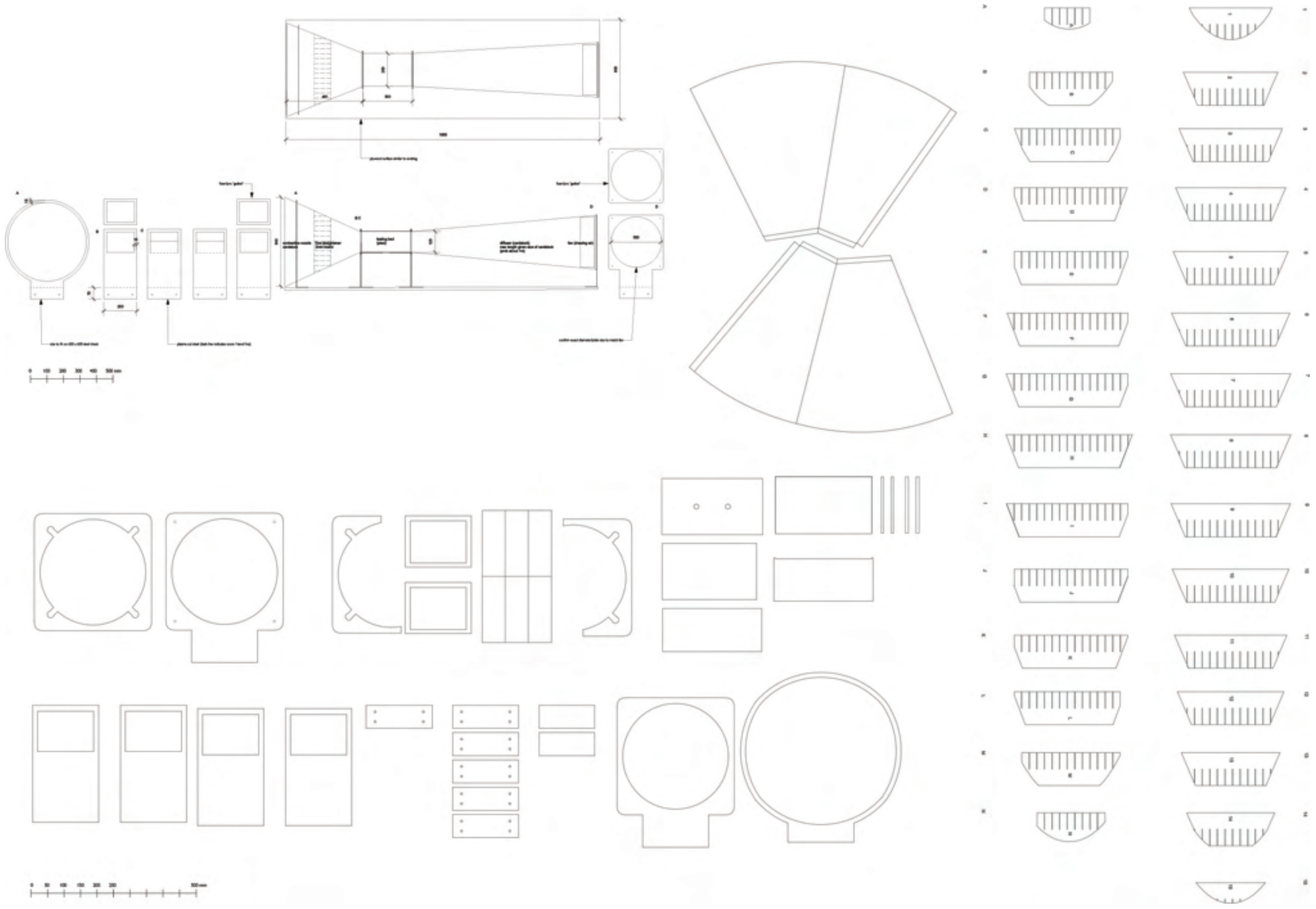
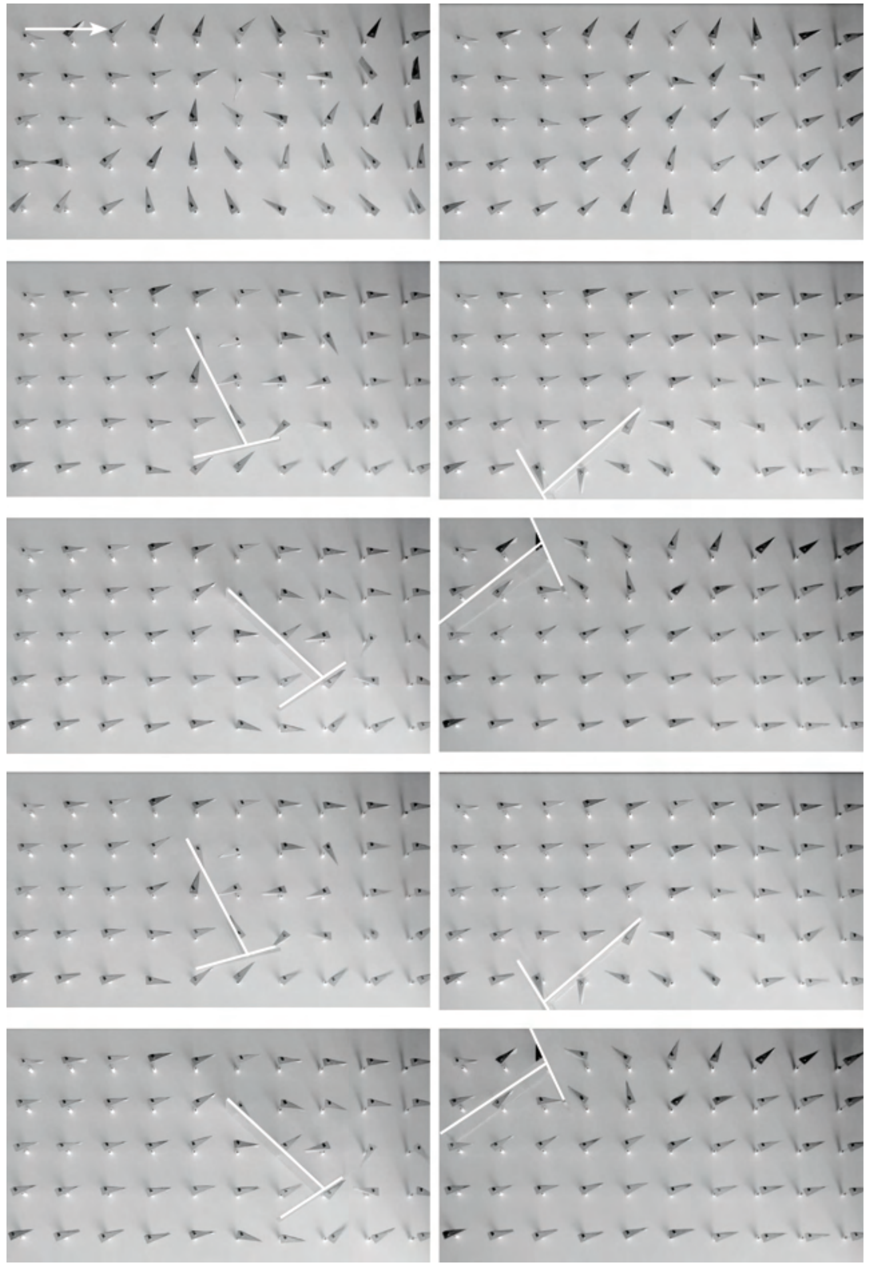


2.23

2.23 Composite fabrication drawing of WT4. Colour designations distinguish between drawing type and fabrication method. This final prototype solidified the development of a design and fabrication workflow. Sketches and two-dimensional drawings established the general organisation of the prototype. The design was then developed as a three-dimensional model, from which fabrication files were generated. Assembly assistance by Emma Bennett.

2.24 Video stills illustrating flow patterns in WT4. WT4 incorporates the rudder grid technique for visualising air movement through the testing bed. The rudders are extremely sensitive to disruptions enabling them to show subtle deviations in air movement. One disadvantage of this technique is that it fails to show material distinctions between laminar and turbulent flow. These flow regime distinctions are explored in more detail in the next chapter.



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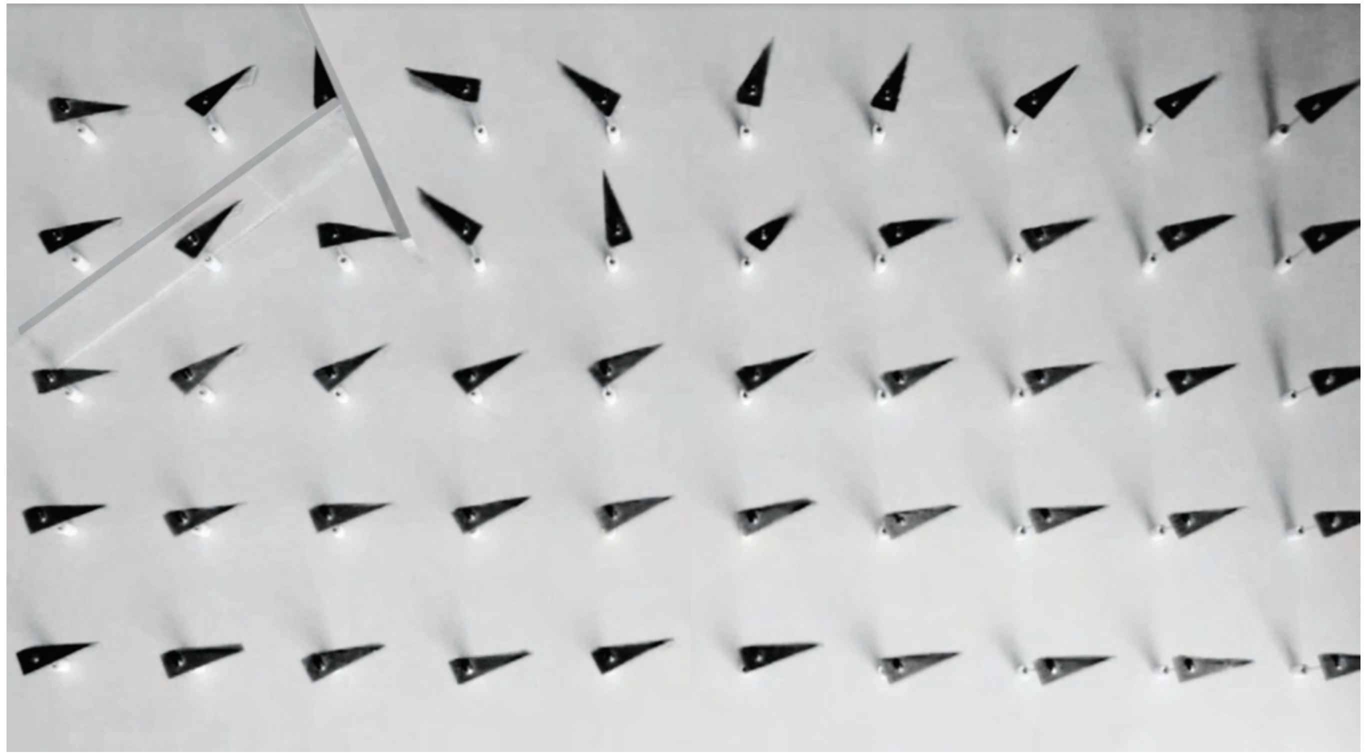
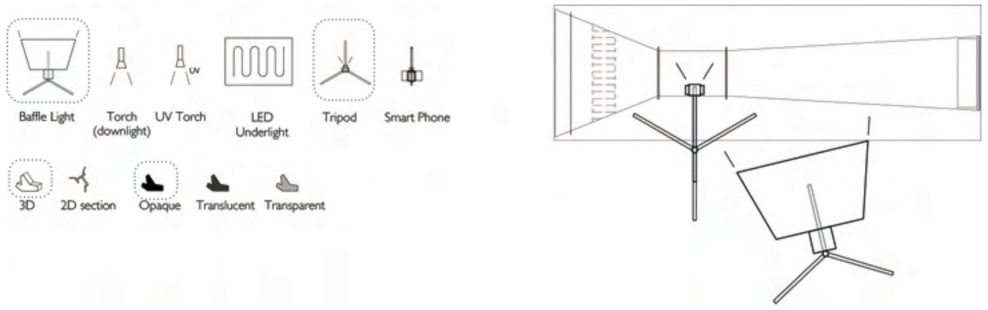


2.25 Enlarged video still of WT4 flow visualisation strategy. The grid of rudders is reminiscent of the *Wind Grid* installation featured in the first chapter. WT4 offers a synoptic view of air movement in a way that was impossible at full scale on Limekiln Line. However, the steady-state environment of the test bed neglects turbulence caused by topography, trees, other ground conditions and boundary layer effects present in the 'real' world. Boundary layer effects are discussed in Chapter 3.



2.25

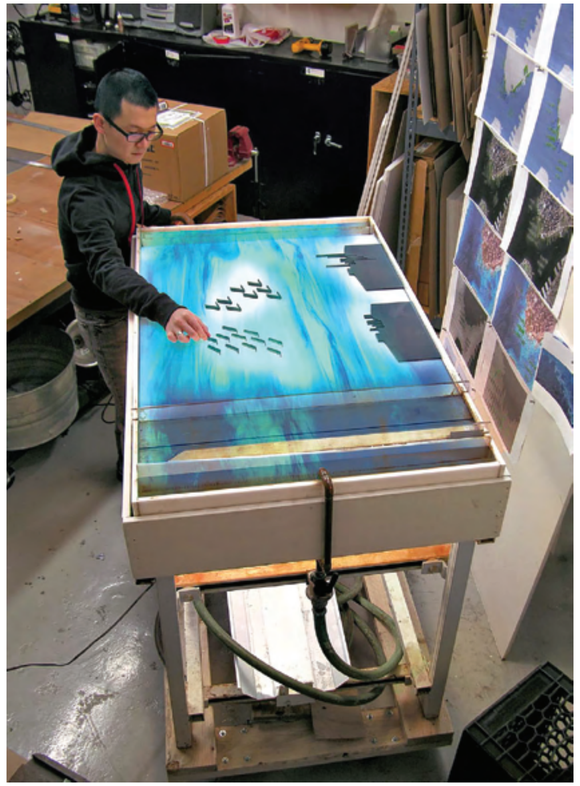
Water tables

Water tables, sometimes referred to as water tanks, are also used for empirical studies of aerodynamic processes. Like wind tunnels, water tables enable visualisation of pressure-induced flow. While their densities are different, water and air share similar flow characteristics. The first wind tunnel, built in 1871, was developed by marine engineer Francis Wenham, who drew from his experience working with water channels. Wenham understood that air and water share similar flow tendencies, facilitating a transfer of approach across media. He was also aware of *inversion*, which applies to working in air and water. 'This concept – that the forces on a body moving through a still fluid are the same as the forces on the body if it is stationary and the fluid flows around … is the central principle for water channels and wind tunnels' (Lee 1998, 8). Scaling formulas such as the Reynolds number enable engineers to apply quantitative findings from one medium (such as water) to understand those in the other medium (such as air).

Water flumes are large tanks which enable the visualisation of flow three-dimensionally like that of a wind tunnel. In water tables, however, flow is read as a two-dimensional slice, rather than a three-dimensional field. Water tables are slightly inclined surfaces upon which a thin, steady sheet of water flows. A dye trough is placed at the high edge of the water table. The architectural model, understood in plan or section, rests in the middle and a drain terminates the end. Dyed water streams from the trough flow along the water surface and around the models, making flow patterns around and through the models evident, ultimately falling over the edge of the water table into a trough containing a drain.

Resources for constructing water tables draw from a range of disciplines, and many are used to study hydrological rather than aerodynamic processes. A water table completed by students at Chiang Mai University featured in Norbert Lechner's *Heating, Ventilation and Cooling* (2009) offers a useful starting point for understanding water table componentry and assembly. A surprisingly relevant discovery, Steven Vogel's introductory textbook for marine biologists, *Life in Moving Fluids: The Physical Biology of Flow* (1984), offers practical guidance for setting up basic qualitative physical flow experiments. Vogel's advice about choosing between working with the medium of air versus water rings true: 'If a choice be made, I would opt for a flow tank rather than a wind tunnel or other air-moving system: forces are greater, ancillary equipment can be simpler, and the use of dye for flow marking is a sure crowd-pleaser' (Vogel 1984, 290).

Landscape architect Catherine Seavitt-Nordenson has used water tables to study sedimentation patterns in Jamaica Bay and, in collaboration with Guy Nordenson and Adam Yarinsky, storm-surge buffers in New York's Palisade Bay (Figures 2.26 and 2.27). MIT's Alan Berger, in collaboration with marine engineer Heidi Nepf, has used water tables to study phytoremediation strategies for Berger's Pontine Marshes Remediation project. Both Seavitt-Nordenson and Berger have developed strategies for integrating site topographies directly into the testing bed.



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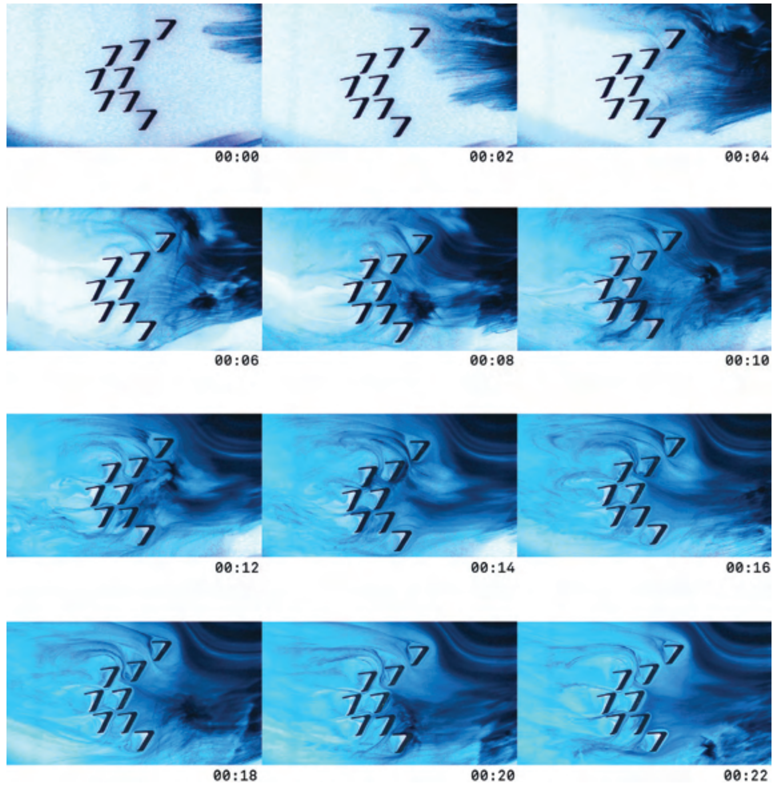


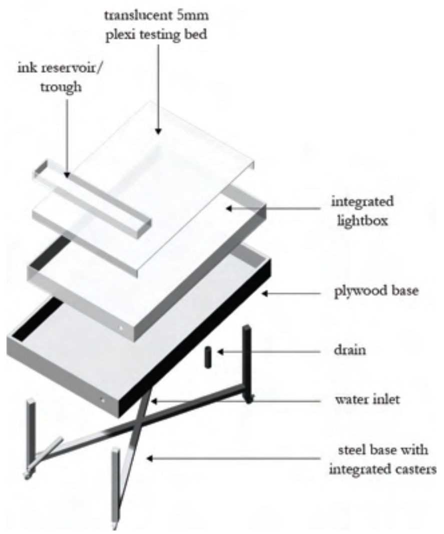
2.27

2.26 Animation sequence with array of v-shaped islands; film stills. © Guy Nordenson and Associates, Catherine Seavitt Studio, and Architecture Research Office, 2010.

2.27 Drafting table and hose water tank. © Guy Nordenson and Associates, Catherine Seavitt Studio, and Architecture Research Office, 2010.

It is far easier to visualise flow as a series of parallel moving lines in water tables than in wind tunnels. However, water tables introduce a set of material challenges distinct from wind tunnels. Water registers even the slightest gradient shift and deflection; it flows through the finest material gap. Creating a controlled steady-state condition of continuous, even water flow requires constructing models with increasing levels of precision, resulting in a prototyping trajectory of increasing fine-tuning and componentry calibration. The concluding section of Chapter 3 elaborates on the role that water plays in the prototyping process as a measure of constructional anomalies.

WAT1

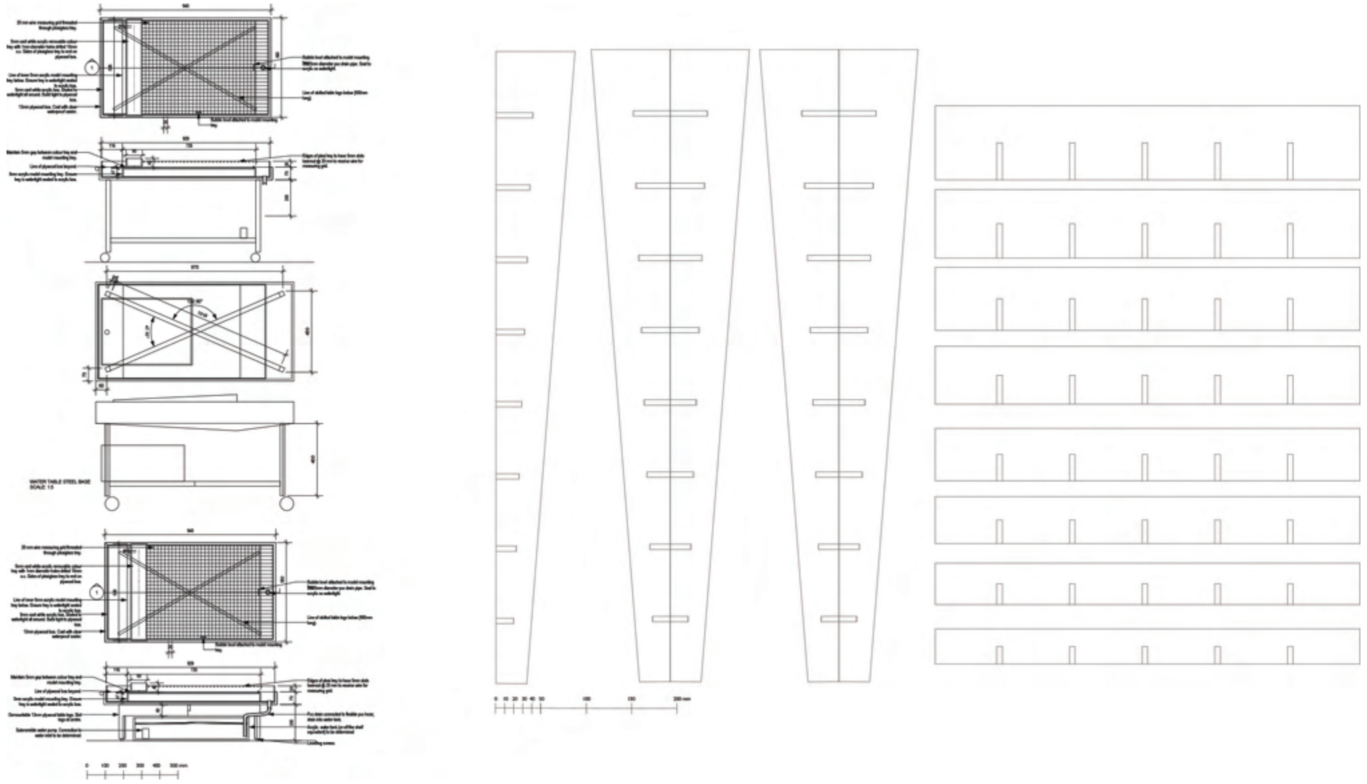


2.28

2.28 Exploded axonometric assembly drawing of the first water table (WAT1). WAT1 developed in parallel to the first wind tunnel prototype (WT1). Both were constructed primarily of plywood and plexiglass, and both proved unwieldy to construct and operate. The 94×55 cm testing bed slotted into a sealed plywood base that incorporated LED underlighting. A 5 mm thick translucent, sloped plexiglass surface nested within the plywood base. A gridded plexiglass undercarriage supported the testing bed, but the surface deflected under its own weight. Despite sealing with silicon sealant, many intersections leaked.

2.29 Photograph of WAT1 in the Edinburgh School of Architecture and Landscape Architecture (ESALA) concrete workshop. To operate the water table, water was fed from a sink tap through a hose bibb attachment to PVC plumbing components integrated into the plywood base. Water filled a reservoir in the plexiglass base before spilling as a thin sheet along the sloped test surface. Dyed water was distributed through in a rectangular plexiglass tray with 1 mm diameter laser-cut holes. At the drain end, water flowed through a plumbing drain into a bucket, where it was pumped back to the sink to drain. Construction assistance by Jamie Henry and Vsevolod Kondratiev-Popov.

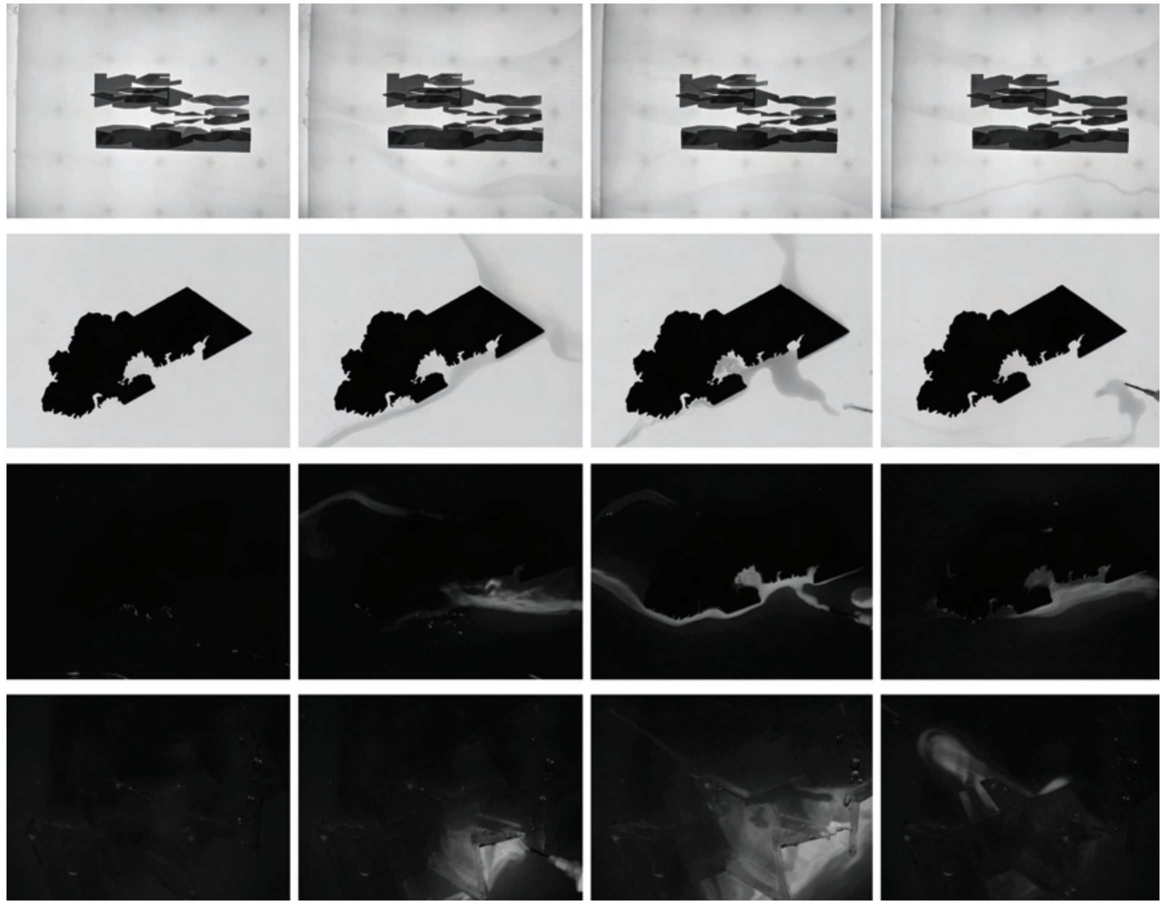
2.29



2.30

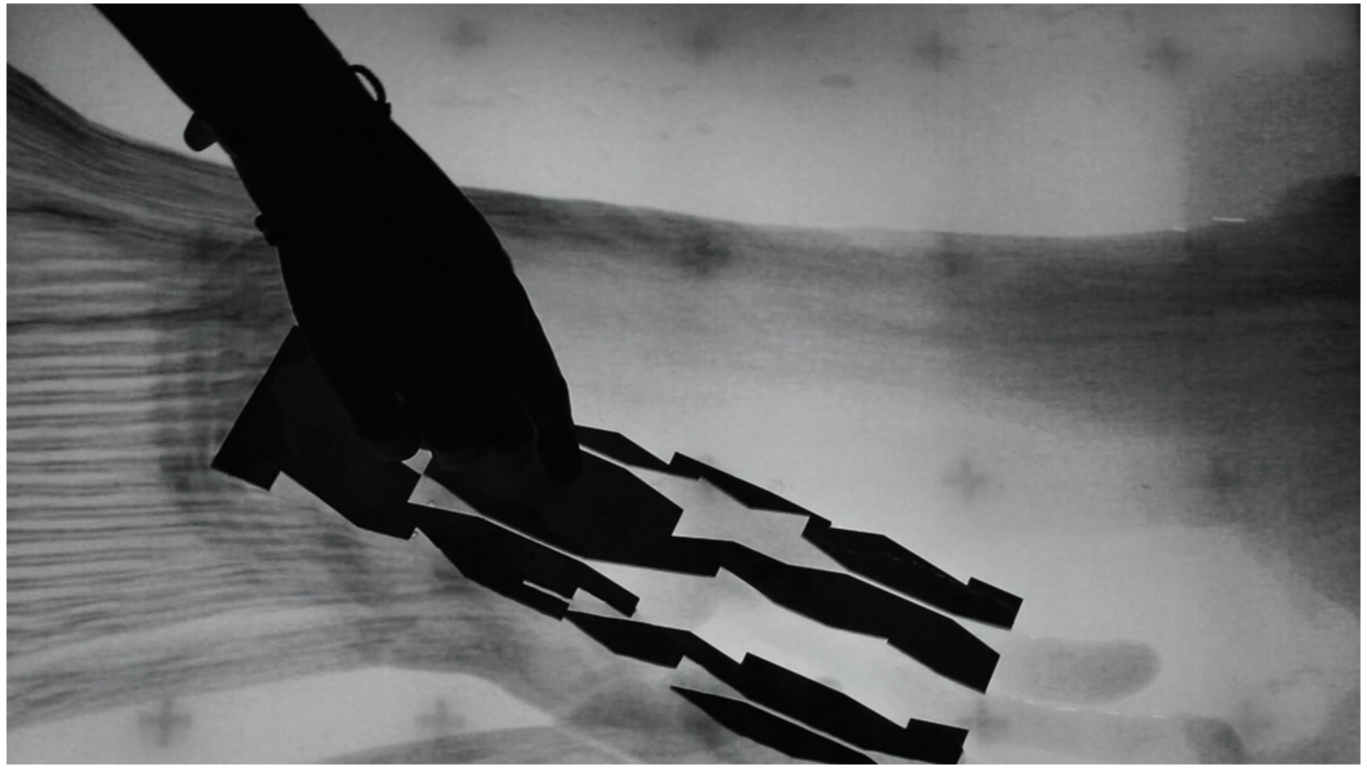
2.30 Composite fabrication drawing of WAT1. Colour designations distinguish between drawing type and fabrication method. WAT2 was developed first as a two-dimensional construction drawing, which served as a template for construction using primarily carpentry tools and techniques. This prototype also incorporated off-the-shelf plumbing materials.

Construction Drawing
Lasercut Fabrication Drawing (instrument)

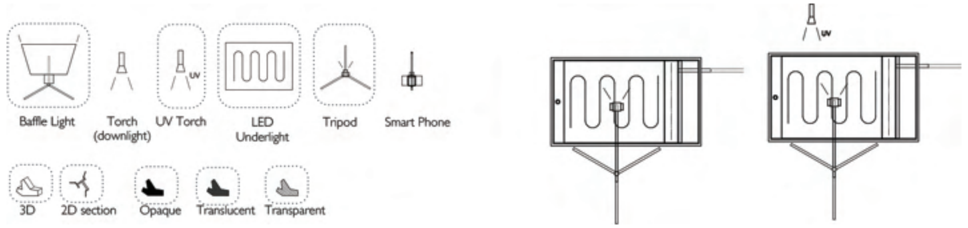


2.31

2.31 Video stills illustrating flow patterns in WAT1. WAT1 tested several flow visualisation strategies. The top two rows of images were uplit from the LED lightbox integrated into the testing bed. Translucent blue plumbers' drain dye diluted in water was used as the flow visualising medium. Both translucent and opaque models were placed on the testing bed. In the lower two rows of images, UV drain dye was introduced to the model and lit with a UV flashlight/torch. A combination of opaque model, uplighting and translucent plumbers' dye created the clearest patterns. Video and photography assistance by Emma Bennett.

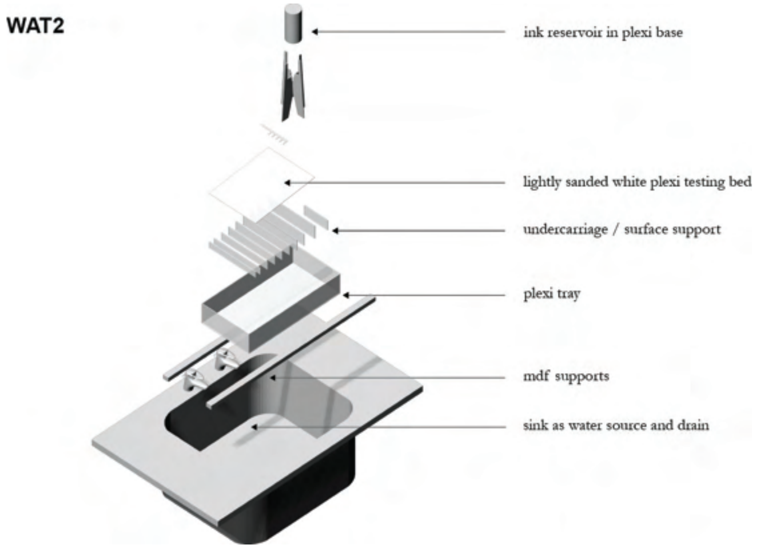


2.32 Enlarged video still of WAT1 flow visualisation strategy. WAT1 failed to create a steady sheet of moving water. The introduction of dyed water highlighted two central defects of the prototype: surface deflection, which caused water to pool towards the centre, and leaks at seams caused by poor sealant. Calibrating the supporting undercarriage of the table surface failed to correct the problem. The material surface was simply too thin to span the testing bed without deflection, and there were too many undercarriage supports to calibrate with required precision.



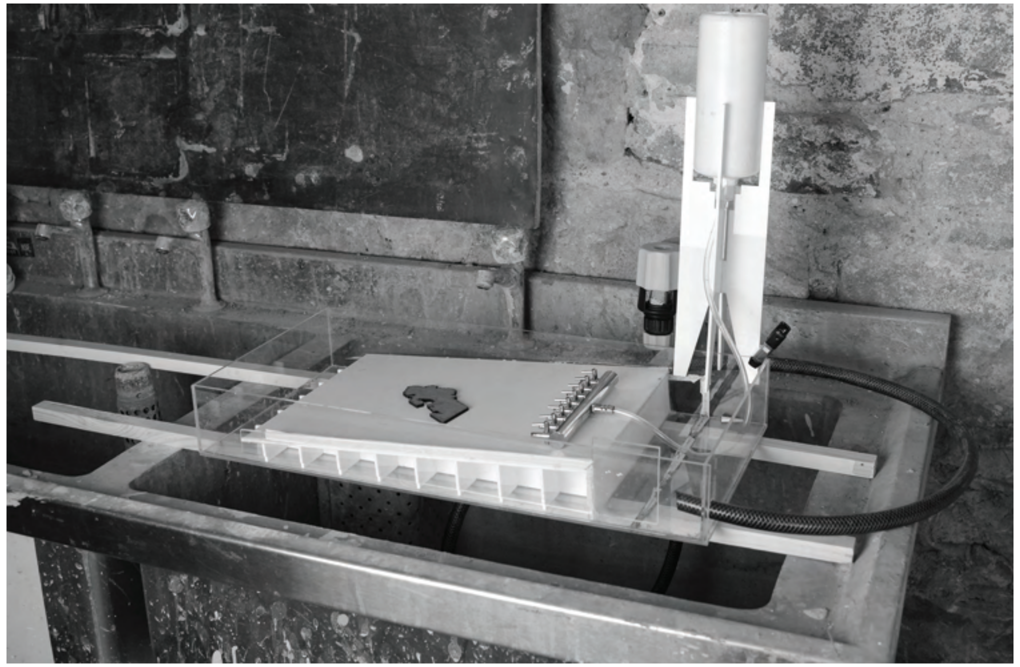
2.32

2.33 Exploded axonometric assembly drawing of the second water table (WAT2). To reduce surface deflection and reduce plumbing cycles, WAT2 was reduced in stature and was integrated into an existing workshop sink. A 50×25×10 cm plexiglass testing bed was supported by a gridded plexiglass undercarriage. The tray received water from a hose connected to the sink faucet, and an outlet at the opposite end drained water directly into the sink. The assembly sat on MDF struts spanning the sink. A repurposed plastic bottle acted as an ink reservoir, distributing lines of ink through plastic tubing to an off-the-shelf aquarium splitter.

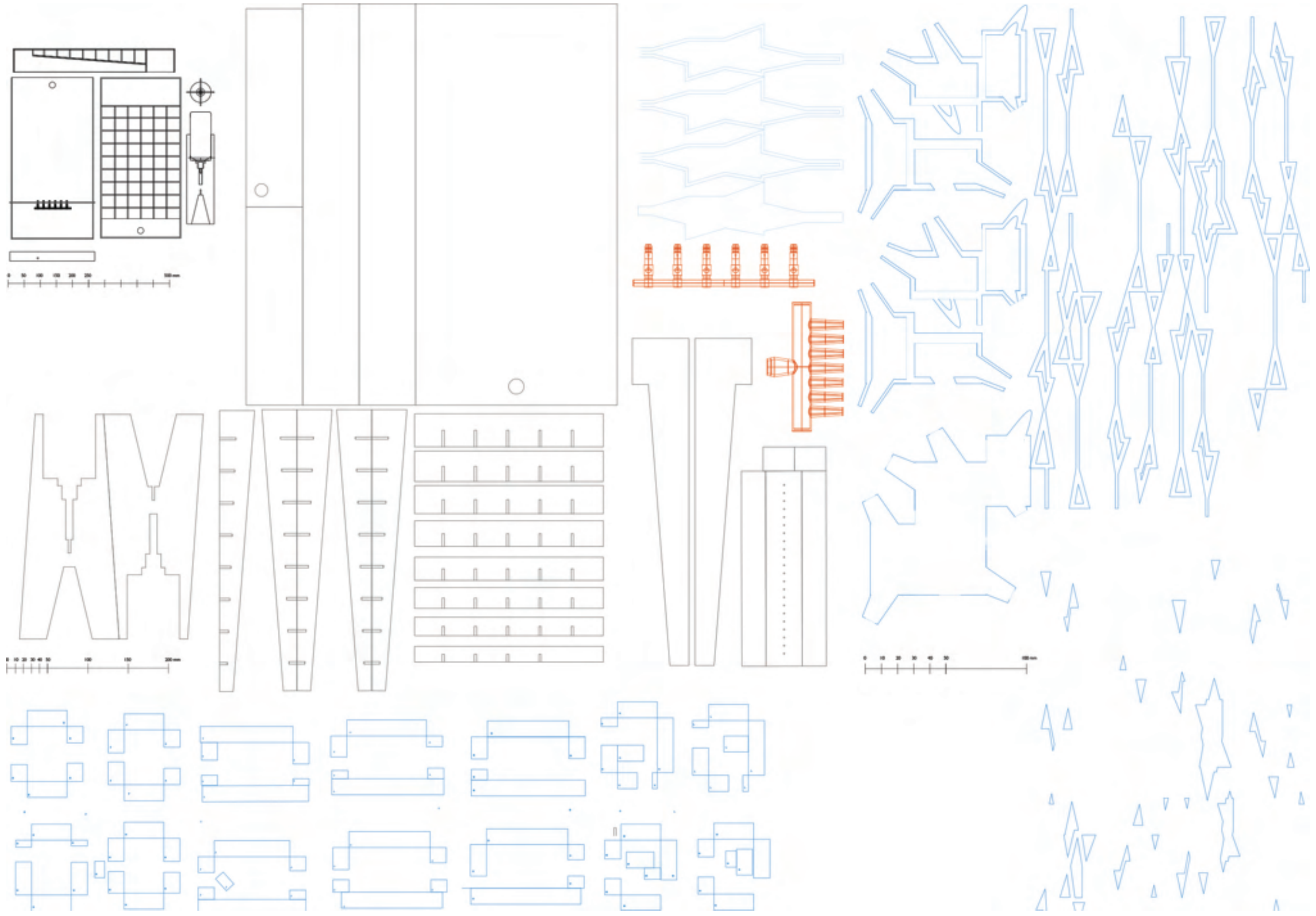


2.33

2.34 Photograph of WAT2. All subsequent water tables responded to the first prototype by becoming smaller to reduce spans and surface deflection. They were digitally fabricated, and the overall size was based on maximising material efficiencies from 50×50 cm plexiglass sheets. They relied on existing plumbing infrastructure – a workshop sink – as support, water source and drain, rather than replicating these water cycles within the device. Whereas wind tunnel prototypes developed along several different trajectories in response to a wider range of discoveries, the water tables developed as subtle, increasingly calibrated, versions of the same general assembly.



2.34

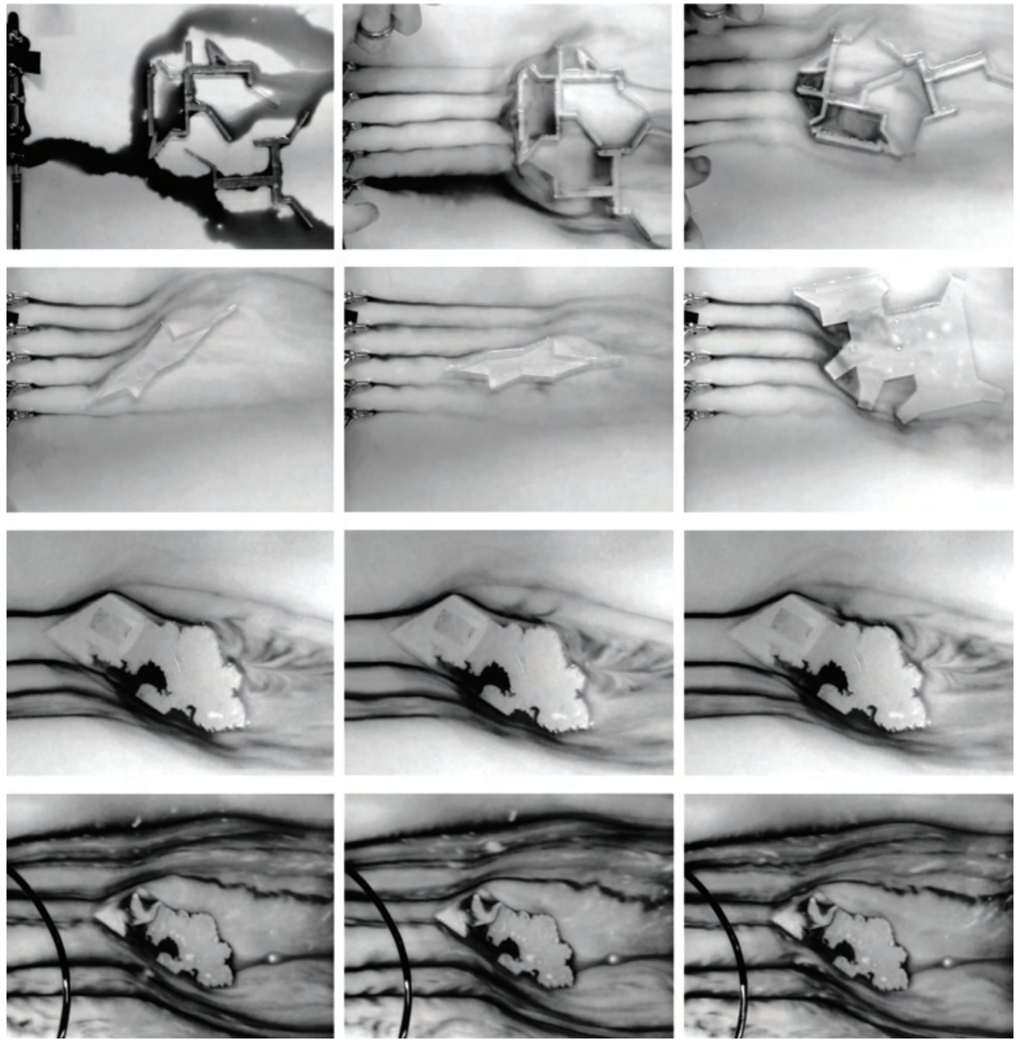


2.35

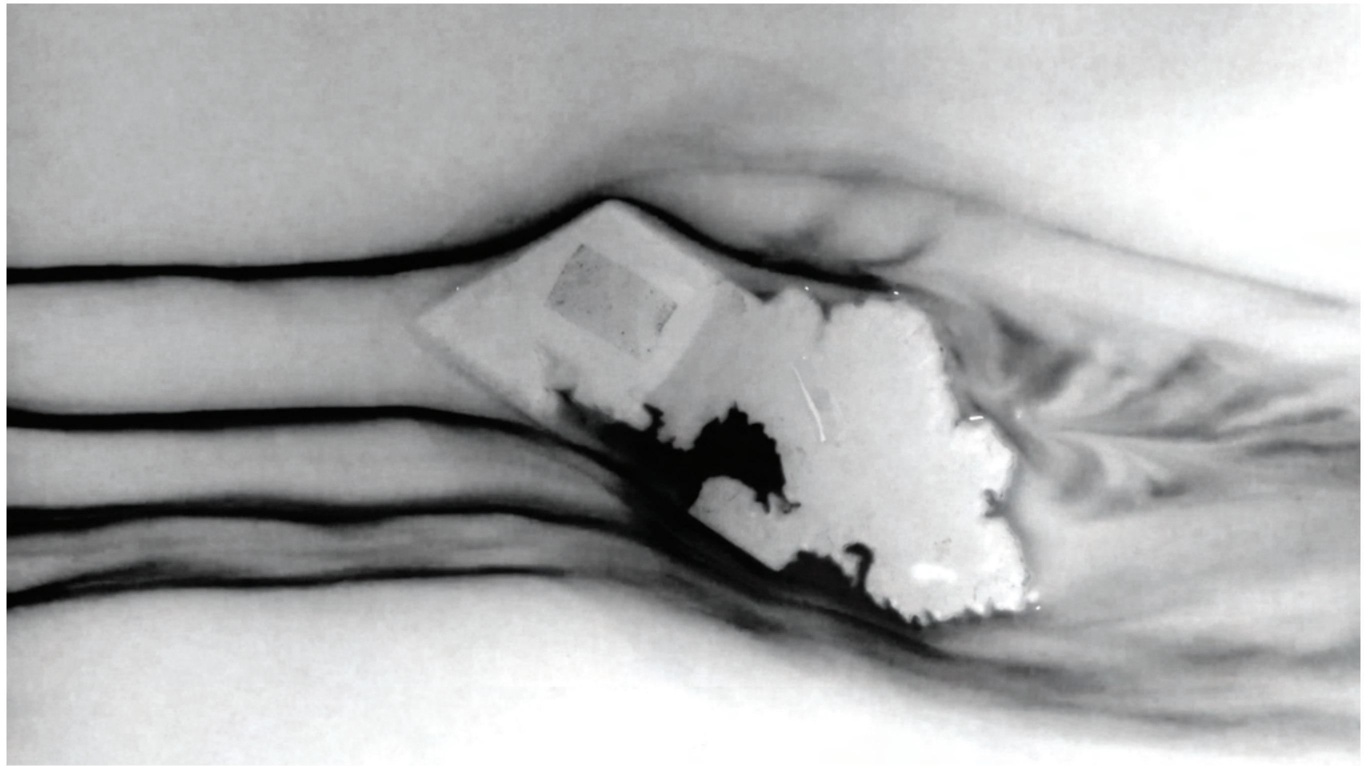
2.35 Composite fabrication drawing of WAT2. Colour designations distinguish between drawing type and fabrication method.

Construction Drawing
Lasercut Fabrication Drawing (instrument)
Lasercut Fabrication Drawing (architecture)
3d Print (instrument)

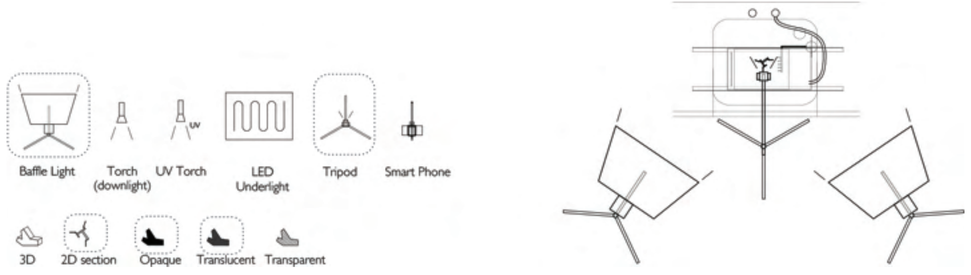
2.36 Video stills illustrating flow patterns in WAT2. A gravity-fed reservoir directed ink through a plastic tube to both off-the-shelf rakes. The first rake was a five-way aquarium splitter with adjustable nozzles. The rake dispersed dye, but the dye patterns were disturbed, likely reflecting irregularity of the internal profile of the splitter. A 10-way aquarium splitter created erratic flow due to differences in pressure from one end of the rake to the other. Video and photography assistance by Emma Bennett.



2.36

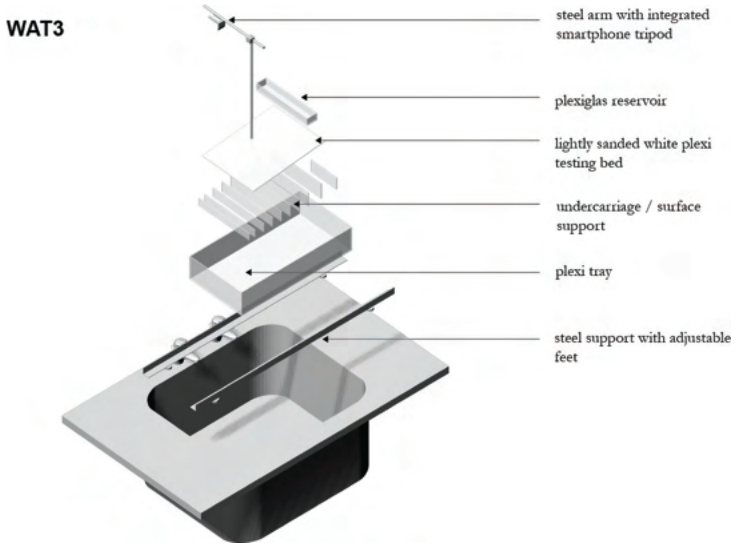


2.37 Enlarged video still of WAT2 flow visualisation strategy. While dye lines through the aquarium splitter were disturbed, they were more legible than those from the first prototype. In this smaller prototype, surface deflection was minimised, and lightly sanding the plexiglass surface reduced beading and improved consistency of water flow.



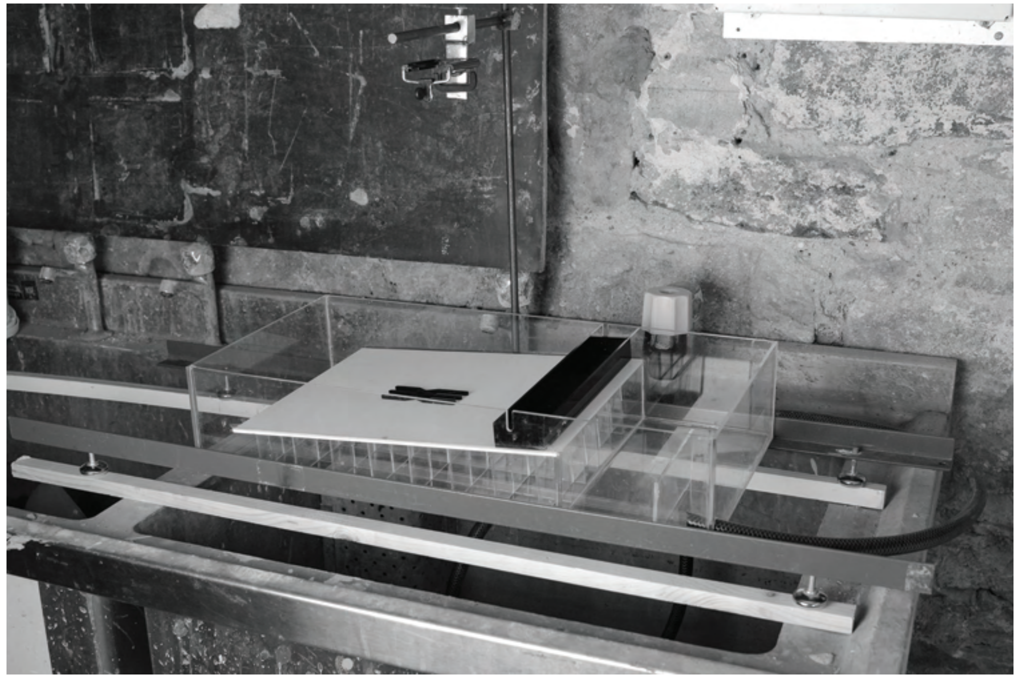
2.37

2.38 Exploded axonometric assembly drawing of the third water table (WAT3). WAT3 retained the general size and configuration of WAT2, but the testing surface was slightly narrower to ensure that it did not bow or deflect in compression. The testing bed sits on a steel base with adjustable feet level for levelling and with an integrated smartphone tripod to improve photography from above.

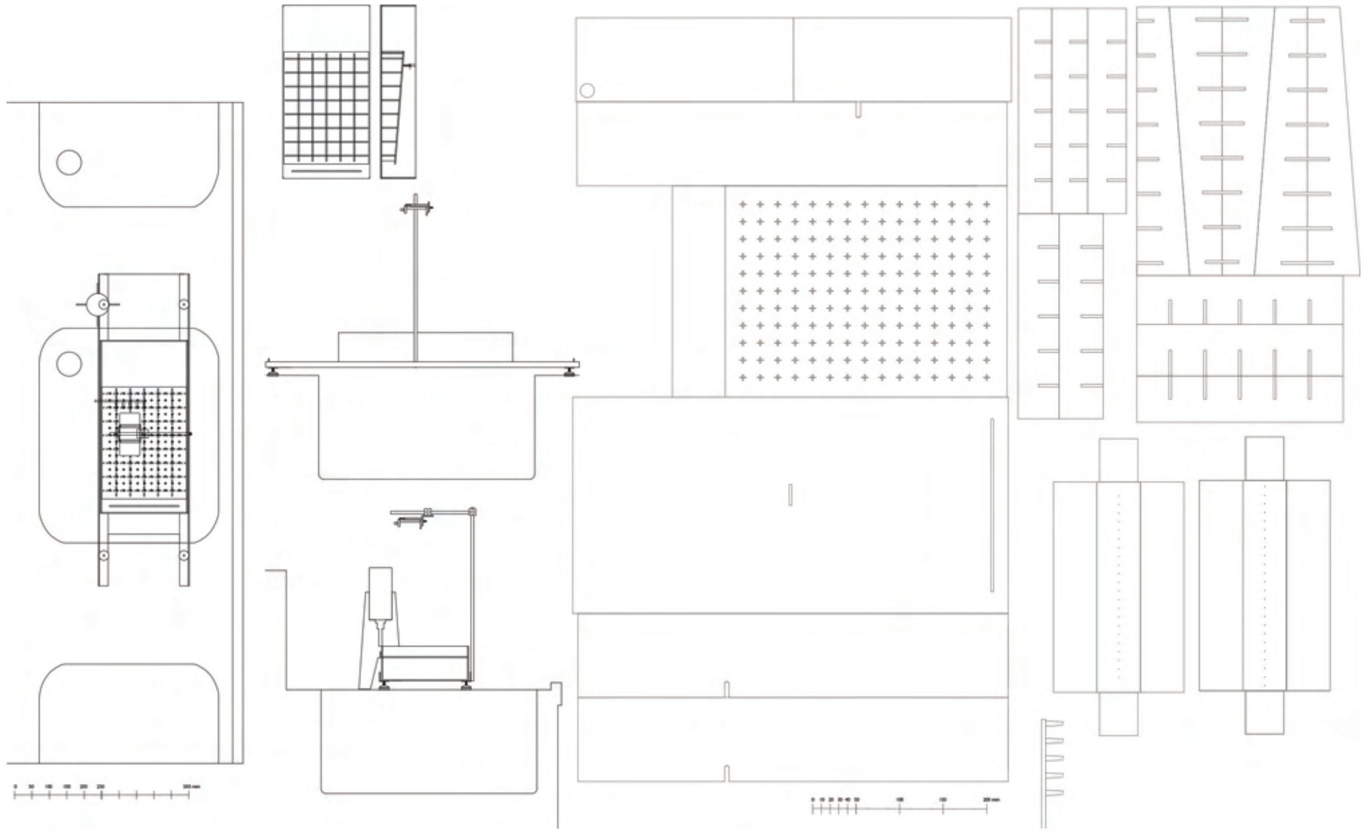


2.38

2.39 Photograph of WAT3.



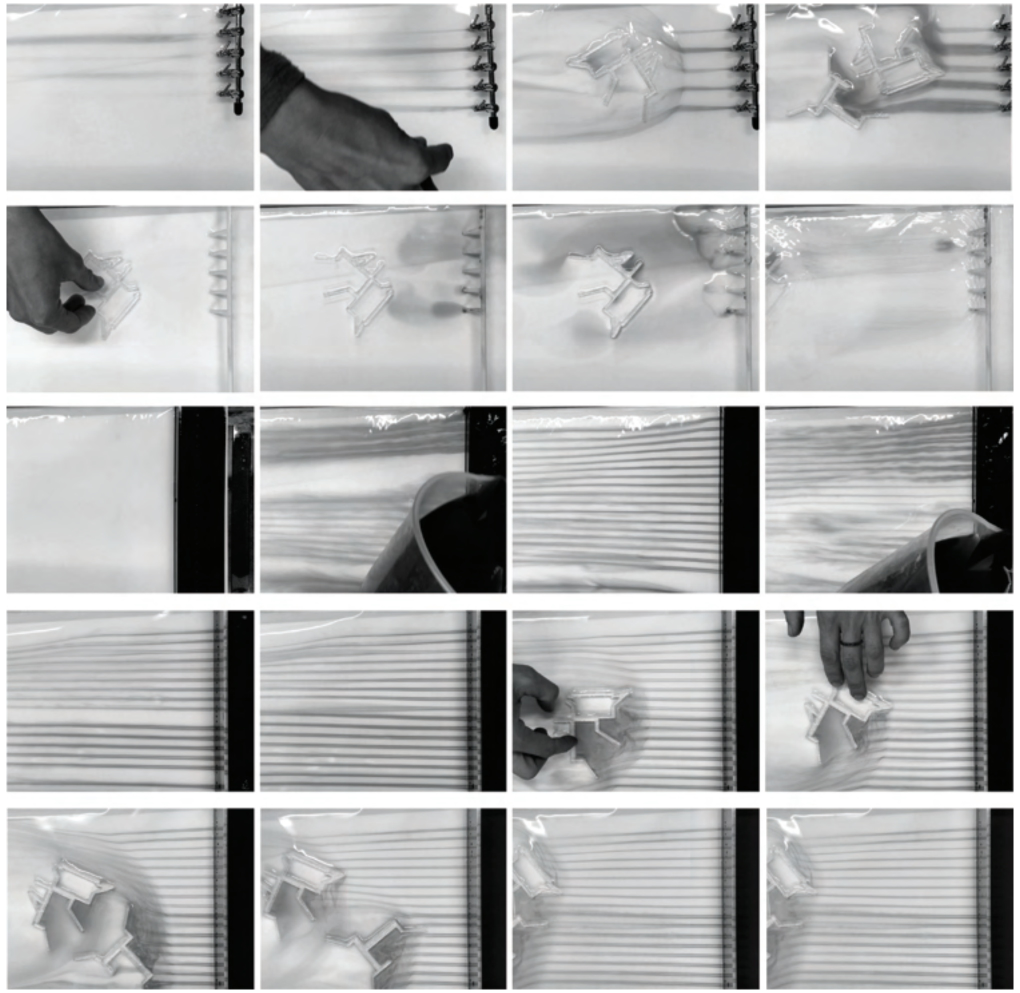
2.39



2.40

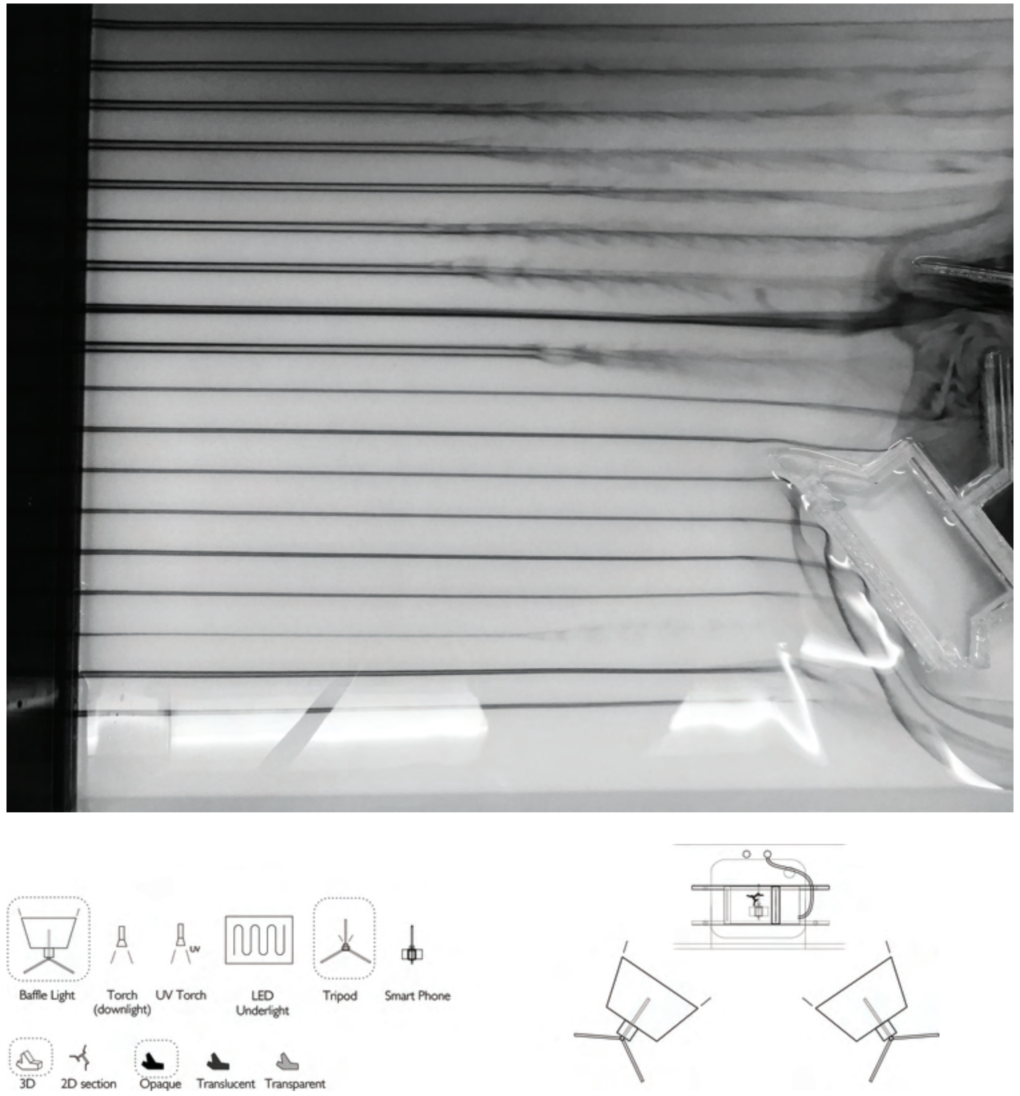
2.40 Composite fabrication drawing of WAT3. Colour designations distinguish between drawing type and fabrication method. WAT3 deviated little from WAT2 aside from the inclusion of custom welded steel base.

2.41 Video stills illustrating flow patterns in WAT3. This prototype tested a range of dye dispersal strategies, including aquarium splitters, 3-D printed rakes and troughs with small outlet holes. Troughs with 1 mm diameter holes created the most consistent, visible field of steady flow lines. However, sectional models placed on the testing bed were destabilised by water pressure, causing them to dislodge from the testing surface.



2.41

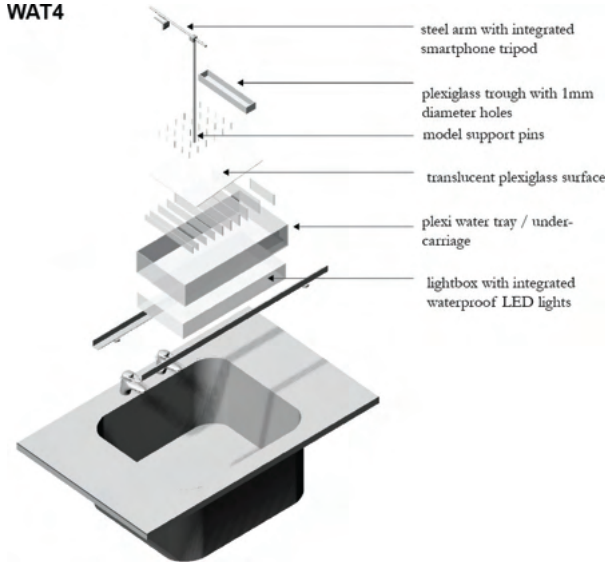
2.42 Enlarged video still of WAT3 flow visualisation strategy. This prototype succeeded in creating a steady-state condition of even, continuous water flow along the full surface of the table. Continuous parallel lines of dyed ink reflected this steady-state condition. Some light reflections from overhead lighting on the model surface were captured in the photograph.



2.42

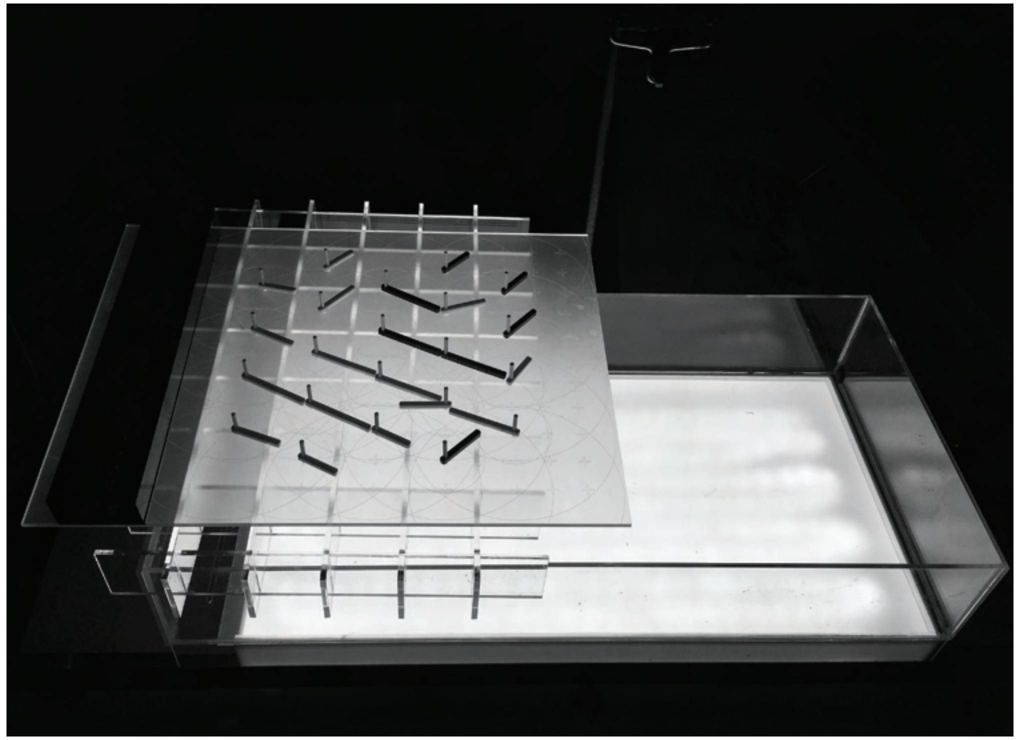
2.43 Exploded axonometric assembly drawing of the fourth water table (WAT4). A lightbox integrated into the base eliminated reflections from overhead lights. A grid of vertical supports integrated into the testing surface acted as a scaffold for models to resist displacement by water pressure.

WAT4



2.43

2.44 Photograph of WAT4. This prototype explored the possibility of integrating model components and drawings into the testing bed surface. The arcs of a series of linear elements attached to the vertical model supports were etched as a drawing onto the surface of the testing bed. This field of shifting lines could represent a series of low walls or edges directing flow through a landscape or a complex interior space.



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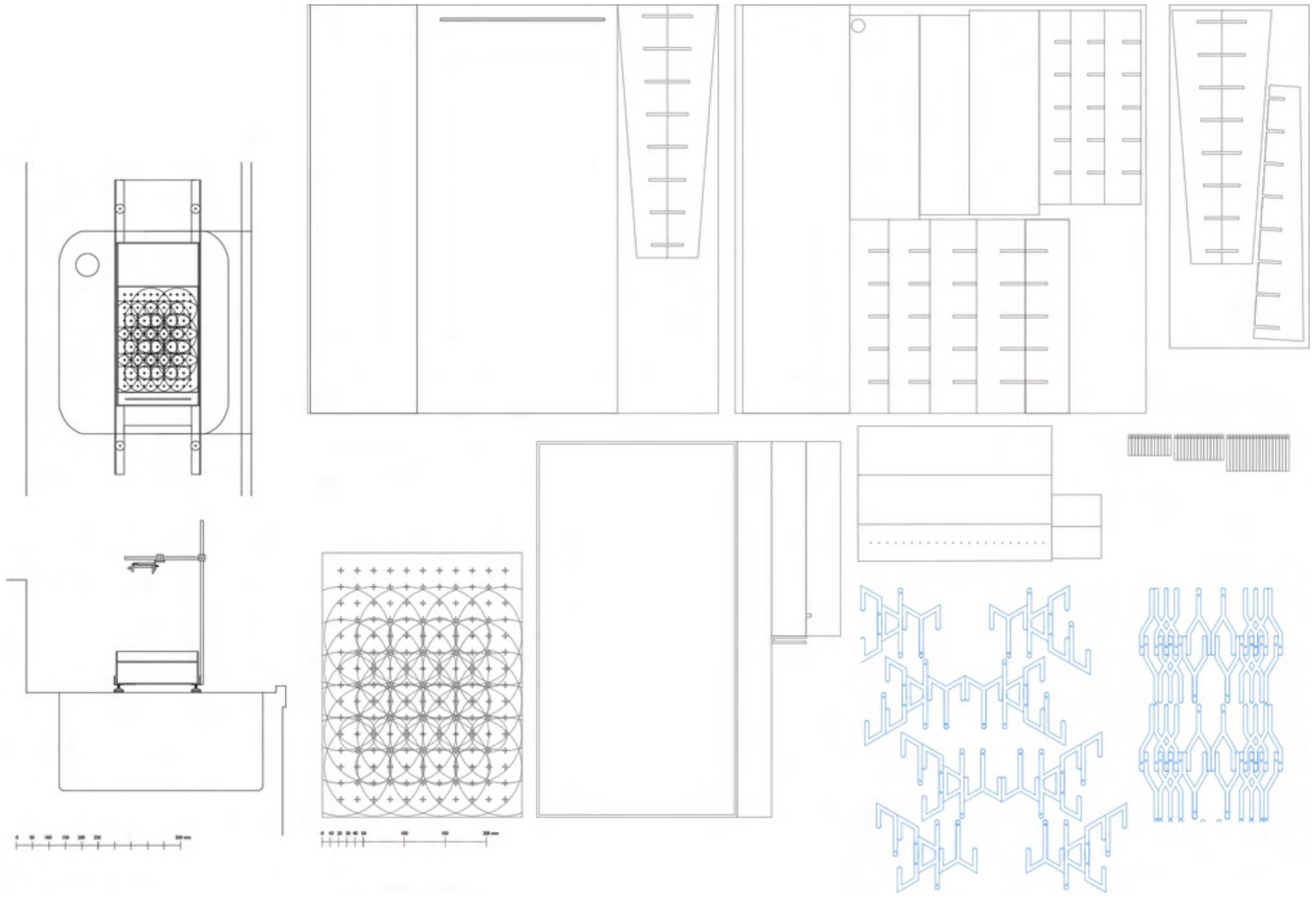
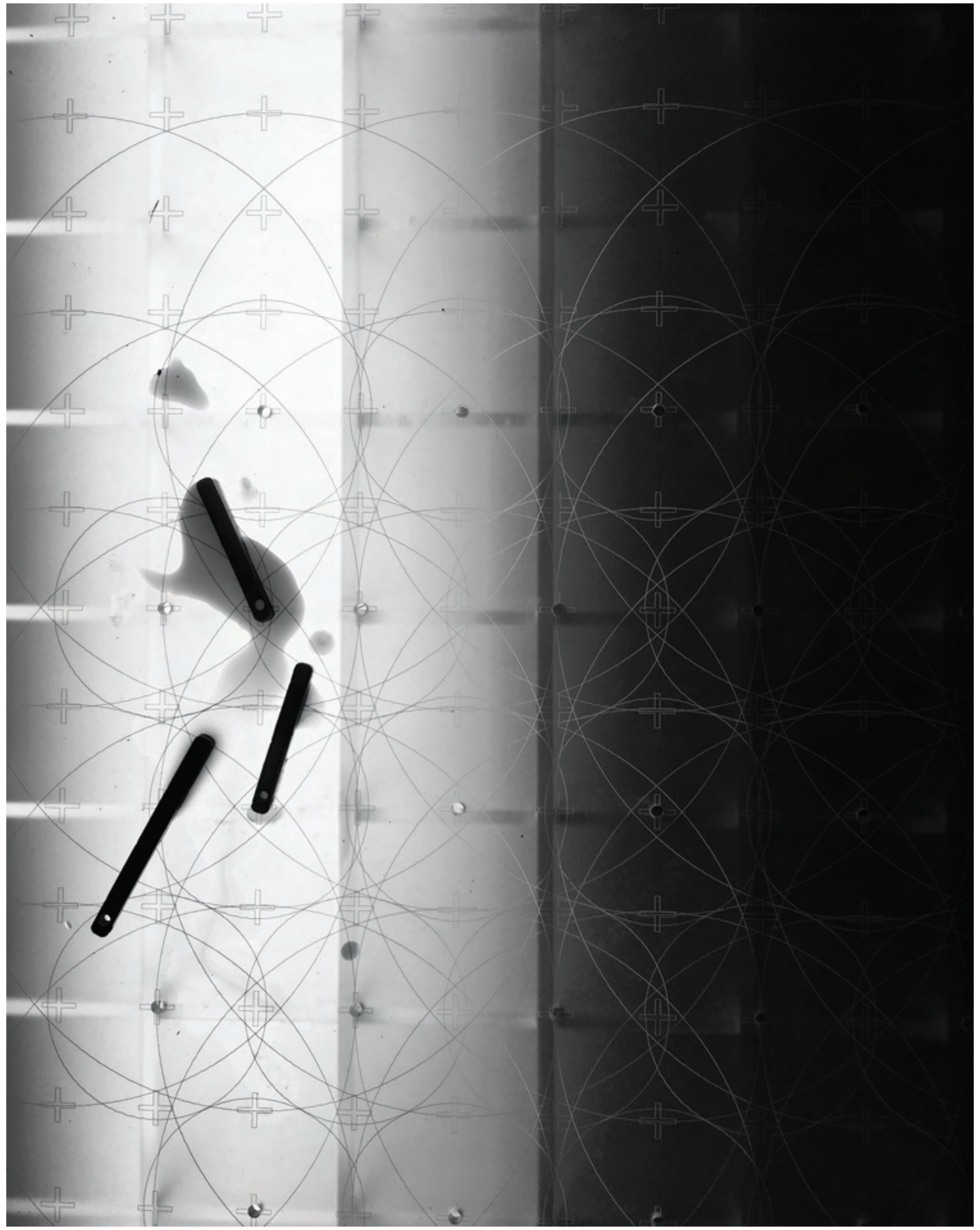


2.45

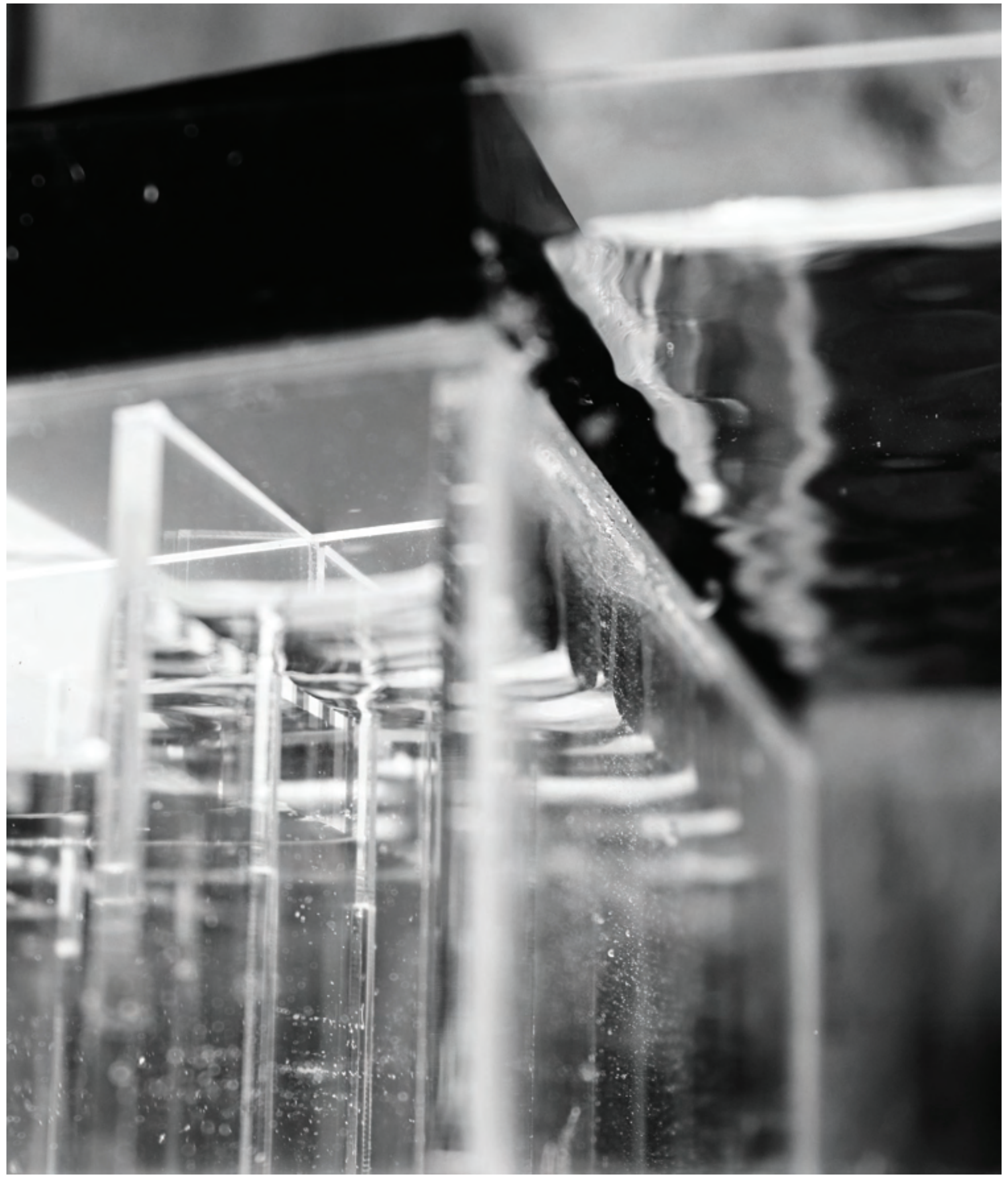
2.45 Composite fabrication drawing of WAT4. Colour designations distinguish between drawing type and fabrication method.

2.46 Photograph of WAT4 testing bed detail. The testing surface became a substrate of lines, light and moving water, expanding architectural speculation to include phenomena such as light, water and wind and their corresponding intensities, gradients and flows.



2.46

2.47 Photograph of the undercarriage of WAT4 filling up with water that leaked through seams from the testing bed above. The trapped pools disturb overall flow clarity on the testing surface while shifting attention to the glowing vessels of water below.



2.47

Filling boxes

Filling boxes simulate airflow due to differences in density – the physical principle driving buoyancy-induced air movement. The technique can be used to test displacement and mixing ventilation strategies. Displacement ventilation typically takes place in temperate and hot climates when a low ventilation inlet allows in cool exterior air and a high outlet purges warm buoyant air. Mixing ventilation takes place when a cooling effect of exterior air is not desirable; a single high inlet allows cool exterior air into the building, where it is mixed with existing warm air.

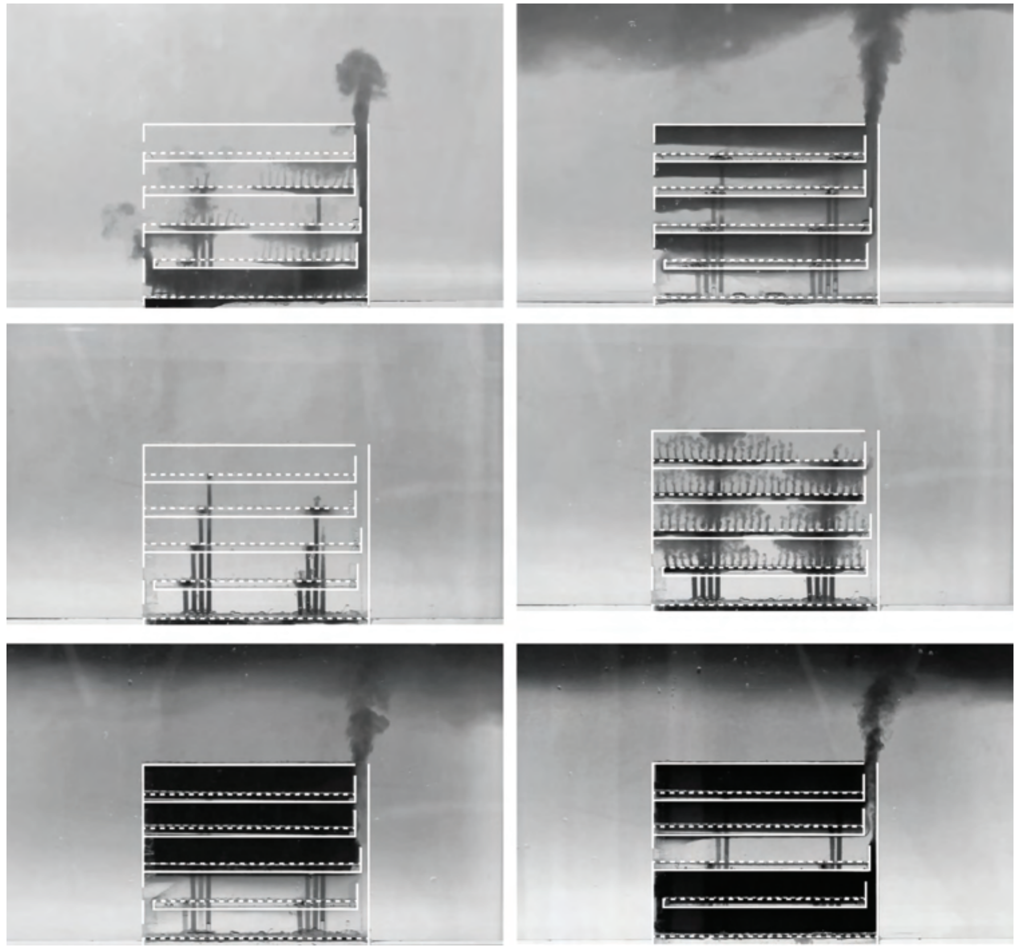
The 'box' that is filled is an architectural model constructed of plexiglass with strategic openings submerged into a tank full of fresh water. The architectural model is filled with denser, dyed salt water, which replicates the introduction of cold air into a warmer environment or, when mirrored, the introduction of warm air into a cooler environment. Because the steady-state environment is easily established in a still tank of water, filling-box models shift focus to the architectural model. Much of the prototyping process involved exploring model configurations with multiple zones, interconnected volumes, sectional variation and variable openings.

The book *Designing Spaces for Natural Ventilation: An Architect's Guide* (Battaglia and Passe 2015), a comprehensive resource, briefly introduces the filling-box technique, pointing to the research of fluid dynamics academics Linden, Lane-Serff and Smeed. Linden, Lane-Serff and Smeed provide a comprehensive overview of the filling box and hint at its architectural applications, noting:

> The experiments that we have made have been restricted to a very simple geometry and some idealized sources of buoyancy. Buildings have much more complicated shapes, with multiple zones and levels, and may be connected to the exterior by a number of different openings at different heights. The flows within these building are, in general, time-dependent and complex, and yet they are of crucial importance to the correct functioning of the building.
>
> (Linden, Lane-Serff and Smeed 1990, 331)

Architect and academic Alan Short, in collaboration with engineers at Cambridge University, has designed many complex, multi-zoned buildings using filling-box models in the early stages of design. These resultant buildings, such as UCL's School of Slavonic and East European Studies, are often punctuated by multiple towers and cascading window openings, formally reflecting flow patterns moving through the building. Similarly, McGill University's Salmaan Craig has refined this experimentation technique, using filling-box models, referred to as water baths, as research and teaching tools for designing low-energy, multiple-zoned, buoyancy-ventilated buildings (Figure 2.48).

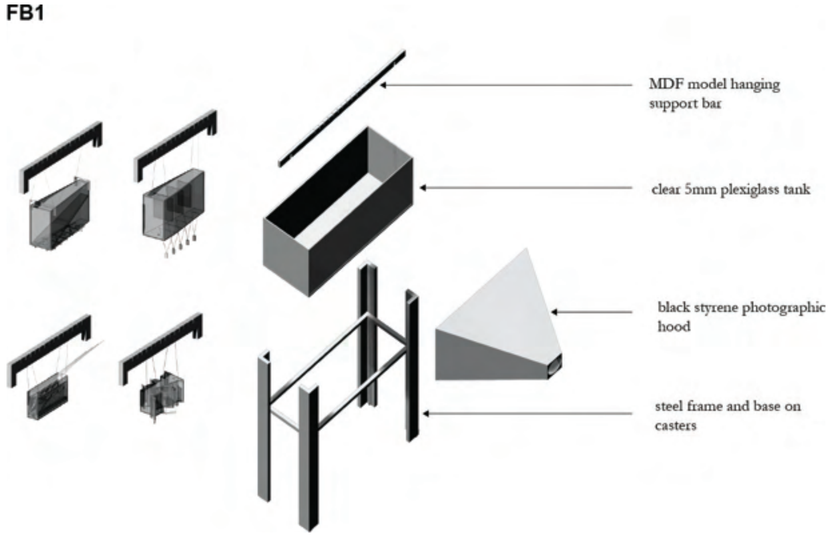
Explored in more detail in the concluding section of Chapter 5, filling-box models highlight distinctions between models as physical artefacts and models as mental ideals. In my prototypes, the architectural models submerged within the filling box are often geometrically complex and tenuously sealed with chemical solvents. They often unintentionally leak, making them distinct from the tightly controlled architectural ideals they represent. Moreover, the filling-box models leak somewhere, situating the model within a much wider atmospheric domain, enabling speculation about environmental co-constructions between model and world. The wider implications of these exchanges are explored in the conclusion to Chapter 5.



2.48

2.48 Video stills of Salmaan Craig's 'flow sculpting' student projects at McGill University. Water bath experiments facilitate design speculations about architectural strategies for climate adaptation. Negar Adipour and Caterina Scattaro, 2019.

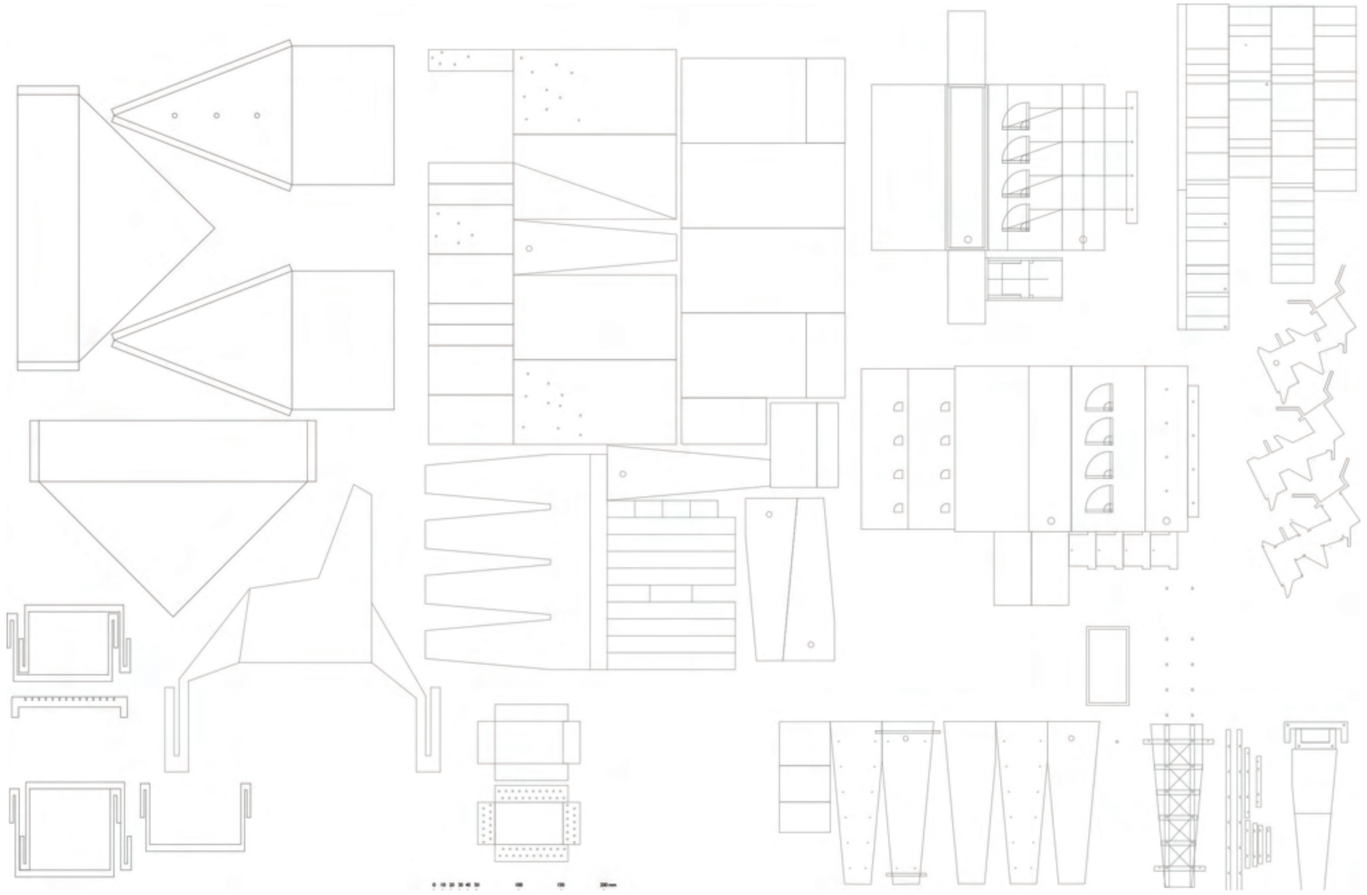
2.49 Exploded axonometric drawing of the first filling-box prototype (FB1). The 79×30×40 cm tank was built out of 5 mm thick plastic that was continuously sealed with plexiglass chemical solvent and waterproof silicon sealant. The first iteration of the tank failed at a seam. After resealing the tank, a steel frame with casters was built around the sides of the tank to provide additional support. A steel pyramid, welded to the steel base, was lined with black plexiglass panels and used as a photographic hood to eliminate background reflections on the tank face.



2.49

2.50 Photograph of FB1. A translucent white plexiglass panel was clipped to the back of the tank and photographic box lights backlight the model to facilitate reflection-free photography. Construction assistance by Malcolm Cruickshank. Photography assistance by Emma Bennett.

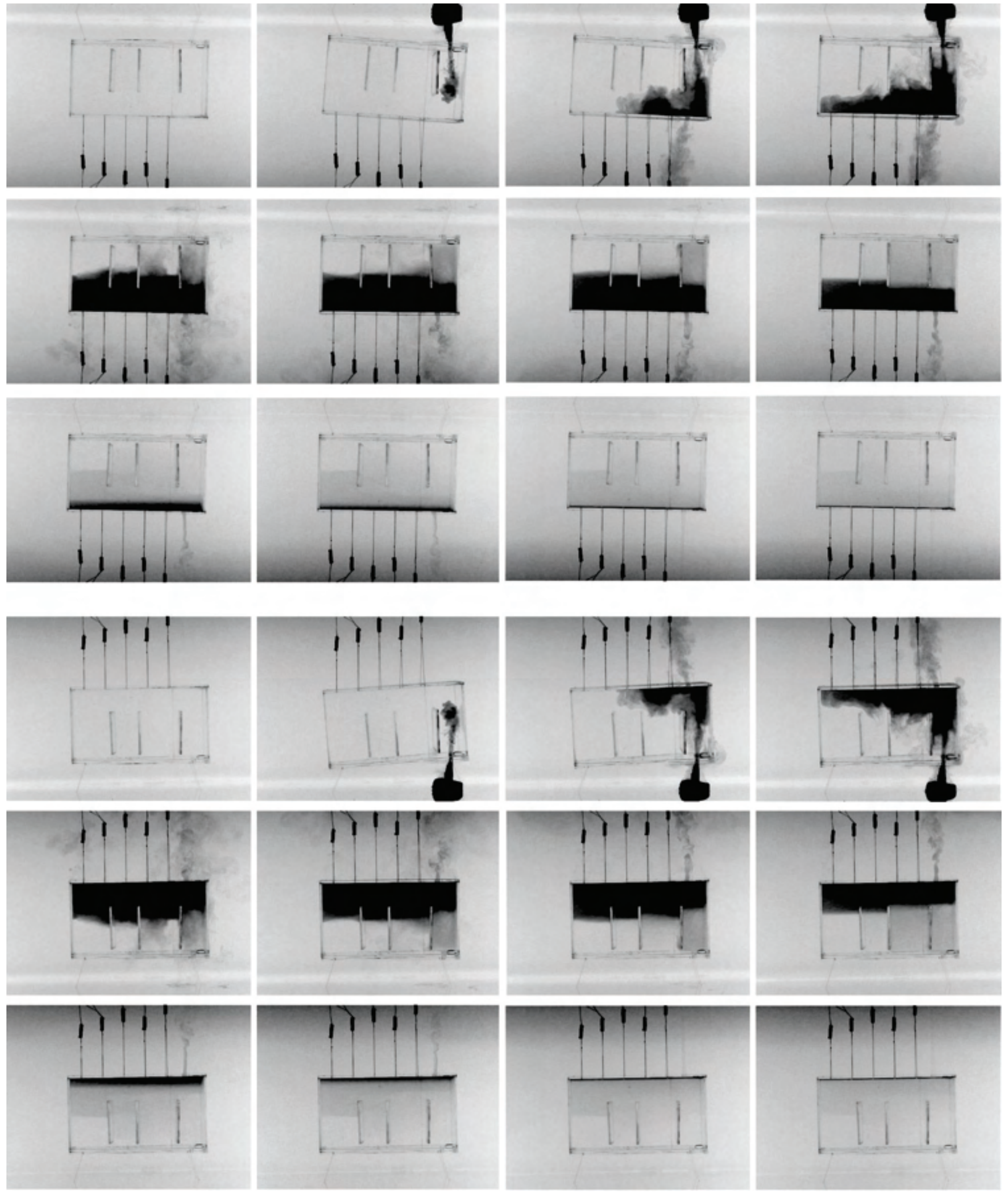
2.50



2.51

2.51 Composite fabrication drawing of FB1. Colour designations distinguish between drawing type and fabrication method. Much of the development of the filling boxes focused on design and testing the architectural models submerged within the tank.

2.52 Video stills illustrating flow patterns through FB1 architectural models. Initial vessels were composed of 3 mm thick plexiglass. Initially hung from a bar spanning the tank, the models floated and shifted, prompting the development of a range of counterweighting, or ballast, strategies. In the upper images, dyed water represents cold water introduced into a warm environment. In the bottom, mirrored images, dyed water represents warm air introduced into a cooler environment.



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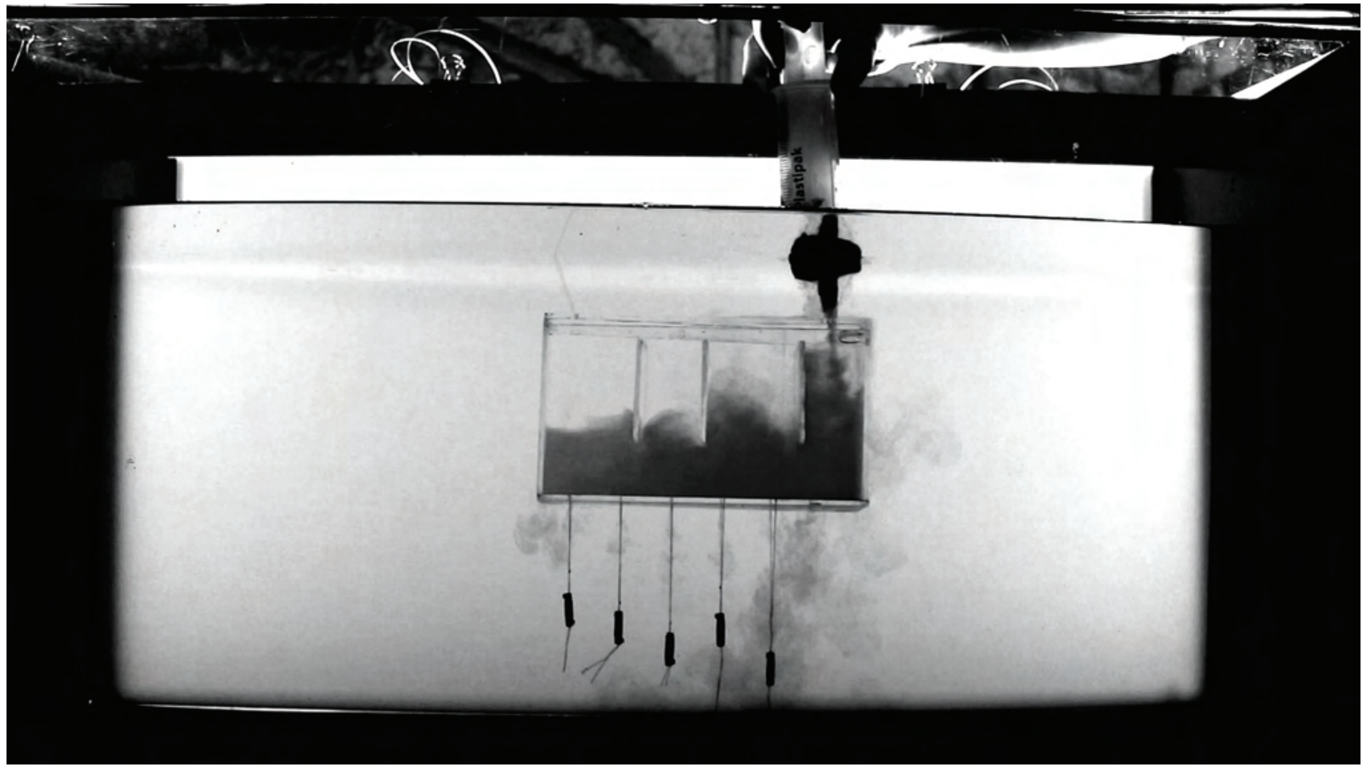
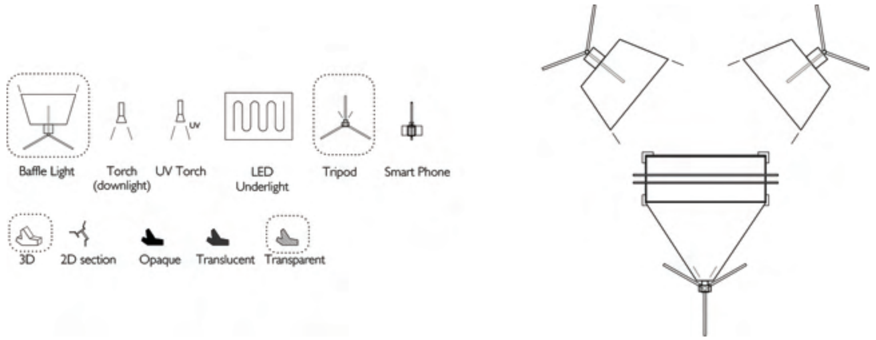


2.53 Enlarged video still of flow patterns through an architectural model in FB1. A plastic syringe injected dyed salt water into the model aperture, destabilising the model and disrupting flow patterns. Internal vertical walls disturb flow patterns and create distinct spatial zones that drain at slightly different rates.



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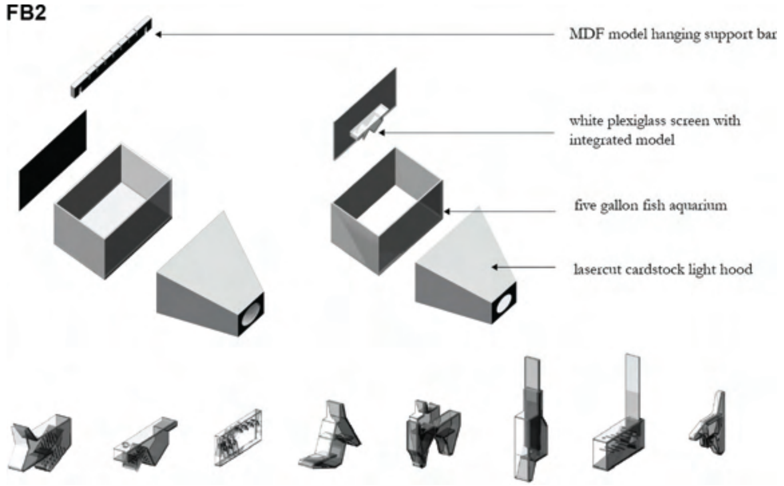


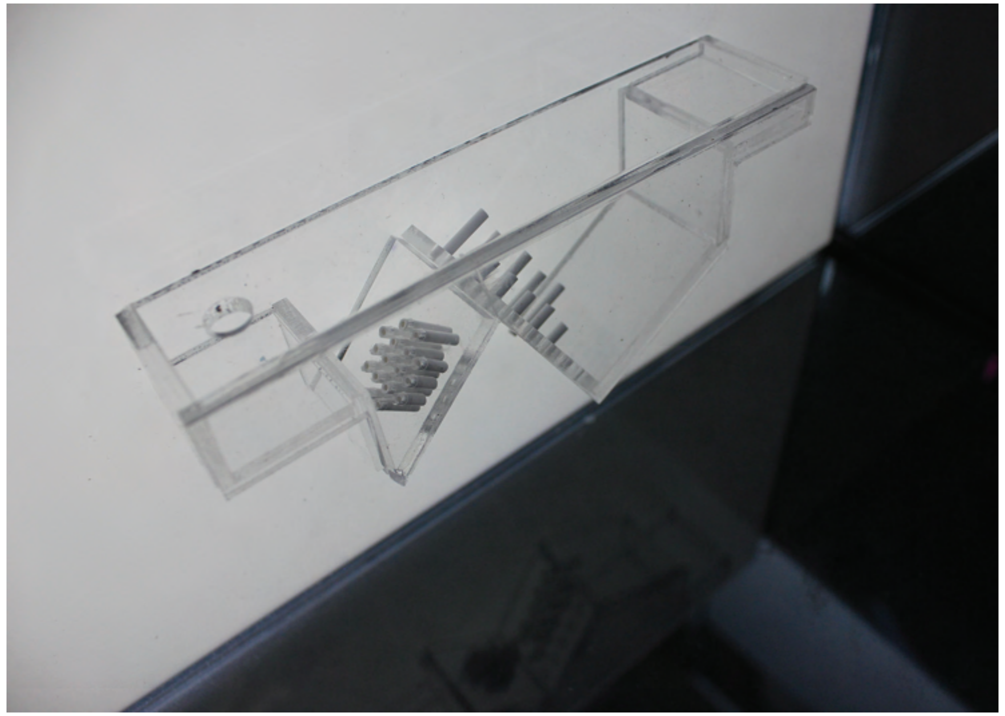
2.54

2.55

2.54 Exploded axonometric assembly drawing of the second filling box (FB2). The tank for FB2 was a 30×20×20 cm off-the-shelf glass aquarium. The reduced volume made the process of filling and draining the tank less cumbersome. Eight different architectural model profiles with a range of opening sizes and locations were tested in the tank.

2.55 Photograph of FB2. Just as the water tables became increasingly reliant on existing workshop plumbing infrastructure to function, FB2 became more integrated into the space in which it operated, a small staff kitchen with sink as water source and window as light source.

2.56 Photograph of FB2 architectural model. In this prototype, architectural models were attached directly to a plexiglass plate attached to the back wall of the tank. This ensured that they remained stable and submerged.



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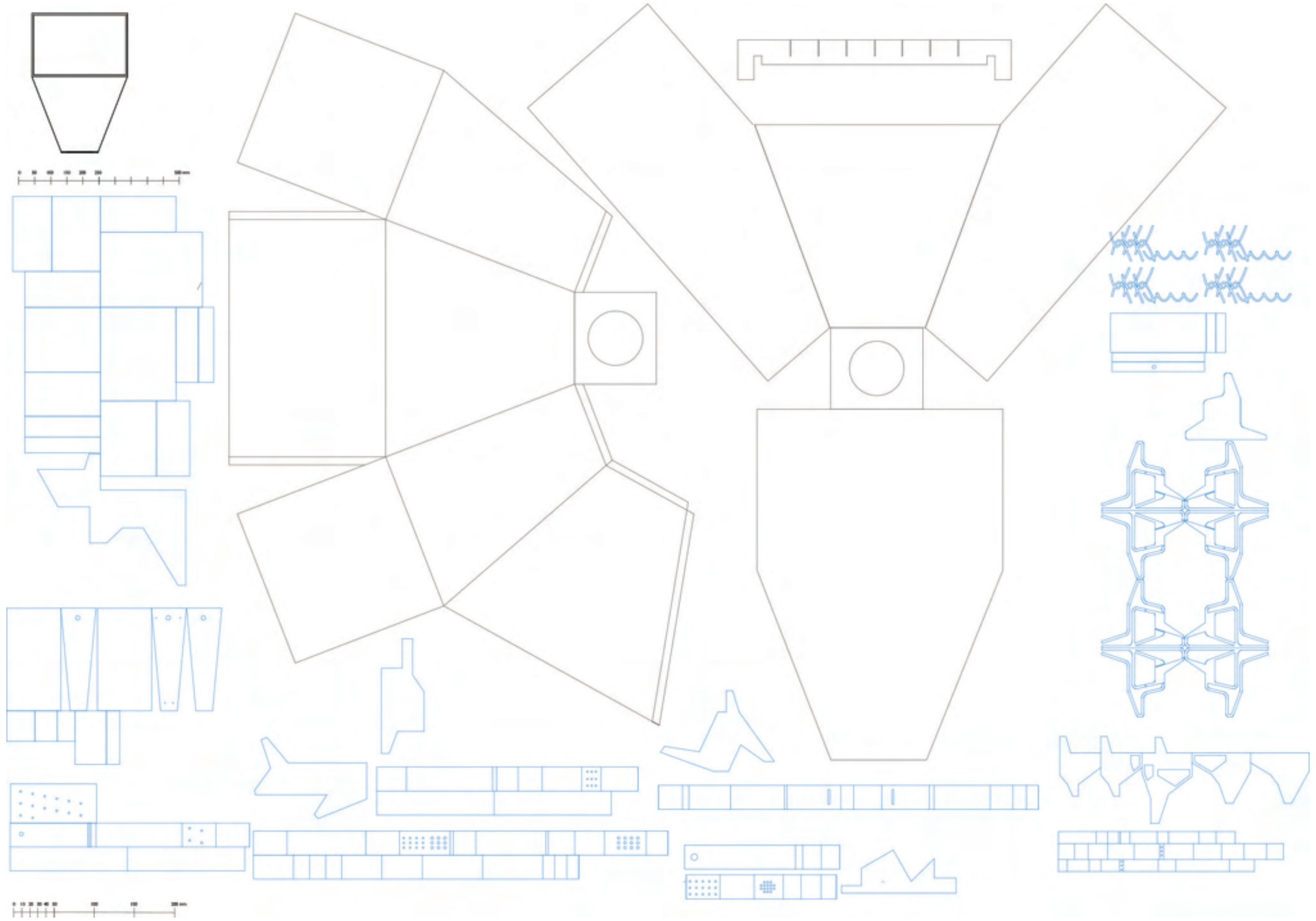
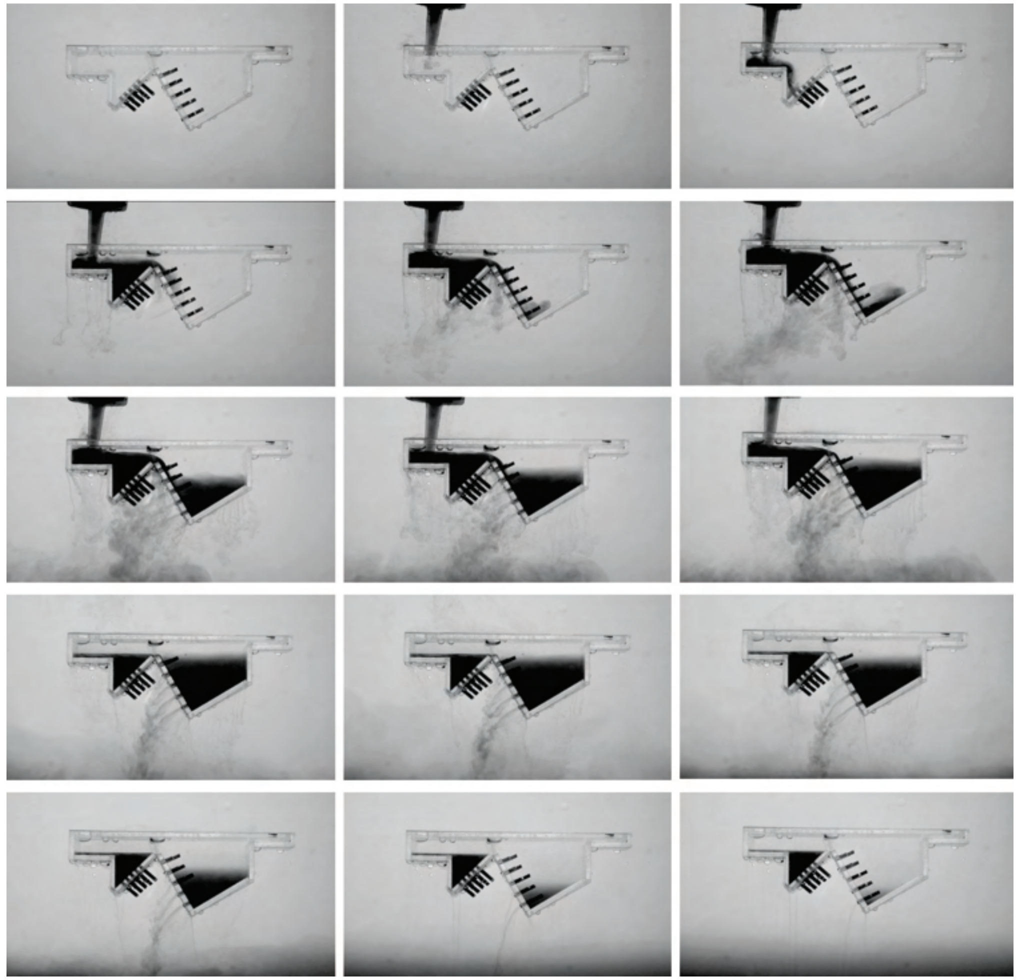


2.57

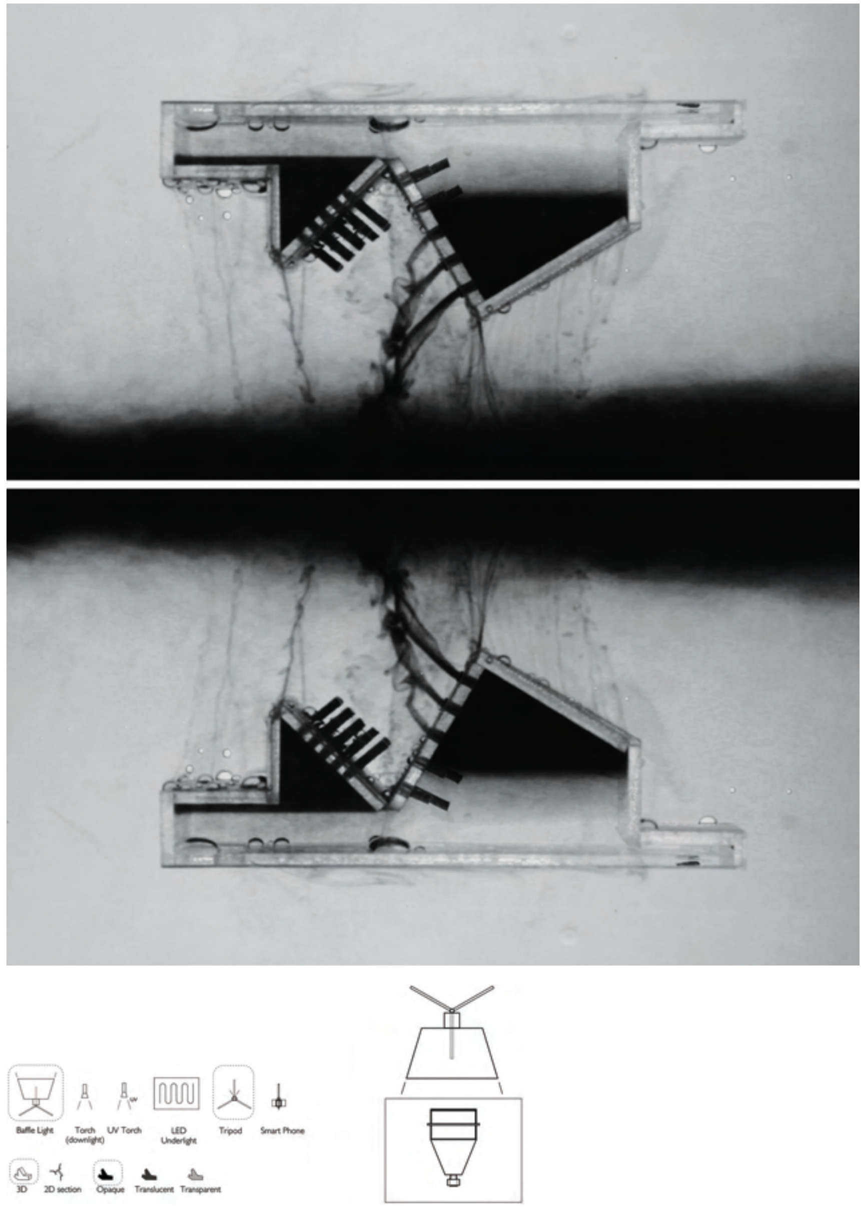
2.57 Composite fabrication drawing of FB2. Colour designations distinguish between drawing type and fabrication method. Fabrication of the filling boxes focused on the architectural models submerged within the tank. These models tested flow patterns through a range of architectural conditions including: a series of small diameter tubes akin to chimneys; two spaces nested within each other; three interconnected spaces; and models with movable internal partitions.

2.58 Video stills illustrating flow patterns through one of the architectural models developed for FB2. The architectural models tested within FB2 were not devised to test specific ventilation strategies, but instead to test a range of modelling approaches that might act as catalysts for future architectural speculations. In this case, the model tested fluid mixing through a series of chimney-like internal and external pipes. It also explored how spatial pockets contain denser water; one side of the model dissipates while the other contains.



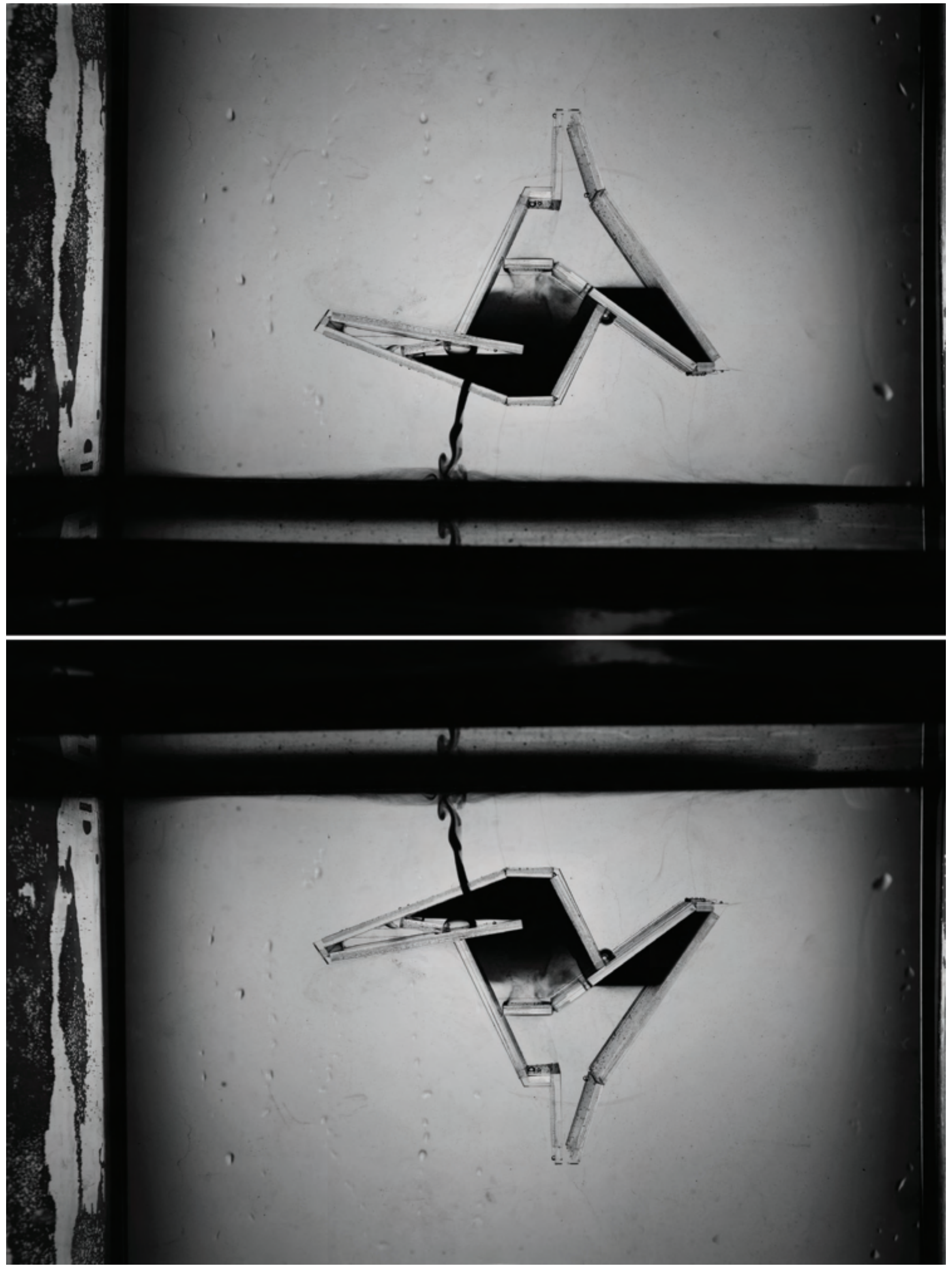
2.58

2.59 Enlarged mirrored video stills of flow patterns through an architectural model in FB2. Video stills were translated from colour images into high-contrast black-and-white images to highlight fluid mixing and stratification patterns. Mirroring the model image illustrates that it can be read either as the introduction of cold air into a warmer environment, indicated in the top image, or the introduction of warm air into a cooler environment, indicated in the bottom image.



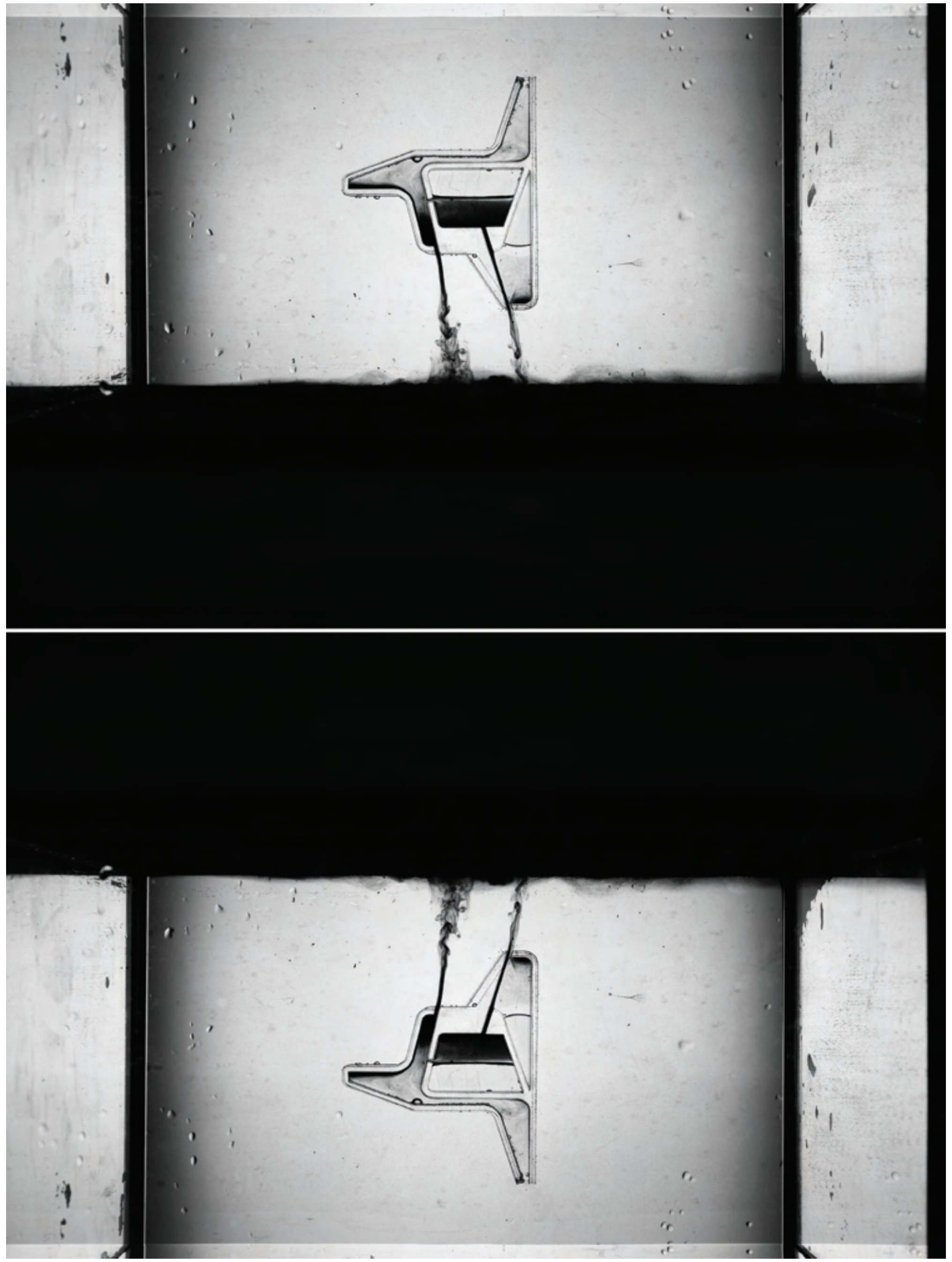
2.59

2.60 Enlarged mirrored photographs of flow patterns through an architectural model in FB2. This model tested the role that oblique geometries and horizontal internal divisions could play on drain patterns through a single outlet. On the top image, cold air falls and drains through an outlet in the base. The bottom image illustrates warm air ascending out of an outlet akin to a chimney.



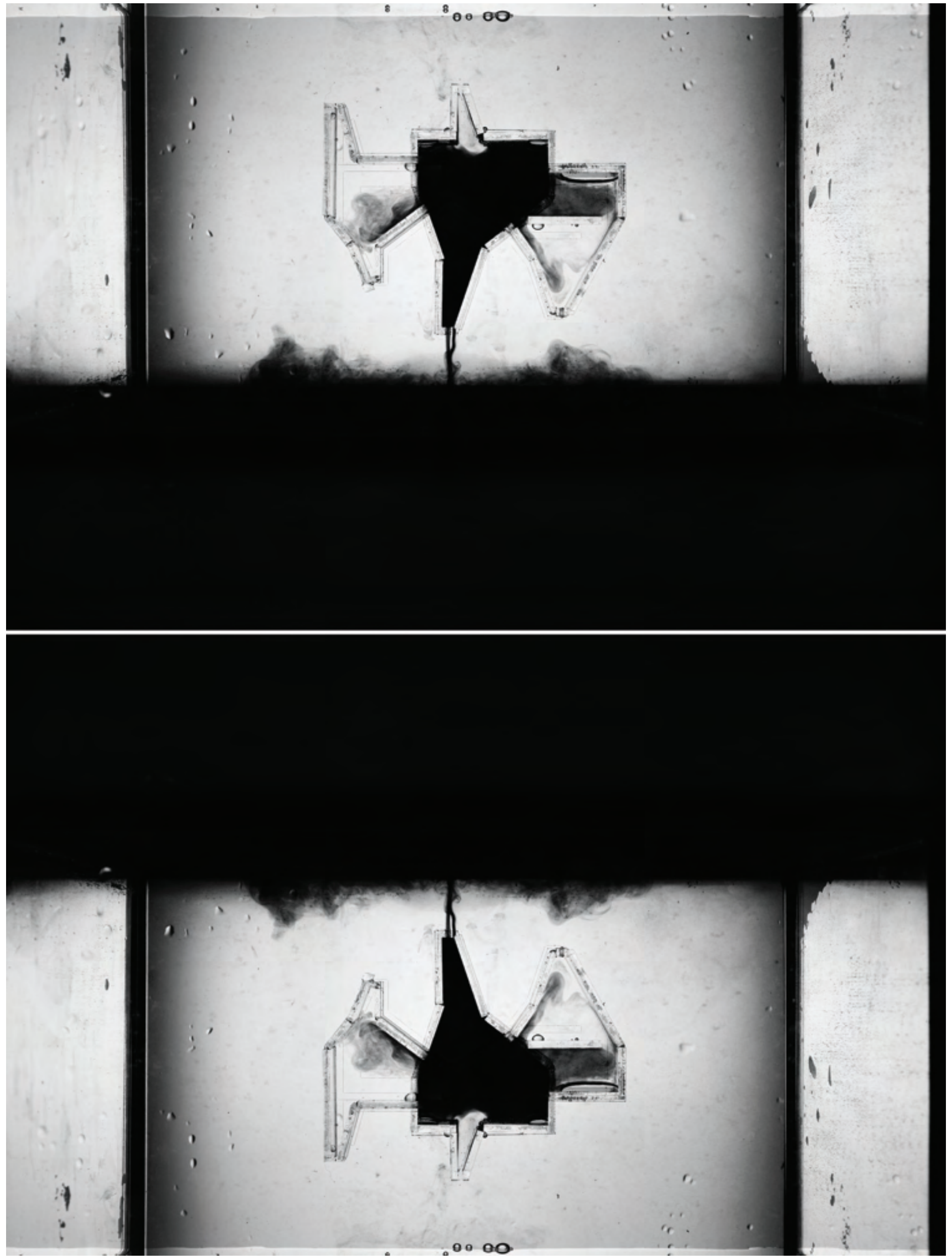
2.60

2.61 Enlarged mirrored photographs of flow patterns through an architectural model in FB2. This model borrowed geometries of David Boswell Reid's 'tubular apparatus' described in more detail in Chapter 5. Spatial pockets trapped cool air (top photo) or warm air (bottom photo) while the rest drained out of two outlets.



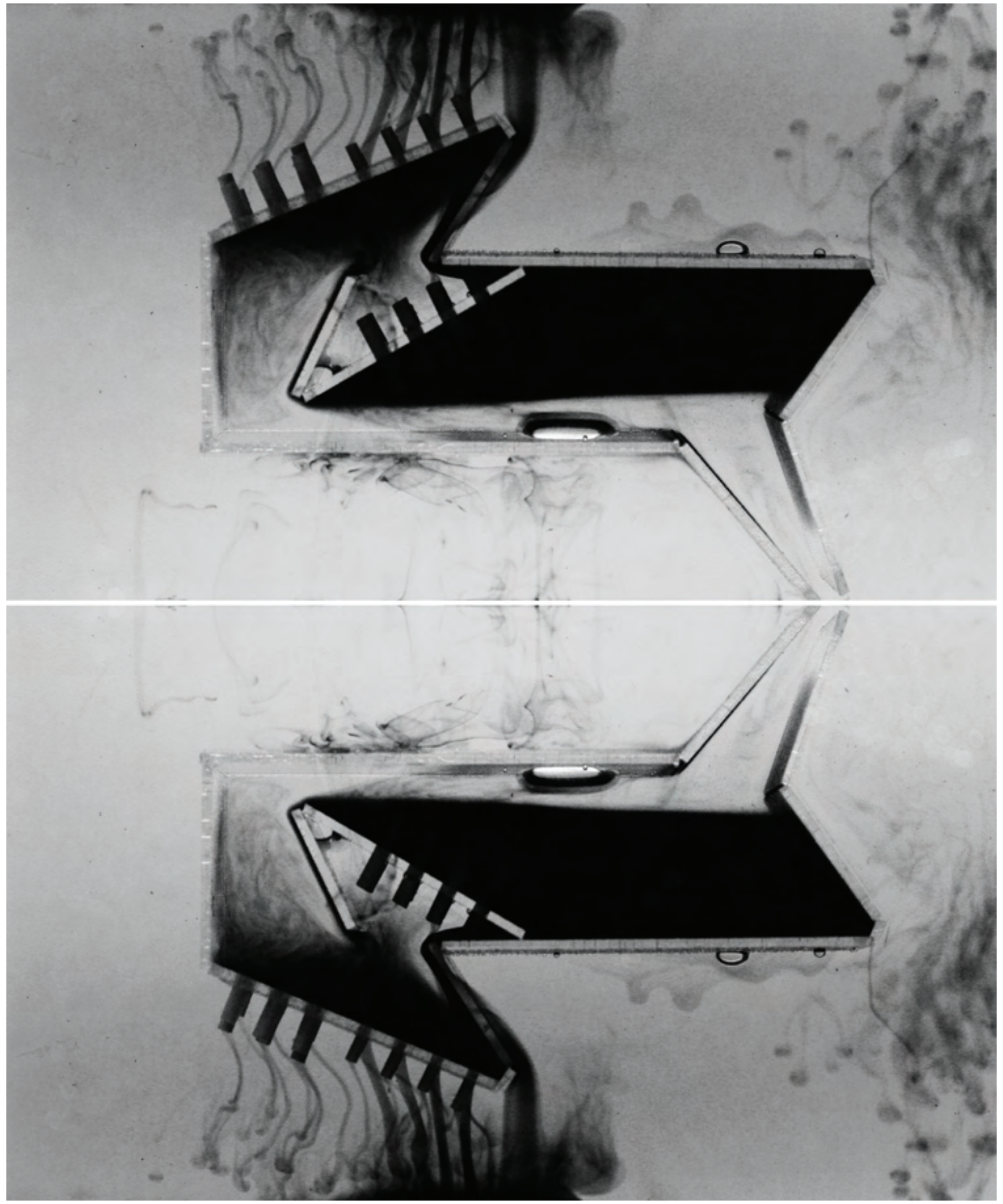
2.61

2.62 Enlarged mirrored photographs of flow patterns through an architectural model in FB2. This model incorporated three separate volumes with openings at their intersections to visualise flow through distinct volumetric spaces. However, much of the flow through each volume was occluded due to the camera's frontal position. Instead, focus shifted to the tank itself as the drained dye increasingly and ominously fills the base or top of the tank.



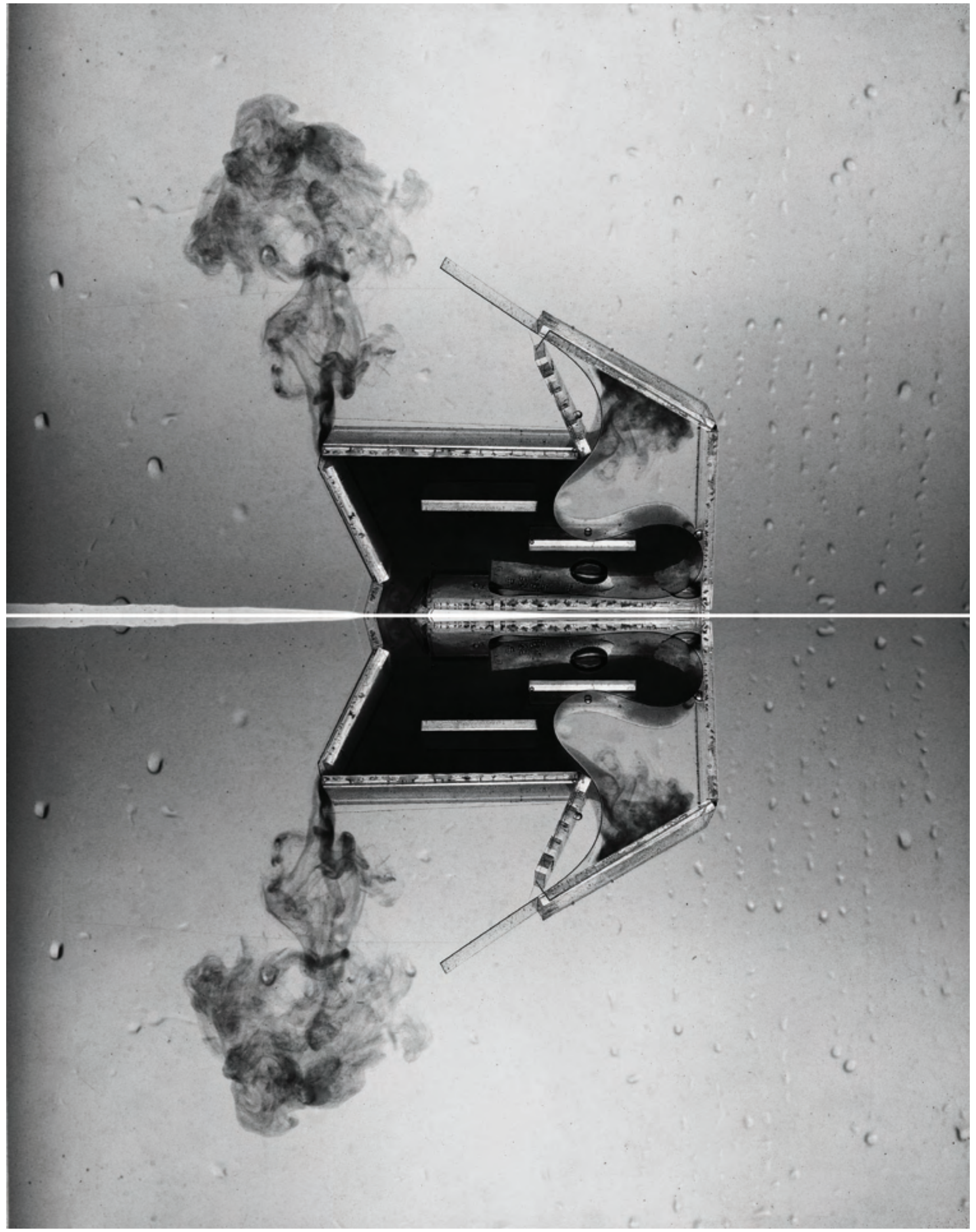
2.62

2.63 Enlarged mirrored photographs of flow patterns through an architectural model in FB2. This model incorporated a series of tubular elements akin to chimneys in the interior and exterior of the irregularly shaped model. Dye leaked out of these tubes as delicate, wispy trails.



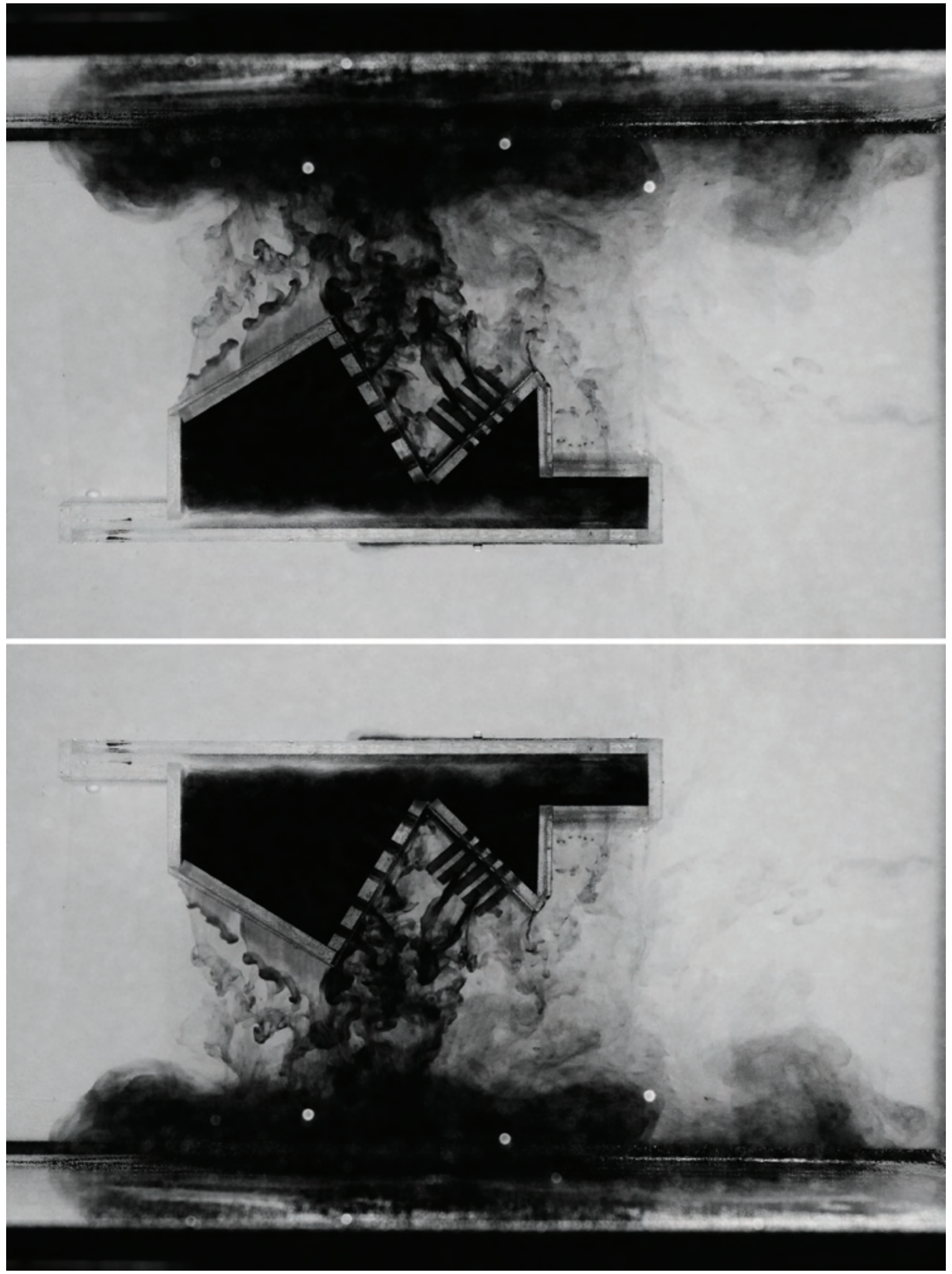
2.63

2.64 Enlarged mirrored photographs of flow patterns through an architectural model in FB2. This model incorporated a thin, internal, movable plastic sheet that contained non-orthogonal space and enabled exchanges between them. Internal and external leaks focused attention on plumes rising within and beyond the architectural model.



2.64

2.65 Enlarged mirrored photographs of flow patterns through an architectural model in FB2. The model incorporated a series of small circular apertures and linear tubes. The photograph was taken just after dye was injected into the model, capturing agitated plumes of dye outletting ominously into the tank beyond. The image is an austere reminder of the invisible, ongoing exchanges between buildings, their emissions and the atmospheric domains they contaminate and alter.



2.65

Chapter 3 | Streamlines and vortices

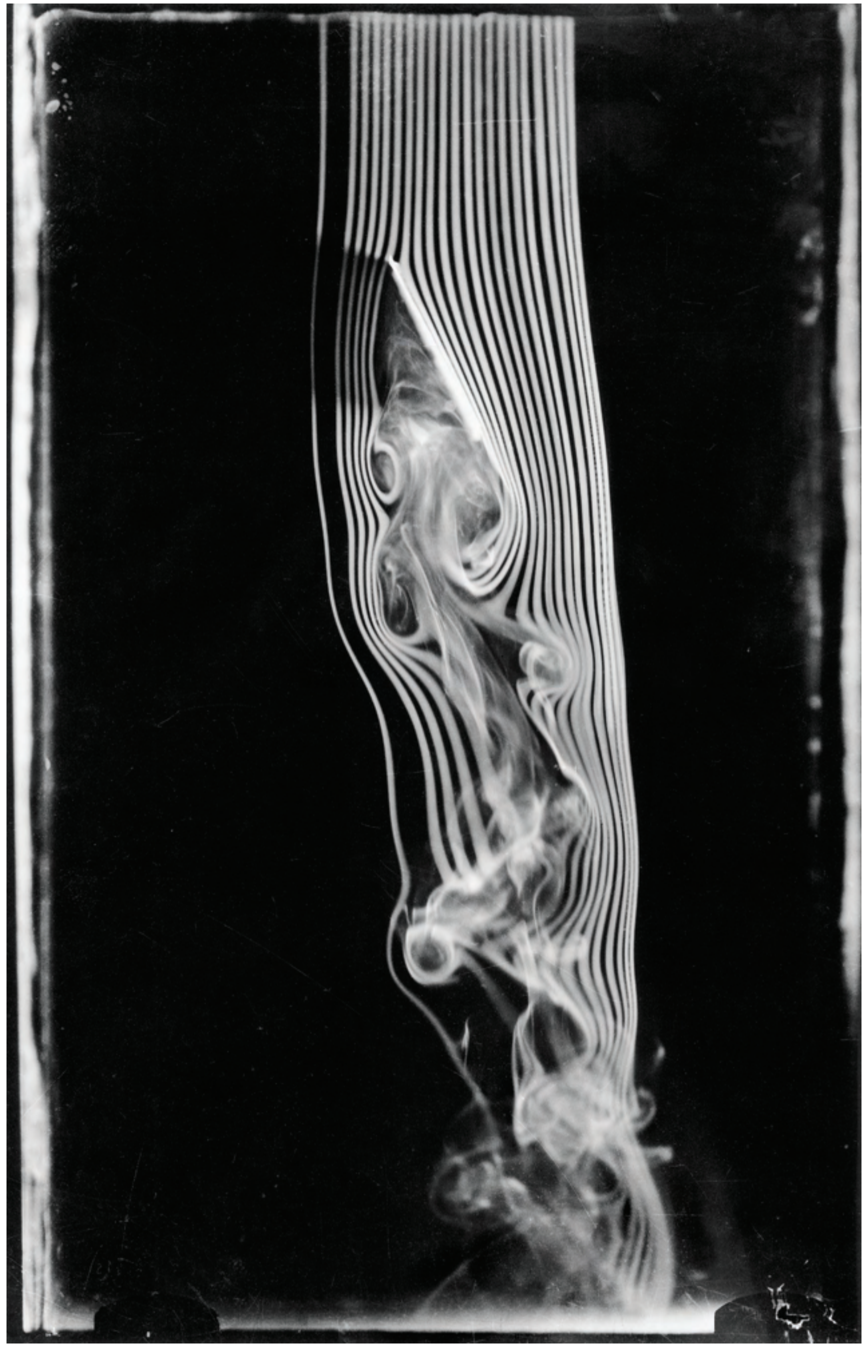
In this chapter, I examine French polymath Étienne-Jules Marey's wind tunnels and the streamlines and vortices captured in associated photographs, looking at early challenges and critiques of flow imagery to cast a more nuanced light on contemporary flow visualisation strategies in architecture today (Figure 3.1). I explore wind tunnels and photographs as a twin project, establishing material reciprocities between flows visualised and workings of the instruments that generate this flow. This chapter moves between the phenomena of air movement and the instrument that generates it, concluding with reflections about the challenges that I faced during the prototyping process of constructing the streamlines that appear so effortless in Marey's wind tunnel photographs. While the curling vortex trails in Marey's photographs are beguiling, this chapter reveals that there is in fact more to be learned about air movement by focusing on the steady, continuous streamlines of undisturbed smoke.

Streamlines and vortices are flow patterns. Continuous filaments of streamlines indicate steady, laminar flow. The trailing curls of vortices reflect turbulent flow. When steady laminar flow hits an obstacle, that obstacle, depending on its surface characteristics and form, causes resistance. Resistance leads to differentials in movement, resulting in turbulence in the wake region of the bluff bodies – obstacles with sharp corners – in particular. Laminar flow is predictable, parallel and fundamentally linear. Turbulent flow is highly irregular, chaotic and notoriously complex. Turbulence is recognised as being one of the most consequential, yet least understood, domains of classical physics. These flow patterns take place within the vast atmospheric domain continuously with varying levels of consequence, ranging from the negligible impacts a gentle breeze has on thermal comfort to extreme impacts associated with natural disasters or the dispersal of airborne contaminants.

Streamlines and vortices are flow regimes in fluid dynamics, yet to focus on these flow patterns purely in scientific or technological terms overlooks their strange materiality, which is active, shifting, perceivable and therefore spatial. When made visible, streamlines and vortices are beautiful and visually beguiling; they invite material speculation. They are strange, complex systems that operate in ways that raise material and spatial questions, questions beyond technical performance.

Streamlines and vortices are also visible reminders of the climate crisis. The

3.1 Étienne-Jules Marey's photograph of a 21-tube smoke-stream wind tunnel. Inclined plane, print from glass negative, 12×9 cm. Lower right inscription in blue ink, emulsion side: '7'; upper left 'P' and along the left side: 'smooth in front' (engraved in the emulsion). Inv. MPN 342.



3.1

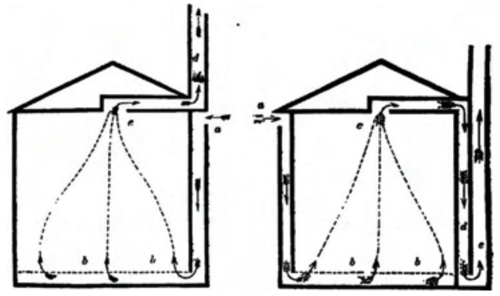
vortex trails of exhaust following an airplane in flight or generated by smokestacks from moving container ships, for example, are potent reminders that climate change is anthropogenic, a human construction that has been irrevocably altered through industrialisation and associated atmospheric emissions. Small atmospheric compositional alterations have expansive climatological consequences that threaten ecological and associated sociocultural and political systems worldwide. It is increasingly clear that we are not passive recipients of the vagaries of climate; we are active agents in its production.

Airflow patterns have impacts across global, territorial, built environment and bodily scales, making them fascinating and consequential subjects of material speculation. Skilful manipulation of airflow in the design process requires a basic understanding of fluid dynamics, but these principles are notoriously complex, and there is a gap between engineering knowledge about airflow behaviour and architectural strategies that engage meaningfully with these behaviours as an integral part of the design process. Architectural theorist Christopher Hight clarifies what is at stake: 'The architect's ability to manipulate environmental conditions has been limited by the discipline's tools themselves, which require either cumbersome technical simulations of fluid dynamics or notational rules of thumb … To engage such processes requires expanding our mindset and toolkit to make knowable such nonvisual phenomena objects' (2009, 26).

Environmental models build on the tradition of engineering experimentation, supplementing the two conventions noted by Hight: 'notational rules of thumb', such as the static environmental diagram, and 'cumbersome technical simulations', such as building performance simulations like computational fluid dynamics (CFD). Neither environmental diagrams nor digital simulation make 'the non-visual phenomena object' of airflow intuitively knowable as a moving, material condition, particularly in the early stages of design. Environmental diagrams rely on static drawings to represent complex dynamic conditions (Figure 3.2). In other words, diagrams neglect to capture an inherent property of moving fluids, their shifting behaviour over time. Moreover, they are projections of hypothetical flow behaviour, failing to reveal substantive properties about the medium of air to their authors.

Unlike drawn diagrams, building performance simulations like CFD can be dynamic in the sense that they can simulate flow over time (Figure 3.3). Moreover, unlike physical experiments, they can generate many results at a range of scales fairly quickly. They also have limitations; they can be complex and time-consuming to use, and they are easily misappropriated by

3.2 David Boswell Reid's ventilation diagrams, indicating supply of fresh air and the discharge of 'vitiated' air through two apartment configurations. The visual language of static building ventilation diagrams has changed very little since Reid's book, *Illustration of the Theories and Practice of Building Ventilation*, was published in 1844. Reid, 1844.



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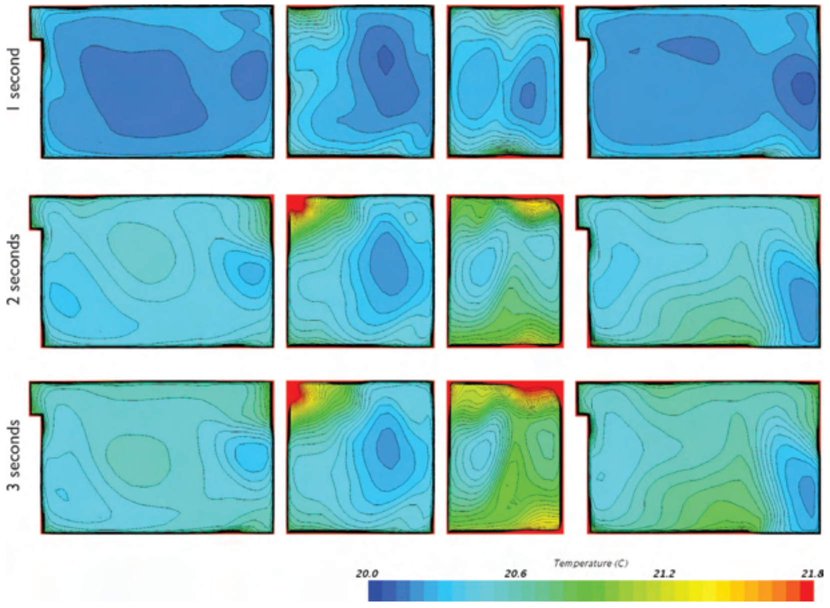


3.3

3.3 Computational fluid dynamics analysis of wind-driven temperature variations over one-second intervals through a low-rise building section. Courtesy of Kim Adamek, 2022.

initiates.[1] A former aeronautical engineer, architectural academic Michelle Addington notes that there were many challenges of using CFD to analyse buildings, such as the lack of empirical data for verifying computational codes used in flow visualisation software (2007). Significant advances to CFD have been made since Addington's critique, and an increasing number of case study projects have been used to verify computational setups and results since. There have also been advances in accuracy of software equations, the development of more intuitive visual interfaces and the codification of best-practice guidelines for using the software (Jo, Jones and Grant 2018). Some wind engineers note that significant progress has been made in the most demanding aspects of CFD use, for example, in wind load evaluation and aerodynamic optimisation (Dagnew and Bitsuamlak 2013). Others suggest that challenges with accurately modelling boundary layer effects and turbulence profiles in CFD persist, making wind tunnel experiments focusing on building aerodynamics more reliable (Phillips and Soligo 2019).

To critique CFD based on numerical inaccuracies, however, is to miss the point of this book. Fundamentally, CFD is not an intuitive design tool for architects. CFD has methodological limitations, particularly in the early stages of design, when key decisions about building form and orientation significantly impact future performance. Digital simulations require a certain level of design resolution before analysis of environmental interaction is possible, limiting their role as an iterative early design tool. Moreover, once a design has been developed, it must be translated from a spatial idea into a volumetric mesh, which can be labour intensive. Setting up a mesh prompts decision-making about quality and size of mesh, parameters that are not intuitive to a designer (Kaijima et al. 2013). Once the mesh is completed, the designer must define parameters about the boundary layer, inlet turbulence and grid densities to generate results. Finally, they must interpret the results, which are often complex and may or may not be trustworthy. For all these reasons, CFD does not lend itself to being an iterative design tool. Lack of access to software and lack of knowledge for using it accurately pose further limitations for architects.

Airflow simulations fundamentally fail to reveal the full range of material properties of airflow, reducing laminar and turbulent flow to a field of vectors and/or colour gradients. This reductive visual language neglects to capture the full material complexity of moving air, a concern explored in more detail throughout this chapter. Environmental models generate visualisations of flow that open insights about air as a moving material condition with a range of complex behaviours, supplementing diagrams and building performance simulations such as CFD.

But what makes a flow visualisation good? And what is the relationship between a physical model that generates flow and the quality of the flow visualisation? In other words, what do the streamlines and vortices of air movement made evident in environmental models tell us about both airflow behaviour and about the environmental model as a physical construction?

This chapter works through these questions, using Étienne-Jules Marey's wind tunnels and their smoke-stream photographs, to establish some of the origins of airflow visualisation in early scientific developments of the late nineteenth and early twentieth century. Marey's wind tunnels culminate a celebrated career, but they have been largely overlooked as objects of speculation. Their marginal status can be attributed to several things. First, while his earlier investigations of bird flight informed developments in aeronautics, the wind tunnels themselves contributed little to aeronautics research. Second, they were some of the earliest but were not the first wind tunnels. Third, while Marey was one of the first to use the smoke-stream visualisation technique, he did not invent the technique. And while Marey was aware that his wind tunnels might be used to test principles of building ventilation, they were constructed in service of architectural or building-science research.[2] At the time of their construction, boundary layer wind tunnels used to test principles of airflow in relation to buildings did not exist. Nevertheless, Marey's wind tunnels are worthy of further scrutiny as objects of design speculation, for they are laden with architectural insights about airflow behaviour, the challenges of flow visualisation and the mechanics of environmental mediation.

Marey's wind tunnels

Marey was an inventor best known for his work devising photographic techniques for capturing incremental views of animate motion, particularly of birds in flight. His 1900–2 wind tunnels are one of the last projects that he developed in his prolific career devoted to using the graphic method and chronophotography to make animate motion visible. This section situates Marey's wind tunnels as extensions of his graphic method and chronophotographic techniques. It illustrates how Marey's wind tunnels, to use Hight's terms, 'make knowable' the 'non-visual phenomena object' of airflow, while also elaborating on what properties of airflow are 'made knowable' in the process (Hight 2009).

Étienne-Jules Marey's work has captured the imagination of disciplines ranging from physiology to aeronautics and from architecture to cinematography. He was an expansive inventor, and his work was broadly disseminated. What allowed his work to captivate such a wide audience and to endure lies in his skilful merging of scientific invention with representational acumen. It is difficult to separate technical invention from visual presentation in Marey's work and this blurring of intent becomes particularly clear in one of his last projects – his wind tunnels and associated smoke-stream photographs. Marey's wind tunnels translate the vast, invisible atmospheric domain into a legible field of high-contrast, moving lines. It is both a representation of air movement and a device that instrumentalises air as a constituent element.

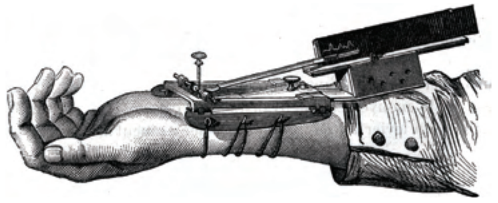
Marey's two primary working methods were the graphic method and chronophotography, and while Marey's wind tunnels deploy neither technique, they are methodologically indebted to both. Trained as a physiologist, Marey's earliest work involved devising instruments, such as the 'pulse-writer', which made blood flow intensities and heart rates visible as a series of lines and curves transcribed on a surface (Figure 3.4). The technique by which these transcriptions were translated from body to instrument to drawing is referred to as the graphic method. Marey did not invent the graphic method, the origins of which can be traced back to the seventeenth century, but he did popularise the technique. In an 1876 lecture, Marey suggests that the intention of the graphic method is to:

> render accessible all the phenomena of life – movements which are so light and fleeting, changes of condition so slow or so rapid, that they escape the senses – an objective form must be given to them, and they must be fixed under the eye of the observer, in order that he may study them and compare them deliberately.
>
> (Marey 1876, 65)

The graphic method was used to translate a vast range of human and animal motion throughout Marey's career, but the defining features remained the same: an 'inscribing apparatus' distilled three-dimensional movement into two-dimensional measurable lines on a substrate, often paper. The essence of Marey's graphic method was that it distilled complex, imperceptible, three-dimensional movement into high-contrast, measurable, two-dimensional drawings.

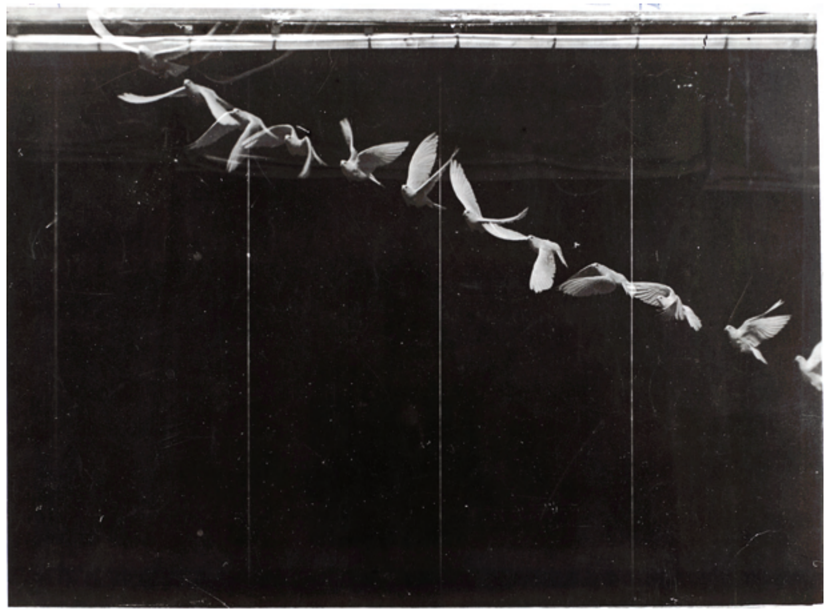
Translations of delicate pressure differentials such as those in Marey's pulse-writer were prone to disturbance. The delicate nature of many of Marey's graphic method recordings meant that slight friction and resultant inertia in the mechanics of the transcribing device could lead to distortions in the transcribed curves (Hinterwaldner 2015). This vulnerability made photography an appealing recording method. Photography offered physical distance between the phenomena being observed and the device recording it.

Marey was a pioneer of many photographic techniques, turning much of his attention to the development of both the devices and the techniques for photographically recording animate motion.



3.4

3.4 Étienne-Jules Marey's 1881 etching of his sphygmograph ('pulse-writer'), which measures blood pressure, transcribing the pulse into a measurable drawing. Trained as a physiologist, the sphygmograph is one of Marey's first graphic method instruments. Courtesy of Wellcome Collection.



3.5

3.5 Étienne-Jules Marey. *Flight of Pigeon*, 1888. Fixed plate chronophotography, 9×12 cm. Image courtesy of Marta Braun. Collège de France.

He calibrated the timescales of his photographs to capture movement that was too fast or, in some cases, too slow to be perceivable by the human eye. He was best known for co-pioneering, along with Eadweard Muybridge, chronophotography, which captured multiple incremental images of animate motion on a single photographic plate, revealing subtle transitions in movement otherwise imperceptible (Figure 3.5). Much of his work moved between the graphic method and chronophotography. Marey often applied high-contrast points and lines onto his subjects before photographing them in motion to make the lines of movement more visible and measurable in the resultant chronophotographs (Figure 3.6).

Through chronophotography of flight, Marey was able to conceive of air as a medium of resistance. His chronophotographic studies focused on how his subjects of flight registered air resistance through wing profiles and movement patterns. Marey completed extensive, increasingly precise, measured investigations of flight patterns of a vast range of species of birds and insects. His work devoted to flight was meticulously documented through drawing and photography, catalogued and published widely, most prominently in *La Machine animale. Locomotion terrestre et aérienne* (*Animal Mechanism: A Treatise on Terrestrial and Aerial Locomotion*, 1874), *Le Vol Des Oiseaux* (*The Flight of the Birds*, 1890), and *Movement* (1895). He came to understand that animate flight was a function of complex interactions between the surface profiles of wings, their range of joint movements and air resistance.

Marey's wind tunnels mark a distinct shift from the subject of movement to the medium through which movement takes place. Art Historian Marta Braun notes:

> towards the end of the century he had entered more deeply into the domain of physics proper: he had concluded his analysis and synthesis of the movements of practically every kind of animal that stirred on the earth or in the air or water. Now Marey turned his cameras on the invisible media through which the movers moved to make visible the motion of waters and of air.
>
> (Braun 1992, 215)

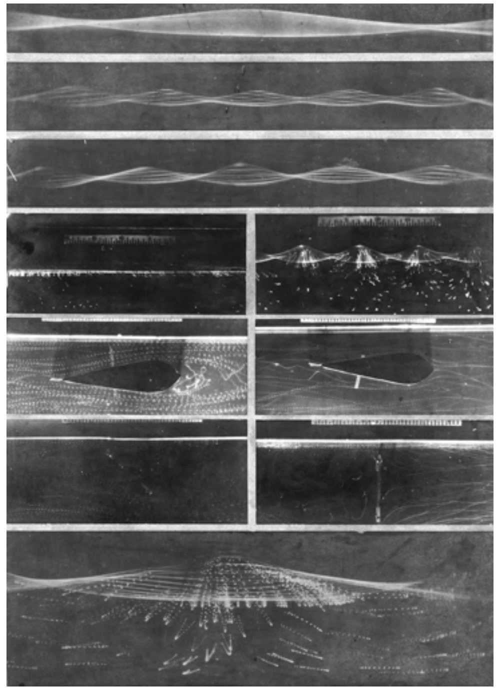
His earliest flow investigations used solid materials, such as fabric on a washing line buffeted on a windy day, as registers of fluid movement. He then developed wave tanks that tracked the motion of water by

3.6

3.6 Étienne-Jules Marey. *Analysis of the Jump*, 1884. **Motion was first captured onto a photographic plate and then translated into a drawing.** Image courtesy of Marta Braun. Collège de France.

introducing wax and resin balls agitated by a propeller. The resultant water tank photographs are the most direct visual precursors to his wind tunnel studies (Figure 3.7). Upon completing the water tank studies, Marey speculated that he might apply these principles to a study of air movement using a wind tunnel that visualised 'threads of gas' movement around obstacles using 'particles of brilliantly lit fluff' (1895).

Instead of using fluff as a tracing material, Marey used smoke. The resultant smooth, moving lines of smoke that erupt into trailing eddies and vortices around linear and cambered profiles reveal a rich material world supporting the mechanics of heavier-than-air flight (Figure 3.8). To achieve the effects captured in Marey's photographs, smoke from burning tinder was drawn through fine silk gauze, which straightened the air currents before they progressed into a viewing chamber, lined on three sides with black velvet. Air was drawn through the chamber using an aspirating ventilator. Documentation promoting a 2004–5 exhibition of Marey's photographs at the Musée D'Orsay in Paris quotes Marey as describing the process:



3.7

3.7 Étienne-Jules Marey. *Study of the Movement of Liquids*, **Chronophotography, no date. These studies mark a shift in Marey's career from focusing the subjects of movement to the medium through which movement takes place.** Paris, Cinémathèque française.

3.8 Étienne-Jules Marey. *Inclined Curved Surface, 36 Degrees Angle*. **Print from glass negative. 10×5 cm.** Inv. MPN 321.

3.8

> Produce a steady stream of air within a closed device with transparent walls; introduce parallel and equidistant wisps of smoke; on the trajectory of these wisps of smoke, place diversely shaped surfaces, at the contact of which they change their course; light brightly and take an instant photograph of their appearance. Such was the programme.
>
> (2005)

The choice of 'brilliant white' smoke, light-absorbing black velvet as a backdrop and magnesium photographic lighting ensured that the workings of the wind tunnel were easily photographed as lines moving over time.

The broadest legacy of Marey's wind tunnel are the rich photographs capturing its workings, which offer a useful primer for principles of airflow behaviour. Marey's photographs were included in an exhibition for the 1900 World's Fair. They were also published in *Scientific American* and *La Nature*, popular scientific magazines with wide readerships at the time (Figure 3.9). More recently, Marey's photographs were featured in an exhibition at the Musée D'Orsay. In Marey's photographs, steady parallel lines of smoke, referred to as streamlines or streaklines, operate in stark visual contrast to the leeward eddies, vortices and dispersed particles of turbulent flow.[3] The two flow regimes meet at the boundary layer adjacent to the model surface, a particularly charged interface that determines the properties of uplift.

To overly aestheticise Marey's photographs is to overlook their intent. Developed in service of the emerging field of aeronautics, the photographs were intended as objects of scientific inquiry.

3.9

3.9 Étienne-Jules Marey, *Studies of Air Movement*, 1901. Beaune. Image courtesy of Marta Braun.

Obstacles placed within the wind tunnels were designed to fine-tune the orientation, or angle of attack, of wing profiles to encourage uplift. Visual analysis of the air movement patterns, of transition zones between laminar and turbulent flow, around wing profiles offered the promise of providing crucial visual evidence for what caused some flying apparatuses to stay aloft while causing others to stall and dive. The crucial deficiency of Marey's wind tunnels at the time was that they could not provide numeric data on air pressure, a crucial parameter for understanding air resistance (Hoffmann 2013).

Marey's wind tunnels were not recognised as a scientific achievement at the time, but his photographs do reveal certain scientific principles – extensive turbulence caused by profiles with high angles of attack; the efficiency of concave (cambered) to linear surfaces; and the general air movement patterns around circular and pisiform shapes. They also reveal how airflow behaves in those spaces between the streamlines and vortices – the conditions that appear as slight gaps, diffusions or shadow voids. These in-between conditions include lines of separation between two flow regimes, wind shadows devoid of air movement and boundary layer conditions.

Boundary layers are particularly important concepts in aeronautics and in architecture. They occur at the interface between surfaces and fluids, where the effects of friction can be substantial. They occur across scales, from the atmosphere to the urban environment to the individual building, explored in more detail later in this chapter. In aeronautics, the boundary layer of a wing profile indicates the transition from laminar to turbulent flow as well as the point at which the two systems separate, which determines crucial uplift properties of a wing profile.[4] Thus, the photographs not only make streamlines and vortices legible, but they also highlight those flow conditions around and in between the two.

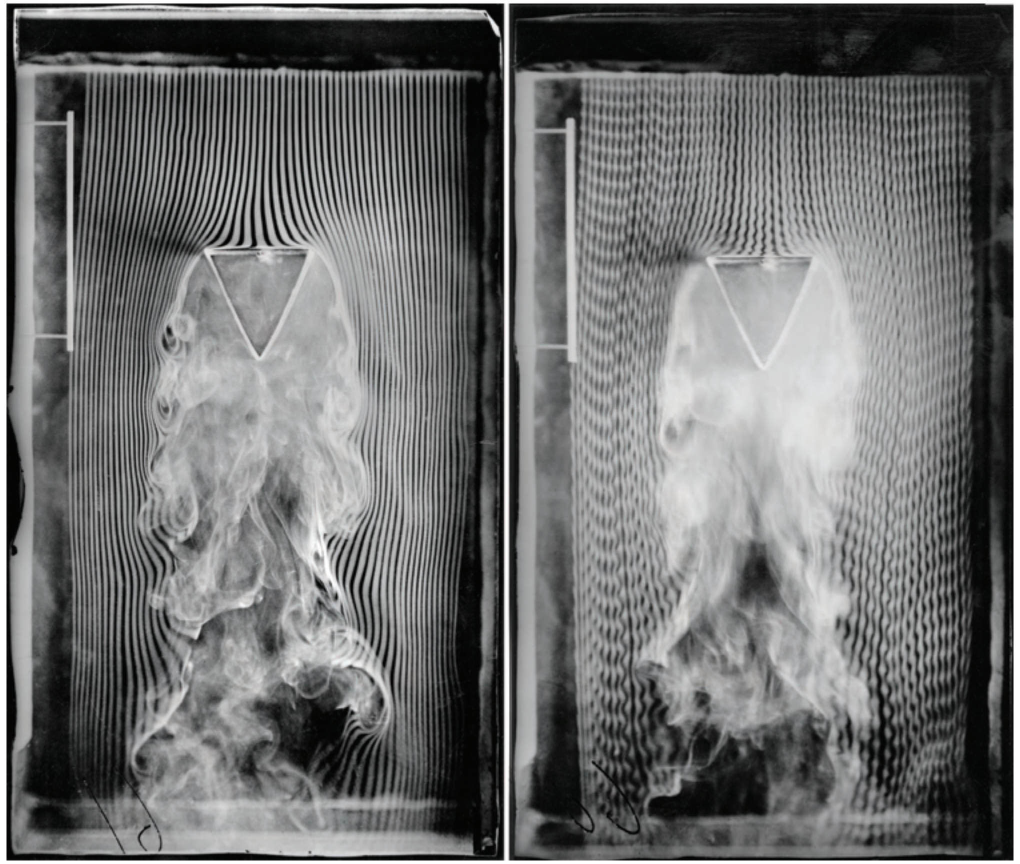
Marey's wind tunnels are clearly indebted to different dimensions of the graphic method and chronophotography. Like the graphic method, the high-contrast smoke filament cords create continuous lines moving through space. The darkened wind tunnel is spatially compressed, creating a flat substrate for registering this movement. A measuring stick attached to the testing bed quantifies this information by registering differences in movement when the smoke is agitated to produce visible waves. Like chronophotography, Marey's photographs make the complex moving phenomena of air registered by smoke fillets legible.

Parallels between Marey's wind tunnels and the graphic method and chronophotography are not simply representational; they reflect a deep awareness of the mechanics of airflow, honed over the extent of his career. Architectural historian Enrique Ramirez has described the changing conceptions of air honed through Marey's different working methods, suggesting that 'with each methodological shift – from optical methods, to the "graphic method", and finally to chronophotography – air was transformed from something that was wholly internal, to something that was external, and, finally to something that negotiated both inside and outside' (2013, 127). Ramirez describes how many of the graphic method transcribing instruments Marey devised early in his career relied on air pressure as a sensitive force-registrar. Rubber tubes, tambours and air pumps drove much of his walking and drawing machines. His 'pulse-writers', equivalents to cardiograms, also translated fluid pressure, in this case of blood flow, into legible lines on paper. Marey's studies of animate motion shifted from internalising and instrumentalising air to understanding air as a vast exterior medium of resistance. He developed techniques for observing how live and mechanical birds and insects displaced air through wing movement, enabling uplift. His wind tunnels operate somewhere between these conceptions of air, instrumentalising and internalising air, straightening and redirecting it, to study air resistance as it operates in a scaled exterior environment.

While there are clear visual similarities between the graphic method and chronophotography, technically neither is deployed in Marey's wind tunnels. Looking to these deviations offers further insights about airflow behaviour. Air is neither composed of perceivable constituent elements nor does it operate according to a clear or consistent durational system, making it difficult to subdivide and incrementally record. Marey's wind tunnel can be understood as a metaphorical drawing machine, drawing lines of visible smoke registered on photographs as air movement patterns. However, it has neither an inscribing apparatus nor does it generate a drawn inscription. Historian of science Christoph Hoffmann has pointed out that unlike much of Marey's work, which attempted to reveal physical processes that were otherwise visually imperceptible, Marey's photographs capture conditions that would have been quite visible to the naked eye when viewing the wind tunnel in person (2013). Relying on instant photography rather than chronophotography, his wind tunnel photographs do not record a sequential progression of discrete movements over increments of time. Instead, they capture a single moment within a moving flow regime (Figure 3.10).

The wind tunnels were also distinctive within Marey's oeuvre in that they operated at scale in contrast to the remainder of his work, which focused mostly on working observationally at full scale. His wind tunnels were part of the distinctively French aeronautical tradition of developing

3.10 Étienne-Jules Marey. *Prism Presenting One of Its Bases to the Current*. Print from glass negative, 12×9 cm. Marey's wind tunnels did not provide numeric data regarding air pressure, crucial for aeronautics research at the time. He did, however, devise a technique for measuring air speed. (right) A vibrating device translates lines of air to waves. A ruler inside the box facilitates measuring distance each wave travels over a tenth of a second. Inv. MPN 344.



3.10

lighter-than-air flying machines through scale-model rather than through full-scale prototypes, which, upon failure, had disastrous consequences. The overarching theme of Marey's work was movement, which he suggests 'implies a double knowledge, namely, that of space as well as that of time' (1895, p. x). The wind tunnels both alter distance through compression and alter time through the speeding up of smoke trails. They shift from merely being devices for facilitating observations of existing phenomena to being models that simulate and alter aspects of the natural world.

As a scale artefact, the testing bed in Marey's wind tunnel translates the atmospheric domain of flight in three profound ways. First, it inverts movement. In the wind tunnel, the sky now moves, and the airplane wing remains fixed. Whereas human flight entails high-speed propulsion of an object through relatively slow-moving air, wind tunnels fix the wings of flight while speeding up air movement around it. Marey explains his understanding of

inversion, introduced in Chapter 2, in *The Flight of Birds* (1890), noting that 'From the point of view of the resistance experienced, whether the solid body be in motion in calm air or whether it be immobile in an air animated with movement is indifferent' (cited in Musée D'Orsay 2005). Second, Marey's wind tunnels translate the fundamentally vast, three-dimensional space of the stratosphere into a relatively small, flattened, two-dimensional space. This distillation establishes limits and boundaries to the gigantic atmospheric domain by containing it and diminishing it in size, making it comprehensible to a viewer. Cultural theorist Susan Stewart suggests that the gigantic is profoundly and distinctively exterior; it is unwieldy, difficult to contain, disorderly. It is beyond the scale of the body, subsuming it (1992). By containing and controlling the gigantic atmospheric world, Marey's wind tunnel creates a new, manageable environment that is legible in relation to the scale of the human body. Finally, Marey's wind tunnels materially translate the diffuse, invisible expanse of the stratosphere to a series of high-contrast, moving parallel lines. This translation, explored further later in this chapter, is especially significant because it starts to hint at origins and implications of the ubiquitous practice of representing air and water as parallel lines today.

Flow visualisation

This section situates Marey's work within a wider context of developments in flow visualisation to highlight traits that make them remarkable. Leonardo da Vinci is generally credited with developing techniques for visualising flow patterns. However, the field matured at the height of Marey's career in the late nineteenth and early twentieth century with discoveries in fluid mechanics and aerodynamics by pioneers such as Ludwig Prandtl, Ernst Mach and Osborne Reynolds.

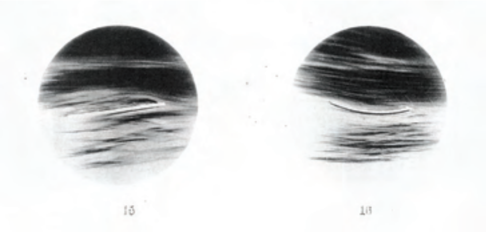
Just as Marey's wind tunnel did not yield substantial new knowledge to the field of aeronautics, he is not recognised as a pioneer of flow visualisation. Unlike Osborne Reynolds or Ludwig Prandtl, both of whom visualised flow associated with discoveries of dimensionless parameters used to calculate flow behaviours, Marey did not popularise any scientific discoveries through his visualisations. Similarly, unlike Ernst and Ludwig Mach, he did not invent a particular visualisation technique.

This section takes a comparative look at the work of three of Marey's flow visualisation contemporaries: German father and son physicists Ernst and Ludwig Mach; German zoologist Friedrich Ahlborn; and British engineer Henry Selby Hele-Shaw. A look to this wider cross-section of flow visualisation developments highlights what makes Marey's work distinct – his ability to materially capture fundamental compositional differences between laminar and turbulent flow.

German physicist Ernst Mach developed several techniques for studying movement of supersonic projectiles. Ludwig Mach adapted his father's work with the supersonic techniques to visualising subsonic conditions. L. Mach tested a range of visualisation media in his wind tunnels including thread, cigarette smoke and heated iron particles (Figure 3.11). As such, he has been celebrated as the pioneer of smoke visualisation techniques. However, while he may have invented the smoke visualisation strategy, the results were visually inferior to those of Marey. Aeronautics engineer Thomas Mueller describes Mach's smoke visualisations as 'faint and difficult to make out' (1983).

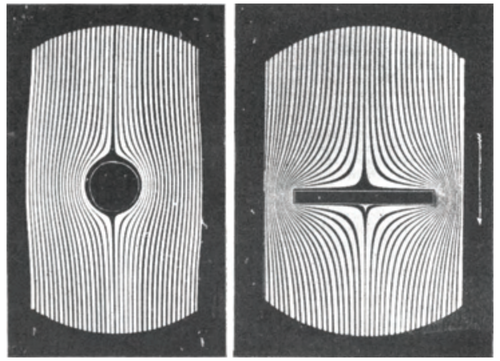
Marey was aware of the Machs' work, as he was of English engineer Henry Selby Hele-Shaw's widely published streamline techniques using coloured glycerine (Figure 3.12). Hele-Shaw's 1941 obituary outlines the mechanics of the technique as follows:

> he arrived at his greatest and even sensational discovery in this field, for which glass plates were mounted within .020 inch of each other, stable stream line flow was established at all the water velocities within which he experimented. Colouring matter (eventually glycerin), introduced at the entry of the thin water sheet through very fine equally spaced holes, appeared from each hole as a clearly defined and stable stream line automatically mapping out the flow.
>
> (Guy 1941, 794–5)



3.11

3.11 Ludwig Mach's (left) streamlines around a plane surface. (right) Streamlines around a slightly curved surface. L. Mach is credited with inventing the wind tunnel smoke visualisation technique, but the smoke was diffuse and faint, lacking the visual clarity of Marey's smoke-stream photographs. Mach (1896) in Christoph Hoffmann, 2013.



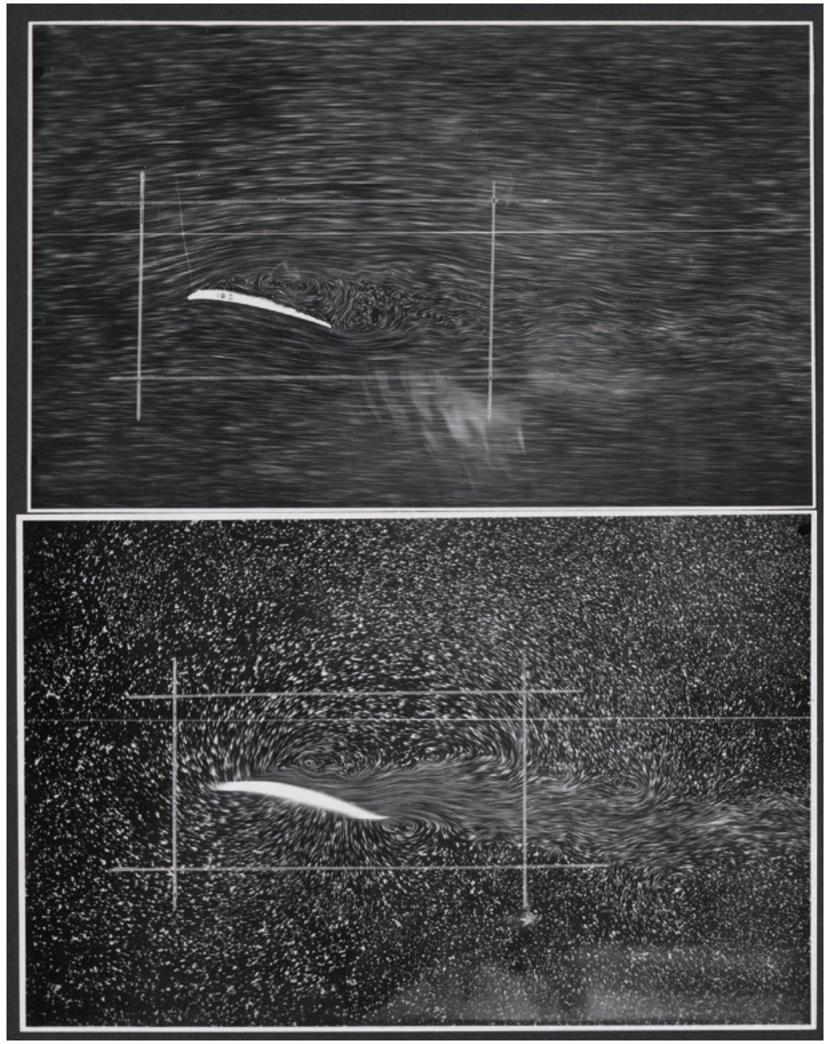
3.12

3.12 Henry Selby Hele-Shaw photographs of flow studies using glycerine to study boundary layer effects of ships moving at sea. Hele-Shaw's flow visualisation technique was used to study ideal fluids and neglected to show the full effects of inertia and turbulence, effects that are common in moving air. Hele-Shaw, 1899.

Hele-Shaw's technique was intended to replicate flow patterns of an ideal fluid, a fictional incompressible fluid with no viscosity, used in scientific experiments to idealise flow conditions. Using glycerine, Hele-Shaw showed linear flow patterns around obstructions with a high degree of contrast and clarity. However, the technique smooths out the swirling eddies and vortices of turbulence, distilling all fluid behaviour to continuous, steady flowing streamlines.

Perhaps most closely aligned with Marey's work was that of German zoologist Friedrich Ahlborn. Art historian Inge Hinterwaldner has analysed Ahlborn's flow visualisation studies in relation to those of Marey, noting their parallel working methods. They both moved back and forth between graphic method, physical experiment, photography and drawing. Both were interested in making transitions between laminar and turbulent flow clearly visible.

There were, however, fundamental differences in how Marey and Ahlborn worked. Their experimental setups differed. Rather than working with air and smoke, Ahlborn found water a better medium for visualising flow patterns. He noted that photographic flashes as well as air straighteners disturbed air movement, altering laminar flow patterns in wind tunnels. Instead, he used water tanks. Club moss spores acted as particulate traces. The spores were materially more like the 'brilliantly lit fluff' Marey hypothesised about using in his initial wind tunnel than the smoke streams he used instead. Ahlborn's photographic experiments tested differences between capturing these flow patterns with both still and moving cameras (Figure 3.13).



3.13

3.13 Friedrich Ahlborn's water tank photographs of laminar and turbulent flow patterns around a cambered form. Ahlborn used club moss spores as the flow visualisation medium. While Marey's camera was stationary, Ahlborn experimented with both fixed (top) and moving (bottom) cameras. Deutsches Museum, Munich, Archive, CD_62750.

Just as was the case with Ludwig Mach's photographs, Ahlborn's photographs lack the high-contrast visual clarity and evident distinction between laminar and turbulent flow clearly distinguished in Marey's photographs. Hinterwaldner notes:

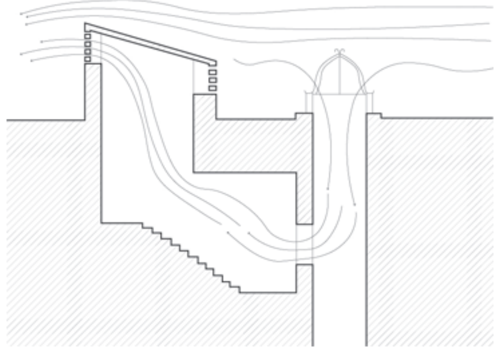
> How intensely must Ahlborn have wished for such an orderly array as the parallel smoke streaks in order to draw the flow lines … He wrote that a simpler situation 'would be the case if the water flowed very slowly in a perfectly smooth and parallel river bed, when the particles would follow one another in lines called "streamlines," and the flow would be like the march of a disciplined army, instead of like the movement of a disorderly crowd, in which free fights tak[e] place at various points'.
>
> (2013, 23–4)

What set Marey's work apart in relation to his peers was the combination of high-contrast visual clarity, achieved by translating air to a series of lines moving through space, without sacrificing legibility or complexity of turbulent flow patterns. Mach and Ahlborn's techniques showed the transition between laminar and turbulent flow as a continuous field (rather than distinct lines) of flow movement. Hele-Shaw distilled flow to legible lines. However, by simulating the fictional flow of an ideal fluid, his technique occludes the complexity of turbulent flow.

Drawing turbulence

Marey's wind tunnels generate airflow as something caught between two and three dimensions. They are clearly three-dimensional objects, yet they generate a slice of moving air deliberately flattened and devoid of depth. They are then flattened further through the lens of the camera, perpendicular to the testing bed and distanced to crop out any surrounding context. And yet they are clearly distinct from drawings of flow patterns. How did Marey's flow visualisations compare to drawn representations of fluid conditions at the time and what are the implications of this legacy today?

In static environmental diagrams of buildings today, arrows with extended linear tails trace the hypothetical flow path of air through the building (Figure 3.14). Often devoid of wider context, the arrows tend to start just outside of the windward side of the building and end just outside of the leeward side of the building. The parallel lines of air movement through the building diverge and converge to indicate how openings constrict and direct air movement.



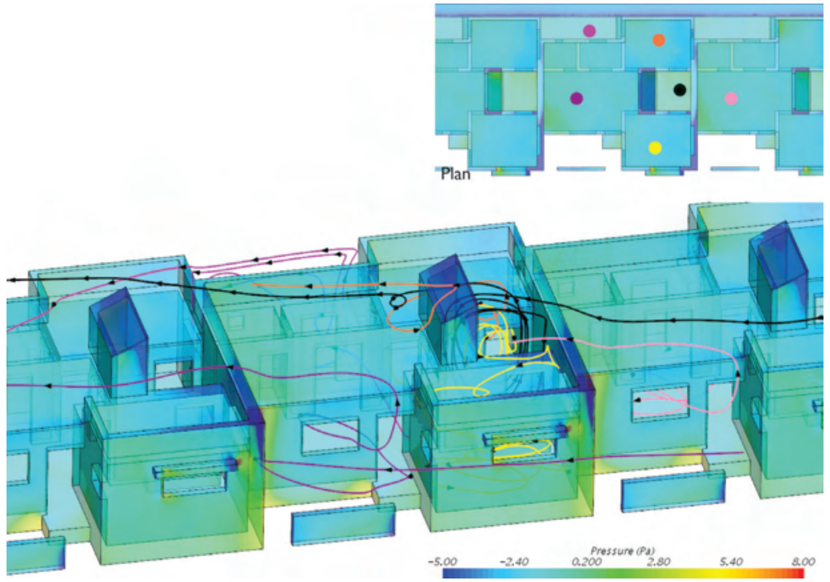
3.14

3.14 Static environmental diagram of a section of the Sidi Krer house pumproom in Alexandria, Egypt. Design by Hassan Fathy. Like many static building ventilation diagrams, airflow is indicated as a series of parallel and slightly diverging continuous lines. Drawing based on Hassan Fathy. Redrawn by Saman Soltani, 2022.

Sometimes the arrow is singular, expanding and contracting in width to denote variations in movement. Other times, the arrows scatter and move like a swarm along the route of hypothetical air movement.

Computational fluid dynamics software offers several settings for rendering outputs, but in most cases, air movement is represented as a vector field or as continuous streamlines. Pressure and temperature differences are indicated through colour gradients often using the same spectrum of colours, which can cause confusion if not properly labelled. At times, these arrows and gradient contour plots converge in a single drawing. Axonometric views give a sense of air movement three-dimensionally but, depending on the view, it can be difficult to spatially correlate flow patterns through spaces (Figure 3.15). A commonality in all these representations is the ubiquity of the vector. Architectural Historian David Gissen has critiqued the almost exclusive reliance on the use of the vector field to represent intensities, forces and fluxes associated with environmental flows. He states:

> Such an environment-idea appears as a sack of quivering data. It contains a pronounced present-ness via the language of physical forces and information, whether we examine the air over a 19th century city, the path of ice in the arctic, or the exchange of capital in the beginning of the 21st century. Many architects imagine all of these things – swirling around architecture, impacting architecture and the physiology of its subjects in a totalizing and immediate manner.
>
> (2012, 51)



3.15

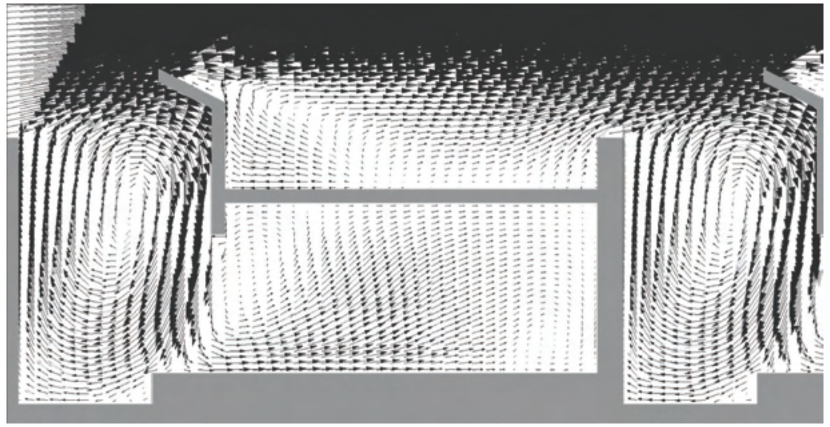
3.15 Computational fluid dynamics (CFD) analysis of airflow through a low-rise residential building organised around exterior courtyards. Pressure intensities are indicated as colour gradients, called contour plots or isocurves in CFD. Vectors indicate the flow path of air through specified rooms and exterior spaces. Courtesy of Kim Adamek, 2022.

Gissen further points out that we have inherited our ubiquitous representational conventions from scientific protocols established in the natural sciences throughout the nineteenth century.

Air movement speed indicated as a vector field, similar to a swarm or grid of wind barbs, draws from traditions in meteorology in the late nineteenth and early twentieth century (Figure 3.16). Passe and Battaglia (2015) note that arrows start appearing on weather maps around 1820. Initially, wind direction was indicated using arrows of fixed length; length of arrow began to correspond to wind intensity in the mid-nineteenth century. Similarly, temperature intensities indicated as topographies or colour gradients, called contour plots or isocurves in CFD, borrow from the language of isotherms, a technique developed by German naturalist Alexander von Humboldt in the early nineteenth century.

Drawings that represent flow as a series of vectors or moving lines are, as historians of science Lorraine Daston and Peter Galison note, idealisations that fundamentally smooth over idiosyncrasies and material nuances of moving fluids. In *Objectivity*, Daston and Galison describe a transition from 'truth to nature' drawn idealisations to 'mechanical objectivity' offered by photography at the turn of the twentieth century (1992). Prior to the widespread use of photography, natural scientists tended towards depicting idealised versions of nature using drawing, etching and paintings. 'Typical was defined in a few ways – either as ideal versions, characteristic exemplars, or averages' (96). These ideals were painstakingly and deliberately constructed, often with the aid of apparatuses such as camera obscura and viewing grids. However, liberties were then applied over these constructed drawings to smooth out imperfection or idiosyncrasies, transforming the observations of many particulars to a single ideal. This active interpretation, definition and recording of what was 'typical' in the natural world marked the honed judgement of the professional.

In contrast, the 'mechanical objectivity' offered by the camera represented the natural world as aberrant and idiosyncratic as made evident through the lens of the camera. Marey's emphasis on precision measure and methodical photographic documentation exemplifies the quest for mechanical objectivity. He so exemplifies it that Galison and Daston begin their lengthy paper by quoting Marey: 'There is no doubt that graphical expression will



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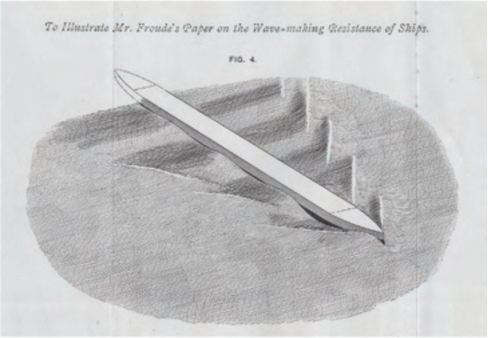

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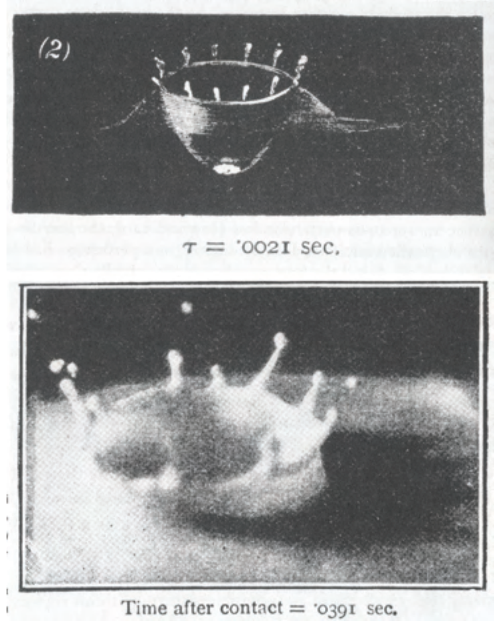


3.18

3.16 Computational fluid dynamics (CFD) analysis of airflow through a courtyard and adjacent interior space. In the two-dimensional section, wind speed is indicated as a velocity vector field organised as a grid. Within the grid, the length of each arrow varies, indicating relative speed. Courtesy of Kim Adamek, 2022.

3.17 William Froude, *Wave System Produced by a Moving Ship*, 1877. Waves patterns of the wake along a moving ship are drawn symmetrically about the ship's central axis. Reproduced from Plate VI in Figure 4 in Froude, W. (1877) in Christoph Hoffmann, 2009.

3.18 Arthur Mason Worthington (top) *The Splash of a Drop, 1895, 4*. (bottom) *The Splash of a Drop, 1895, 44*. The etching imposes symmetries not evident in a photograph of the same process, illustrating Daston and Galison's distinctions between 'truth to nature' drawn idealisations and 'mechanical objectivity' offered by photography. Worthington in Daston and Galison, 2010.

soon replace all others whenever one has at hand a movement or change of state – in a word, any phenomenon' (81). They go on to suggest that

> Others might cry out to salvage the 'insights of dialectic,' the 'power of arguments,' the 'insinuations of elegance,' or the 'flowers of language,' but their protestations were lost on Marey, who dreamed of a wordless science that spoke instead in high-speed photographs and mechanically generated curves; in images that were, as he put it, in the 'language of the phenomena itself'. (81)

Photographs capture the phenomena of air movement in a way that is distinctive from drawn idealisation of the same conditions. Shapeshifting, unpredictable flows resist idealisation. Attempts to impose symmetries or apply consistent regulating geometries result in unconvincing representations. Consider British engineer William Froude's 1877 drawing of perfectly symmetrical wave patterns caused by resistance of a ship moving through water (Figure 3.17). Or consider the imposed symmetry in Arthur Worthington's 'drop splash' 1877 prints in relation to the asymmetrical variations of the same phenomena captured in his 1893–5 photographs (Figure 3.18). Both illustrate how forced symmetry and smoothed-over aberrations, characteristics of drawn idealisations, result in fluid drawings that appear the opposite: frozen.

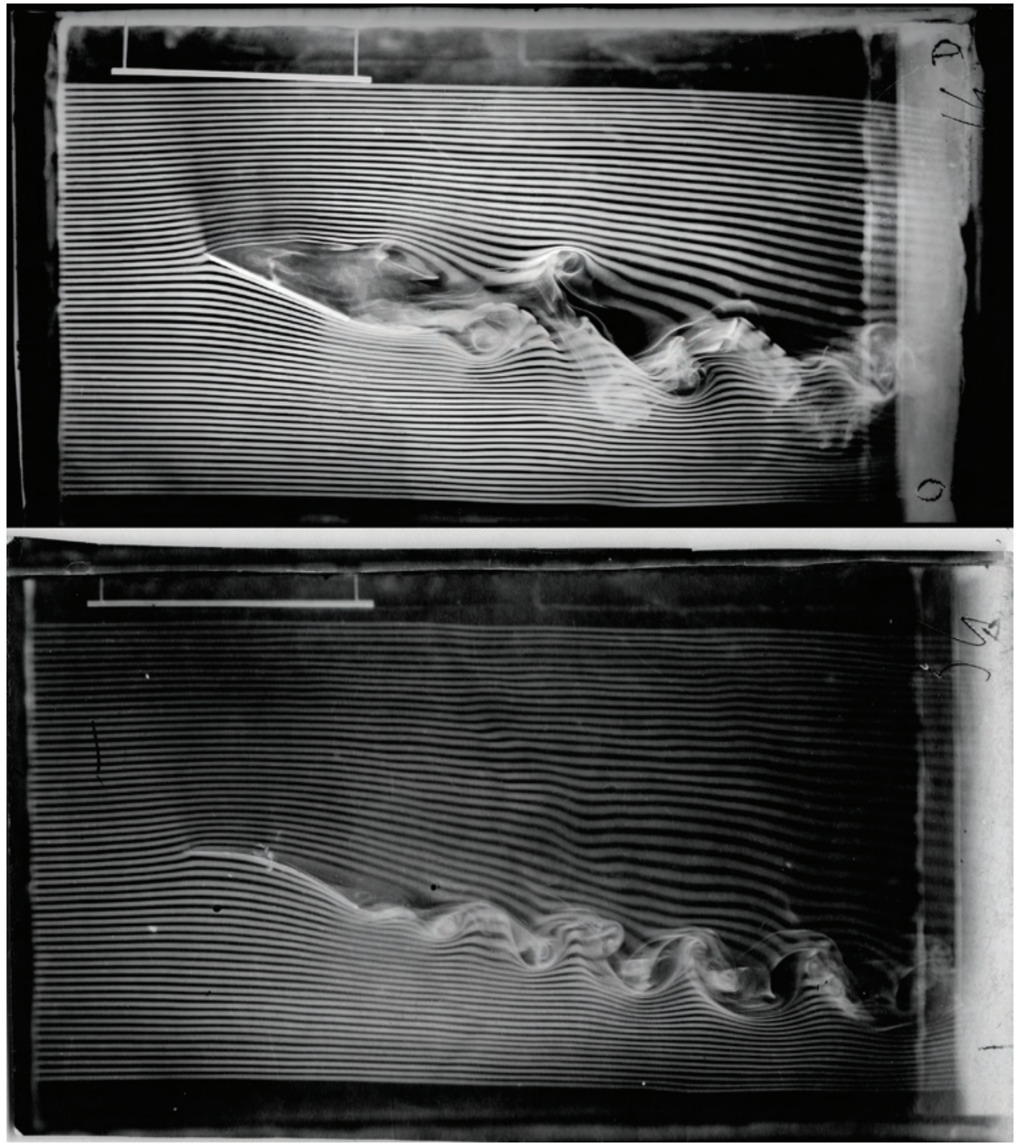
3.19

3.19 German aviation pioneer Karl Wilhelm Otto Lilienthal's streamline drawings hypothesise airflow patterns around a linear and a cambered wing profile. These drawings were published in *Birdflight as the Basis for Aviation*, recognised as the first textbook about mechanical flight. Lilienthal, 1911.

Turbulent flow is erratic and unpredictable, making it challenging to draw in a materially convincing way. Lilienthal's 1896 airplane wing profile drawings sit in contrast to Marey's wind tunnel photographs of the same profiles (Figures 3.19 and 3.20). Both present air movement around a linear and a cambered profile. Lilienthal's drawings become suspect when compared to Marey's photographs of similar conditions. In Lilienthal's drawing, small eddies reflecting turbulence run along the full extent of an angled linear obstruction. Turbulence appears as a continuous band offset from the plane causing it; resultant eddies are equal in size and extent. Marey's photographs depict flow around a similar angled line differently. A low-pressure zone devoid of air movement – a wind shadow – extends into the wake zone of the wall. There are no signs of turbulence immediately above or below the wall. Instead, a vortex trail extends on the leeward side starting roughly midway along the line. Lilienthal's drawings of a cambered line also reflect flow pattern inaccuracies. His drawing indicates that the camber gently redirects flow, which remains laminar throughout. There is no indication of turbulence in the drawing. Marey's photographs of a similar profile, on the other hand, show that while air does deflect continuously along the underside of the camber, there is a separation zone around it and a vortex tail on the trailing edge.

Even flow drawings copied directly from photographs lack the clarity and behavioural complexity evident in photographs of the same phenomena. Marey's flow visualisation contemporary Friedrich Ahlborn often re-drew photographs of his model experiments, presumably to make them more legible. One example shows a drawing of airflow around a rectangular form emerging from the ground (Figure 3.21). The drawing, which re-works a photograph of the same behaviour, is accurate in the sense that it replicates areas of laminar versus turbulent flow made evident through photography of model studies. However, the drawing appears a caricature. Drawing flow as a series of lines reduces complexities of flow patterns evident in the photography – which range from linear to particulate movement and from blurry to focused movement. Attempts to draw moving fluids seem to introduce a different understanding of resistance, a metaphorical resistance that

3.20 Étienne-Jules Marey. (top) *Inclined Plane, 20 Degrees Angle*. Print from glass negative, 10×5 cm. (bottom) *Inclined Curved Surface*. Original paper print, 8.8×5.2 cm. Marey's photographs differ from the hypothetical flow patterns in Lilienthal's drawing, particularly in relation to the turbulent flow patterns in the wake zone of both profiles. Images were mirrored to achieve consistent orientation with Lilienthal's drawings. (top) Inv. MPN 315 (bottom) Fond Noguès no 51/31.

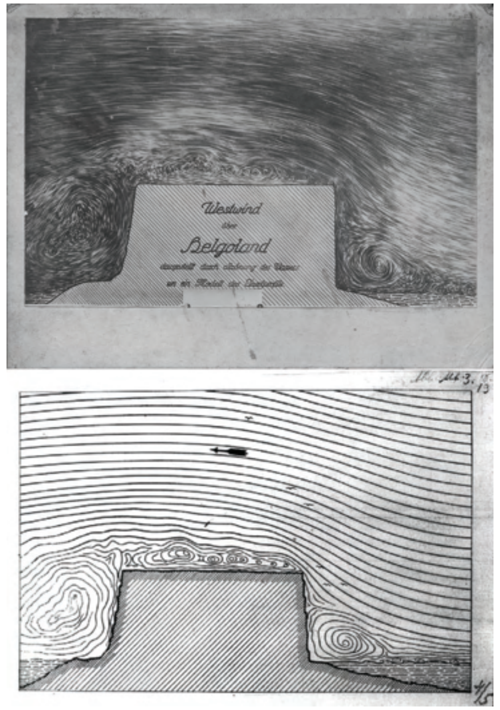


3.20

results from a conceptual misalignment between subject and medium.

Chapter 1 introduced historian of science D. Graham Burnett's distinction between analogical and ontological models. Burnett suggested that one trait of ontological models is that they can cause physical traits 'to be manifest – and hence allow for the revealing, touching, tweaking, or accessing of … the actual forces and stuff at issue' (2008, 44). Marey's photographs enable visual access to the actual 'forces and stuff' at play in relation to pressure-induced airflow around physical obstructions. They do so in a way that is materially distinct from drawing, partly because drawings of flow are often idealisations, but also because there are properties of turbulence that resist being translated into drawn lines altogether.

3.21 (top) Photograph of Friedrich Ahlborn's water table club moss spore flow patterns studying wind patterns at Heligoland. (bottom) Ahlborn's flow-line drawing based on the photograph. Deutsches Museum, Munich, Archive, CD_62749.



3.21

In Marey's wind tunnels, the addition of focused lines of smoke highlights key material distinctions between laminar and turbulent flow. Marine biologist Steven Vogel describes laminar flow as a flow regime in which the 'layers' of fluid 'move in an orderly, unidirectional pattern … more or less parallel to each other in smooth paths … in it, the large- and small-scale movements of the fluid are the same' (1984, 37). In contrast, in turbulent flow, 'fluid particles move in a highly irregular manner even if the fluid as a whole is travelling in a single direction. There are intense small-scale motions present in directions other than that of the main large-scale flow' (1984, 38).[5] Turbulence has the following traits: unsteadiness; three-dimensionality; randomness; dissipation; and irregularity. Its exact form, shape and disposition is nearly impossible to predict. While laminar flow can fundamentally be understood as a linear condition, turbulent flow, which is reflected by chaotic particulate movement, is non-linear by nature. This non-linearity makes drawing turbulence and all its manifestations in a convincing way nearly impossible.

Modelling streamlines

Continuous streamlines are relatively effortless to draw; erratic turbulence is less so. The inverse condition is true when working directly with air as a physical material. In wind tunnels, turbulence is effortless to create; modelling streamlines in a steady-state environment, on the other hand, is immensely challenging. Every disruption to steady flow, constructional defect and disruption beyond the model itself creates turbulence. This section takes a closer look at the mechanics of Marey's wind tunnel and the dialogic relationship between the instrumentation of the wind tunnel and the flow patterns it generates. It shows that while it may be relatively effortless to achieve in drawings, creating continuous, smooth lines in a wind tunnel is nearly impossible, hinting at further material properties of moving air.

Marey's wind tunnels created an idealised, steady-state environment which rarely exists in the real world. In reality, turbulence is everywhere. The swirling atmospheric blanket with its constantly changing states and shifting thermal fronts does not operate as a controlled, continuously flowing steady-state system at any scale of observation. At the planetary scale, there are very few conditions in the atmospheric domain in which laminar flow takes place. There is a very slight laminar boundary layer a few millimetres adjacent to the surface of the ground. However, the atmospheric boundary layer, which can extend several kilometres vertically, is a meteorologically charged zone of turbulence and energy exchange (Oke 1978).

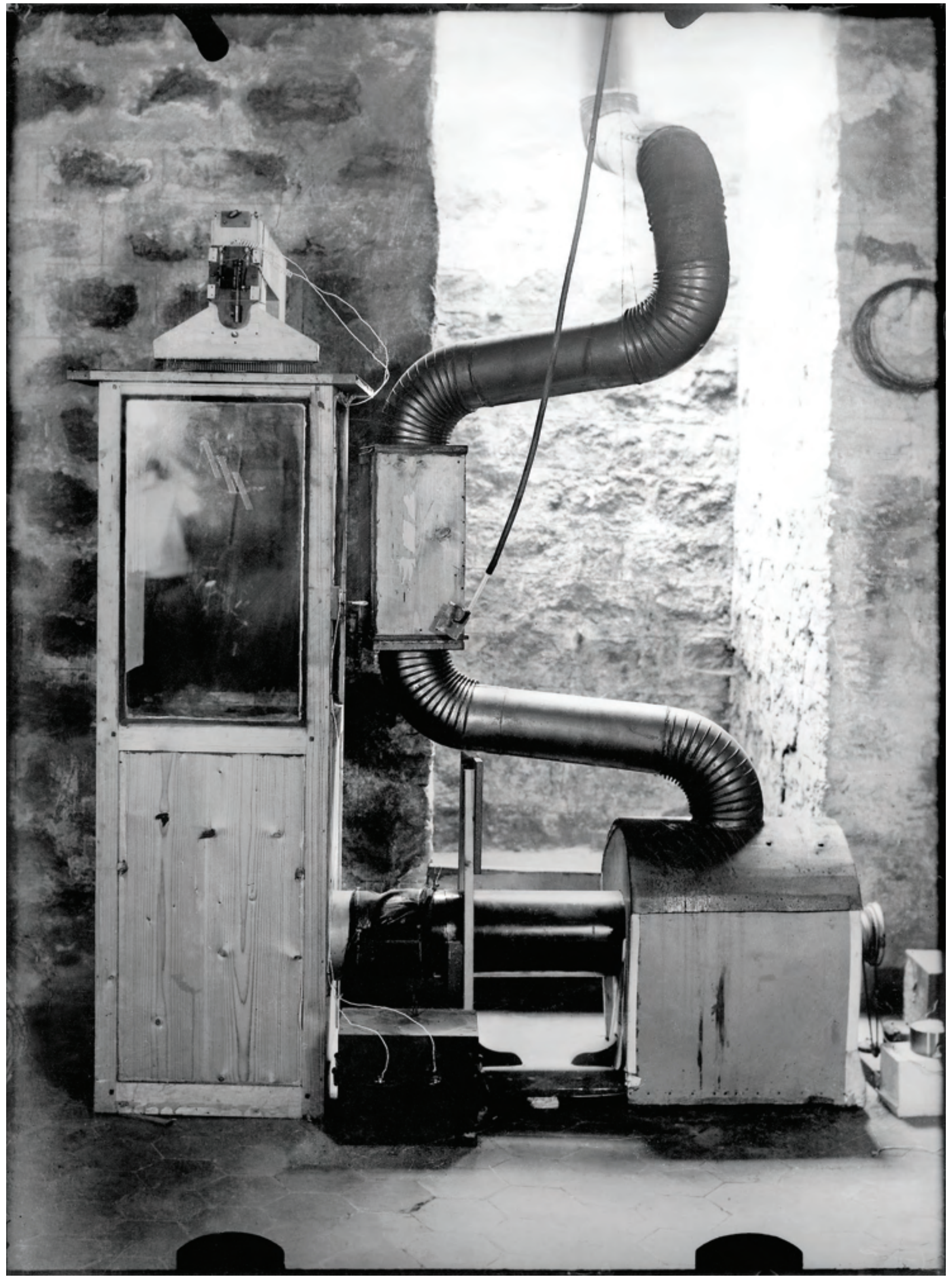
While aeronautics research aims to minimise airflow resistance to facilitate uplift, buildings benefit from building up pressure differentials. Indeed, pressure-induced ventilation strategies such as cross-ventilation are reliant on buildings acting as deliberate obstacles to air movement. Obstacles create differentials, which drive flow. Buildings designed to facilitate passive ventilation are deliberately not 'streamlined' design artefacts intended to minimise air resistance, but are the opposite – bluff bodies, or obstacles intended to build it up. Building ventilation experts Ulricke Passe and Francine Battaglia press this point:

> In the context of atmospheric air flow, every building can be considered an obstacle to the local and regional scale of the wind system. The air has to move around the obstacle or through the obstacle, and the shape of the building as well as its orientation and position influences the flow pattern around and through the building. The building builds up resistance against the flow, and this resistance results in the necessary pressure differential to force the flow of air through a building following the designed flow path.
>
> (2015, 83)

Marey was aware of the paradox of creating a steady-state interior environment to represent a disrupted exterior one, noting that 'it is hardly possible, indeed, to study the resistance encountered by the body subjected to a steady and known wind speed; only powerful blowers could meet these requirements, which hardly exist in atmospheric movement' (Marey 1890, translated in Ramirez 2013). Each of Marey's successive wind tunnels comes closer to creating this paradoxical steady-state interior, marked by continuous lines of smoke.

Marey completed his first wind tunnel prototype in 1900. The first three versions, which incorporated 11, 13 and 21 tubes, respectively, to disperse smoke, required fine-tuning both in the workings of the apparatus and in the photographic techniques used to capture their effects. They pushed air through the testing bed, causing unnecessary turbulence. The final wind tunnel incorporated 57 tubes within a 152 cm × 61 cm × 90 cm section lined on three sides with glass and with black velvet on the fourth (Figure 3.22). This iteration

3.22 Étienne-Jules Marey. *Photo of the Smoke Machine*, print from glass negative, 12×9 cm. Marey's final wind tunnel appears as a mechanical assemblage of wooden boxes, exposed wires, cables and flexible ducts. It is, however, best understood as a sensitive environmental instrument, a device easily prone to disruption. Inv. MPN 102.



3.22

drew air through the testing chamber. Smoke produced by burning tinder was fed into the upper air chamber and drawn into the glass chamber through the 6 mm diameter tubes, which were distanced 6 mm apart. The smoke was then drawn through fine silk gauze with equal warp and weft, which straightened the air currents before they were let into the chamber via an aspirating ventilator that drew air to the other end of the chamber.

The wind tunnel was integrated into an existing chimney in the Institut Marey in Paris, using it to exhaust smoke and magnesium fumes. Enrique Ramirez has explored the architectural implications of this move, likening Marey's wind tunnel to an experiment with mechanical ventilation (2013). Wind tunnels are sometimes defined as ducts, and they act as such, containing, capturing, speeding up, straightening and directing air movement through the testing bed. Ramirez refers to the separate chamber of the testing bed as a 'glass chimney', suggesting that it adds 'another "layer" that separates the air produced inside the device from the rest of the Institut. This layer was one of representation' (199). The wind tunnel was a machine for ventilation and a viewing portal into an environment in miniature.

It is hard to reduce environmental models to a single word. In the most reductive sense, wind tunnels have been described as ducts, tools, devices, apparatuses, experiments, machines and facilities. In my working definition of environmental models, I refer to the overall assembly intentionally as instruments, drawing from insights revealed through Marey's work and my own prototypes. This term may seem counterintuitive when viewing Marey's final wind tunnel. In photographs, it appears a robust, somewhat clunky, assembly of wooden boxes and flexible ducts, making the connection to a mechanical system more apt. Solid, rectilinear and vertical, it also appears more akin to cabinetry than to one of his earlier graphic method instruments. The assembly sits in stark contrast to delicate wisps of curling smoke that it generates. To fully appreciate the workings of the wind tunnel requires seeing it less as a robust assembly and more as a sensitive machine with highly calibrated componentry.

A look to Marey's finely tuned graphic method instruments yields important insights about challenges of creating the steady-state condition constructed within the wind tunnel testing bed. Marey's graphic method instruments were delicate and prone to disturbance. As noted earlier, slight frictions and resultant inertia in the transcription devices of Marey's early instruments could cause significant distortions in the resultant transcriptions, making the detached camera an appealing alternative recording device (Hinterwaldner 2015). Working with smoke as a drawing medium proved equally, if not more, sensitive to external disruption. The *Scientific American* article featuring Marey's wind tunnel noted that it too required stasis to operate properly:

> When the ventilator is set in motion the air is aspirated and draws with it the smoke, and the latter descends in a series of vertical cords which may reach as long as three feet if the air of the room is perfectly still. This is not always easy to realize as often the movements of the operator are sufficient to cause a perceptible deflection of the air-currents.
>
> (Anonymous 1902, 75)

So sensitive was Marey's wind tunnel that even the slightest disturbance, such as the movement of the operator, would disrupt the steady-state interior (Figure 3.23). For the wind tunnel to operate as intended, the air in the room in which the tunnel sat had to remain 'perfectly still'.

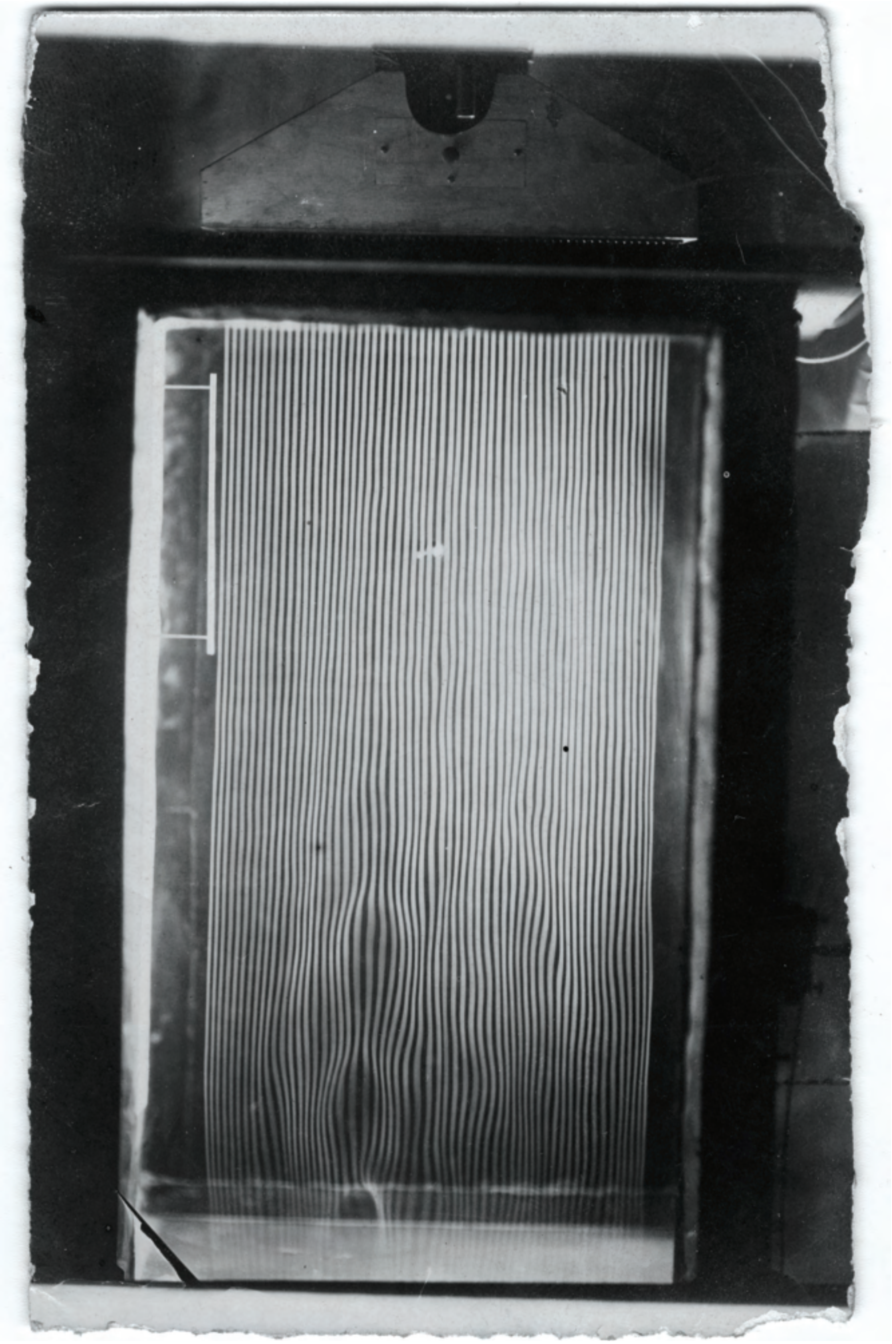
Just as his 'pulse-writer' sensitively transcribed subtle differentials of blood pressure as a series of lines on paper, the wind tunnel registered the unintentional blips caused by external disruptions as deviations in the steady smoke streams. In the wind tunnel, the 'transcribing device' which transferred external disruption into the testing bed was air in the form of vibrations transferred through the base of the wind tunnel to the testing bed. Moreover, despite the physical distance that the camera offered, flash photography and the heat caused by permanent illumination altered air currents too much.[6] When viewing Marey's wind tunnel as a full-scale construction, it is best understood as a calibrated instrument prone to disturbance.

The wind tunnel is an instrument in dialogue with phenomena of air movement. Like buildings, wind tunnels are fundamentally mediation devices. I have traced some of these mediating, or in-between, conditions throughout this chapter. The wind tunnel was neither a graphic method instrument nor was it recorded using chronophotography, yet it clearly drew from insights revealed through both techniques. Carefully calibrating air behaviour to create a steady-state field, it oscillates between conceptions of air as force transmitter and air as a field of resistance. The wind tunnel was a physical construction that translated a vast domain into a flat two-dimensional field, caught somewhere between a model and a drawing. It generated an interior steady-state condition as a representation of an exterior variable one. It was held somewhere in between exterior and interior, integrating itself into an existing chimney to exhaust smoke, while being reliant on an entirely undisturbed interior to operate smoothly.

From streamlines to streamlining

Marey's wind tunnel and associated photographs establish flow visualisation as a process of negotiation between air materialised through the addition of smoke, finely calibrated wind tunnel components and external disruptions that impact steady-state conditions. Analysis of Marey's photographs hints at airflow's extreme sensitivity to both constructional anomalies and external disruption. It was not, however, through a careful review of Marey's work that these insights were initially revealed to me. They were revealed, instead, through the iterative process of designing, making and operating wind tunnel and water table prototypes that drew from Marey's work. It was only through attempting to emulate the striking visual effects in Marey's smoke-stream photographs that an appreciation for them as physical achievements emerged.

3.23 Étienne-Jules Marey. *The Machine in Operation but Without Obstacle*, original paper print, 12×7.7 cm. Slight deflections in the lower third of the trailing lines likely reflect external disturbances that have been transferred as vibrations through the wooden casing into the testing bed interior. Inv. Fonds Noguès no 12.



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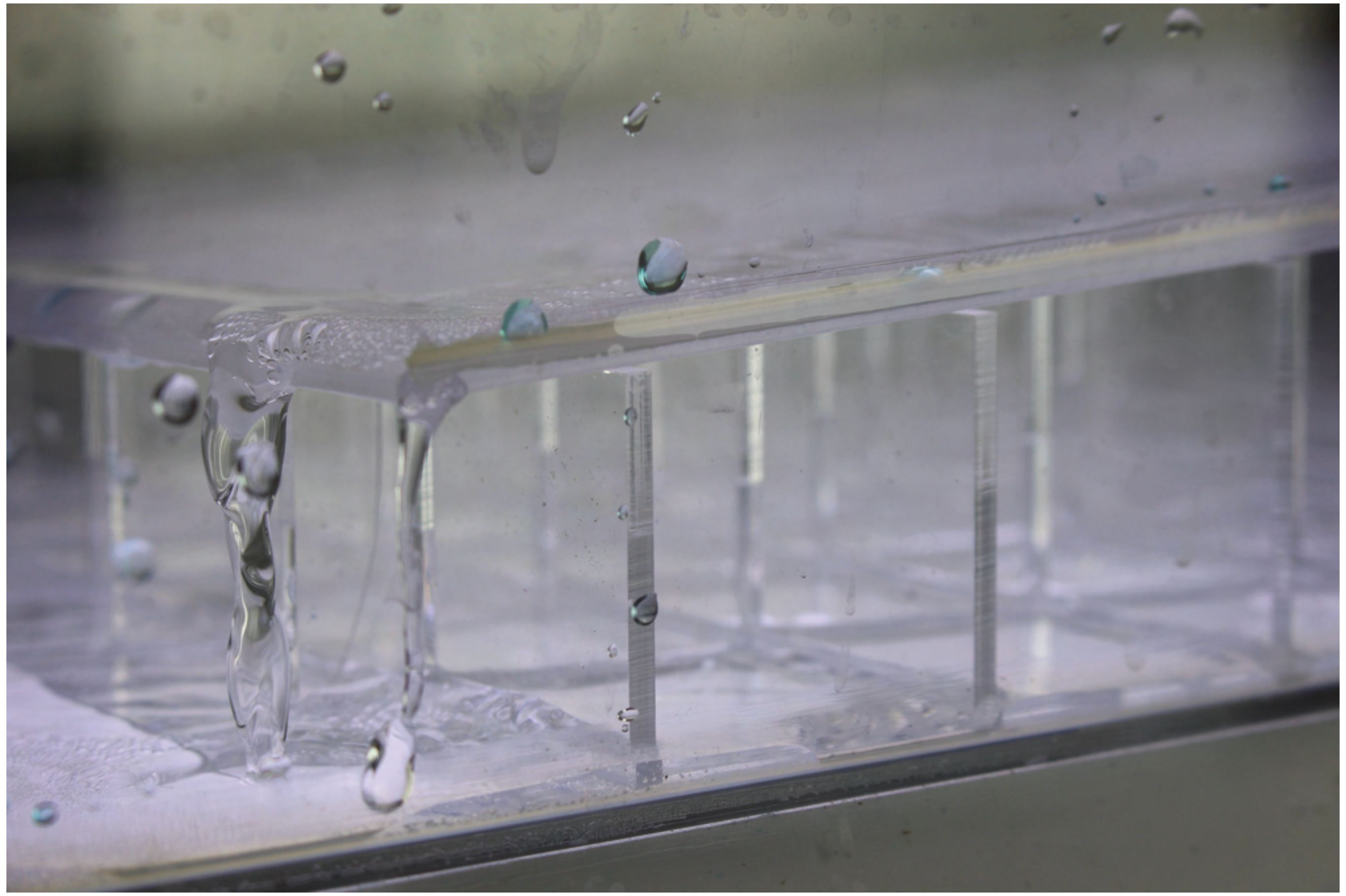


3.24

3.24 Detail photograph of water table four (WAT4). Working with air and water as constituent design materials necessitates tight-tolerance construction to prevent either deflections caused by tight fits or gaps caused by loose fits.

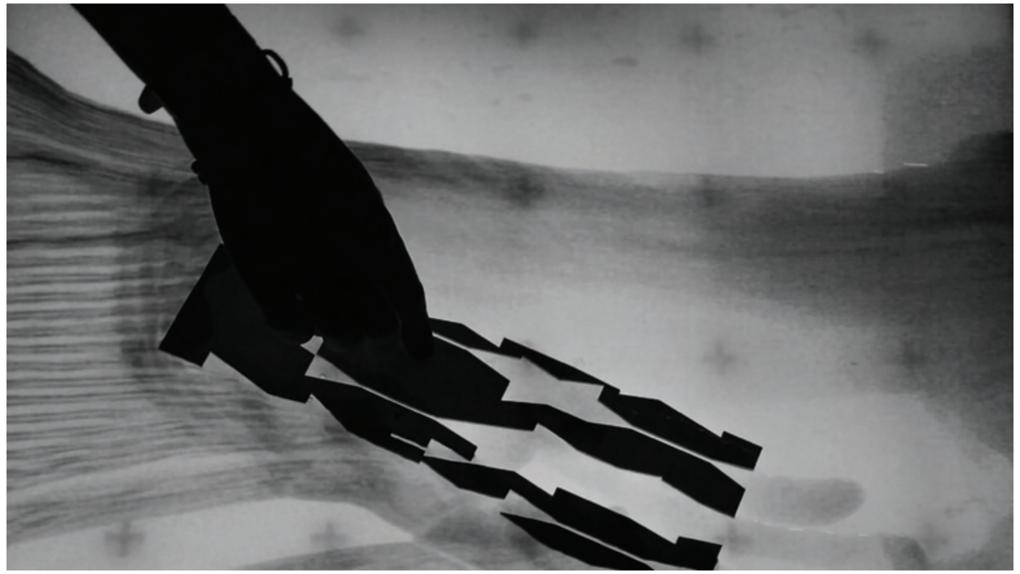
My first wind tunnel and water table prototypes began roughly in parallel, and they share similar design trajectories. Both adapted DIY and engineering resources using architectural tools and techniques. Wind tunnels and water tables were both prone to disruption, which necessitated an increased focus on establishing stability. The level of precision required to construct a watertight or airtight vessel far surpasses that required for conventional architectural models, where subtle gaps or misalignments have a negligible impact (Figure 3.24). As a result, the prototypes transitioned from carpentry methods of construction, initially more visually akin to Marey's wind tunnel, to digital fabrication, which offered increased precision. Both diminished in size to cope with material deflections and gaps that disrupted achieving a steady-state interior. Finally, the two model types became increasingly reliant on and integrated into existing workshop infrastructure for support.

As presented in Chapter 2, I initially assessed the prototypes according to their ability to create a steady flow field made evident by continuous smoke or dye streamlines. This goal was continually stymied, validating the significance of Marey's work. Over time, I focused attention on details of vulnerable joints and seams, developing a tectonic approach informed by the trial-and-error process of design and construction. These two variables – the development of a steady-state condition and that of a clear tectonic logic – are not independent. They are in fact deeply intertwined, reflecting the deep reciprocities between instrument and phenomena. Solidity, stability and precision of model construction enabled the construction of steady, visible flow fields.

There were also differences between the prototyping trajectories of the wind tunnels and water tables. It became evident early on that visualising steady streamlines was far more achievable in water than in air. As a result, achieving legible, steady flow – visible through streamlines – became the key focus of water table prototypes (Figures 3.25–3.28).

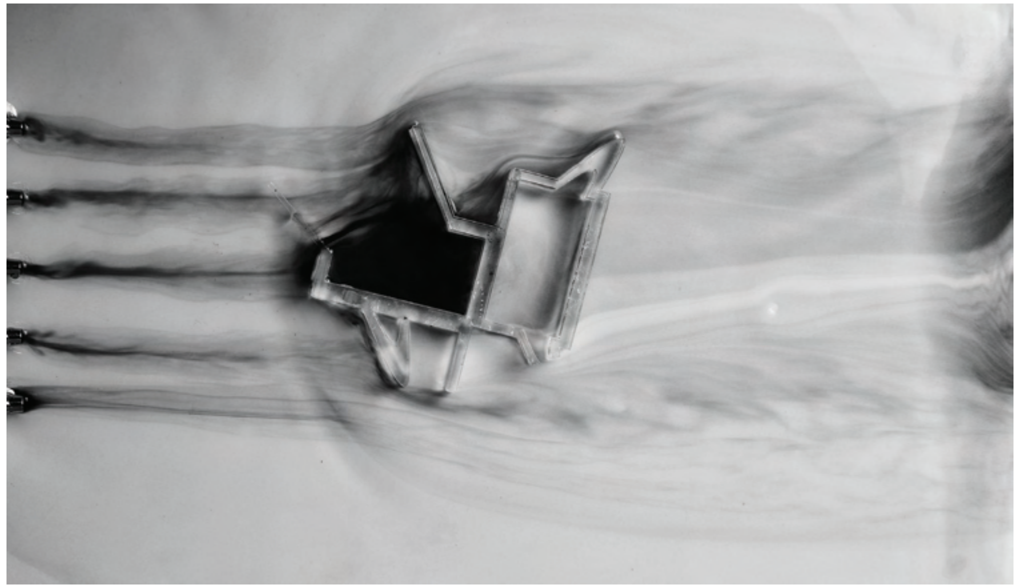
Water acted as a measure of constructional defects. It registered even the slightest gradient shift and deflection. It flowed through the finest material gap. In the first prototype, dye streamlines highlighted two key constructional failures: surface deflection, causing water to pool towards the centre, and leaks at seams caused by poor sealant. The material surface was too thin to span the testing bed without deflection and its reliance on multiple support points and edges compromised establishing a consistent, level surface. Subsequent prototypes became

3.25 Video still extract of flow visualisation in water table prototype 1 (WAT1). Water table prototypes were assessed according to their ability to create steady streamlines of ink dye. The surface of WAT1 deflected substantially, causing water to pool to the centre.



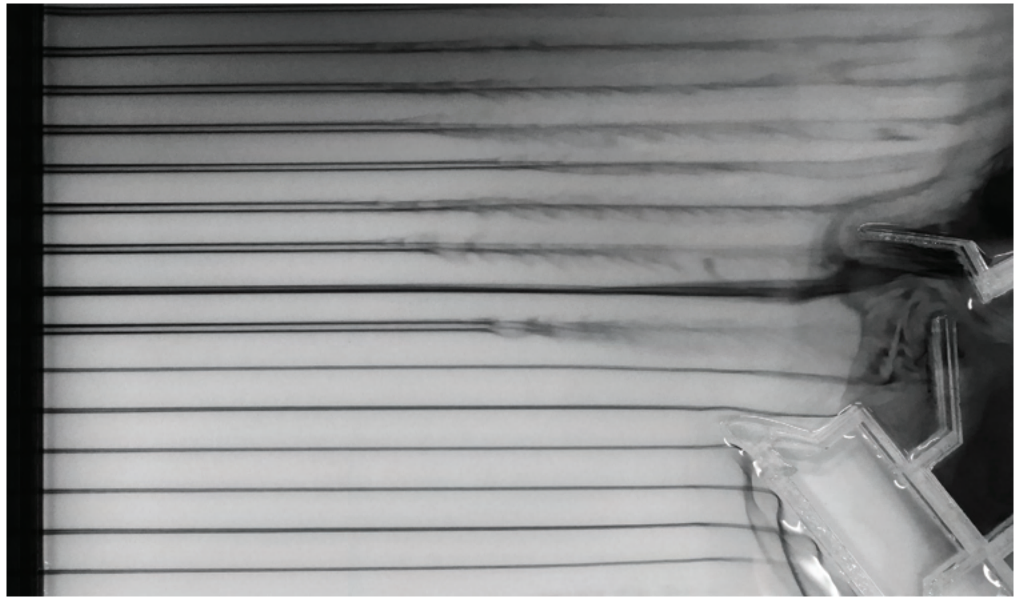
3.25

3.26 Detail photograph of flow visualisation in water table prototype 2 (WAT2). The second prototype diminished in size, reducing material spans and resultant deflections. However, diffuse and irregular dye patterns reflect turbulence generated by the inner profile of the dye dispersal nozzles.



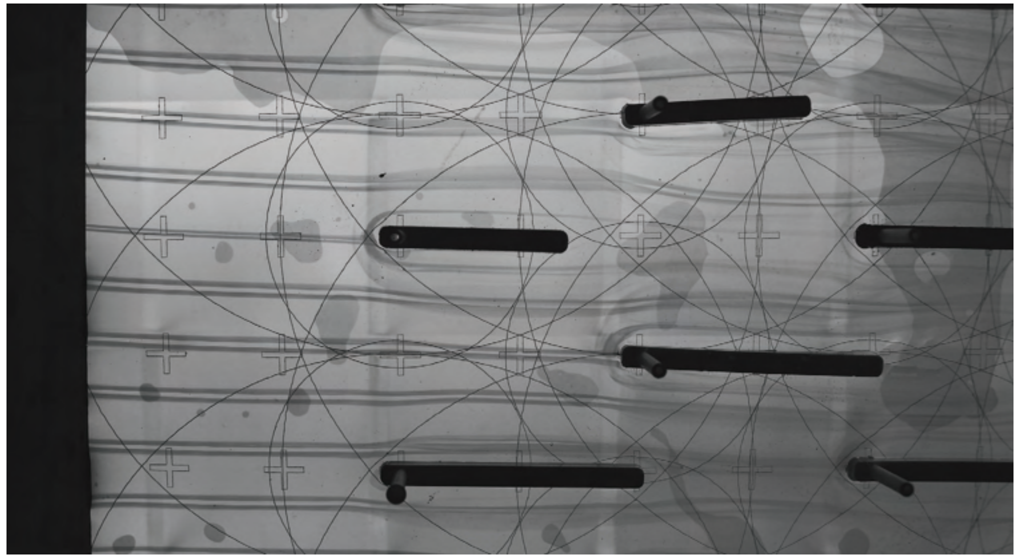
3.26

3.27 Detail photograph of flow visualisation in water table prototype 3 (WAT3). The third prototype succeeded in creating a surface of steady streamlines. The effect was brief – a function of the limited capacity of the ink reservoir – and the streamlines degraded slightly along the testing surface. Nevertheless, the generation of steady flow was a success that seemed increasingly impossible to achieve.



3.27

3.28 Detail photograph of flow visualisation in water table prototype 4 (WAT4). The final prototype incorporated a light table below and a translucent surface to eliminate reflections from overhead lighting, returning to insights learned from WAT1. However, water leaked between the model surface and the testing bed, compromising visibility.



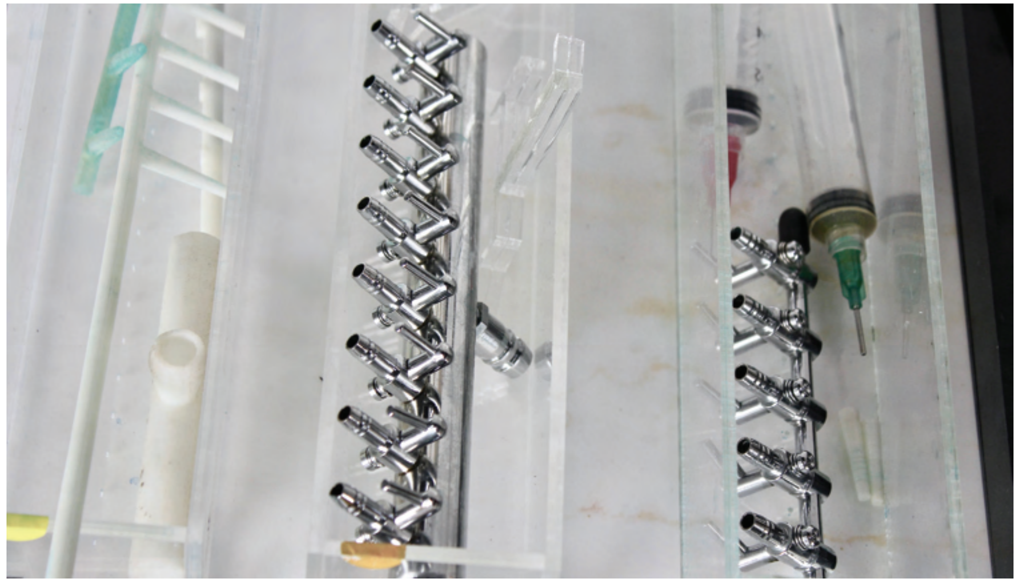
3.28

more diminutive to reduce spans and constructional tolerances. A series of both off-the-shelf and custom fabricated components were developed to disperse dye lines, but these too disrupted flow (Figures 3.29 and 3.30).

The prototypes became increasingly integrated into workshop infrastructure, relying on utility sinks for support, water source and drainage. The third prototype successfully created a steady-state surface of streamlines, an achievement that had seemed increasingly beyond grasp. However, water continued to act as a measure of constructional anomalies. In the fourth and final prototype, which incorporated underlighting to counteract light reflections on the surface of the water, water again pooled along deflections and leaked through gaps (Figure 3.31). Focus shifted from the thin moving sheet of water on the top surface to the grid of slowly rising and falling tables of water below (Figure 3.32). It is impossible not to read these effects spatially as an eerie underworld of glowing, watery chambers inviting inhabitation.

The wind tunnels developed along a different trajectory, progressing from creating legible streamlines of smoke to creating a streamlined interior. The idea that the reduction of air friction on a moving object other than an airplane might impact its form prompted the Machine Age streamlined design style in the 1930s. No designer better articulated the streamlined agenda than industrial designer Norman Bel Geddes (Figure 3.33).[7] For Bel Geddes, streamlining merged technical interest in optimising vehicular performance through aerodynamic design principles, with creating a newfound aesthetic that represented an image of progress and aspiration. Of course, this principle applied to the exterior

3.29 Photograph of devices used to distribute dye on the water table surfaces, each of which presented challenges in generating continuous streamlines. Devices included stainless-steel aquarium airflow splitters, custom 3-D printed nozzles, syringes and troughs with integrated holes of varying diameters in the base.

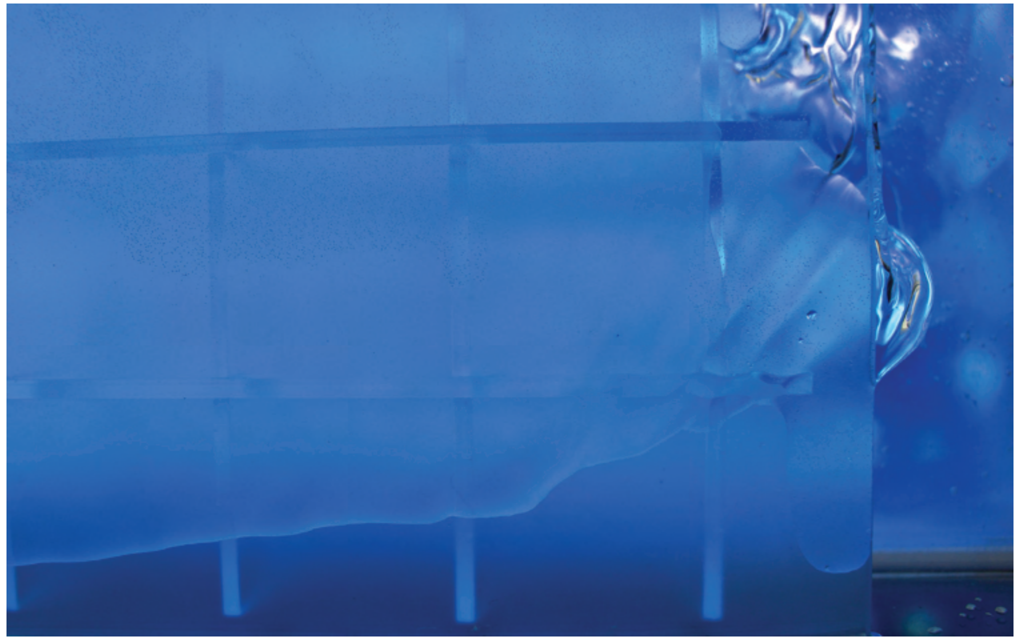


3.29

3.30 Detail photograph of flow visualisation in water table prototype 2 (WAT2). Dye dispersed through aquarium airflow splitter nozzles generated fuzzy paths caused by the irregular inner profile of the nozzles.

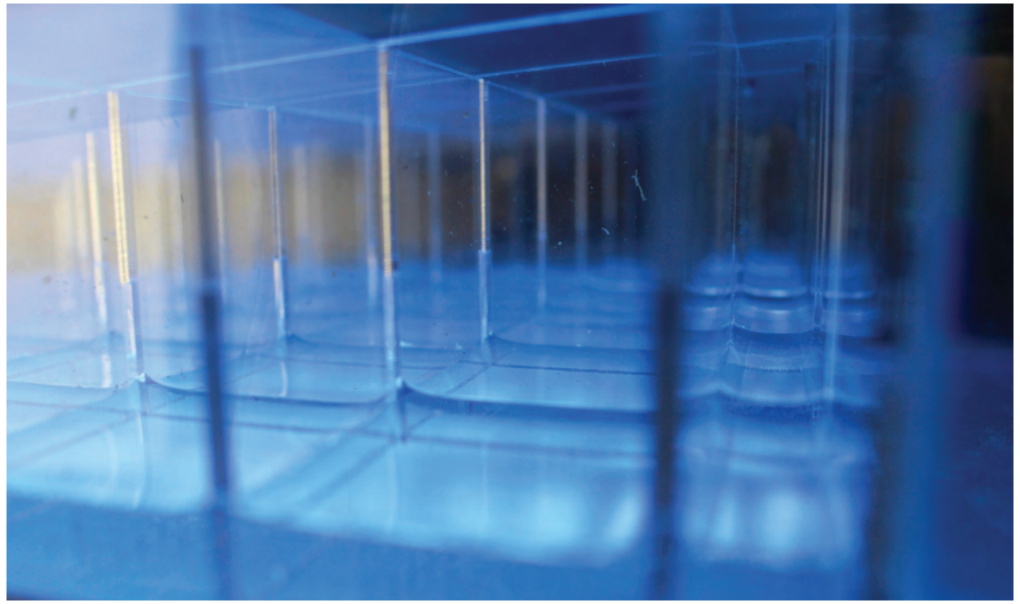
3.30

3.31 Detail photograph of WAT4 testing surface. Each consecutive water table was a refinement of the one before. However, calibrating a watertight device that generates a steady sheet of water requires levels of precision not generally necessary in architectural models. The surface of the final prototype again deflected at the edges, causing water to pool towards the centre.



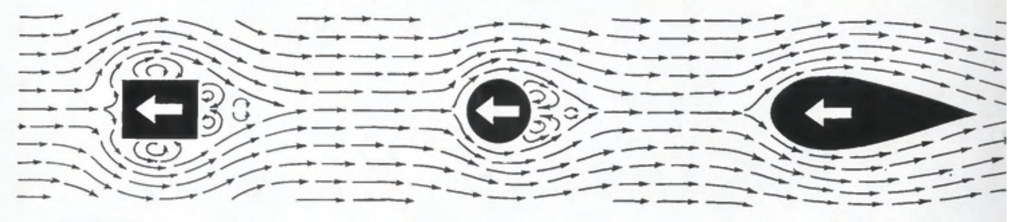
3.31

3.32 Detail photograph of the undercarriage of WAT4. Water leaked through faulty seams on the testing surface into the undercarriage below, gradually flooding the gridded cells at different rates, drawing attention to the ethereal, glowing underworld.



3.32

3.33 Industrial designer Norman Bel Geddes's diagram illustrating the principles of streamlining. Bel Geddes popularised the term in the 1920s, initially using the concept to design vehicles that increased fuel efficiency by reducing air resistance. Bel Geddes, 1932.



3.33

3.34 Photograph of studio as it accumulated prototype componentry. In contrast to the water tables, early wind tunnel prototypes failed to produce legible airflow patterns. Focus instead shifted to developing a more coherent detailing and material strategy for the expansion and contraction cones, seen pinned up on the wall and in the back corner of the studio.

3.34

forms of designed objects. In my prototypes, the logic of streamlining applied to the interior instead as all physical obstructions and supports were externalised to ensure continuous, even flow in the testing bed.

Initial wind tunnel prototypes placed more attention on individual components than on how those components connected or retained stability both independently and as a composite assembly (Figure 3.34). The first prototype was marked by awkward material intersections and instability (Figures 3.35–3.38). The second prototype, designed initially as a digital model, appeared to levitate within the digital environment (Figure 3.39). In

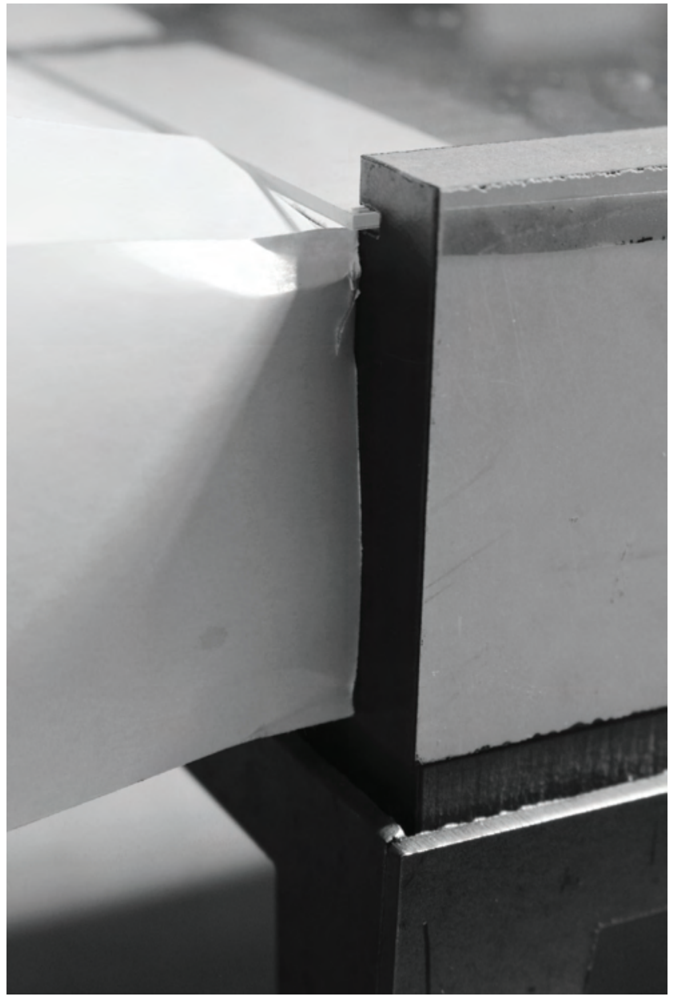
3.35

3.36

3.35 Photograph of the first wind tunnel prototype. Lacking a coherent constructional strategy, the first wind tunnel was unwieldy to assemble and to operate.

3.36 Detail photograph of WT1. Large expansion and contraction cones on either end of the testing bed were difficult to manoeuvre and to secure into place. Constructed of large, thin sheets of single-coated poster board, the cones deflected under their own weight, requiring inner supports that generated turbulence through the cone. Receiving tabs were prone to tearing at intersections.

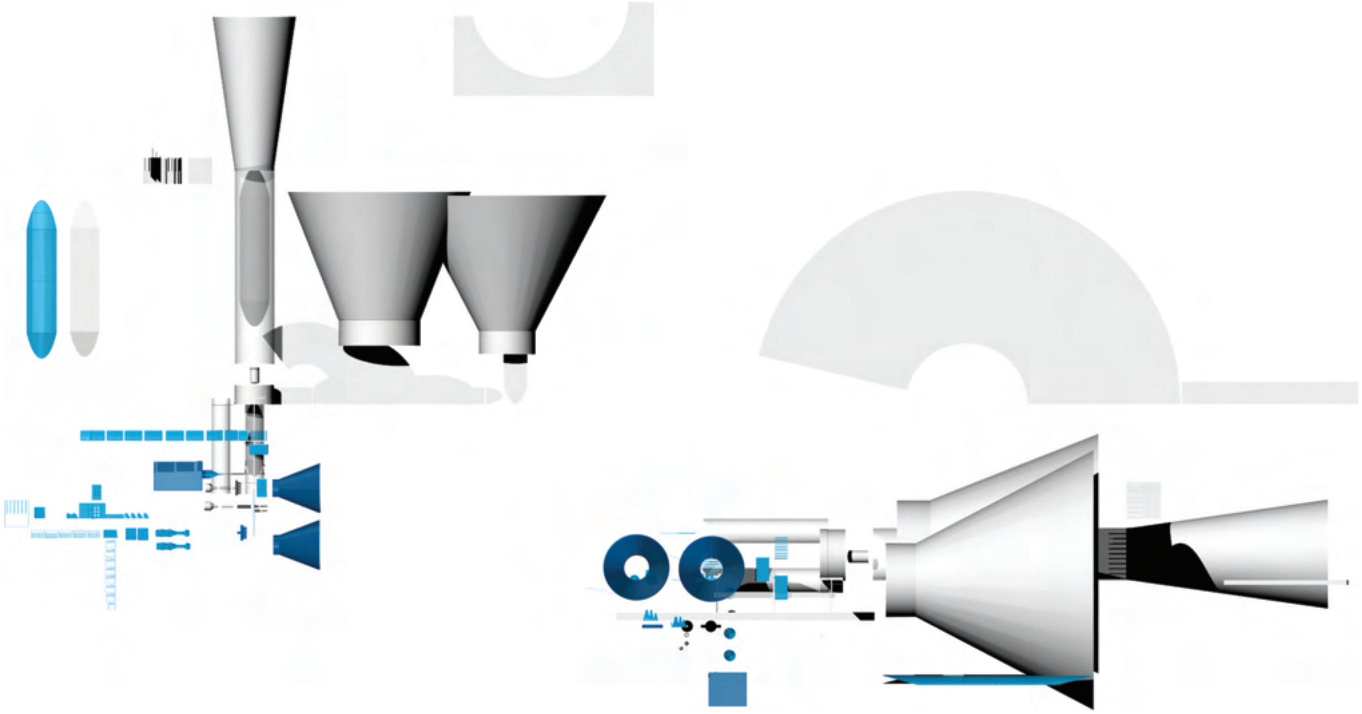
3.37



3.38

3.37 Detail photographs of WT1. The intersections between expansion and contraction cones and the testing bed were tenuous due to the varying geometries of the cones, testing bed and support base. A combination of manual and digital fabrication methods resulted in imprecise connections and awkward, force-fitting of components.

3.38 Detail photographs of WT1. A combination of manual and digital fabrication methods resulted in imprecise connections such as this intersection between crushed contraction cone and the testing bed.



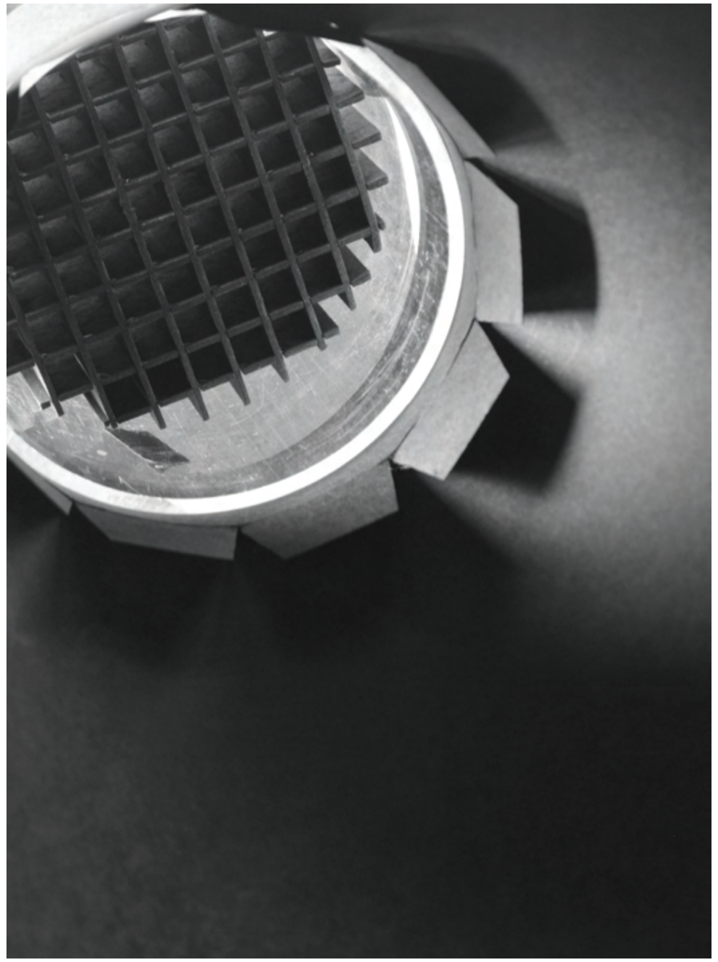
3.39

3.39 Digital drawing of WT2. To increase componentry fit and overall precision, WT2 was designed as a three-dimensional model. Incorporating a cylindrical, rather than rectangular, testing bed ensured smooth transitions between components.

its physical manifestation, it too visually hovered, relying on consistent smooth-fit lapped joints for continuity (Figures 3.40 and 3.41).

The final prototype, with gasketed joints, incorporated insights from the first and second. On the one hand, it relied on interior streamlined construction practices to ensure smooth material and geometric transitions and equal distribution of forces. On the other hand, it responded to gravitational forces and sensitivity to exterior disturbance through a material assembly that anchored and provided stability (Figures 3.42–3.45). In that way, the final wind tunnel prototype is also caught in between, in this case in between aeronautics and architecture. It is akin to an aircraft constructed inside out, creating a continuous, smooth, interior (rather than exterior) surface to reduce air resistance. It visually hovers in space as a series of smoothly transitioning geometries while also remaining solidly grounded, requiring anchoring and rigidity for stability.

Environmental models make the 'non-visual phenomena object' of airflow legible through careful negotiations between solid material vessels and componentry that carefully contain, alter and direct fluid movement. They enable visualisation of laminar and turbulent flow regimes and the crucial transitions between the two. They create steady-state interiors as a



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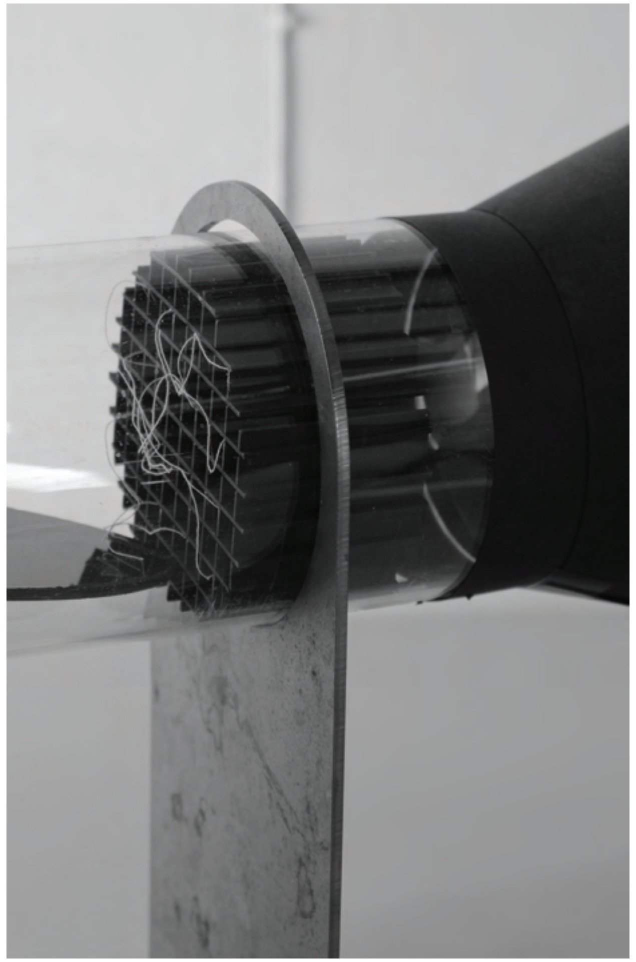


3.41

3.40 Detail photographs of WT2. The second wind tunnel became more diminutive and developed a clearer tectonic strategy, relying on lapped joints and friction-fit components.

3.41 Detail photographs of WT2. Externalised steel frames offered support and ensured that the interior remained free of additional elements which can disturb steady interior airflow.

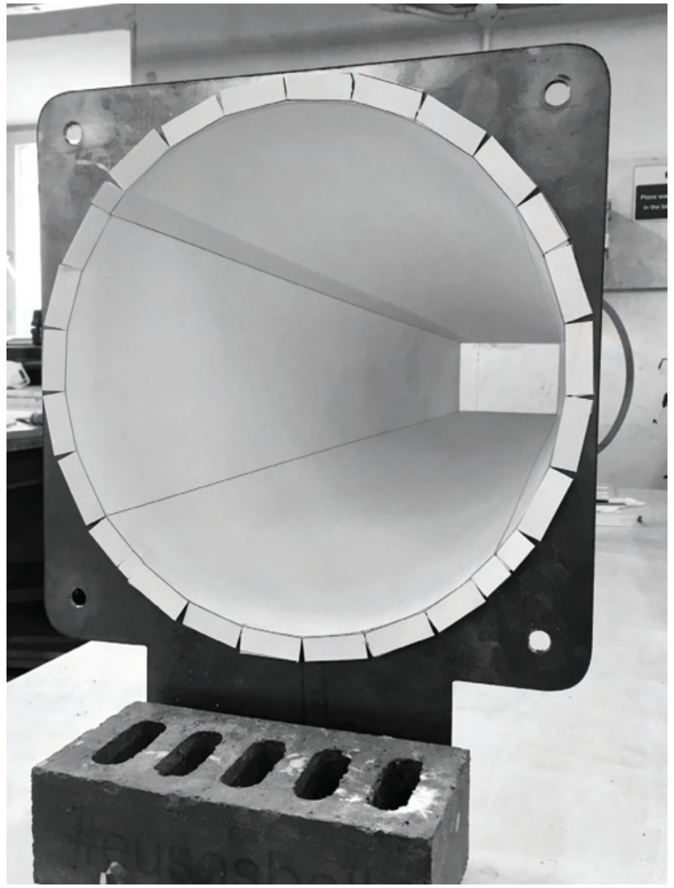
3.42

3.43

3.42 Detail photograph of WT4 steel frame support system. The final wind tunnel returned to the size of the original but relied on a consistent detail at the intersections for stability and coherence.

3.43 Detail photograph of WT4 steel frame support system. Doubled-up exterior frames with gasketed joints clipped together seamlessly receive each component. Frames were attached to a table base to reduce internal disturbance from beyond the testing bed.

3.44



3.45

3.44 Detail photograph of WT4 intersection between a steel frame and contraction cone. A steel ledge received the testing bed.

3.45 Detail photograph of WT4 intersection between steel frame and the fan side of the expansion cone. Transitions between all components in the interior were obstruction-free, ensuring the interior is streamlined.

starting point to replicating exterior conditions that are chaotic. Resisting a singular identity, they share characteristics with instruments, mechanical assemblies and building infrastructure. They are both full-scale artefact and scale models, both representations and simulations. It is these many conditions, or rather the oscillations between them, that make them fertile tools for design speculation.

Notes

1. Michelle Addington (2007) provides a thorough account of the development of CFD and some of the particular challenges of using CFD analysis on buildings at that time. Ulricke Passe and Francine Battaglia (2015) also note that thermodynamic principles are notoriously complex, and that modelling thermal exchanges between solid materials and airflow is computationally intensive. Kiel Moe has also offered critiques of computational fluid dynamics (2010). Wind engineers such as Blocken (2014) and Phillips and Soligo (2019) give more technical accounts of challenges associated with using CFD to visualise airflow around and through buildings.
2. In a 1901 article in *La Nature*, Marey notes: 'One may easily conceive the multiplicity of problems that may be solved by this method. We have described it in detail, so that it may be used by all those who are concerned with aviation, propelling in fluids, ventilation, all things related to movements of air' (cited in Musée D'Orsay 2005).
3. The linear cords of smoke in Marey's wind tunnel are referred to as streamlines throughout this chapter. In physics, streamlines describe the overall motion of a flow field for use in flow calculations. The lines of smoke in Marey's wind tunnel are technically referred to as filament lines (also referred to as a pathlines). In steady flows, streamlines are the same as filament or pathlines.
4. In the built environment, obstacles and surface roughness characteristics generate a very unstable boundary layer, particularly when compared to those in open, rural areas. More recent wind tunnels used to study airflow around buildings are called atmospheric boundary layer (ABL) wind tunnels, and they replicate the roughness factors of the urban environment to facilitate more accurate flow patterns.
5. In 1883, Osborne Reynolds noted this distinction by observing how water currents altered depending on speed of flow in pipes. Reynolds determined basic rules for transition between laminar and turbulent flow and developed the Reynold's number, which enables experiments in water to be transferred to understand movement of air.
6. The sensitivity of Marey's wind tunnel was not a function of constructional defects. It was an open-circuit tunnel, as opposed to a fully contained closed-circuit tunnel. All open-circuit wind tunnels are easily disturbed by conditions beyond and within the wind tunnel itself. They can be impacted by draught and physical obstructions in the same room; they are also prone to destabilising leaks associated with perforations for sensors or flow visualisation elements (Bradshaw and Pankhurst 1964).
7. Bel Geddes's 1934 *Atlantic Monthly* article 'Streamlining' outlined the history of streamlining as a fluid dynamics concept and elaborated on how this scientific concept inaugurated a design style.

Chapter 4 | Climate control

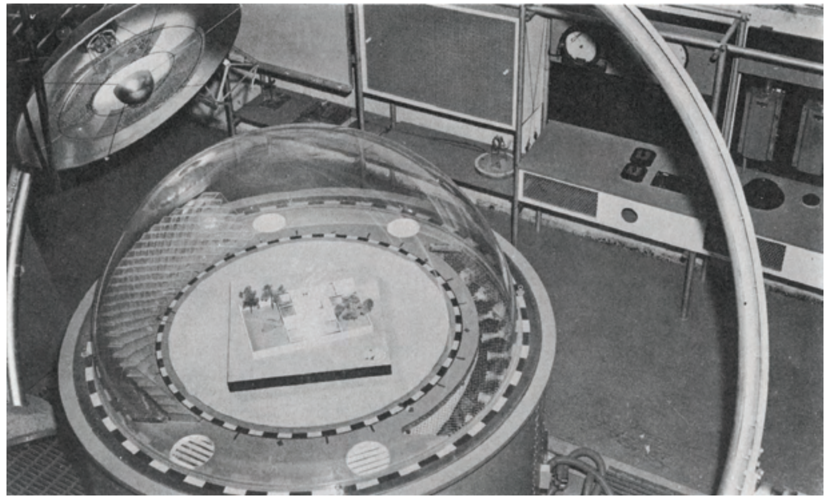
Chapter 3 explored environmental models as devices that mediate between the phenomena of moving air and the instrument that produces it. In this chapter, Victor and Aladár Olgyay's thermoheliodon illustrates how environmental models mediate between physical models and their target systems, or those aspects of the world being modelled. Featured in the appendix of Victor Olgyay's (2015) canonical 1963 *Design with Climate: Bioclimatic Approach to Architectural Regionalism*, the thermoheliodon was an advancement of the heliodon – an environmental model that simulated not only solar trajectories on architectural models, but also wind and thermal conditions (Figure 4.1). Considered a failed experiment at the time, the thermoheliodon remains a potent physical distillation of two emerging post-war, data-driven conceptions of weather and climate. It also condenses in a single artefact two conceptions of architecture that mediate these environments, one based on selective filtration and the other on encapsulation. This chapter explores the thermoheliodon's model/target relations and concludes with reflections on the *Working Prototypes* exhibition, which situated my environmental models as objects nested within many environmental systems.

Models establish dialogues with those attributes of the world being modelled. Calvino's character Mr. Palomar reflects on the dialogic relationship between model and world:

> A delicate job of adjustment was then required, making gradual corrections in the model, so it would approach a possible reality, and in reality to make it approach the model … even the most rigid model can show some unexpected elasticity. In other words, if the model does not succeed in transforming reality, reality must succeed in transforming the model.
>
> (1999, 98)

The world shapes construction of the model and the model, in turn, shapes construction of the world.

Traits included or excluded from a model reflect designer intent as well as larger cultural values held at the time of their construction. In *Architectural Model as Machine*, Albert Smith suggests that models partake 'in the definition of a culture's cosmos' (2004, 62). Models not only mirror values, but they have the capacity to shape them, at times leading to the paradigm shifts suggested by Burnett's analogical/ontological model distinction



4.1

4.1 **Victor Olgyay, *View of the Thermoheliodon and Instrument Panel*, from *Design with Climate*, 2015 (2nd ed.). Understood as an improvement on the heliodon, the thermoheliodon also tested wind and thermal conditions on scaled architectural models.** Princeton University Press, reproduced with permission.

presented in Chapter 1. As such, models are reflective, mirroring both conscious and unconscious priorities at the time of their construction. Models are also projective, offering new conceptions and interpretations about the subjects of their representations.

In scientific models, those full-scale attributes in the world that a model represents are referred to as a model's target system.[1] In an engineering experimentation chamber, the target of the environmental phenomena in the testing bed is that phenomena at full scale – the space of wind flow from a given direction or of solar trajectories for a set latitude. Similarly, in a conventional architectural presentation model, the referent of that model is the future building that the model represents. Environmental models therefore appear to have at least two target systems: those of the architectural proposition and those of the environmental phenomenon. This chapter elaborates on how Victor and Aladár Olgyay's thermoheliodon reflects two at times contradictory conceptions of weather and climate, as well as two persisting conceptions of environmental architecture.

The Olgyays are best known as pioneers of bioclimatic design principles which have informed many contemporary technical textbooks. They co-authored *Solar Control and Shading Devices* (1957), which was a comprehensive overview of solar mitigation strategies for buildings designed in a regionally modified International Style. In a subsequent book, first published in 1963, *Design with Climate: Bioclimatic Approach to Architectural Regionalism* (2015), Victor Olgyay extended the techniques outlined in *Solar Control and Shading Devices* to a broader range of environmental conditions, outlining a comprehensive bioclimatic design method that strengthened the foundations of contemporary sustainable design.

Design with Climate concludes with an appendix featuring photographs, itemised drawings, research statements and technical descriptions of the thermoheliodon. The thermoheliodon was intended to test thermal performance of buildings, comparing interior building thermal conditions in relation to a simulated exterior climate. While *Design with Climate* is far-reaching and its legacy extensive, the thermoheliodon has received less attention likely because funding for the project was not renewed and it remained an incomplete project. The thermoheliodon is worthy of closer attention because it acts as a distillation of many of Olgyay's worthy ambitions outlined in the book.

Until recently, scholarship surrounding the Olgyays and the thermoheliodon was limited. Daniel Barber's *Modern Architecture and Climate: Design before Air Conditioning* (2020) fills that gap, extensively contextualising the Olgyays' work in relation to larger discourse surrounding climate mediation and regionalism in the post-war period.

This chapter offers a reading of the models and targets in the thermoheliodon, presenting two emerging post-war, data-driven conceptions of environment and two conceptions of architecture that mediate these environments. The chapter concludes with a deliberate misreading of the thermoheliodon as an architectural model. Olgyay's bioclimatic designs are contrasted with hermetically sealed buildings of the same period, reflecting two persisting environmental design approaches: those that mediate between and those that resist their exterior surroundings. Our climate models have become more sophisticated and our architectural responses more nuanced in the intervening years. However, the thermoheliodon stands out because it condenses in model form contrasting ideals and aspirations about climate control in service of optimising interior thermal comfort. Many of those ideals, particularly our prevailing models of building climate control, persist.

The Olgyays' thermoheliodon

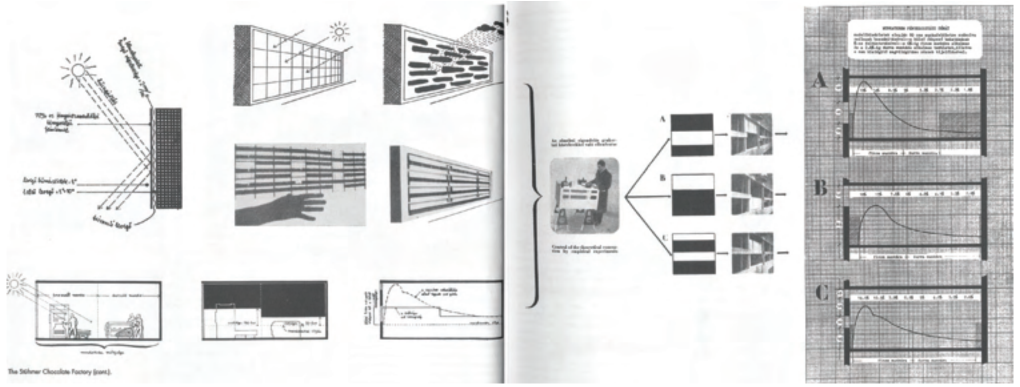
Twin brothers Victor and Aladár Olgyay were accomplished and recognised architects in Budapest, Hungary, before emigrating to the United States in 1947. Their practice in Budapest included a portfolio of housing and institutional projects designed in the International Style. Just as architects such as Le Corbusier, Walter Gropius and Richard Neutra were exploring climatic adaptations to modern buildings in the inter-war period roughly between 1920 and 1940, the Olgyay brothers developed regionally modified adaptations to their designs, focusing initially on solar mitigation. For example, their last and most well-known building in Hungary, the Stühmer Chocolate Factory, is attuned to its environmental context through careful spatial organisation, shading and a passive 'ventilating' façade. As Victor W. Olgyay Jr. notes in an introductory essay to the new and expanded edition of *Design with Climate*:

> The factory design coordinates the operational needs of the facility with optimal environmental conditions; for example, storage is put in dark areas, and tasks requiring brighter light are located in brighter areas. They conducted extensive daylight model testing to inform the size and location of fenestration under various daylight conditions. In addition, they designed an ingenious ventilating facade calculated to passively mitigate solar heat gain.
>
> (2015, xiii).

A series of diagrams and design development models produced for the project indicates a clear interest not just in attuning the building to its local climate, but in honing design methods for doing so (Figure 4.2).

The Olgyays used physical models to test solar principles early in their career. An

4.2 Victor and Aladár Olgyay, ***The Stühmer Chocolate Factory*, republished in *Design with Climate*, 2015 (2nd ed.). The factory was one of the last projects they completed in Hungary before emigrating to the United States. Analytic diagrams, static environmental sections and empirical model tests support analysis of solar shading principles.** Princeton University Press, reproduced with permission.



4.2

4.3 Victor and Aladár Olgyay, ***The Stühmer Chocolate Factory* (detail), republished in *Design with Climate*, 2015 (2nd ed.) The Olgyays used the large-scale model on trestles, described as an empirical experiment, to take interior light readings.** Princeton University Press, reproduced with permission

4.3

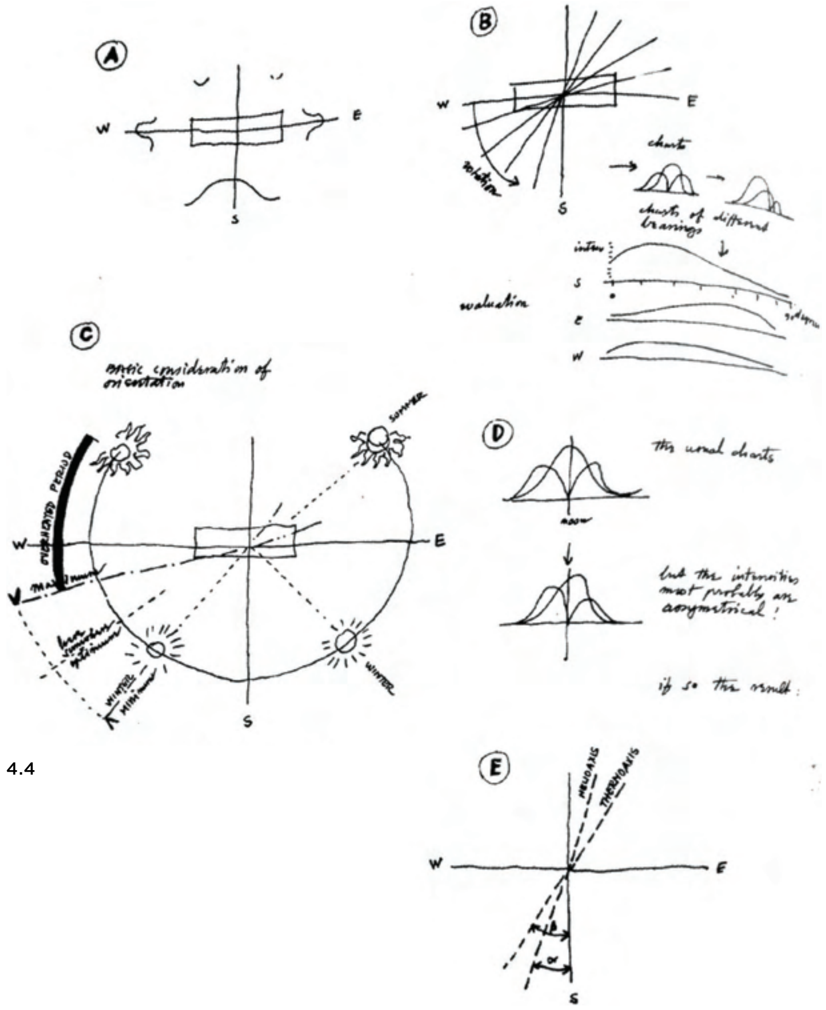
image of the Stühmer Chocolate Factory, captioned 'control of the theoretical conception by empirical experiments', shows a large-scale physical model of the factory sitting on trestles (Figure 4.3). A model 'operator' appears to be taking light readings of three different shading strategies to compare interior daylight distribution. The large-scale model, placed outside in the 'real' sun, sits in stark contrast to images of the International Style model subsumed within the constructed environment of the thermoheliodon, providing a glimpse of the Olgyays' methodological trajectory. Whereas the Stühmer model prioritises the architectural design and its relationship to a single environmental process, sunlight, the diminutive model in the thermoheliodon invisibly reconciles, through a sensored interface, data about increasing numbers of simulated environmental parameters.

When the Olgyays arrived in the United States in the late 1940s, suburban housing design and building climate control were the locus of many interrelated concerns. Within the context of the ensuing Cold War, technologies developed by the military were adapted to the domestic sphere. Seen as signs of progress, such technological advances were also means of asserting national identity. Meanwhile, there was an increasing desire to assert regional housing identity as a response to the homogenisation of large-scale suburban development. Publications in popular magazines about new design styles both captured the optimism of modern life while also promoting a desire for regional identity.

Architects had specific concerns about environmental performance of the hastily constructed, lightweight wood-framed homes in suburbia. Summer overheating – a function of poor building orientation, increased amounts of paving, decreased shade from trees and poor insulation – was a particular concern. While air conditioning was viable, fuel costs made it a luxury. At the same time, thermal comfort expectations were becoming more stringent. Building climate control increasingly became a focal point of design conversations. 'Controlling' interior building climate entailed developing methods for reconciling exterior and interior climatic demands. Lack of accurate and consistent regional climate data as well as techniques for codifying and applying the data to architectural design methods, however, proved obstacles to this agenda.

James Marston Fitch's *American Buildings: The Forces That Shape It*, published in 1948, provides a good yardstick for understanding the state of designing in response to environmental conditions roughly at the time that the Olgyays arrived in the United States. Fitch's book elaborates on key climatic principles influencing building thermal performance. However, he laments the lack of established techniques for testing these principles in a rigorous, repeatable and transferable manner. For example, Fitch refers to a study, one of the first of its kind in the United States, conducted by H. and H. N. Wright (who developed the first heliodon in 1939), that quantified insolation values based on building orientation in New York City and made orientation recommendations accordingly. While useful, the study was only relevant for that site; there were no suggestions for how to transfer this approach to other latitudes.

Within this broader context, the Olgyays' professional focus shifted from establishing a practice to pursuing academic careers focusing on principles of building science. They took academic appointments at University of Notre Dame, then MIT and finally at Princeton. Their early research was a direct outgrowth of the agenda to develop precise environmental design techniques that could be adapted to a range of climate zones, building on related research taking place at the time on solar architecture.[2] One of their earliest attempts at refining a rule-of-thumb passive design strategy appears in Aronin's *Climate and Architecture* (1953). A series of building orientation diagrams examine the asymmetry of thermal gain on west and east sides of rectilinear buildings in temperate climate zones (Figure 4.4). The conclusion, now widely circulated, indicates that an orientation shift of the east side of the building slightly north reduces west-southwest overheating.[3] The Olgyays' 1957 book *Solar Control and Shading Devices* builds further on this research, outlining methods for designing appropriate solar shading placement, configuration



4.4

4.4 Victor and Aladár Olgyay, *Temperate Building Orientation*, diagram featured in Jeffrey Aronin's 1963 *Climate and Architecture*. The diagram outlines the Olgyays' refinements to the rule-of-thumb principle of building orientation in a temperate climate zone about an east–west axis to maximise winter and minimise summer solar gain. Redrawn by author from Aronin, 1963.

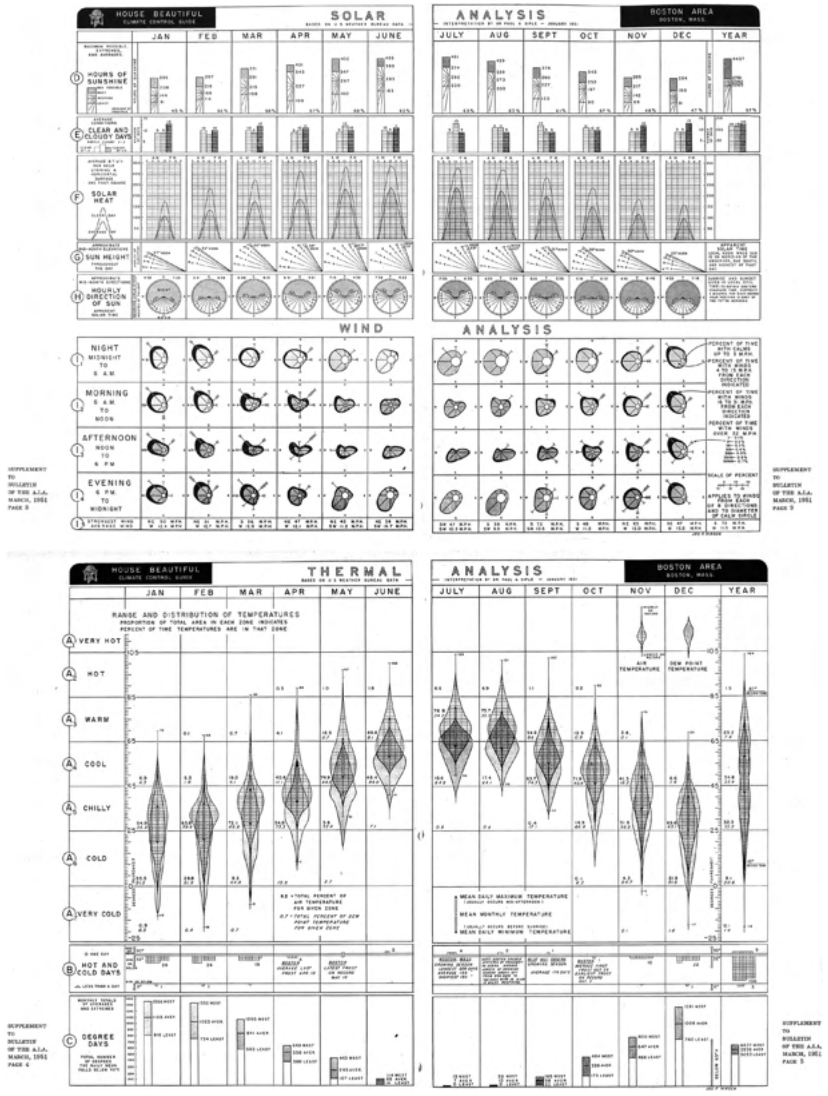
and orientation based on understanding of solar trajectories, over- and underheating periods and shading criteria of different architectural shading devices.

While Aladár continued research focusing on solar mitigation, Victor Olgyay shifted focus to codifying and synthesising a more comprehensive range of climatic variables. At the time, solar trajectories were easily predicted given a site's latitude. Expanding variables of concern to include designing around wind, humidity or material thermal properties required more nuanced regional-specific climate data. During the mid-twentieth century, this data had only very recently been codified and disseminated. From 1949 to 1952, *House Beautiful* magazine and the American Institute of Architects (AIA) collaborated on the Climate Control Project, a series of publications examining houses as case studies. The project popularised regionally designed, environmentally attuned houses while also codifying and disseminating regional climate data to architects.

Climate Control Project case study houses were predicated on utter site specificity: 'the very reason it's a remarkably good house would make it a bad house if it were ever repeated on another lot. For the very core of its perfection is that it is perfect for its site' (Colean 1949, 200–1). One of the defining features of the series was the publication of regional climate data developed by *House Beautiful*'s climate consultant, military geographer Paul Siple. The first article of the series, published in the *AIA Bulletin*, included a 21-page spread of climatic and corresponding design data for Columbus, Ohio (Figure 4.5). Similar data for other cities were included in the publication series. The data presented was comprehensive and graphically compelling; it included solar, thermal, wind, humidity and precipitation analysis as well as corresponding design guidelines for site layout, building orientation and interior organisation. Further design recommendations were made for wall, floor and roof composition as well as for foundations and basements. Victor Olgyay's 1951 article 'The Temperate House' in *Architectural Forum* contributed to this conversation, laying the groundwork for calculation procedures that could be applied to a broad range of climatic conditions. Olgyay went on to include a modified version of the AIA Regional and Climate Analysis chart for the New Jersey–New York region in *Design with Climate*.

While general principles associated with bioclimatic design were understood

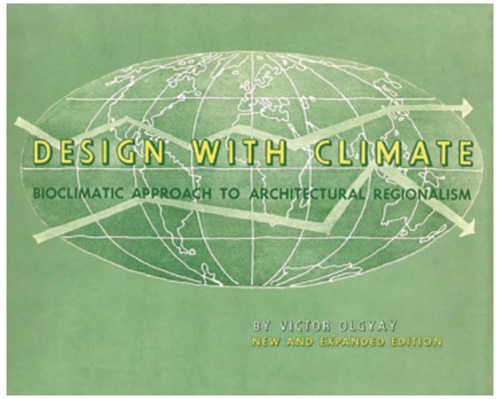
4.5 The American Institute of Architect's 1951 Bulletin, *Regional Climate Analysis and Design Data for the Boston Area* (selected sheets). The Bulletin supported *House Beautiful* magazine's Climate Control Project. Extracts from the Bulletin were later incorporated into Olgyay's *Design with Climate*. Supplement to the Bulletin of the AIA, March 1951. Courtesy of the American Institute of Architects Archives.



4.5

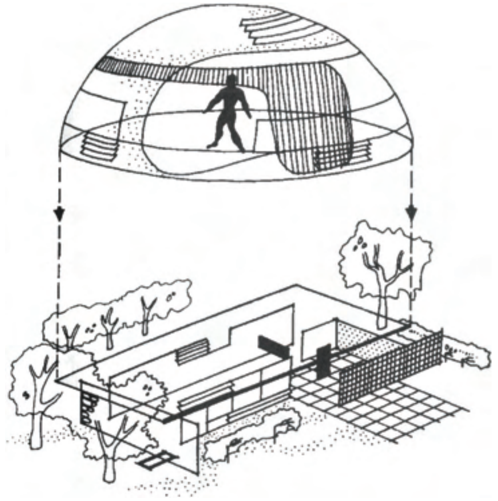
before *Design with Climate* was published, the book provided a comprehensive methodology for calibrating these techniques to the climatic and microclimatic particularities of a given site (Figure 4.6). *Design with Climate* hones specificity in what were otherwise rule-of-thumb guidelines regarding building form and orientation while presenting strategies that could be adapted based on regional climate analysis. This was accomplished through the development of a very specific 'bioclimatic' design method, which entailed reconciling interior thermal comfort expectations with exterior climatic conditions. Mediating between these two 'environments' (exterior and interior) was the central focus of Olgyay's method, and it is one that directly informs the conception and execution of the thermoheliodon (Figure 4.7).

Olgyay's bioclimatic method as outlined in *Design with Climate* is based on four seemingly simple steps: (1) analyse climate data; (2) evaluate thermal comfort needs; (3) develop technical awareness of siting, building orientation, shading requirements, building form, ventilation and indoor temperature requirements; and (4) hone an architectural response synthesising the above three findings. In a condensed form, Olgyay's technique involved analysing climate data to determine building over- and underheating periods, examining this criterion in relation to desired interior thermal comfort conditions, developing landscape and architectural responses to mitigate between these existing exterior conditions and a desired interior condition, and then refining the design accordingly. Application of this method is described in its most distilled form as climate → biology → technology → architecture, reflecting the range of disciplinary concerns required to complete the bioclimatic design process (Olgyay 2015, 11). The procedural techniques for carrying out this method include complex radiation charts, shading masks and sol-air building surface impact diagrams.



4.6

4.6 Victor Olgyay, *Design with Climate: Bioclimatic Approach to Architectural Regionalism* book cover, from *Design with Climate*, 2015 (2nd ed.). Originally published in 1963, a second edition was released in 2015. The book continues to inform technical textbooks in architecture. Princeton University Press, reproduced with permission.



4.7

4.7 Victor Olgyay, *Theoretical Approach to Balanced Shelter*, diagram from *Design with Climate*, 2015 (2nd ed.). Princeton University Press, reproduced with permission.

4.8

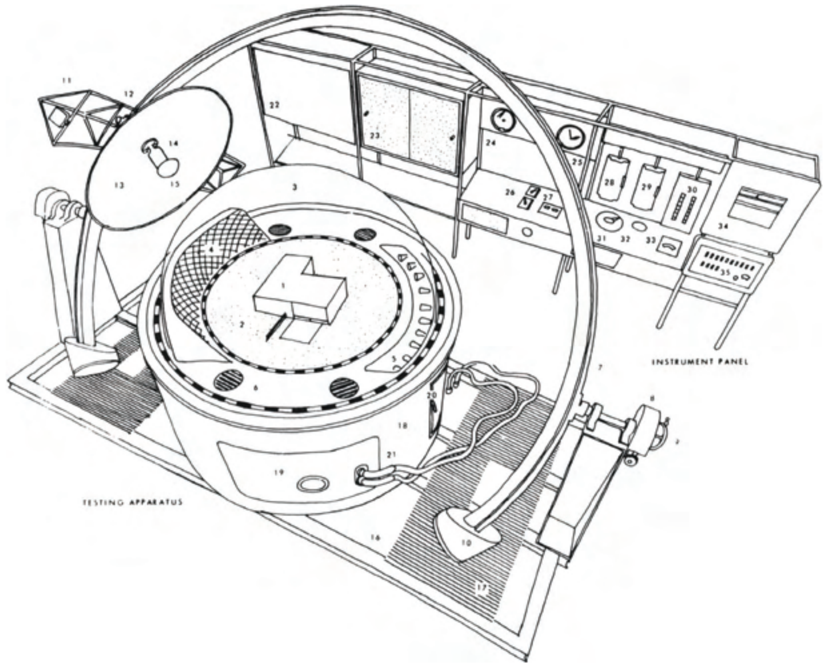
4.8 Photograph of the Princeton Architectural Laboratory where Victor and Aladár Olgyay developed the thermoheliodon, 1951. The lab was designed to facilitate architectural experimentation associated with experiential environmental principles. The central dome, mirroring the thermoheliodon dome within, facilitated daylight studies of models. Jean Labatut Papers, C0709, Manuscripts Division, Department of Special Collections, Princeton University Library.

Environmental models such as heliodons and wind tunnels, referred to as empirical experiments, are one of many tools used by Olgyay to test and validate his bioclimatic design method. *Design with Climate* concludes with a series of appendices, one of which features a series of drawings and photographs of the thermoheliodon.

In 1955, the Olgyays, with mechanical engineer A. E. Sorenson, received a two-year, $19,000 US National Science Foundation grant to study 'thermal behavior of buildings by means of study of models' (Anonymous 1955, 289). This funding supported development of the thermoheliodon. The device and its supporting control panels roughly filled a small room. The focal point of the room is an elaborate apparatus with a dizzying array of environmental simulation devices including a wind tunnel, a heliotrope with a motored 5,000-watt bulb sun, temperature sensors, air conditioning units and heating coils. Intended as an improvement on the heliodon, which simulates solar trajectories on architecture models, the thermoheliodon also tested thermal performance of scaled architectural models. In drawings and photographs included in *Design with Climate*, the model being tested is the *Phoenix Balanced House*, a prototypical design responding to the hot arid climate zones of the United States. The model is a small element within a series of elaborate nested environments, dramatically overshadowed by the elaborate componentry encasing and surrounding it.

The thermoheliodon was housed in the Princeton Architectural Lab, a former stable converted by the director of Princeton University School of Architecture's graduate programme, Jean Labatut, in 1947 (Figure 4.8). The lab was a space of building experimentation and experiential learning that hosted visitors including Louis Kahn, Richard Neutra and Buckminster Fuller; the significance of Fuller's contributions will be explored later in this chapter. A kind of 'live experiment' for structural, experiential and environmental concerns, the lab included architectural elements such as a glass cube outfitted with scaffolding and lighting rigs and an artificial sky, which supported the Olgyays' research on daylighting (Clarke 2013). A plexiglass dome integrated into the roof of the lab enabled daylight analysis of architectural models by the Olgyays while also architecturally reflecting the domed thermoheliodon contained within.

The thermoheliodon was still a work-in-progress when described in the appendix



4.9

4.9 Victor Olgyay, *Explanatory Drawing of the Thermoheliodon*, from *Design with Climate*, 2015 (2nd ed.). **Olgyay describes the thermoheliodon as a 'laboratory machine' composed of two things: an 'environmental testing apparatus' that includes model base, dome and all associated simulation componentry; and an 'instrument panel' that contains switches, controls and measuring instruments for the simulation devices.** Princeton University Press, reproduced with permission.

of *Design with Climate* (Figure 4.9). At that time, six years after the grant had expired, the team was still investigating problems related to thermal scaling criteria to ensure that the 'model systems … are geometrically, dynamically and thermally similar to their prototypes' (Olgyay 2015, 183). The central failure of the thermoheliodon was related to difficulties in accurately monitoring interior climatic conditions due to problems with scaling thermal capacity of building materials. Daniel Barber notes,

> The buildings the Olgyays inserted into the device were tested for shape and orientation, but the internal climatic conditions could not be adequately monitored because of the difficulty of scaling up the thermal capacity of materials – a small brick operates very differently, in thermal terms, than a large brick. The modelling of the radiation of stored heat was also difficult to model at scale.
>
> (Barber 2014)

The Olgyays subsequently applied for a grant to test full-scale thermal requirements of building materials to hone similarity criteria for the architectural models. However, the grant was unsuccessful, stymying progress.

The thermoheliodon can be understood as an ambitious model analogue to *Design with Climate.* Just as the methods described in the book focus on whole-building thermal performance based on many interrelated climatic criteria, the intention of the thermoheliodon is to 'investigate … the integrated effects of the thermal environment and to investigate the application of thermal balance principles to building design and construction' (Olgyay 2015, 180). The thermoheliodon and Olgyay's bioclimatic design methods outlined in *Design with Climate* both attempt to distil an increasingly complex array of environmental conditions. Both operate at vastly incommensurate scales, trying to reconcile the meteorological with the physiological. In both, buildings become a complex interface between two environmental systems: a given exterior environment defined by regional climate data and a desired interior environment defined by increasingly narrow physiological thermal comfort standards. Reconciling these two environmental scales and sensibilities proved impossible in the thermoheliodon; the point of failure was the sensored interface of the building model envelope where these two environments met. These limitations reveal a lot about how climatological systems were conceived at the time and how these conceptions, in turn, informed models of environmental architecture. A closer look at the thermoheliodon reveals some of the competing conceptions of both environment and architecture emerging at the time, much of which resonates today.

Two model environments

Neither static nor unidirectional, the relationship between a model and its target system(s) is complex and dynamic. In many cases, models do not have a single target system. Environmental models, for example, demonstrate at least two sets of relationships between model and target systems. Firstly, there is the architectural model and the version of its projected building as understood at full scale. Secondly, there is the environment simulated in the model and its equivalent conditions operating at full scale in the world. Because of its ambitious intent and physical complexity, the thermoheliodon raises questions about what constitutes both model(s) and target systems(s). The thermoheliodon is a complex, nested system of controlled environments that extend from the contained laboratory of the building to the encapsulated dome of the testing bed to the bounded interior of the *Phoenix Balanced House* model placed within it.

What exactly, then, constitutes the model and the target of the thermoheliodon? Olgyay describes the thermoheliodon as a 'laboratory machine' composed of two things – an 'environmental testing apparatus' that includes model base, dome and all associated simulation componentry; and an instrument panel that contains switches, controls and measuring instruments for the simulation devices. Does the model refer simply to the architectural model being tested within the thermoheliodon? Could the thermoheliodon be understood as a model of the climatological world? What sets the limits of the model – the footprint of the scale building, the enclosing dome, the entire testing apparatus, the room that contains it along with the computing machines, or something else?

The thermoheliodon's expansive environmental ambitions make identifying a target system equally complex. Target systems refer to the selected attributes of the physical world that a model represents. Within the hemispheric dome, the thermoheliodon simulates selected meteorological conditions, in theory, for any site in the world. Does the target system operate at the scale of the planet, representing this accumulation of all potential locations and all potential times? Or does it operate at the scale of a single place and moment in time that represents a specific building site?

Representations of the thermoheliodon featured in the *Design with Climate* appendix fail to fully address these questions. The limits of Marey's wind tunnel were set precisely by the 'objective eye' of the camera, which zoomed into effects on the testing bed. In comparison, drawings and photographs of the thermoheliodon seem far less considered. Orthographic drawings include the entire thermoheliodon apparatus and neglect the architectural model altogether. One axonometric drawing includes the architectural model as well as the instrument panel beyond. Photographs of the thermoheliodon vary in terms of vantage point and extent of framing. When compared to Marey's careful photographs of the wind tunnel testing bed, Olgyay's photographs of the thermoheliodon seem hasty and ill-composed. It is an artefact viewed from many vantage points at several scales rather than one.

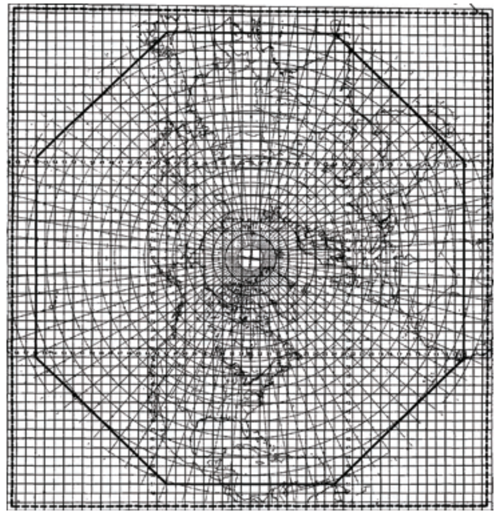
Because the thermoheliodon is a device for testing designs developed using the bioclimatic method, an appropriate starting point for defining models and the target systems of the nested environments of the thermoheliodon is *Design with Climate*'s mantra: climate → biology → technology → architecture. This sequence suggests that two target systems are at work in the thermoheliodon. The first is the climatological world – the externalised environment simulated around the scale architectural model. The second starts in the biological world – the interiorised environment of thermal comfort contained within the envelope of the scale architectural model. How were these environments characterised at the time?

The exterior climate of a given site is the starting point for all Olgyay's work. For Olgyay, climate is at its most basic level raw data, a series of inputs to be used as a means towards the end of creating a climate-balanced interior. In *Design with Climate*, Olgyay outlines a four-step method for achieving a climate-balanced house. When describing the first stage of this bioclimatic method, Olgyay writes: 'Climate data of a specific region should be analyzed with the yearly characteristics of their constituent elements, such as temperature, relative humidity, radiation, and wind effects. The data, if necessary, should be adapted to the living level. And the modified effects of the microclimatic conditions should be considered' (Olgyay 2015, 11). The AIA/*House Beautiful* Climate Control Project established the data groundwork by codifying the records produced by the United States Weather Bureau. These meteorological datasets were graphically translated into regional climate analyses charts, regional timetables of over- and underheating periods, radiation charts for specific latitudes and building material time lag tables.

The thermoheliodon was referred to in the *Daily Princetonian* as *The Weather Maker* because it simulated ambient exterior 'weather' and related impacts on interior 'weather' contained within the scale architecture model (Bolgard 1955). The emphasis on *weather* is important because it highlights the role of the thermoheliodon in generating short-term, local and immediate conditions based on longer term averages established through climate data acquisition.

The thermoheliodon reflects a particular spatial conception of meteorological space, one of a hemispheric data matrix, honed by developments in the meteorological sciences at the time. Edwards's *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (2010) recounts a shift that took place mid-twentieth century from ground-level to sky-level meteorological data acquisition. Weather balloons, airplanes and other aerial craft facilitated

this shift from horizontal data acquisition to vertical data acquisition. A corresponding representational shift took place in the meteorological sciences from presenting weather as a flattened two-dimensional plane indicated with isobars (curved lines on a weather map that join places of equal pressure) to a complex projection of three-dimensional space subdivided into a matrix of cells (Figure 4.10). Edwards notes, 'In the period 1950–1960 … two-dimensional models gave way to three-dimensional ones, and model grids expanded to include the entire northern hemisphere' (2010, 126). Simultaneously, as analogue methods of visualisation gave way to digital methods of visualisation, 'the regularly spaced, abstract grids of computer models … shifted forecasting from a fundamentally qualitative, analog principle (isolines) to a fundamentally quantitative, digital one (precise number of grid points)' (Edwards 2010, 126). The atmospheric world was increasingly understood as a dense dome mesh of meteorological data collection points.



4.10

4.10 Drawing of a 'Quasi-hemispheric' meteorological model grid. The drawing reflects new aerial modes of meteorological data acquisition emerging in the mid-nineteenth century.
F. G. Shuman and J. B. Hovermale, *An Operational Six-Layer Primitive Equation Model*, *Journal of Applied Meteorology* 7, no. 4 (1968), 528. Published 1968 by the American Meteorological Society.

Unlike Marey's wind tunnel, which presents airflow as a visible material process, the thermoheliodon presented environmental processes as numerical processes. The thermoheliodon reflects the way physical environmental models were used more broadly at the time in other disciplines, as predictive devices in an emerging computational era. Whereas Marey's wind tunnel fell within the tradition of the reductive mimetic model, simplifying the variables of observation and presenting them through carefully cropped photographs as objective truth, Olgyay's thermoheliodon falls under a different tradition, that of a totalising environmental model that attempted to replicate many interrelated variables simultaneously.

Meteorologists understood both the value and limitations of this kind of totalising model used to conduct controlled experiments. By the 1940s and 1950s, meteorologists understood that the complexities of atmospheric interactions far exceeded what a physical model could achieve. Edwards's description of the appeal of the 'controlled experiment' in meteorology reads as a direct description of the thermoheliodon:

> If you can simulate the climate, you can do experiments. God-like, you can … make the sun flare up or dim … You can cook the Earth, or freeze it, and nobody will even complain. Then you can watch and see what happens … In a laboratory experiment, you

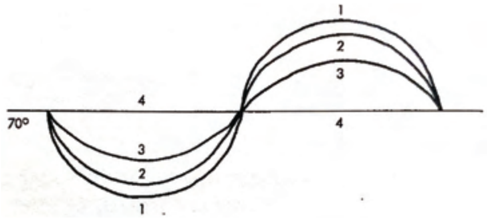
> create a simplified situation, blocking out most of the real-world's complexity while retaining a few variables you can manipulate. (2010, 140)

As Edwards notes, meteorologists concluded that there were limitations to such models. Meteorological systems and processes were simply too large and complex and were predicated on interactions that could not be distilled; digital models using numerical processes promised to address this gap.

What were some of the characteristics of this data-driven notion of weather and climate? In the meteorological sciences, weather was understood as dynamic, quantifiable, controllable, stable, predictable and therefore within the full grasp of human comprehension. Meteorologists at the time had a 'widespread belief that global atmospheric flows might display predictable symmetry, stability, and/or periodicity. Research aimed at finding such predictable features remained active throughout the 1950s' (Edwards 2010, 141). While drawings and models present the thermoheliodon as a static artefact, in fact, its machining would have been dynamic, yet highly regulated; it would have balanced dynamic flux with predictable periodicity. For example, the electrical sun was designed to move along its arcing rail and the model base was designed to rotate to simulate airflow directionality. It was even designed to accelerate time; a 'day', marked by the passage of the electronic sun, arced across the model in just under an hour.

Olgyay's valuation of this climatic data varied from adversarial to invigorating. In his article, 'The Temperate House', he states: 'The climate is the architects' true adversary' (1951). In *Design with Climate*, he describes the central problem of house design as 'securing a small, controlled environment within a large-scale natural setting – too often beset by adverse forces of cold, heat, wind, water, and sun' (Olgyay 2015, preface). In *Solar Control and Shading Devices*, the Olgyays write that sun exposure 'attacks the building' and is 'punishing' (1957, 7). Elsewhere in the same book, however, weather is described as 'invigorating' and 'stimulating' (Olgyay and Olgyay 1957, 14). The range of characterisations, from hostile to inviting, is entirely consistent with Olgyay's methodology. Ultimately, Olgyay's characterisation of climate varied according to its distance from desired thermal comfort standards. The further away the exterior climate from desired interior conditions, the more antagonistic the relationship.

The key aim of a building designed using Olgyay's method was to create a 'climate-balanced' building which resisted adversarial environmental factors while amplifying advantageous factors, to 'flatten the curve' of climatic variability in the building interior. Olgyay's 'Flattening the Temperature Curve' diagram illustrates this point. The diagram is organised around a horizontal line, which corresponds to a baseline of 70°F (Figure 4.11). A series of arcs both above (signifying overheating) and below (signifying underheating) the baseline indicate design strategies to help reach the desired baseline: microclimatology, climate balance of structure and, as a last resort, mechanical heating and cooling.



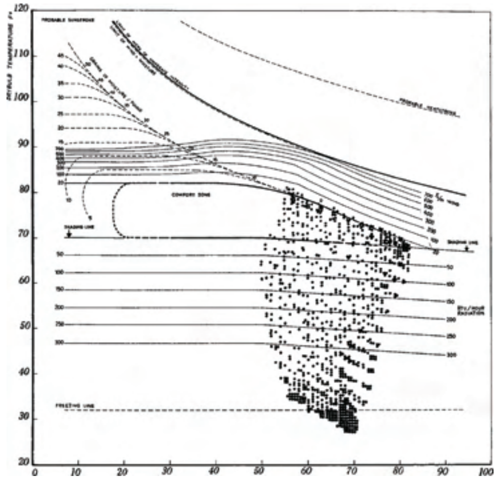
4.11

4.11 Victor Olgyay, *Flattening the Temperature Curve from Environmental Conditions (1) by Microclimatology (2) and Climate Balance of the Structure (3) to Mechanical Heating or Cooling (4)*, from *Design with Climate*, 2015 (2nd ed.). The diagram outlines the goal of the bioclimatic design method to 'flatten the temperature curves' between erratic exterior environment and optimised interior environment. The horizontal baseline reflects an ambition of total thermal homogeneity, ultimately achieved through mechanical supplements. Princeton University Press, reproduced with permission.

The perimeter of the models tested within the thermoheliodon were lined with temperature sensors to measure exterior as well as interior temperatures. As such, the second environmental model/target system of the thermoheliodon was based on biological criteria, or on creating a climate-balanced building interior of thermal comfort. For the second stage of the bioclimatic method, Olgyay writes:

> Biological Evaluation should be based on human sensations. Plotting the climate data on the bioclimatic chart at regular intervals will show a 'diagnosis' of the region with the relative importance of the various climatic elements. The result of the above process can be tabulated on a yearly timetable, from which measures needed to resort comfort conditions can be obtained for any date. (Olgyay 2015, 11)

In brief, Olgyay's method entailed plotting average temperature and humidity data onto bioclimatic charts to determine overlaps with thermal comfort zones (Figure 4.12).



4.12

4.12 Victor Olgyay, *Bioclimatic Evaluation for New York-New Jersey Area; Each Point Represents Hourly Data over Ten-Day Periods throughout the Year*, from *Design with Climate*, 2015 (2nd ed.). The central bubble on the chart indicates a zone of thermal comfort, which can be extended depending on shading and wind patterns at any given moment. Princeton University Press, reproduced with permission.

The Olgyays were not the first to visually correlate climate data to comfort. Air conditioning pioneer Willis Carrier developed psychrometric charts in the early 1900s, mapping the physical properties of moist air to calibrate the mechanics of air conditioning. Comfort charts that correlated thermal conditions to human physiology were developed in the 1920s by ASHVE (the American Society of Heating and Ventilating Engineers), the predecessor to ASHRAE (the American Society of Heating, Refrigerating and Air-Conditioning Engineers). However, Aladár Olgyay first used the term 'bioclimatic chart' in 1952 (Barber 2020). Bioclimatic charts, which were presented in a range of formats, effectively correlated shade, solar radiation, relative humidity and wind speed to determine when 'thermal comfort' was achievable throughout the year. The Olgyays' bioclimatic chart generally indicated humidity levels along the x axis and dry-bulb temperature on the y axis. The comfort zone 'bubble' of idealised temperature and humidity combinations sat in the central portion of the chart. Daily, weekly or monthly averages were plotted on the chart to determine the conditions under which thermal comfort could be achieved throughout the year. This constellation of data tremored and shifted over the course of the day, month and year, rendering itself as a cloud of thermal possibilities.

A series of lines roughly parallel to the comfort bubble's perimeter corresponded to other climatic variables – such as BTUs of radiation in the winter or wind speeds in the summer – that extended the comfort zone. These 'in-between' zones just beyond the bubble were the most charged area for the designer. They indicated times of year when the comfort zone could be extended through architectural calibration. Operable windows could facilitate cooling; shading devices could reduce overheating; and window placement could encourage thermal gain.

Fundamentally, the interior environment, constructed and controlled, took precedence over the exterior environment in Olgyay's bioclimatic method. The exterior environment was a given condition to work around, to use selectively. The interior environment was a construction, an artefact altered by the designer through careful design modification. The prioritisation of interior climate reflected increasing thermal comfort expectations perpetuated at the time on two competing fronts. On the one hand, air conditioning manufacturers focused on codifying thermal comfort using psychrometric charts in the pursuit of creating mechanically conditioned homes. On the other hand, popular magazines such as *House Beautiful* promoted climate-responsive house design that was utterly attuned to the particularities of a given site and less reliant on mechanical processes. Both factions were focused on the issue of controlling interior conditions in service of thermal comfort, but the mechanisms for achieving this goal and their resultant architectural manifestations could not have been more different.

Willis Carrier advocated for a model of total mechanical environmental control – an internalised interior devoid of meaningful contact with the outside world. Kiel Moe describes a 1952 house sponsored by the Carrier Corporation as starting a 'revolution' because it, 'need not depend on natural ventilation. Ells and wings wouldn't be necessary. Only a few windows need have a movable sash. The bathrooms needn't require a window. Windows, doors and even the rooms themselves could be placed to suit the convenience of the owner, not to catch a breeze' (2010, 49). Carrier's revolutionary model of architecture offered an image of a controlled and buffered, exclusive and exclusionary suburban life.

House Beautiful's 'Climate Control' case study projects promoted a counter model of climate-responsive design to that of Carrier – one utterly attuned to the particularities of temperature, solar and wind exposure, and humidity levels on a particular site to reduce mechanical heating and cooling demands and their associated energy costs. This model of living was promoted as easy and carefree; the editor of *House Beautiful*, Elizabeth Gordon, presented the Climate Control Project as a 'research project, the aim of which was to make your life easier, by showing you

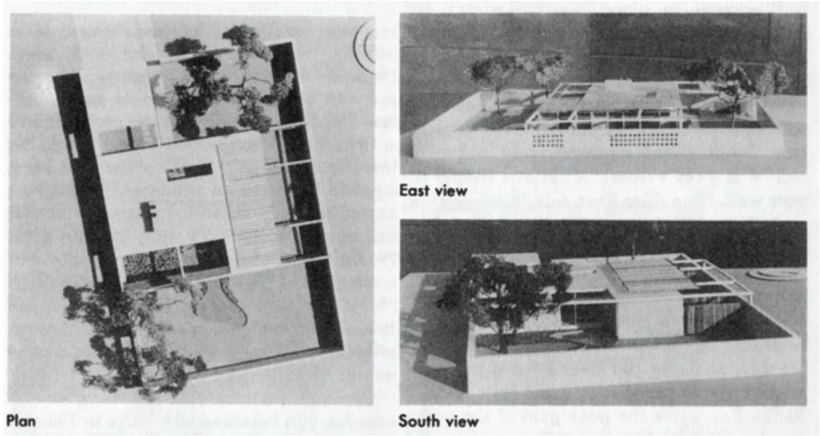
how to improve your comfort' (1950, 173). As Gordon elaborated, thermal discomfort affected work performance, caused physical strain and even altered one's personality. While the mechanisms for achieving climate control varied and their architectural manifestations could not have been more different, both appealed to similar sensibilities about thermal comfort and the value of living an exclusionary suburban life. Willis Carrier would have likely agreed with Gordon's sensitive characterisation of human physiology: 'feeling just a little too cool, a little too hot, really raises the dickens with body and soul' (1950, 174).

For Olgyay, there would have been much at stake in 'flattening the curves' to achieve thermal comfort. In its most ideal form, the interior environment was relatively static, 'balanced', and 'flattened', achieving a narrow bandwidth of comfort required to keep its sensitive occupants content and productive. Technological progress was marked by thermostability. Olgyay's bioclimatic conception was predicated on the idea that 'man' was the central measure of progress and that creating an optimised interior would contribute to the construction of an optimised life, one in which its human occupants would both physically and emotionally flourish. This model of thermal comfort in principle was relatively easy to achieve within a sealed, mechanically controlled building. Creating this ideal using his bioclimatic design method, on the other hand, placed a great deal of responsibility on the architect to create a highly attuned building envelope, one that could respond to the range of meteorological 'inputs' impacting it.[4]

Two architectural models

Trying to define what constitutes 'the model' and its corresponding target system in an environmental model raises important questions about the role of the model both within and beyond the context in which it was made. A central argument of this chapter is that models operate in two important capacities – both as reflections of value systems held at the time of their construction as well as more speculatively as artefacts open to interpretation and future speculation. It is by opening readings of what constitutes a model and/or target system and reflecting on new relationships between the two that the model plays a defining role in shaping new conceptions of the target system and vice versa. In other words, it is through the interpretive dialogue between models and their target systems that new conceptions of both might emerge.

The architectural model featured in photographs of the thermoheliodon, tasked with mediating these two model environments, is described elsewhere in the book as the Phoenix 'Balanced' House, a prototypical bioclimatic design based on climatic data for Phoenix, Arizona (Figure 4.13). The house was one of a series of prototypical 'balanced' houses designed for each of the major climate zones in the United States: hot arid, hot humid, temperate and cool. The model is similar to drawings of a competition proposal Victor and Aladár completed in 1957 for a solar home in Phoenix sponsored by double-glazed window manufacturer Libby-Owens-Ford. Organised around a courtyard, the project uses a combination of solid and screened



4.13

4.13 Victor Olgyay, *Adaptation of Principles in Phoenix Area*, model photographs from *Design with Climate*, 2015 (2nd ed.). The *Phoenix Balanced House* is featured in photos of the thermoheliodon. Olgyay, 2015. Princeton University Press, reproduced with permission.

perimeter fencing, trees and roof overhangs to temper the harsh Phoenix sun.

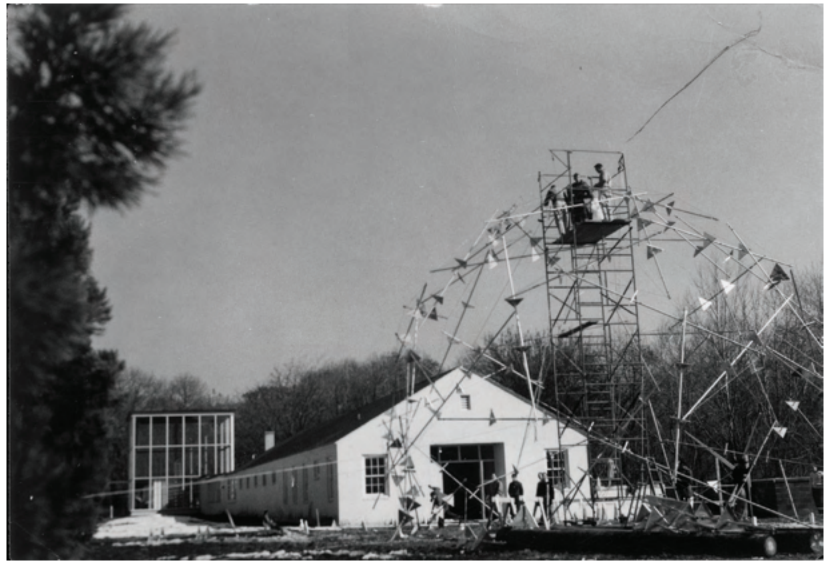
Within the thermoheliodon, the perimeter of the model is lined with sensors, 'thermistors for interior heat measurements and thermocouples to measure exterior temperatures' (Olgyay 2015, 181). The interface of the model's exterior environment and interior environment is the building envelope. The envelope was tasked with the weighty responsibility of not only accepting desirable exterior conditions while limiting undesirable conditions, but with doing so for multiple environmental variables over multiple timescales simultaneously along multiple building faces. The point of failure for the thermoheliodon was the interface where these two environments met, which failed to resolve thermal scaling properties.

Just as the *Phoenix Balanced House* model proves the point of technical failure in the device, it also reflects some tensions in Olgyay's work and the Climate Control Project. Despite Olgyay's interest in utter climatic specificity and corresponding architectural fine-tuning, the architectural model is marked by its generic features. This tension between generic and specific, between global and local, was mirrored by conflicts in the stylistic intention of his work – to develop regional modifications to a style, the International Style, whose foundations were based on establishing thermal continuity through total mechanical control anywhere in the world. There were similar tensions in his bioclimatic method. While Olgyay's method required nuanced modification of climate data to reflect specificities of microclimate conditions, he provides little advice on how to make these fine-grained, site-specific adjustments. He notes, 'Since the AIA cover general climatic conditions – or macroclimate – of a region, any specific application should be modified to some extent by the surroundings of the building in question – the microclimate' (Olgyay 2015, 26). The vacillation between general and specific application of climate-control strategies is also evident in the *House Beautiful* 'Climate Control Project' case studies. On the one hand, the initiative was intended to create houses that were utterly unique and particularly tailored to a site, while on the other hand, broad-brushed approaches to dealing with vast climatic zones characterised the work. In one *House Beautiful* article, the author, Wolfgang Langewiesche, suggests 'let's try not for perfection. Let's be content to do nothing very wrong and to do the main things approximately right' (1950a, 216).

Victor continued to design residential projects between 1958 and 1963, completing over 20 projects in Princeton, New Jersey. Victor applied the bioclimatic method to develop the designs; the resultant projects are largely reminiscent of mid-century modern projects, similar stylistically to that of Richard Neutra. A photograph of one of these projects, 151 McCosh Circle in Princeton, is included in an introductory essay by Victor's son, Victor W. Olgyay, for the 2015 edition of *Design with Climate*. In the photograph, the house is marked by an expressive floating, folded ceiling that extends outside to form a roof overhang. Expansive full-height glazing lines the (likely south-facing) entry façade. Clerestory glazing contributes to the hovering effect of the roof. Curtains are drawn inside. The house is almost entirely cast in shade due to trees in the yard. The role that the windows play in terms of either capturing solar gain or encouraging airflow is unclear. In this particular photo, the house appears cohesive and well-designed, but its role as a highly responsive environmental mediator is less evident. Perhaps for Olgyay, the optimal bioclimatically designed building was more of a mental ideal than an actual design proposal. As he writes, 'the ideal structure in the ideal location might be able to keep physical sensations wholly within the comfort range' (2015, 31). Attuning this ideal to every possible climatic combinatorial possibility would have required a seemingly impossible array of architectural modifications. Olgyay's focus shifted away from practising to focus on research and teaching after Aladár died in 1963 (Olgyay V. W. 2015).

Models are reductive distillations – both their reading and misreadings reveal new understandings of models and their targets. Historian of science D. Graham Burnett describes those productive moments in which a dialogue emerges between a model and its target system. He suggests that it is the oscillations between a physical model and what is represented by its target system that allow the model to become a 'thinking' tool, opening new conceptions of the model and the world that it represents. Models are also both physical artefacts and mental ideals. With that in mind, there is another model of architecture suggested by the thermoheliodon: that of its domed enclosure and associated simulation componentry. This model is both a physical distillation and an idealisation of another mode of environmental management, that predicated on encapsulation rather than environmental mediation.

By conceiving of the thermoheliodon's domed enclosure as an architectural model, focus shifts back to what appears to be Olgyay's key priority in thermoheliodon: the development and calibration of the elaborate apparatuses, controls and devices that simulate an exterior environmental condition within the domed enclosure. When conceived of this way, the totally climate-controlled interior of the thermoheliodon dome is analogous to other models of climate control ascending at the time. As both air conditioning systems and curtain wall technologies gained sophistication, the same period gave rise to both built and speculative projects that were reliant on hermetically sealed, climate-controlled interiors. Skyscrapers, often prone to overheating



4.14

4.14 Photograph of Buckminster Fuller's 40-foot diameter dome constructed at the Princeton Architectural Lab in 1953. Jean Labatut Papers, C0709, Manuscripts Division, Department of Special Collections, Princeton University Library.

and devoid of orientation or any meaningful attempts to temper harsh direct sunlight, proliferated. Closer in form to the thermoheliodon dome, projects such as the 1960 Climatron, the Missouri Botanical Garden, gained recognition as the first air-conditioned hemispherical greenhouse (Kallipoliti 2018).

The hermetically sealed bubble was as much a physical form as a technological ideal. In 1965, Reyner Banham's well-known 'environmental bubble', illustrated by François Dellegret, reduced dwelling to a single transparent bubble technologically supported by a groovy sound system and supporting air conditioning unit. As Lydia Kallipoliti has noted, these closed 'bubble' worlds, informed by a new public consciousness of the fragility of the Earth and the promise of space travel, were conceived of as closed systems containing 'a conditioned and measured version of a simulated piece of nature' (2018, 13). Buckminster Fuller's domed projects of the 1950s and 1960s exemplify the ideal of encapsulation as environmental management strategy. Fuller's domes merge an architectural sensibility (a physical model) with a theoretical sensibility (a conceptual model). The reading of Fuller's dome resolves some of the curious contextual, spatial and scalar ambiguities raised by the nested layers of environmental control in Olgyay's thermoheliodon. The Olgyays were familiar with Fuller's work; Fuller spent time doing research in the Princeton Architectural Lab, constructing an early *World Game* model, while the Olgyays were based there (Barber 2020) (Figure 4.14).

Consider Fuller's 1960 *Dome over Manhattan*, completed with Shoji Sadao (Figure 4.15). The speculative three-kilometre radius dome over Manhattan was intended as a structurally efficient shelter that selectively filtered undesirable exterior environmental conditions, particularly snow, while simultaneously mechanically generating an ideal interior environment. It was intended to create a world within a world, a sealed bubble, notionally reducing heat loss while transforming Manhattan in winter to a sub-tropical greenhouse.

Fuller and the Olgyays' agendas were very different in scope and intent. The Olgyays were interested in developing methods that were widely applicable and buildable. Fuller was a 'whole-world' thinker and a radical speculator. Most of his projects, particularly the most expansive, were more polemical than practical. Nevertheless, when considering environmental management strategies as ideal

4.15

4.15 Buckminster Fuller and Shoji Sadao, *Dome over Manhattan*, collage, 1960. The Estate of R. Buckminster Fuller.

types, their work shares some overlaps. Both pioneered working methods that conceived of environmental conditions numerically as data. Just as the architectural model in the thermoheliodon was literally a sensored interface between interior and exterior climatic conditions, some of Fuller's early projects were designed with literal data matrices embedded into the enclosure. His geoscopes, for example, displace the sensored interface of Olgyay's architectural model to the dome enclosure, creating the kind of three-dimensional hemispheric data matrix used in meteorological modelling at the time. Olgyay conceived of the meteorological world as dynamic, shifting and data-rich, Fuller 'conceived of the universe itself as an energetic-informational continuum, something dynamic, and always transforming' (Fuller in Hays 2008, 169). The world was at least partially conceived by both Olgyay and Fuller as a dense data matrix (of meteorological data in Olgyay's case and of a wider range of resource data in Fuller's).

Fuller's architectural approach, while rigid in shape, was conceptually more flexible, locatable and adaptable than the Olgyays'. This is largely due to the speculative nature of his projects. Nevertheless, this flexibility was enabled by associating energy efficiency with material efficiency. The thermoheliodon's domed enclosure, understood as a model of architecture, offers a countervailing view about the relationship between energy minimisation and human progress. This view starts to address some of the curious inversions – between interior and exterior, between the domestic and global scales, between infinite specificity and utter consistency – raised by the *Phoenix Balanced House* model.

Olgyay and Fuller's architectural projects were of course very different in form and intent. Olgyay's architecture relied on calibration of form, orientation and environmental accessories (shades, overhangs, screens, etc.) to negotiate the interface between exterior and interior climates. Fuller's domes bypassed architectural complexity for structural and environmental efficiency, following a structural template and environmental response that was replicable across a range of scales and climates. Whereas Fuller understood his domed enclosures as environmental filters, he relied on mechanical means to create interior thermal comfort. The building envelope was both a climatic filter as well as a climatic generator. When describing the *Dome over Manhattan*, Fuller notes,

> From the inside there will be uninterrupted contact with the exterior world. The sun and moon will shine in the landscape, and the sky will be completely visible, but the unpleasant effect of climate, heat, dust, bugs, glare, etc. will be modulated by the skin to provide a Garden of Eden interior.
>
> (Hays 2008, 3)

In Fuller's work, the domed interior environment is, as is the dome of the thermoheliodon, an entirely climate-controlled space – a hermetically sealed environment that generates its own programmed thermal and airflow requirements, creating an interior climate of thermostability. It is an entirely closed-loop system in which environmental inputs are internally controlled. Fuller's domes offer a different vantage point from which to consider the relationship between the general and the specific, the local and the global that contrasts that of Olgyay's bioclimatic architectural designs. Fuller's projects operate from the outside, the global perspective, to the inside, rather than the opposite. One of the first design thinkers to understand that material and energy resourcing was fraught with global-scale inequities, Fuller developed a comprehensive planetary logic for his work that allowed him to bypass questions of regional identity and to design in a way that was both universally applicable (without modification) while also being notionally energy efficient.

The Olgyays' bioclimatic design method, as tested within the thermoheliodon, focused on designing environmentally calibrated, regional architecture that balanced out climatic extremes. Fuller's domes, on the other hand, are conceived of as being infinitely locatable, operating anywhere on Earth, bypassing the question of contextual specificity. Fuller's encapsulations offered comfort in the most adversarial climates – deserts, the Arctic, rainforests. Conceiving of the thermoheliodon's domed enclosure as an architectural model shifts focus back to what appears to be Olgyay's key priority in thermoheliodon: the development and calibration of the elaborate apparatuses, controls and devices that simulate an exterior environmental condition within the domed enclosure. When conceived of this way, the total environmental control required to simulate exterior environment can be understood in relation to these more radical views of climate control and the corresponding global vantage points they suggested emerging at the time.

Models of environmental design

Good models act both reflectively and projectively. At the time, the thermoheliodon revealed, through its workings and methodological intentions, prevailing views about both its interior and exterior environmental target systems. The perimeter of the architectural model contained on the testing bed struggled to reconcile these two climates – one given and one constructed. Viewing the domed enclosure as an architectural model offers a counter model of environmental management, one predicated on total climate control. The thermoheliodon reflected two models of environmental design and their associated working methods and embedded value systems; both continue to shape conceptions of environmental design in architecture today.

Environmental, ecological and sustainable discourse in architecture has matured and intensified over the past half-century. The Olgyays were working at a time before global warming and all associated social and ecological consequences were part of public discourse. Their working methods and intentions, however, inform conceptions of environmental design today in competing ways. The legacy of the Olgyays' work is expansive. Their bioclimatic design strategies are still referenced in canonical technical textbooks such as Steven Szokolay's *Introduction to Environmental Science: The Basis of Sustainable Design* (3rd ed., 2014), Norbert Lechner's *Heating Cooling and Lighting: Sustainable Design Methods for Architects* (4th ed., 2014), and Mark DeKay's *Sun, Wind, and Light: Architectural Design Strategies* (3rd ed., 2014). In the 50 years since the publication of *Design with Climate*, some of the gaps in Olgyay's method have been filled. New models of thermal comfort reconcile passive design strategies with a broader bandwidth of thermal comfort expectations. For example, adaptive models of thermal comfort, necessary for passive design in anything but the most ideal climatic contexts, expand Olgyay's ideal of interior of 'thermostability' and 'climate balance'. The adaptive model of thermal comfort challenges the prevailing view in the 1950s that climatic fluctuations were disruptive, suggesting instead that experiential variability to a point is desirable. Moreover, mixed-mode, or hybrid, methods of environmental control establish a middle ground between entirely passive and entirely active modes of building environmental management.

Many of the methods outlined in *Design with Climate* went on to inform the development of contemporary thermal modelling software such as the Autodesk software Ecotect.[5] Just as the thermoheliodon remained a work-in-progress due to challenges associated with thermal scaling of building materials, computational algorithms for reconciling scale effects continue to impact software development. The Olgyays' attempted to synthesise and codify scientific principles, weather data and building science into a step-by-step method intended to aid the design process for architects. However, many of their techniques were and remain overly complex and unintuitive, particularly in the earliest stages of the design process in which it is difficult to reconcile so many variables simultaneously. Today, there are many software packages available to test principles of daylighting, airflow and thermal exchange. However, no single software can synthesise all these concerns intuitively and legibly in the way that mirrors the Olgyays' aspirations. Methodological complexities persist when working between a range of digital modelling and simulation platforms and between design concept and application of technical principles.

There are clear legacies of the two models of environmental management suggested by the *Phoenix Balanced House* and the thermoheliodon dome. The former model, informed by vernacular adaptation

4.16

4.16 Glenn Murcutt, Wendy Lewin and Reg Lark, *The Riversdale Boyd Education Centre in New South Wales, Australia*. The project epitomises the 'selective' model of environmental design, relying solely on architectural elements such as solar fins, roof overhangs and operable windows for passive heating and cooling. Oz.tecture, Architecture Foundation Australia. Photograph: Anthony Browell.

and regional specificity, relies on building configuration, orientation, window locations and associated architectural componentry for largely passive environmental control. This approach is indebted to the principles of bioclimatic design, requiring careful analysis of local and microclimatic conditions to design a building attuned to its site. British architect and academic Dean Hawkes refers to this design approach as the 'selective mode' of environmental control, building on earlier use of the same term in Reyner Banham's canonical *The Architecture of the Well-tempered Environment*, published in 1969. The defining features of this mode are reliance on building fabric, built form, orientation and window placement to prioritise passive environmental strategies.

Australian architects Glenn Murcutt, Reg Clark and Wendy Lewin's entirely passively heated and cooled *The Riversdale Boyd Education Centre* is an example of a 'selective' building (Figure 4.16). The form and configuration of the building are aligned to maximise solar gain. Moreover, architectural components such as window projections, roof overhangs, vertical fins and operable interior screens selectively filter solar gain, air movement and light, seasonally aligning interior comfort expectations with exterior weather conditions. This approach resonates with David Leatherbarrow's *device paradigm*, described as a way of scripting architecture's environmental performance through adjustable componentry such as shading devices, moving screens or operable windows (2009).

Hawkes contrasts the 'selective mode' of environmental response with the 'exclusive mode', which is marked by compact building form, total environmental control and lack of specificity with regards to building orientation (Hawkes 2001). The thermoheliodon dome reflects this countervailing 'exclusive' model of environmental design, one that relies on the building envelope to act as a total climatic buffer in service of creating a highly controlled interior environment. Fuller's dome was notionally energy efficient, but its efficiency was predicated on constructing a hermetically sealed environment.

4.17

4.17 Grimshaw Architects, *The Eden Project* in Cornwall, UK. The project epitomises the 'exclusive' model of environmental design, entirely encapsulating the greenhouse interiors to construct distinct Rainforest and Mediterranean biomes. Photograph: Tiago Pinto da Costa.

There are two contemporary models of sustainable design that rely on creating a sealed barrier from the exterior to minimise energy consumption. First, encapsulated, closed-loop buildings often take on bubble forms and attempt to contain specific biomes distinct from that in which they are sited. Grimshaw and Partner's *Eden Project* is a contemporary exemplar, building on earlier legacies of space exploration, autonomous house movements and radical 1960s and 1970s experimental architecture (Figure 4.17). A second legacy of Fuller's dome and the 'exclusive' mode of environmental design is Passivhaus-certified construction. Passivhaus concepts emerged in the late 1970s in Saskatchewan, Canada, where building research transitioned away from active solar design principles – which incorporated elements such as sunspaces and Trombe walls to trap and absorb solar radiation for reradiation during cooler periods – to use of superinsulation to prevent heat loss altogether (Barber 2021). Passivhaus entails creating a highly insulated, tightly sealed building envelope, a bubble, albeit in a very different material form, that operates as a climatic buffer, containing a homogenous interior thermal environment. Passivhaus projects are marked by their solidity, airtightness standards and relatively compact building forms. While the form and materiality of Passivhaus projects are a visual antithesis to Fuller's often expansive, transparent domes, they do share the trait of relative formal continuity combined with airtight construction methods.

Nested environments

As digital workflows for optimising buildings increase in complexity, the thermoheliodon is a reminder of the value of working with objects in the physical world. Models open imaginative engagements and dialogues with the worlds they represent. Unlike the infinitely scalable digital environment, physical models are fixed in size. The physical model's materiality is set. Moreover, they are situated in a physical context, in a room or a workshop or a laboratory around which people can gather and speculate, test and hypothesise. Unlike the black box of the computer, these physical models in their spaces of production have the attendant environmental effects of those spaces to collude or contend with. Both Marey's and the Olgyays' laboratories effectively integrate their building environmental systems in their environmental model systems. Marey's wind tunnel relies on an existing chimney to expel exhaust. The Olgyays' laboratory is topped with a dome, intended for use with daylighting experiments, that twins that of the thermoheliodon.

4.18

4.18 Photograph of the ESALA (Edinburgh School of Architecture and Landscape Architecture) concrete workshop. The workshop was an ad hoc space intended for materials and structural experimentation. Designing the *Working Prototypes* exhibition within the space raised questions about the relationship between models and the environments in which they are nested.

The spaces in which environmental models are constructed and used act as additional layers of environmental mediation within a series of nested environments, from the model to the testing bed, and from the workshop to the world beyond. In 2018, I exhibited the 10 prototypes featured in Chapter 2 in a concrete casting workshop at the University of Edinburgh. The exhibition was spatially planned in a way that mirrored the organisation of Chapter 2: as a series of chronological prototypes, highlighting the materiality and tectonics of each prototype at full scale while also featuring photographs and videos of their flow visualisation strategies. Typically used for large-scale concrete casting and structural testing, the concrete workshop was not a formal exhibition space (Figure 4.18). It is the opposite of an inert, windowless white box. Instead, it had distinct spatial, material and infrastructural qualities that reflected its intended use as a workshop. A series of hanging fluorescent lights on a single non-dimmable switch acted as the only source of artificial lighting in the space. Mechanical ducts and electrical conduits ran exposed throughout. A concrete mixer, safety supply cabinets and a large rig for supporting heavy objects took up much of the floorspace. The space was volumetrically ad hoc, with ceiling heights, a mezzanine, door heights and window locations without any meaningful alignments. Natural light, entering from the lites of exit doors on two sides of the room, was unevenly distributed. Used mainly to test structural capacities of large-scale concrete casts, the workshop was dark, moody and appeared in a continuous shroud of cement dust.

Before the exhibition, I thought of environmental models as acontextual in two competing ways. On the one hand, the interior steady-state environment in the model interior represented anywhere in the sense that the models abstracted airflow in a way that enabled it to represent any context. This need to replicate many places is a defining feature of the model as experimental chamber. On the other hand, the interior environment in the testing bed of the model represented nowhere in the sense that the steady-state condition replicated a fictional exterior condition devoid of the boundary layer effects operating in the real world. Steady, streamlined airflow is not the airflow of the built environment. Moreover, my prototypes were acontextual in that they lacked a fixed home. They were designed to be autonomous, mobile and internalised: worlds within worlds. They often moved between my office, the architecture workshop, the concrete casting workshop and a small kitchen at the end of the hallway to my office.

4.19

4.19 Photograph of WT4 taken from a mezzanine above the concrete workshop. When viewed from this new vantage point, the wind tunnel hovers within its steel frame structure.

Photography further decontextualised the models, occluding external environmental conditions deemed distracting. Light baffles were integrated into model frames to eliminate reflections of surrounding spaces. Overhead lighting was turned off, eliminating background reflections in the process. Lighting was integrated into or behind prototypes, focusing attention on the internal workings of the model. Light, physical disturbances and clutter that might reflect on the testing bed surfaces were liabilities requiring erasure.

Planning the exhibition prompted consideration not only of how to best present prototypes individually and relationally, but also how to best do so with consideration to the qualities of the space in which they sat. The exhibition opened new vantage points for viewing the environmental models, from the outside in rather than the inside out (Figure 4.19). From the outside in, models took on new presence as material artefacts in their own right (Figure 4.20). A series of photographs of the environmental models document them as artefacts that, rather than occluding environmental phenomena, amplify them depending on lighting conditions and vantage point.

Considering the research workshop as a space of production, the environmental models read in some cases as extensions of this workspace just as Marey's wind tunnel was an extension of his physiological research station and just as the Olgyays' thermoheliodon relates to the domes of the Princeton environmental lab (Figure 4.21). There was an ambiguity as to where the artefacts of the exhibition started and ended in the space (Figure 4.22). One water table was integrated into an existing sink (Figure 4.23). Wind tunnels and adjacent mechanical ducts became visually analogous. Reflections off plexiglass surfaces extended materiality and views of the space beyond. Other reflections blurred distinctions between model interior and building exterior (Figure 4.24). Strategic lighting focused views rather than occluding them, creating focal points of intensity and shadowy pause (Figures 4.25 and 4.26). The exhibition placed the environmental models into a context of floating dust, exposed ducts, raw stone and material production. They became at times extensions of existing

4.20 Exhibition photograph of WT1 and WT4 hovering in front of filling-tank mirrored model images. A steel tension cable attached to the stone wall provided an offset support for hanging drawings. Filling-tank components were attached to a steel radiator with rare earth magnets.

4.20

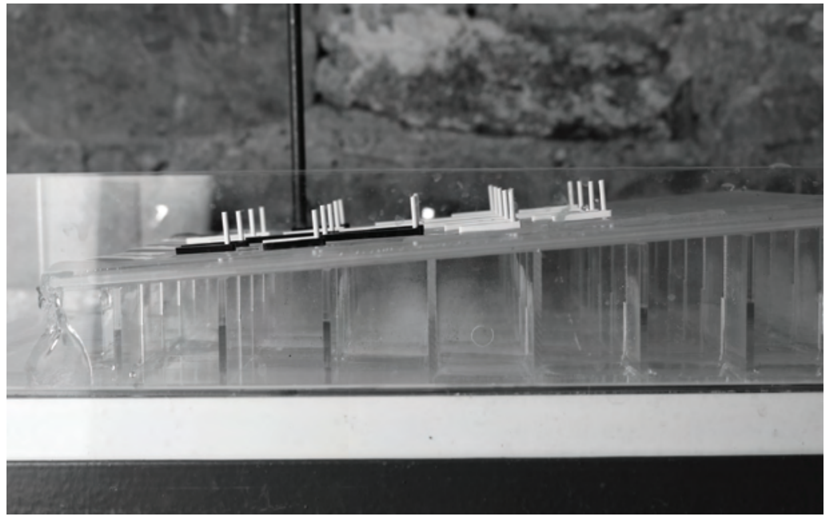
4.21 Photograph of a plywood table on trestles containing WAT2 and WAT4. The table sits between an existing stainless-steel sink where WAT3 is set up. Photographs of the water table flow visualisation studies were attached to an existing steel duct. An existing stone wall, aluminium support frame and a tangle of electrical cords and conduit form the backdrop to the work. A video projection, photographic soft-box light, and water table with integrated lightbox act as the only light sources for this area of the exhibition.

4.21

4.22 Photograph of WT1 adjacent to rough exposed stone walls in the ESALA concrete workshop. The exhibition placed the models as objects within the space of their production, acting as extensions of these spaces.

4.22

4.23 Photograph of the WAT3 resting on an existing sink in the ESALA concrete workshop. The unevenly stacked, rough stone walls of the workshop act as a visual counterpoint to the highly calibrated watertight vessel.



4.23

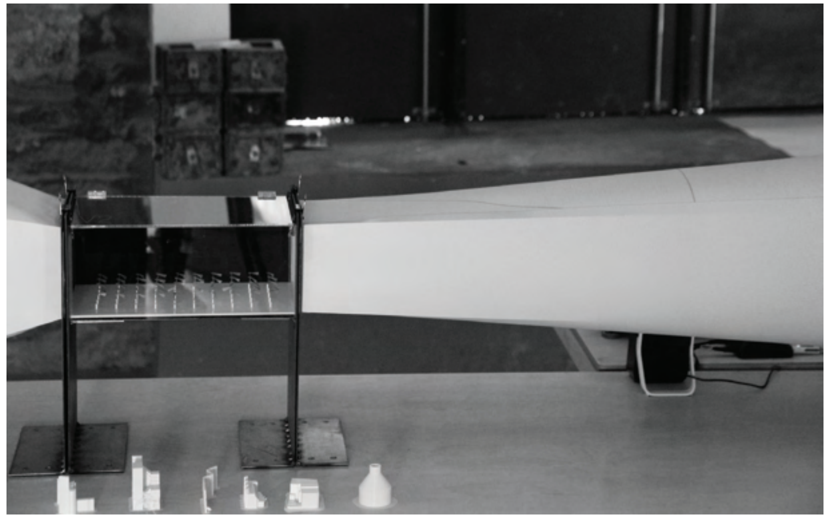
4.24 Photograph of FB2 adjacent to an exterior door backlighting the model. The wired glass of the door, seen through the tank, acts as a perspective drawing machine, framing views to the loading dock beyond.

4.24

4.25 Photograph of a plywood shelf with steel angle lip clamped on either side to the ledge of an existing concrete hanging rig for support. Spotlights focus on the surface. Photographic stills hang from the top of the rig in the dark similar to contact sheets drying in a photography darkroom.

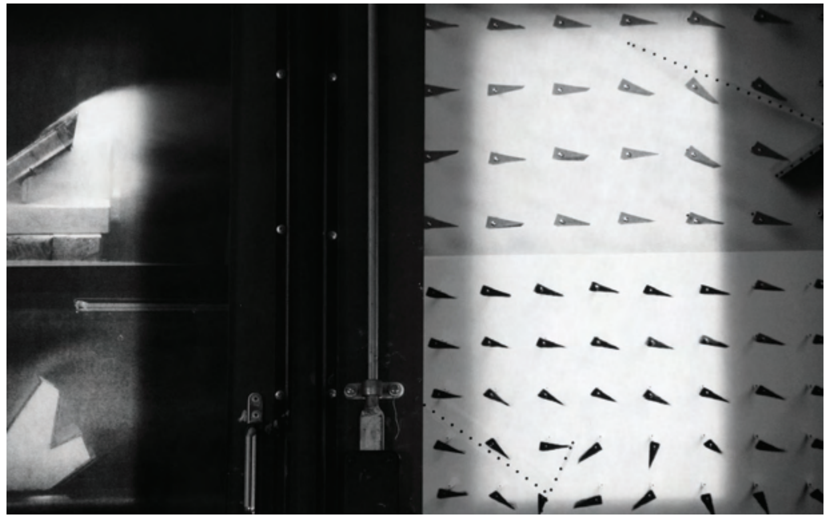
4.25

4.26 Photograph of WT4 hovering in front of a monolithic concrete loading deck beyond.



4.26

4.27 Photograph of wind tunnel flow visualisation photographs attached with rare earth magnets to steel exit doors. The photographs were backlit through the door lites.



4.27

infrastructure, receptacles for projections and backdrops for suspended dust particles highlighted by projector lights (Figures 4.27 and 4.28). From the enclosure that breathes to the hemispheric dome that contains, this final context situated models as constructed environments within constructed environments, as infrastructural and environmental extensions of the spaces of their production.

4.28

4.28 Photograph of the backlit entry exhibition banner. Architectural elements within the workshop were coopted as extensions of the models. Door lites backlit photographs; projectors spotlit surfaces; photographic lights backlit drawings. Flow visualisation lighting techniques were coopted as exhibition planning principles.

Notes

1. In architectural models, the full-scale condition in the world that a model depicts is referred to as a referent. The relationship between a representation and its referent has been the subject of substantial theoretical reflection in architecture and the relationship between a model and its target system has been the subject of significant reflection in the philosophy of science. For this chapter, the term 'target' is used throughout to refer to a representational referent.
2. Passive solar house design principles were understood at the time, but they required refinement. In the 1930s, George Frederick Keck and William Keck pioneered passive solar house design principles. However, these designs were prone to summer overheating, and design was predicated on only general principles of orientation. See Reynolds, 'The Roots of Bioclimatic Design' (2015); and Barber, *Modern Architecture and Climate: Design Before Air Conditioning* (2020).
3. This diagram advances the work of Augustin Rey, Justin Pidoux and Charles Barde's 'heliothermic' theories for urban building orientation in 1912 Paris, which went on to influence Le Corbusier's heliothermic axis in Ville Radieuse (1930). Victor Olgyay includes a section in *Design with Climate* crediting related theories of sol-air building orientation, including that by Rey, Pidoux and Barde, Ludwig Hilberseimer and Henry Wright among others.
4. Neither Olgyay nor the Climate Control Project proposed eliminating mechanical systems altogether. Designing mechanical systems were the final stage of Olgyay's bioclimatic method. Similarly, guidance provided by the Climate Control Project prioritised passive means of heating and cooling, but advised supplementing as needed with mechanical heating and cooling. Nevertheless, both focused almost entirely in their writing on passive strategies.
5. Some of the earliest digital building simulations were being developed roughly in parallel with the development of the thermoheliodon. Tamami Kusuda, as one of the first to work with building performance simulation, noted that the first ASHRAE paper featuring a computational technique was published in 1959. His pioneering work digitally simulating interior thermal environments of bomb shelters for the US National Bureau of Standards was published in 1964, a year after *Design with Climate* was published (Kusuda 2001). For more information about the legacy of the Olgyays in relation to the development of Ecotect, see David Leatherbarrow and Richard Wellesley, 'Performance and Style in the work of Olgyay and Olgyay', 2014.

Chapter 5 | Plumes

Each case study in this book has established dialogues between at least two of the four defining features of environmental models: the phenomena of air movement, the instrument producing this phenomenon, the models of architecture they reveal, and the worlds that they target. Chapter 3 explored Marey's wind tunnel in relation to the phenomena of moving air and the instrumentation of the wind tunnel as a sensitive device registering air resistance. Chapter 4 presented the Olgyays' thermoheliodon as reflecting two data-driven views about weather and climate and two models of environmental management in buildings – one based on selective filtration and the other on encapsulation.

This chapter returns to the phenomena of air movement – focusing on plumes of thermal buoyancy – while introducing a third model of environmental design: one shaped by thermodynamic processes. David Boswell Reid's convection experiments, featured in the 1844 book, *Theories and Practices of Building Ventilation*, act as the focal point for this investigation. Reid's experiments were simple, consisting in glass test tubes, coloured water and a naked flame. It is because of this simplicity that the experiments can be seen as representations of convective processes across many scales – from the architectural model to the physical experiment to the constructed prototype to the full-scale building – each of which were central to Reid's working methods. Reid's approach to non-mechanical design has renewed significance because it suggests novel strategies for designing low-carbon, naturally ventilated buildings, concerns heightened today by the COVID-19 pandemic.

Buildings are objects of resistance to moving air, creating pressure differentials both inside and outside of their walls. Positive pressure builds up on the windward side of a building, resulting in a negative pressure zone on the opposite side. Openings enable air to flow from high- to low-pressure zones. Marey's wind tunnels make airflow associated with these differentials in air pressure evident as a series of either continuous or dispersed moving lines of smoke. Marey's wind tunnels were also reliant on another principle of airflow – buoyancy. Exhausted smoke from the tunnel was expelled into a chimney in the Institut Marey; this smoke, warmer and less dense, rose out of the chimney, drawing in fresh air from below. The process of flow due to differences in temperature govern buoyancy-driven airflow.

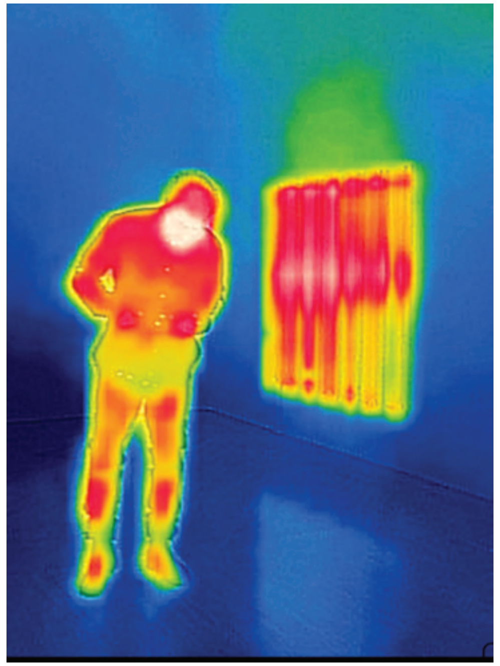
Plumes are the equivalent flow patterns to the streamlines and vortices in Marey wind tunnels for buoyancy-driven airflow.

5.1

5.1 Smoke plumes rising from a controlled fire in the Gulf of Mexico after the Deepwater Horizon offshore oil spill. Wikipedia Commons.

They occur when a fluid of one composition moves through that of another composition. Differences in composition may be chemical or thermal, but their differences drive flow across many scales of the built environment. At regional scales, plumes are often visual indices of carbon-intensive industrial processes, signalling pollution or contamination. Exhaust rises from industrial plants as thick white plumes. These white plumes are easily associated with clouds or with notions of cleanliness, often occluding that they are in fact full of toxins. Thick black-grey smoke plumes arise from uncontrolled wildfires, shifting and dispersing harmful particulates according to prevailing wind patterns. Aerial views of oil spills reveal iridescent plumes of contamination across the surface of the body or water in which it was spilled. These same oil spills, under controlled burning, emit black plumes of toxic smoke (Figure 5.1).

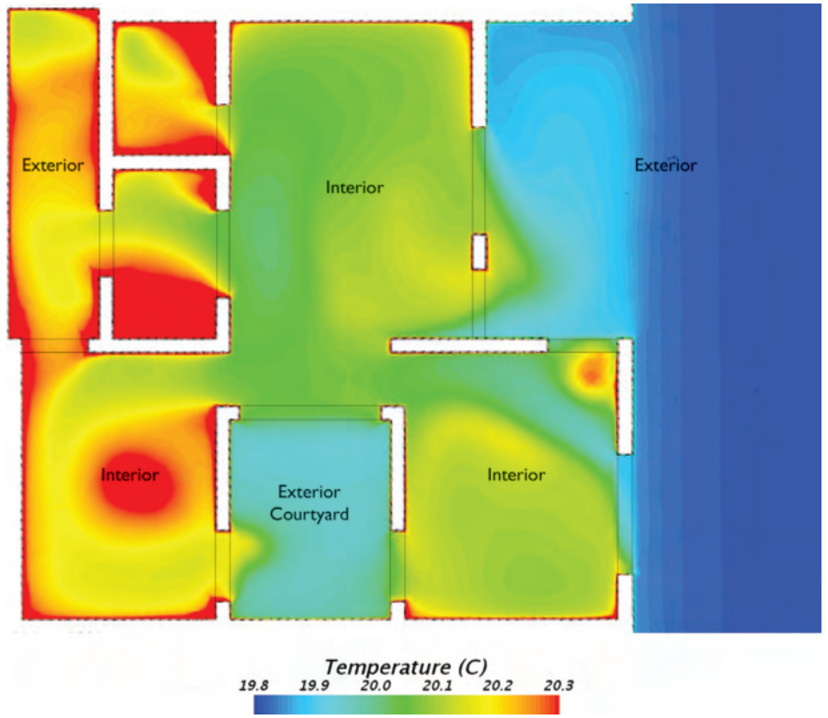
At the building scale, heat sources that drive differentials in air movement vary from internal heat gains associated with lighting and machinery to passive solar gains and to mechanical devices such as radiators and furnaces dedicated to that task. The location of heat sources and heat sinks, as well as air inlets and outlets, determine these flow patterns. Emitted heat rises as indiscernible plumes, often creating visceral currents of air movement through a space. Thermal imaging captures these currents of movement as infrared radiation, translating them into colour gradients transitioning between blue, red, yellow, orange and green (Figure 5.2). As mentioned in Chapter 3, temperature intensities indicated as topographies or colour gradients are referred to as contour plots or isocurves in computational fluid dynamics (CFD), and they have become the dominant visual language for describing thermal exchanges in buildings today (Figure 5.3).



5.2

5.2 Philippe Rahm, *Climatic Apparel/About a Worker*, 2022. Photograph included in the exhibition, *Infrared Portraits of the 21st Century* at the Camera Museum in Vevey, Switzerland, 2021. Courtesy of Philippe Rahm, 2021.

At the scale of the occupant, the body itself is both a source and a register of thermal differentials. This is most evident at the boundary layer, the interface between the skin's surface and space beyond, a principle introduced in relation to both aeronautics and ground surface turbulence in Chapter 3. Aeronautical engineer-turned-architect Michelle Addington describes the charged interface of the boundary layer as a techno-spatial phenomena in which two energetic 'fronts' meet, creating a perceivable exchange: 'Thermodynamic boundaries are not legible and tangible things, but instead are zones of activity, mostly non-visible. In this zone of activity – the boundary – the truly interesting phenomena take place. This is where energy transfers and exchanges form, and where work acts upon the environment' (Addington and Schodek 2005, 51–2). Comfort is dependent on many factors within this boundary layer: clothing, activity level, interior temperature, humidity and air movement rates, to name a few, hindering wide consensus on thermal comfort. Buildings also have boundary layers. When it is cold outside, buildings leak heat, often through faulty seams or materials with poor thermal resistance. When it is warm outside, the opposite process takes place, with heat migrating into the building through paths of least resistance. The plume, as it leaks from inside out or outside in through a seam, connects the detail back up to the regional and planetary scales of atmospheric exchanges.



5.3

5.3 Plan view of a low-rise building with exterior courtyards indicating wind-driven temperature changes in interior and exterior spaces. Courtesy of Kim Adamek, 2022.

This chapter explores the capacity for buoyancy-driven airflow to act as the primary determinant of a building's form and introduces an associated model of environmental management in buildings, one predicated on thermal differentiation. David Boswell Reid's convection experiments act as the focal point for this investigation. Featured in the 1844 book, *Theories and Practices of Building Ventilation*, Reid's test tube experiments could be considered some of the first environmental models, scaled abstractions of air movement through an architectural space. In the experiments, glass vials full of water were heated from below by a small flame. The introduction of dye revealed flow patterns. They illustrated the principle of convection, the mode of thermal exchange marked by the mixing of fluids. Reid was trained as a physician, and the scientific methods he used to test ventilation principles were far-reaching, ranging from designing breathing instruments, to conducting physical experiments within existing spaces, to implementing full-scale mock-ups, to designing full-scale building ventilation schemes, most notably for the House of Commons at the Palace of Westminster. Each experiment, prototype and mock-up that Reid constructed established dialogues between heat sources and the vessels they impact, from the sensing body to the calibrated room and to the breathing building.

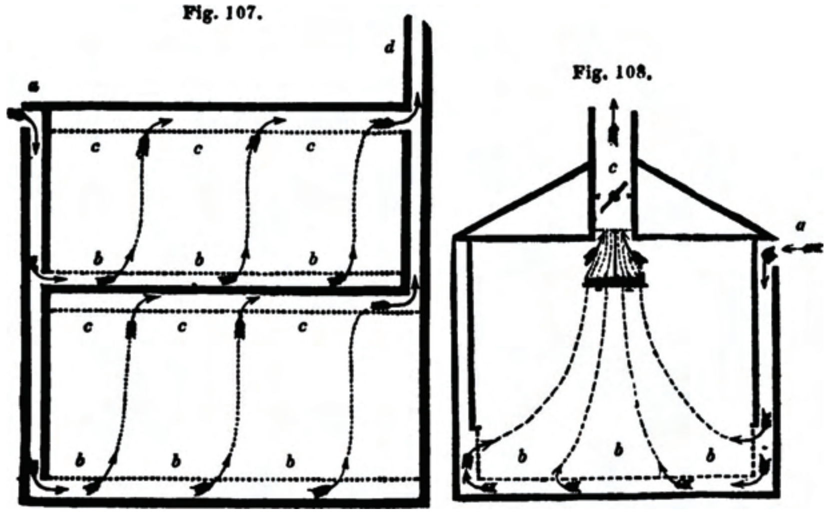
When considering the inherent and enduring qualities of air movement, architectural historian Daniel Barber notes that 'the history of nonmechanical practices is also about possible futures' (2020, 13). This chapter moves between the early moments of the codification of building ventilation practices and the present day, both marked by heightened anxiety over the spread of airborne contagions. Completed before the codification of thermal comfort using bioclimatic principles, Reid's work also reveals challenges associated with achieving thermal comfort consensus. His work established a practice of non-mechanical conditioning and ventilation of spaces, impacting their form, configuration and furnishing. In this way, Reid's approach to architecture establishes a foundation for understanding a third contemporary model of environmental architecture – buildings organised in relation to thermodynamic principles. The chapter concludes with a series of reflections on my filling-box model experiments, which invariably leak. As the models leak into the tank beyond, they are viscerally situated within a much wider context of atmospheric immersion and planetary-scale environmental change.

Reid's convection experiments

David Boswell Reid was trained as a medical doctor at the University of Edinburgh in the 1830s. He later became a lecturer in practical chemistry, eventually within a laboratory of his own design. He is best known as the ventilation consultant to architects Charles Barry and Augustus Pugin for extensive renovations to the Palace of Westminster following a fire in 1834. These varied disciplinary roles equipped Reid with an ability to conceive of pneumatic principles across scales using a range of methods. He devised methods for conditioning air and then moving it via buoyancy primarily within hermetically sealed environments. Air, its composition, its role in impacting public health, and its conveyance through buildings were Reid's entwined preoccupations. All these concerns were methodically outlined in his 1844 book, *Illustrations of the Theory and Practice of Ventilation*, one of the first textbooks on building ventilation.

Illustrations of the Theory and Practice of Ventilation is largely a plea for architects to take seriously the panoply of real ('lethargy') and perceived ('premature aging') threats caused by inadequate building ventilation. The book reminds the reader of the daily assaults and 'rough and rude treatment to which the lungs are subjected' (1844, 7). Reid's pleas are convincing and his claims wide-reaching, appealing to both emotion and intellect, of the urgency of the evils of *vitiated* air – collective exhalations, usually offensive, sometimes pathogenic – at the time. His main concerns were motivated by his role as a physician, focusing on the real and perceived effects of airborne disease. For Reid, air was a harbinger of contaminants from pollution outside or contagions inside, requiring continual purging. Over the past nearly two centuries, air quality in cities and buildings has substantially improved due to changes in public health, sanitation and pollution mitigation. Nevertheless, renewed concerns about inadequate building ventilation prompted by the COVID-19 pandemic revalidates the significance of Reid's work.

Illustrations of the Theory and Practice of Ventilation offers theoretical and practical guidance about the composition of air and its ideal distribution, through written reflections and diagrammatic illustrations. The intent of the book is to disseminate knowledge about developments in pneumatic science in the 50 years preceding its publication to improve public health in the United Kingdom. Reid was particularly interested in codifying and standardising ventilation rates and thermal comfort standards, noting that 'much of the misunderstanding that prevails, too generally, in respect to ventilation, arises from the extreme diversity of standards which different individuals consider essential to their comfort' (1844, 11–12). His book is expansive and comprehensive. The style of writing is succinct despite its length. It is



5.4

5.4 (left) David Boswell Reid's ventilation diagram indicating supply of fresh air and the discharge of 'vitiated' air through two apartments sharing the same air source and discharge and (right) the application of a lamp as a heat source under the ventilation discharge to accelerate air movement. Reid, 1844.

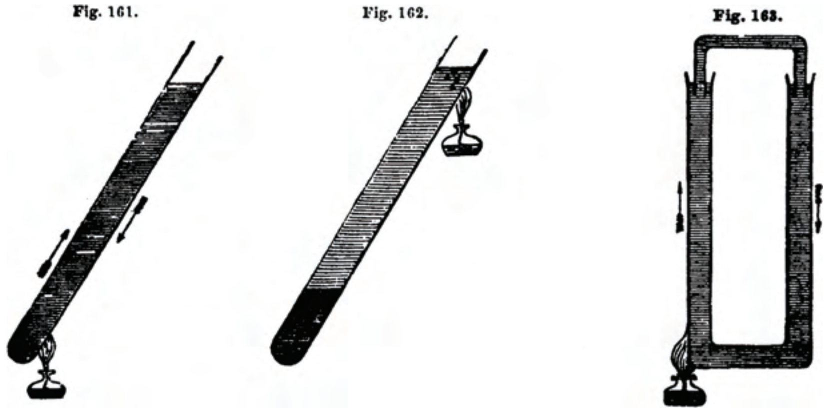
organised as 857 separate paragraph-long bullet points.

Reid came to know air, its composition and its flow characteristics through observation and material experimentation across scales. A vocal advocate for the integration of basic material science education in elementary schools, he understood the value of learning about the 'material world' by 'training the eye and the ear to observation, and the hand to manipulation' as a means of intellectual development (1844, 23–4). He believed in the value of learning empirically, using simple observation-based experiments. His approach to education was an early form of experiential, material-based learning: 'Let him content himself with plain apparatus, such as may be purchased for one or two pounds, or even with nothing more than a bottle, a bent tube, a few jars, and such materials as are everywhere accessible' (1844, 22). The experiments, while simple, act as microcosms of the thermal domains we are all immersed within:

> On the small scale, the movements induced in air by a variety of temperatures, can be shewn very beautifully by heating the air in a large glass shade or jar, after introducing various portions of phosphorous, of different sizes and forms, and supporting them within this shade or jar, at a height of one or two inches.
>
> (1844, 101)

Reid also offered guidance for visualising air currents at full scale using an 'exceedingly minute thread, which is inclined in any direction by the slightest movement in the atmosphere, or by producing a little smoke with a very small coil of brown paper' to 'trace the currents' of air movement (1844, 140). These simple experiments are one of a remarkable range of strategies Reid devised to verify and make evident the composition of air, to determine ideal ventilation rates and to devise strategies of natural ventilation within individual rooms and entire buildings.

Reid's straightforward approach applied to his drawn illustrations as well, which pepper *Illustrations of the Theory and Practice of Ventilation* (Figure 5.4). Completed before the advent of film photography, the book includes drawings of airflow through small-scale experiments, mechanical devices and buildings of a range of congregations and configurations including churches, apartments, hospitals and greenhouses. Aside from some stylistic flourishes to the arrows, Reid's descriptive airflow diagrams are familiar. They look like the kind of static environmental diagrams, referred to as 'vectored space' drawings by architectural historian David Gissen, commonplace in technical textbooks today (2006). At the time, however, these airflow drawings required explanation. Reid notes, 'The feathers of the arrows are intended in all the diagrams, to indicate the ingress of air, and the barbs the discharge, which the body shews its course' (1844, 79).



5.5

5.5 (left) David Boswell Reid's convection experiment diagrams illustrating how the location of heat sources drive flow patterns though a test tube and (right) how a tubular apparatus with a low heat source drives a convective loop. Both illustrate thermodynamic processes governing water heating systems in buildings. Reid, 1844.

Reid's drawings are the kind of idealisations that marked the honed judgement of the scientist described in more detail in Chapter 3. They smooth over idiosyncrasies of flow patterns, rendering the complex currents of moving air as simple lines with arrows indicating general flow patterns. What makes the illustrations distinct is their stylistic continuity given their number and range. The book includes over 300 hand-drawn illustrations, ranging from basic physical experiments to complex spatial organisations. Reid's drawings pay particular attention to the inlets and outlets of airflow into and through a room, and to heat sources that drive or accelerate this flow, reflecting his awareness of how heat drives air movement through space.

The material world of physical experiment and the economy of the flow drawing converge approximately halfway through the book, when Reid introduces two experiments that made the mechanics of airflow due to convection visible (Figure 5.5). The first drawing shows two test tubes filled with dyed water. One is heated from below, and the other is heated from above by a candle. The liquid in the former tube is overlaid with arrows indicating water movement and a corresponding uniformity of colour; liquid in the latter tube remains stratified, suggesting stasis. Reid elaborates:

> fig 161 represents a tube with coloured litmus water below, and common water above. A lamp applied above heats and evaporates the water there, and no further change is observed. But if the lamp be applied below, then the cold water there being expanded, the colder colourless water descends below it and pushes up. In this manner, a continuous circulation is maintained, till, from the constant mixture of the ascending and descending currents, a uniform heat is observed.
>
> (Reid 1844, 245–6)

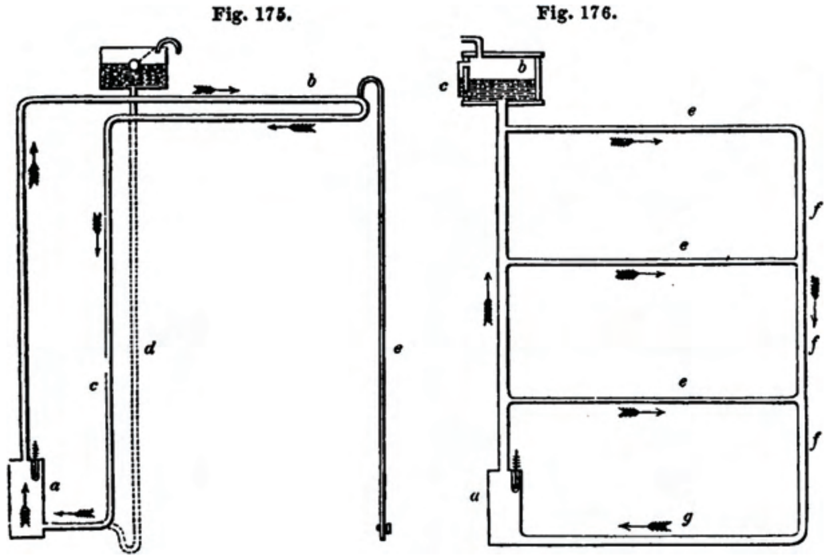
A second, more elaborate model applies these principles more directly to buildings. Described as a 'tubular apparatus', the experiment is 'well adapted for shewing the manner in which hot-water apparatus operates, water being placed in one limb and coloured water in the other. The fluid moves upwards in the limb to which the heat is applied, descending in the opposite limb' (Reid 1844, 246). In one experiment, the glass apparatus represents a mechanical system that is organised as a convective loop. A boiler heats water. This heated water is distributed to a reservoir or to an individual room. Cooled water descends back to the boiler, where it is heated, and the process continues. A series of architectural diagrams – of hot houses, drying houses and churches – follow descriptions of these experiments (Figures 5.6 and 5.7). They illustrate some possible configurations of 'hot water' systems. But, Reid admits, the possibilities of application are endless: 'Hot-water apparatus is made in an endless variety of forms according to the purpose to which it is applied, and the circumstances under which it has to be constructed' (1844, 250).

The utter simplicity of Reid's test tube experiments enables them to represent a vast array of architectural possibilities. This simplicity sits in contrast to the elaborate mechanics of both Marey's wind tunnel and the Olgyays' thermoheliodon. It is perhaps because of their reduction in complexity that they readily invite further speculation, suggesting ways of reading the tubular apparatus less as a mechanical assembly and more as a series of interconnected spaces.

Reid's test tube experiments can be read as architectural models. In this reading, water represents air, and the convective process takes place due to the natural tendency for buoyant (hot) air to rise. One can imagine further iterations of Reid's 'tubular apparatuses' that test other, more complex, spatial configurations. Imagine a series of experiments with further modifications – glass vessels of increasingly complex shapes and configurations, heated at different locations. In these models, dyed water would continue to make the processes of convection evident, but within air rather than water. The configuration of the chambers might expand and change shape accordingly. The focus of the model would therefore shift from representing the organisation of mechanical pipes to the organisation of architectural space. The tubular glass apparatuses become vessels of interconnected spaces and their corresponding interiorised thermal exchanges. The model transitions from being a scientific explanatory device to a device for spatial speculation akin to the fantastical glass-blown *Imaginary Architectures* of El Último Grito (Figures 5.8 and 5.9).

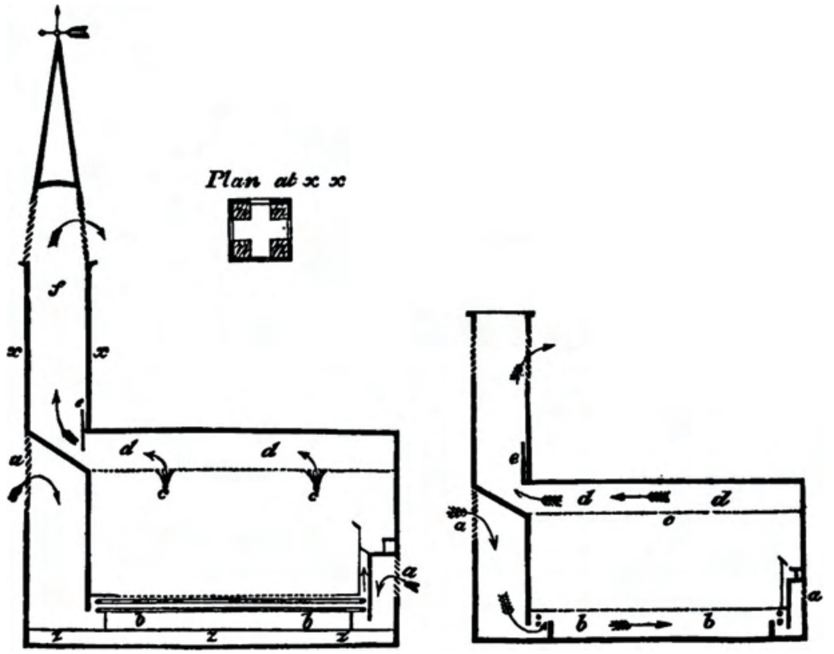
We can read Reid's convection experiments as architectural models because they are three-dimensional scale representations of thermal phenomena that take place within a full-scale contained interior space. Further, we can understand them as *environmental models* because they materialise the process of convection within the controlled environment of the test tube. The phenomena modelled is the process of thermal transfer that takes place due to fluid temperature differentials, which drives convection. Much like the addition of smoke to Marey's wind tunnel, flow is visualised through the addition of a new material, dyed water, to clear water. Reid's test tube models do not look like the mechanical systems he designed, but they

5.6 David Boswell Reid's diagrams indicating two hot-water heating system configurations. In both schemes, a boiler heats water and drives flow through an ascending and then descending pipe loop, ultimately feeding lukewarm water back into the boiler. Reid, 1844.



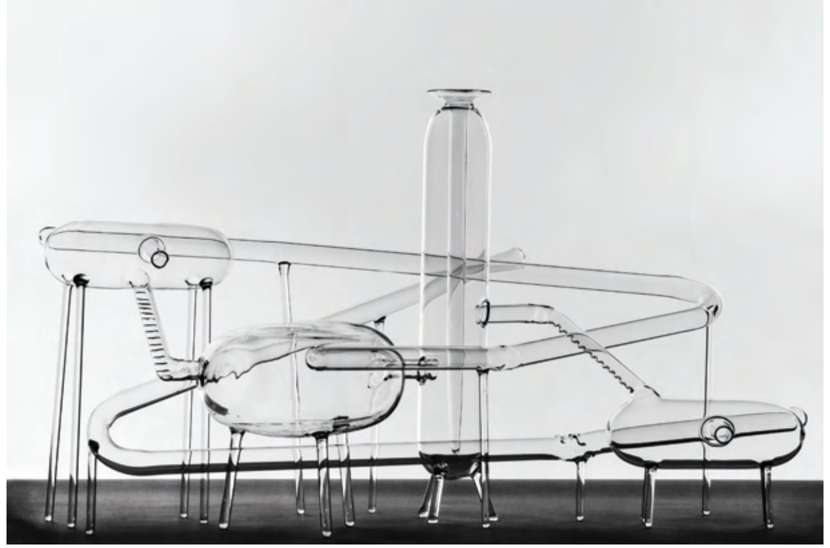
5.6

5.7 David Boswell Reid's diagrams describing a strategy for moving fresh air through poorly ventilated churches while minimising cold air draughts. Air is drawn into outlets (a), into a low equalising chamber (b), and then drawn out through the church spires driven by gas burners (c). Reid, 1844.



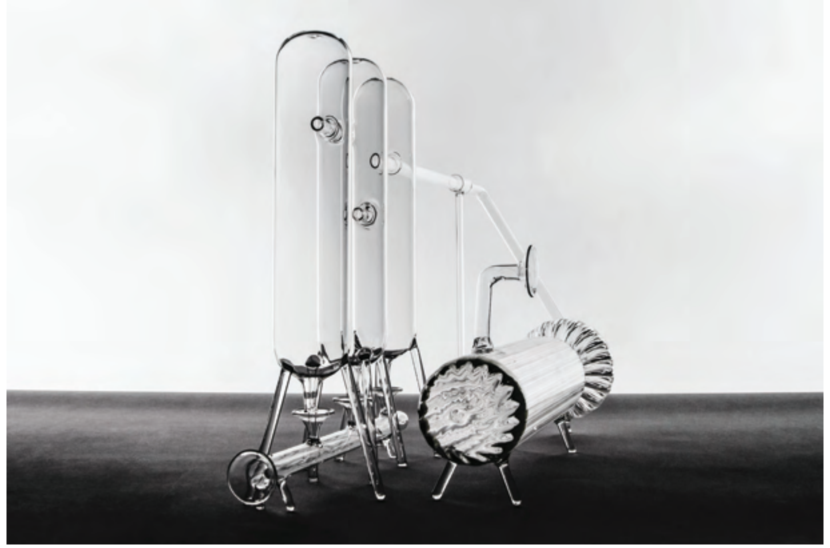
5.7

5.8 El Último Grito, *Mine Shaft* from 'A Rematerialisation of Systems_Industries', 2013. The interconnected glass vessels and tubes create imaginary architectural spaces borrowing from the logics of industrial architecture. As speculative objects, they operate somewhere between material prototypes and scale models. Courtesy of El Último Grito, 2013. Photograph by POI.



5.8

5.9 El Último Grito, *Chemical Plant* from 'A Rematerialisation of Systems_Industries', 2013. Courtesy of El Último Grito, 2013. Photograph by POI.



5.9

do behave like them. They make the hidden mechanisms of convection evident; they make, to use D. Graham Burnett's words, 'the actual forces and stuff at stake' visible.

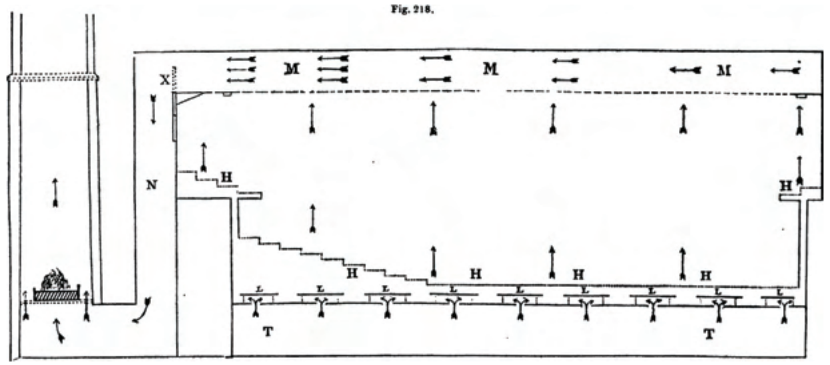
Architecture as experiment

The hidden mechanisms of buoyancy-driven airflow, revealed through Reid's drawings and experiments, establish the foundations of his architectural interventions. Ultimately, the human body was the locus in which these concerns across scales converged. Reid saw respiration and ventilation as both intertwined and analogous processes. The inhalations and exhalations of building occupants prompted the need for appropriate ventilation. At the same time, buildings *breathed* through ventilation: 'respiration consists in the alternate inspiration and expiration of air … the object being to remove the vitiated air which is exhaled in the lungs, and to supply a corresponding quantity of fresh air' (1844, 168).

Reid understood the body as a thermal sensorium that both consciously and unconsciously registered alterations to its environment. He completed a series of experiments directly on the human body to determine air supply levels required for healthy respiration. These experiments, ranging in size and scope, were precursors to the climate chambers used in the 1960s and 1970s to codify thermal comfort requirements. In one particularly harrowing experiment, he used himself as a test subject to see how long he could lie in an 'airtight oblong metal box' with the door soldered shut (the answer: 'one to two hours') (1844, 179).

The project that enabled Reid to hone the dialogue between respiration and ventilation, between body and building, was indirectly prompted by combustion. Following a fire in 1834 that did extensive damage to the Palace of Westminster in London, Reid was hired as a ventilation consultant to architects Charles Barry and Augustus Pugin for the New Houses of Parliament. Over the course of a remarkable 17 years, Reid collaborated primarily with Barry to develop a series of strategies for ventilating and controlling climate in an incredibly complex architectural and political context. Henrik Schoenefeldt has provided a detailed account of this full process based on extensive analysis of archival documentation in *Rebuilding the Houses of Parliament: David Boswell Reid and Disruptive Environmentalism* (2020). Fundamentally, while Barry's initial scheme relied on strategies of cross-ventilation through the debating chambers, Reid's relied on the stack effect within a hermetically sealed interior. This strategy was seen as less disruptive to the occupants but proved far more complicated to effect.

Reid initiated his study of Westminster by constructing a physical model in his Edinburgh laboratory. Refinements to the model led to the next scale of work; he was commissioned to build a temporary debating chamber at Westminster, which was used actively for full parliamentary procedures for many years. This inhabitable, full-scale mock-up was, according to Schoenefeldt, 'a form of occupied prototype – situated somewhere between model and actual building, and in terms of their



5.10

5.10 David Boswell Reid's section indicating the ventilation strategy for the House of Commons. Air is let into an equalising chamber in the floor, ascends evenly through perforations in the floor to a ventilating chamber in the ceiling, from which it then ascends down and out of a chimney, aided by heat from a fire. Reid, 1844.

function, as a design tool, somewhere between field test (POE) and simulation' (Schoenefeldt 2020, 69). Numerous alterations and tests were completed within this prototype over its life, acting as a kind of living laboratory for user feedback. Members of Parliament were regularly asked to provide feedback about thermal comfort. They often disagreed among themselves, achieving little clear consensus, but the discussions nevertheless prompted subsequent modifications over many years.

This occupied prototype, at the scale of a room, went on to inform a centralised ventilation strategy for the entire palace. While Reid's ventilation scheme for the House of Commons was substantially modified over the course of his time advising on the project, the basic principles governing its organisation remained similar (Figure 5.10). Much like his convection experiments, the space was effectively conceived of as a kind of tubular apparatus, drawing air in, conditioning it and moving it up and through the debating chamber via convection. Initially intended by Barry for decorative effect, tall neogothic spires drew high and clean air into the basement. Air was then 'conditioned' – either heated or cooled and cleaned – through a combination of fire, water jets, ice and screens. Conditioned air was equalised and then released into spaces above through perforations in the floor, baseboards and furnishings. Warm air ascended and was eventually outlet through another vertical shaft – a central tower – sometimes with the aid of an integrated fire at the base.

Reid deployed this elaborate buoyancy-induced ventilation system to create even airflow through the sealed interior environment of the debating chamber. Doing so enabled constant and controllable airflow, immune to the vagaries of temperature and intensities of wind. Reid notes that wind was 'too uncertain and unequal in its operation' (1844, 121). His strategies are similar to displacement and stack effect ventilation schemes today. However, the thermal differentials at play in Reid's scheme were much more pronounced than any contemporary stack-ventilation systems. Substantial waste heat from gaslights, fireplaces and boilers created strong convective currents that travelled great distances (Schoenefeldt 2020).

Reid relied on two principles that initially appear at odds with each other. On the one hand, his designs were predicated on creating a hermetically sealed space. To eliminate the sometimes harsh and unpredictable air movement created by opening windows, he constructed a sealed environment, which enabled predictable steady supply of conditioned air. While we tend to associate hermetically sealed environments with mechanical heating and cooling, in Reid's case, conditioning was achieved non-mechanically. Air was drawn in through towers, moved through contained interior space, and then expelled back out through towers often heated with fires to drive differentials. Many of his schemes appear to be vessels within vessels. The internal vessel contained a space of inhabitation. The vessel surrounding it drew air in, conditioned and moved it into the interior vessel, and then expelled it back out through the surrounding vessel.

The supply of continually flowing, conditioned air into a hermetically sealed space was laborious and tedious, prompting extensive manual adjustments to the many dampers, air filters, water jets and fires supporting the system. Both exterior fluctuations in weather and interior fluctuations in occupation prompted recalibration of the system. Daily logs, combined with user testimony, enabled refinement of the system. The space was continually modified in response to user feedback by Members of Parliament who used the space. Tedium aside, the range of componentry devoted to the task was remarkable.

This was an architecture of mist, ice, blasts, flows and fire deployed to an end that was far less exuberant and charged than the forces and elements driving it suggest. Like Olgyay's ambition of 'flattening the curves' of thermal variation between interior and exterior, Reid's conception of thermal comfort was predicated on near imperceptibility. Comfort was marked by atmospheric subtlety, a subtlety in which thermal conditions were neutralised and atmospheric effects and flows dampened. Reid believed that air movement and thermal differentials within his buildings should be imperceptible. He notes:

> the perfection of ventilation consists in the free supply of air so completely attuned to, and in harmony with, the frame upon which it acts, that its operation is not perceived. It should steal so gently upon it, that the attention is not roused into any consciousness of its presence. It may then be termed an acclimated atmosphere. Rude and local currents, whether cold or hot, always indicate imperfections, which should be banished or controlled wherever permission can be obtained.
>
> (Reid 1844, 84).

This ideal proved unattainable due to three key challenges. First, it proved nearly impossible to achieve thermal comfort consensus among the Members of Parliament. Second, the building required near constant maintenance and tedious attunement to rapid fluctuations in weather patterns outside of the building. Finally, the nature of changing occupation of the debating chambers generated further radically divergent thermal fluctuations within the space. Ultimately, Reid's centralised ventilation strategy for the entire palace was abandoned in favour of a decentralised one. While he became responsible for ventilating the House of Commons, ultimately the scheme was replaced by a more responsive, steam-driven system.

Many of the precursors to contemporary mechanical systems were available to Reid, so his decision not to include them is worth consideration. Except for occasional use of fans, he was generally averse to incorporating steam-driven mechanical equipment available at the time. He was opposed to forced ventilation, believing that machines were uneconomical in their fuel consumption and more complicated in their workings. Why use a mechanised process when one might use natural processes and architectural elements instead? Reid notes:

> If, however, it be proposed to use a mechanical power for the same purpose, machinery in the first place, more or less simple, must be prepared. Power must be applied to the machinery by manual labour, by water, by a steam-engine, by a weight wound up from time to time, or in some other way, and however small the power actually required at any particular moment may be, it is more liable to accident, and more skill is required to maintain it in action. A chimney, therefore, from its extreme simplicity, and from the comparatively trifling attendance which it requires, is always preferable in numerous situations … further, when properly finished at the top, the wind acts as a power, and, without any fire, often determines the ascent of air.
>
> (Reid 1844, 94)

Instead, Reid relied on building form, configuration and adaptation of architectural components and furnishings to move the flow of air, relying on buoyancy to drive the design process. He reflects,

> architectural arrangements have too often been considered independently of ventilation; protection from without, and stability and beauty of structure, are not the sole requisites for architectural perfection … instead of placing the supply and regulation of air so much in the background, it ought, in reality, to form one of the primary features of every architectural structure in which a defense is offered from the external elements.
>
> (1844, 6)

Reid's architecture was an architecture of fire, ice, water, towers, chimneys, cowls, adjustable louvres and filters, perforations and elaborately interconnected chambers.

The most architecturally expressive element of Reid's ventilation scheme were modifications to Barry's neogothic towers, which were modified many times in location and height to act as either wind towers, drawing air in, or chimneys, drawing air out. Towers and chimneys (the taller the better!) were portals for air. Whirling cowls and moving louvres were architectural components that caught or blocked wind. Strategically perforated baseboards, flooring and furnishings doubled as vents. Ceiling heights took shape to encourage thermal stratification. Interconnected chambers, ducts and plenums below occupiable spaces conveyed air through a vast invisible network. As Schoenefeldt notes, Reid's approach to architecture was based on two ideals: 'first, that the empirical method can be used to answer questions about architectural form; second, that the functional requirements of ventilation, lighting and acoustics should be the primary determinants of form' (Schoenefeldt 2020, 251). Reid's ventilation

scheme, much like his 'tubular apparatus' revealed an architecture of interconnected spaces with heat sources driving flow, reflected a conception of architecture as a vessel shaped by thermodynamic processes.

Thermodynamic figures

Kiel Moe uses the term *thermodynamic figuration* to describe how 'diverse forms of energy become primary determinants of architectural figuration and performance' (2010, 119). Reid's architecture is an example of such a thermodynamic figure. Chapter 4 introduced two other models of environmental buildings: one based on filtration and the other on containment. Both models rely primarily on building enclosure to modulate thermal conditions, and both aimed for interior thermal stasis. Conceiving of architecture as a *thermodynamic object* is a third model of environmental architecture. The thermodynamic model of architecture establishes interior space as the primary arena of speculation and – *unlike* Reid's architecture – thermal *variability* is the desired effect.

The 2009 publication of *Harvard Design Magazine* titled *(Sustainability) + Pleasure, Volume 1: Culture and Architecture* marks a useful starting point for understanding the significance of this thermodynamic framework within a wider context of sustainability in architecture. When the magazine was published, the title was strikingly incongruent. The disconnect between sustainability and pleasure, between an architectural movement legitimately focused on austerity, accountability and minimising risk, and extreme emotional satisfaction – pleasure even – was provocative. What could possibly be pleasurable about resource depletion, global inequities and potentially devastating climate change scenarios underpinning the dominant discourse surrounding sustainable design at that time?

The magazine contained a series of articles that challenged and expanded upon conventions of sustainable design. At the time, discourse in sustainability focused primarily on quantification, on establishing and applying metrics that measured energy consumption, traced material processes and established strategies for analysing building life cycles. To put this in context, the accreditation scheme BREEAM (Building Research Establishment Environmental Assessment Method) was established in 1990. LEED (Leadership in Energy and Environmental Design) awarded its first projects in 2000. The International Green Construction Code, the first code to establish a 'whole-systems' approach to sustainable design, was published in 2009, the same year that *(Sustainability) + Pleasure* was published.

In *(Sustainability) + Pleasure*, the articles collectively suggest recovering a more explicit design agenda for sustainability in architecture. This agenda re-framed energy as material, experiential and temporal rather than as a depleting quantum. Buildings became vessels for thermal effects rather than ecological or performance-driven objects. People became subjects experientially immersed in environments rather than the subjects of air quality and thermal comfort tests. The editor of the issue was Spanish architect and scholar Iñaki Ábalos, who later co-authored with Renata Sentkiewicz the 2015 book *Essays on Thermodynamics: Architecture and Beauty*. The issue included articles by other scholars, theorists and practitioners who went on to actively shape and challenge fundamental frameworks for thinking about the relationship between architecture and climate. It included writing and design projects by Swiss French 'meteorological' architect Philippe Rahm – explored in more detail later in this chapter – German philosopher Peter Sloterdijk before the first *Spheres* trilogy, *Bubbles*, was published in 2011, and French philosopher Bruno Latour before his writing about Gaia and climate change politics.

These alignments between thermodynamics and architecture can be read as a critique of early conventions of sustainable design in a several ways. The approach shifted from the almost solitary focus on carbon-based energy sources by expanding the bandwidth of 'energetic concerns' in architecture. This framing progressed Kiel Moe's 2007 provocations calling for an alternate to the 'thermodynamically pessimist paradigm', which dominated architectural discourse about sustainability. He suggested instead that, 'there is in fact no real energy shortage. There is only a crisis of human choices in respect to our energy practices' (Moe 2007, 24). Scholars such as Moe and William Braham have gone on to write extensively about the many entanglements between architecture and energy while also developing complex methods of energy accounting that are not solely focused on carbon metrics.

Another important contribution from *(Sustainability) + Pleasure* is how the thermodynamic framing of architecture shifted focus from third-person bioclimatic analysis to first-person experiential awareness of environmental effects. In one article featured in the issue, Christopher Hight uses the term *somatic architecture* to describe the non-visual dimension of energetic exchanges evident in buildings. He describes the thermal effects of occupying the University of New South Wales's Faculty of the Built Environment building, the Red Centre by Mitchell, Giurgola and Thorp, as a 'three-dimensional matrix' of effects generated through the calibration of architectural componentry and materials. Hight notes,

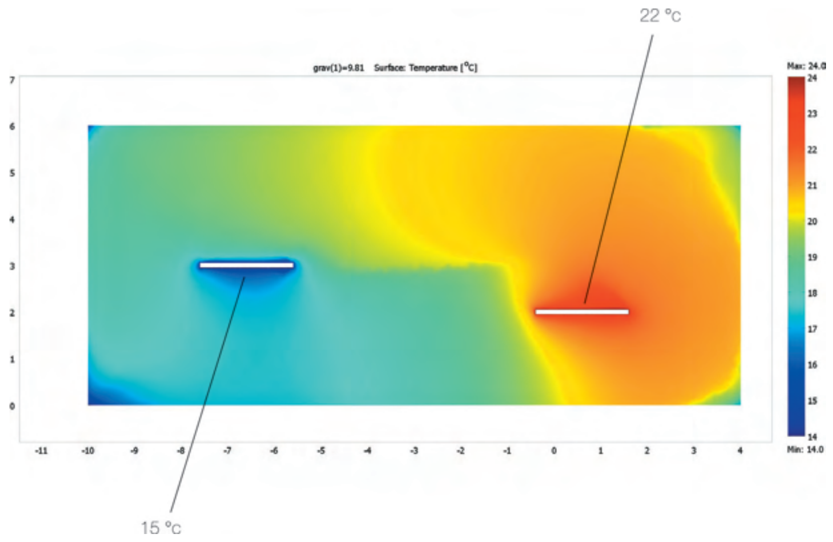
> All of these devices create uncanny effects, such as subtle drafts and even breezes that seem not to come from the outside, but to be exhaled from the interior. Sometimes these were pleasurable: a cool, fresh breeze rising vertically in the middle of the building … Stepping from one room to another could mean entering a different climate as light levels, temperature, and humidity levels shifted. The result is a three-dimensional matrix of sensation that is not so much seen as felt.
>
> (Hight 2009, 25)

More recently, Silvia Benedito's *Atmosphere Anatomies: On Design, Weather, and Sensation* invites a paradigm shift in thinking about space as atmospheric. Her thesis is carefully supported by environmental experiential drawings, photography and careful analysis of a series of meteorologically charged buildings and landscapes including Lina Bo Bardi's SESC Pompéia Community Center and Lawrence Halprin's Sea Ranch, among others. Benedito notes that understanding space as atmosphere situates 'the human as a sensate being in osmotic exchange with the surrounding world … being-in-space means becoming entangled with the weather-world, at times delightful and nourishing, and at other times toxic and threatening' (2021, 32). Benedito borrows the term 'weather-world' from British anthropologist Tim Ingold, who writes extensively about environmental perception. Ingold notes that writing about weather is conspicuously absent from anthropological and archaeological accounts about the 'material world', where focus is not on the medium of weather but on its precipitative manifestation as puddles or snow drifts. Instead, he notes: 'In reality, of course, the landscape has not already congealed from the medium. It is undergoing continuous formation, above all thanks to the immersion of its manifold surfaces in those fluxes of the medium that we call weather – in sunshine, rain, wind and so on' (2011, 130).

There are architectural antecedents to Hight's notion of the 'three-dimensional matrix of sensation', Benedito's framing of space as atmosphere and Ingold's weather-world. Lisa Heschong's 1979 *Thermal Delight in Architecture* explores a range of rich cultural associations with thermal contrast in buildings. Heschong illustrates how vernacular buildings, Finnish saunas, Japanese baths and Frank Lloyd Wright's hearths elicit delight through thermal contrast. Similarly, the characterisation of space as a matrix of thermal sensation corresponds to Reyner Banham's 'power-operated' mode of environmental management, illustrated by the example of the campfire and its surrounding thermal environment of shifting gradients (1984, 18–19). Stanford Kwinter's characterisation of architecture as 'a space of propagation, of effects' shifts focus from materiality and form to spatial effects (2001, 60). These characterisations of space as thermal sensorium sit in contrast to the Olgyays' unattainable 'flattened curves' of thermal comfort and the aspired atmospheric subtlety of Reid's ventilation schemes.

Some degree of variation in the thermal environment is inevitable in passive and mixed-mode strategies of environmental management in buildings. However, neither Olgyay nor Reid had a framework for valuing this variability at the time. It would be more than a century after Reid's work at Westminster that entirely stable models of thermal comfort, aided by mechanical systems, would be fully codified. In the late 1960s, Danish engineer Ole Fanger defined optimal interior thermal comfort conditions, marked by stability and narrow bandwidth of cool, dry and still indoor air. The static, isothermal model of thermal comfort has been instrumentalised by HVAC designers, ASHRAE (The American Society of Heating, Refrigerating and Air-Conditioning Engineers) and architecture building codes for decades since.

The notion of *alliesthesia*, coined by French physiologist Michel Cabanac in 1968, offers a counter thermal comfort framework; it considers the inevitability and desirability of thermal variability



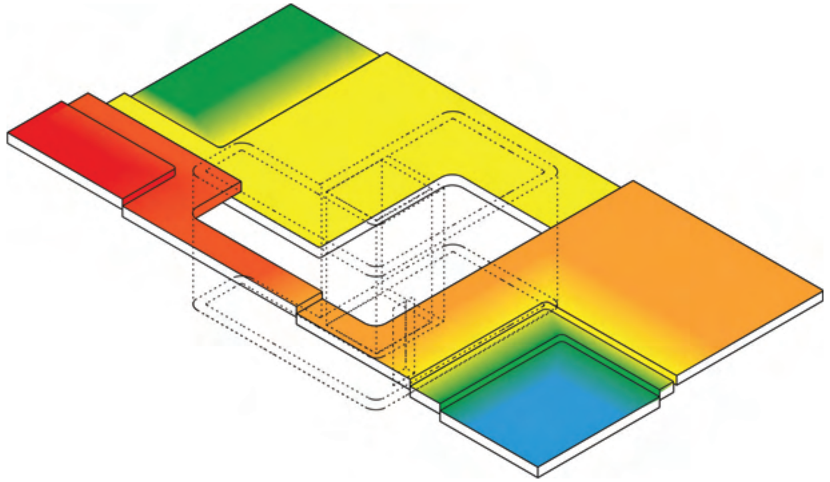
5.11

5.11 Philippe Rahm, *Interior Gulf Stream*, plan drawing, 2008. In the scheme, a cold source on the high side of the apartment and a warm source at the low end generate a continuous convective loop in the open space. Courtesy of Philippe Rahm, 2008.

in buildings. Alliesthesia, a critique of static, isothermal comfort models codified in the same period, is instead 'a conceptual framework to understand the hedonics of a much larger spectrum of thermal environmental than the more thoroughly researched concept of thermal neutrality' (Parkinson and de Dear 2014, 288). Alliesthesia describes the pleasure of occupying variable thermal environments, suggesting that thermal comfort is perhaps more elastic and variable than previously codified. Cambridge scholars Koen Steemers and Mary Ann Steane suggest using the term *environmental diversity* to describe causal relations between environmental processes and architectural space, suggesting that 'the conscious shaping of diversity, that is to say, the conscious orchestration of the dynamic patterns of environmental variation, is made possible by the appreciation of its spatial and temporal aspects' (2004, 9).

While designers such as Iñaki Ábalos and Sean Lally have developed an approach to designing architecture driven by energetic gradients and thermal differentials, the person who exemplifies this approach is Philippe Rahm. Rahm refers to his work as 'meteorological architecture', exploring 'the formal, programmatic, and ecological potential of thermal imbalance and climatic asymmetry' (2009a, 34). Rahm's meteorological architecture foregrounds natural processes such as convection, radiation, pressure and evaporation and physical laws such as the Bernoulli principle to shape architectural space. He aligns these processes with differentials or imbalance and ascribes aesthetic value to thermodynamic processes: 'the rise of thermodynamics in the 19th century … tipped the aesthetic notion of imbalance from one of ugliness to one of beauty' (Rahm 2009a, 33).

One of Rahm's early projects, *Interior Gulf Stream, Housing and Studio for Dominique Gonzalez-Foerster*, exemplifies this approach (Figure 5.11). The project proposes an apartment organised as a convective loop, consisting 'of an asymmetrical distribution of heat in the house, creating a convection movement in the entire space' (Rahm 2009b, 38). A cold (15˚C/60˚F) source on the high side of the apartment and warm source (22˚C/72˚F) in the low side creates a continuous current much like that in Reid's glass apparatus. This current creates a diversity of thermal zones, ranging from 12˚C/54˚F to 20˚C/68˚F, around which domestic spaces are organised. Infrequently used ancillary spaces such as laundry rooms are situated in the coolest zones, and sedentary well-used spaces such as living rooms are in the warmest zones. The project is both experiential and instrumental, responding to Swiss building codes that prescribe desirable interior temperatures ranges according to the use of space.



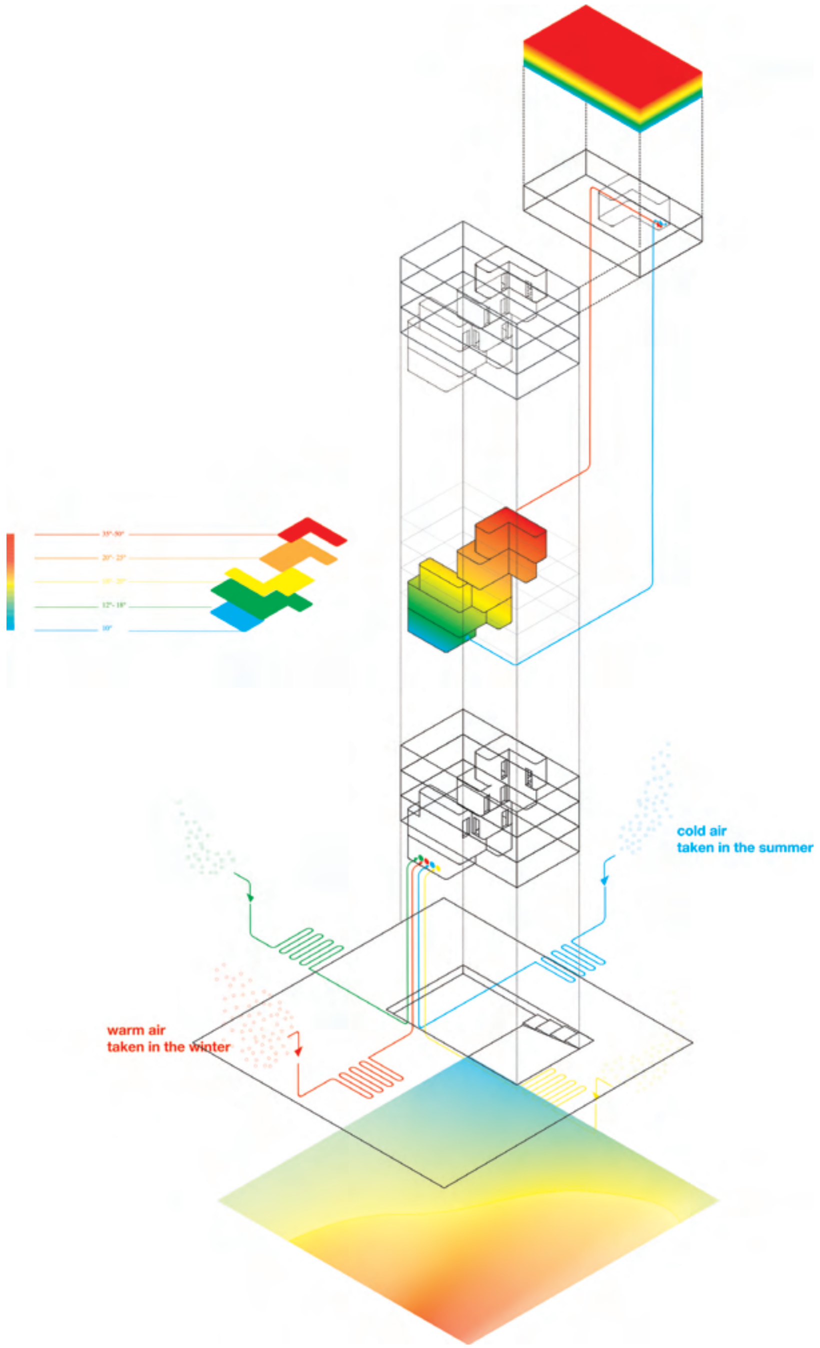
5.12

5.12 Philippe Rahm, *Convective Apartments*, plan oblique drawing, 2012. A progression of the *Interior Gulf Stream*, the convective apartments are also organised as a thermal landscape driven by convection, in this case driven by ground source heat. Different uses are aligned with different thermal conditions. Sedentary spaces such as living rooms are higher and warmer; active spaces such as the kitchen are lower and cooler. Courtesy of Philippe Rahm, 2012.

Rahm's drawings of *Interior Gulf Stream* as well as a later, related project, *Convective Apartments*, use conventions like those of meteorological maps and thermal imaging cameras (Figures 5.12 and 5.13). Vectors indicate air movement into a geothermal network. Gradients transitioning between bright blue, orange, yellow and red indicate variations in temperature, frozen in a single moment in time. These drawings challenge some conventions of architectural orthographic drawings, which generally include the stable, fixed organisation of walls, roofs and floors. Instead, in Rahm's drawings, there is no explicit enclosure or bounding walls. Context is reduced to more thermal gradients. All the 'stuff' that typically remains invisible in an architectural drawing – space, heat, luminosities – are foregrounded in the drawings. This vibrantly coloured space of thermal variability is objectified and contained within a hermetically sealed box.

While both Rahm's and, much earlier, Reid's architectural speculations can both be defined as thermodynamic figures – actively shaped by thermal differentials – their approaches differ in significant ways. Much of these differences can be attributed to the fact that Rahm's projects are mechanically serviced, relying on radiating surfaces and heat pumps to drive flow. Rahm's designs are hermetically sealed in a materially mute enclosure. Aside from the geothermal tubes servicing the *Convective Apartments*, there are few supporting architectural components such as chimneys, cowls or baffles for channelling and directing air movement. The differentials in Rahm's world are subtler and more controlled than in Reid's. The sectional qualities of Rahm's work are less expressive, lacking the towers and plenums devoted to generating and driving flow patterns. If Reid's thermodynamic architecture is one of fire, ice and towers, Rahm's is one of gentle currents and subtle sectional variation. Rahm's projects featured here are ultimately architectural speculations, not physical experiments like Reid's. They are concepts developed and presented within the force-less environment of digital space. They are idealisations of architecture in an entirely airtight space, perpetual thermal motion machines that never dissipate or leak.

5.13 Philippe Rahm, *Convective Apartments*, exploded axonometric drawing, 2012. Courtesy of Philippe Rahm, 2012.



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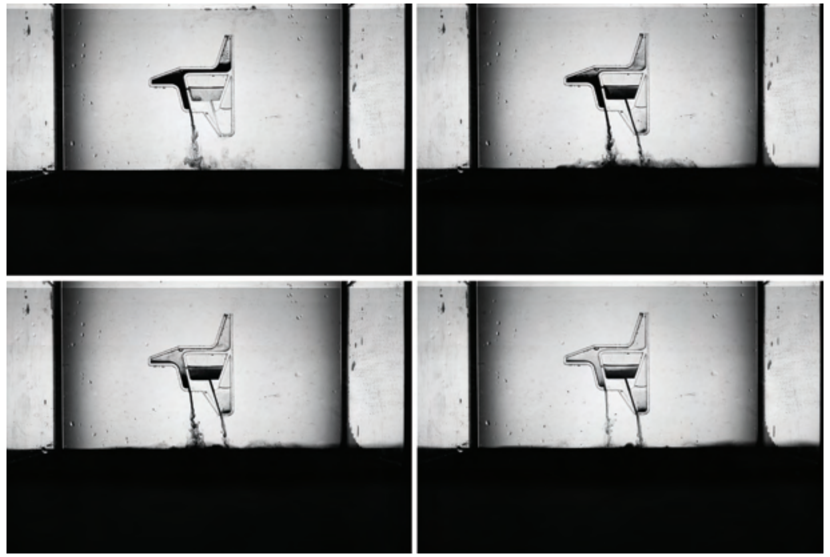


5.14

5.14 Photograph of FB2 model C flow visualisation time-lapse study. The model contains a series of pockets that fill up and steadily drain, highlighting the co-constructions between building and atmosphere.

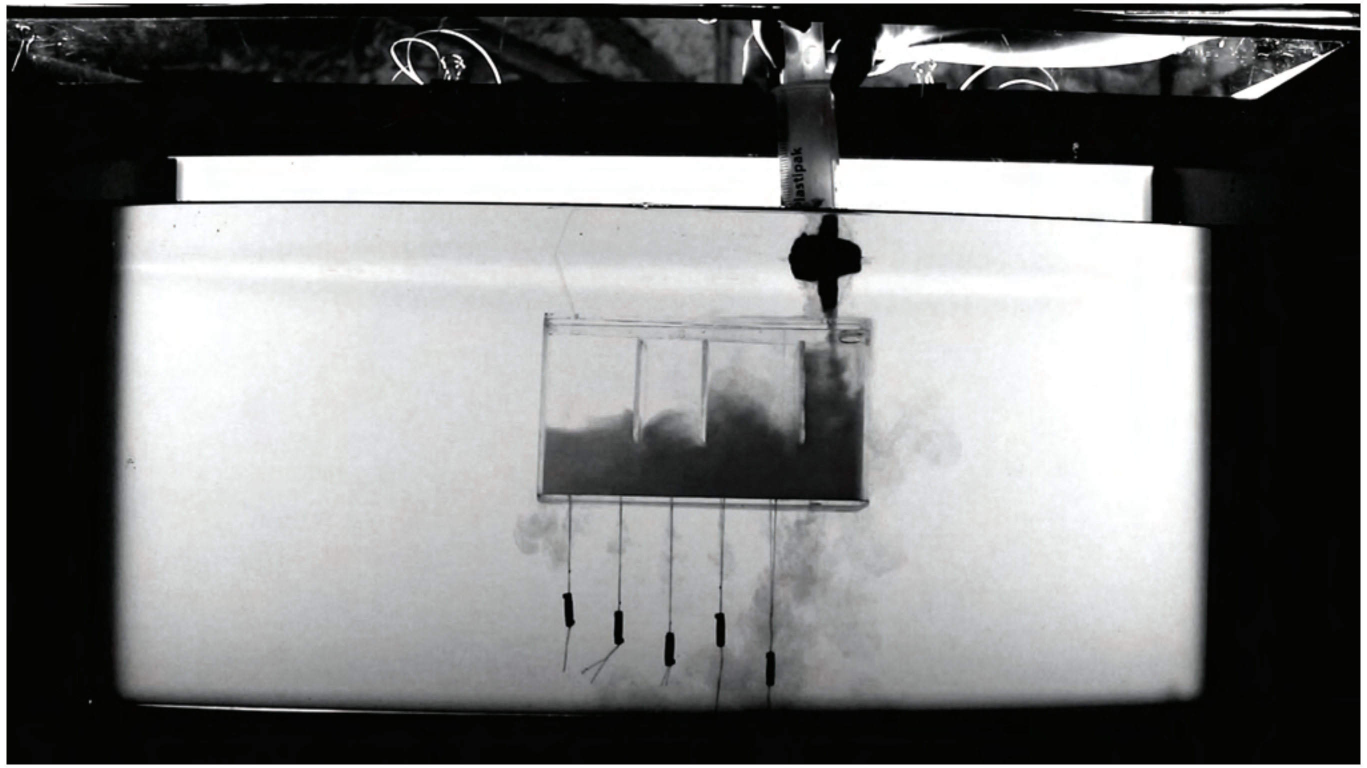
Persistent leaks

A recurring feature of filling-box models is that they leak. Often these leaks are unintentional. Seams between surfaces, held in place with chemical solvents, inevitably fail. Surfaces do not entirely align, leaving gaps. The filling-box models leak, slowly and persistently, eventually reaching a state of equilibrium with their tank surroundings (Figure 5.14). Neither digital simulations nor static environmental diagrams unintentionally leak. It is the persistent avoidance of leaks that makes physical constructions distinct. Just as no plexiglass model is fully watertight, inevitably leaking at seams and intersections, no building is completely airtight or leak-proof.

The significance of the leak in the model is three-fold. The leak reminds us that the physical model is distinct from the mental ideal that it represents. As Ulricke Passe and Francine Battaglia note, 'a homogenous interior climate as imagined by Buckminster Fuller or Yves Klein in the 1960s is an illusion and does not comply with the physics of fluid flow and motion' (2015, 10). Conceptions of architecture as containers for thermodynamic processes are models in the sense that they are idealisations. No building operates as an entirely contained closed-loop system, and even those filling-tank models with no intentional outlets, like the supposedly airtight buildings they represent, leak, inaugurating exchanges with the environments in which they are immersed.

The persistent leak highlights that thermodynamic systems attempt to equalise. Just as it is tempting to focus solely on the beautiful swirls of turbulences in Marey's photographs, when viewing the filling-tank photographs, it is tempting to focus on the swirling plumes and wispy trails marking thermodynamic differentials (Figure 5.15). These effects and their strange figurations are beguiling. However, the swirling plumes are but station points to a state of equilibrium in the tank. After the initial disruption induced by injecting saline solution into the model, a slow and steady process of dispersal begins (Figure 5.16). In its final state, the architectural model sits within a subtle static gradient of dyed water. The architecture of the filling-tank transitions from being a vessel of charged thermal differential to a vessel held in equilibrium within its surroundings, draining and receding from view (Figures 5.17–5.20).

Most important, as the model drains, the leak shifts focus from the source of the leak to the destination of the

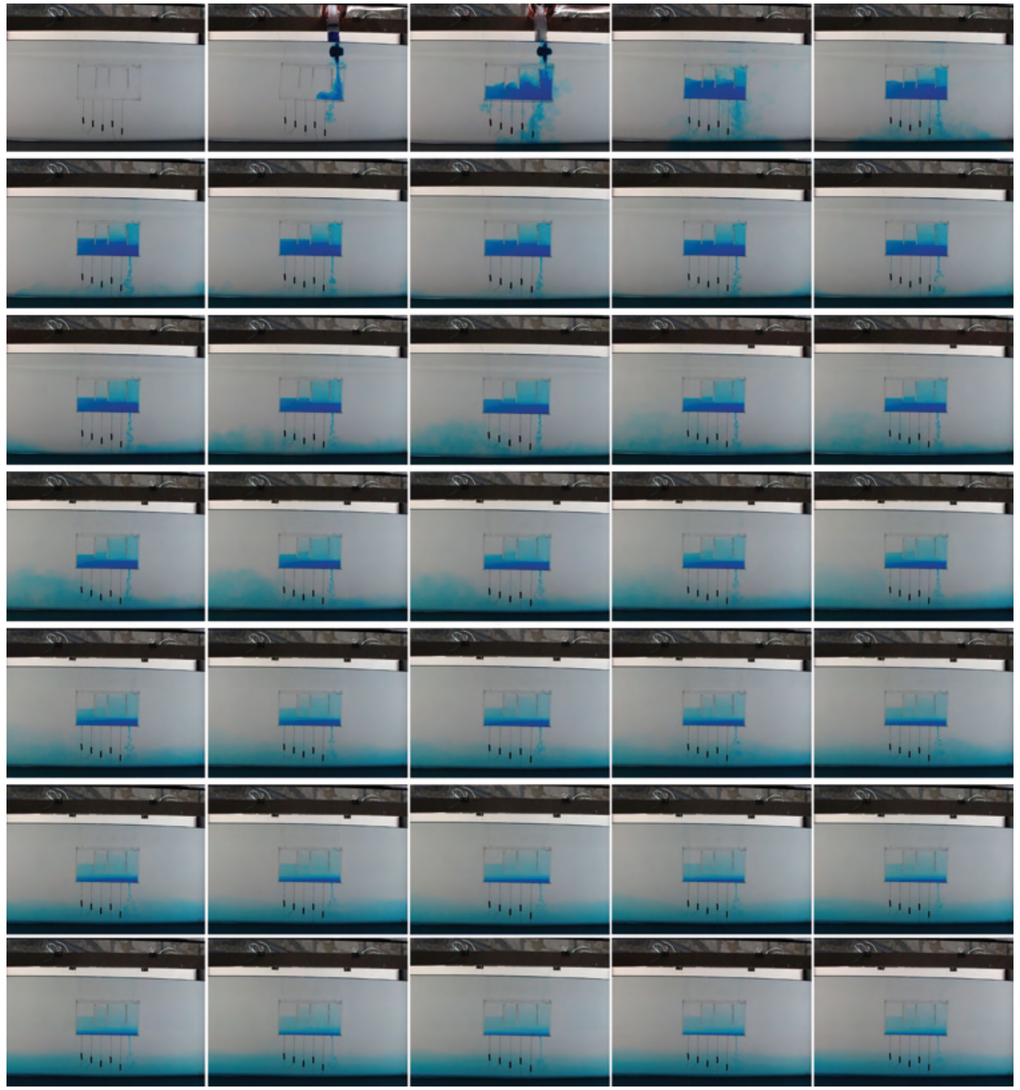


5.15

5.15 Photograph of FB1 flow visualisation study capturing the initial injection of salt water into the model, which disrupts the steady-state model interior.

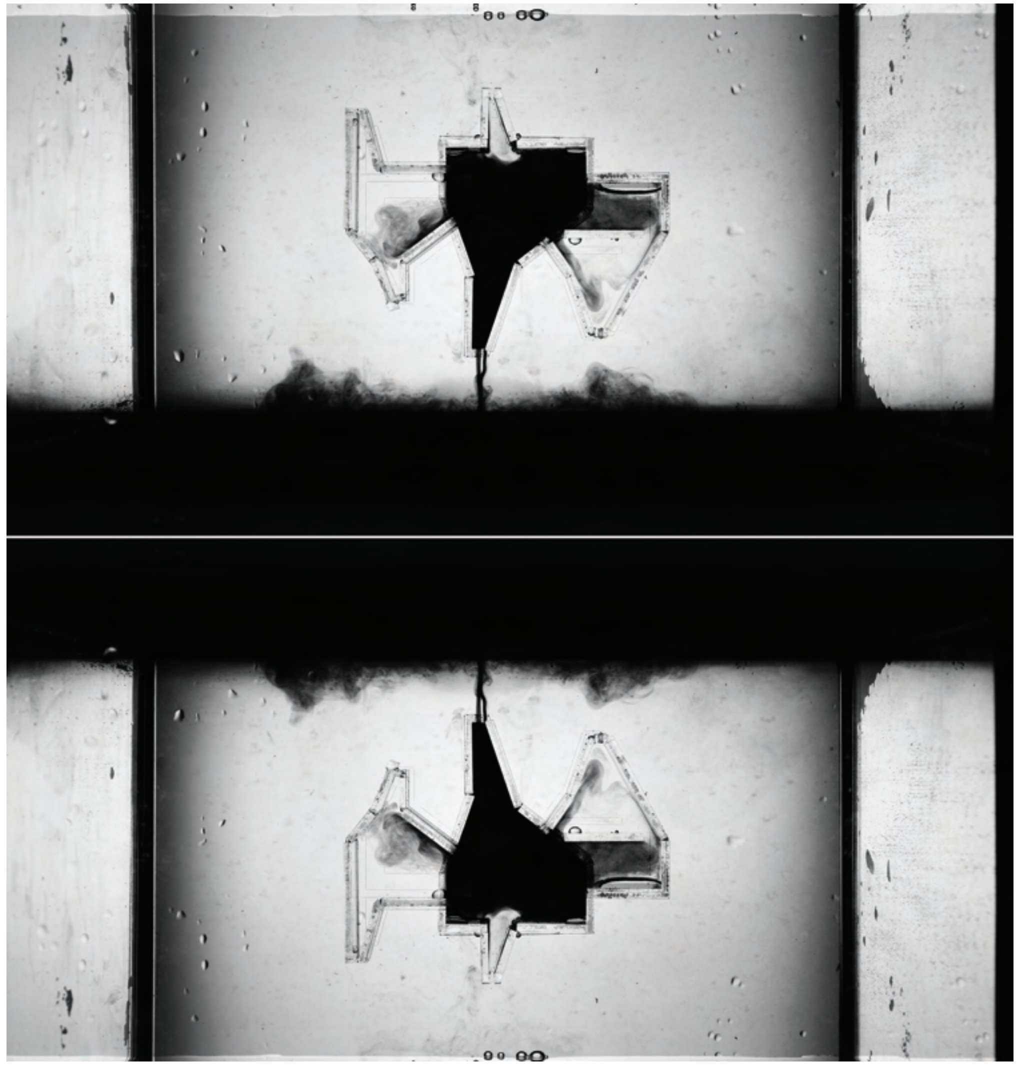
leak (Figures 5.21 and 5.22). Filling-tank models represent nested environments in which buildings are metaphorically 'tanks' submerged within the 'tank' of the atmospheric dome of the sky. The models remind us that buildings are in constant collusion with and are often destabilised by their atmospheric surroundings, requiring tethering, anchoring or grounding for stability. The filling-tank models leak, and they leak somewhere, and that somewhere leaks beyond, inaugurating a series of cascading environmental effects. In doing so, they establish connections across a vast range of scales of atmospheric exchange. The leak places buildings within a context of possibility and consequence, acting as reminders of Evangelista Torricelli's observation in 1644 (when describing his discovery of the sensitive air-weighing instrument, the barometer) that 'we live submerged at the bottom of an ocean of the element air' (in West 2013, 66).

5.16 Time-lapse video stills of FB1 model as it slowly drains. While it is tempting to focus on the swirling plumes and wispy trails marking thermodynamic differentials in the first few seconds of the injection of salt water, in reality, the model drains slowly, steadily and undramatically over several minutes, moving to a state of equilibrium.



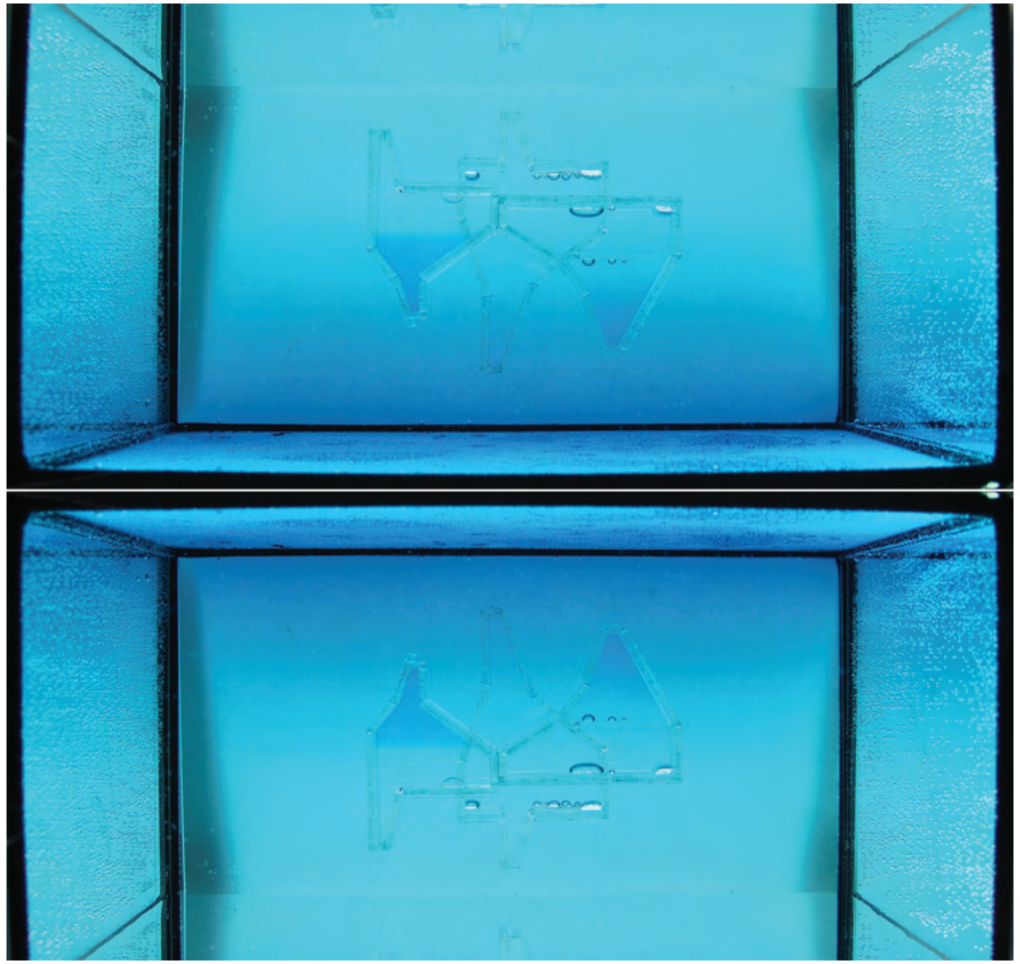
5.16

5.17 Photograph of FB2 model D flow visualisation study. The high-contrast image dramatically captures buoyancy-driven flows through three interconnected volumes and then into the tank in which they drain.



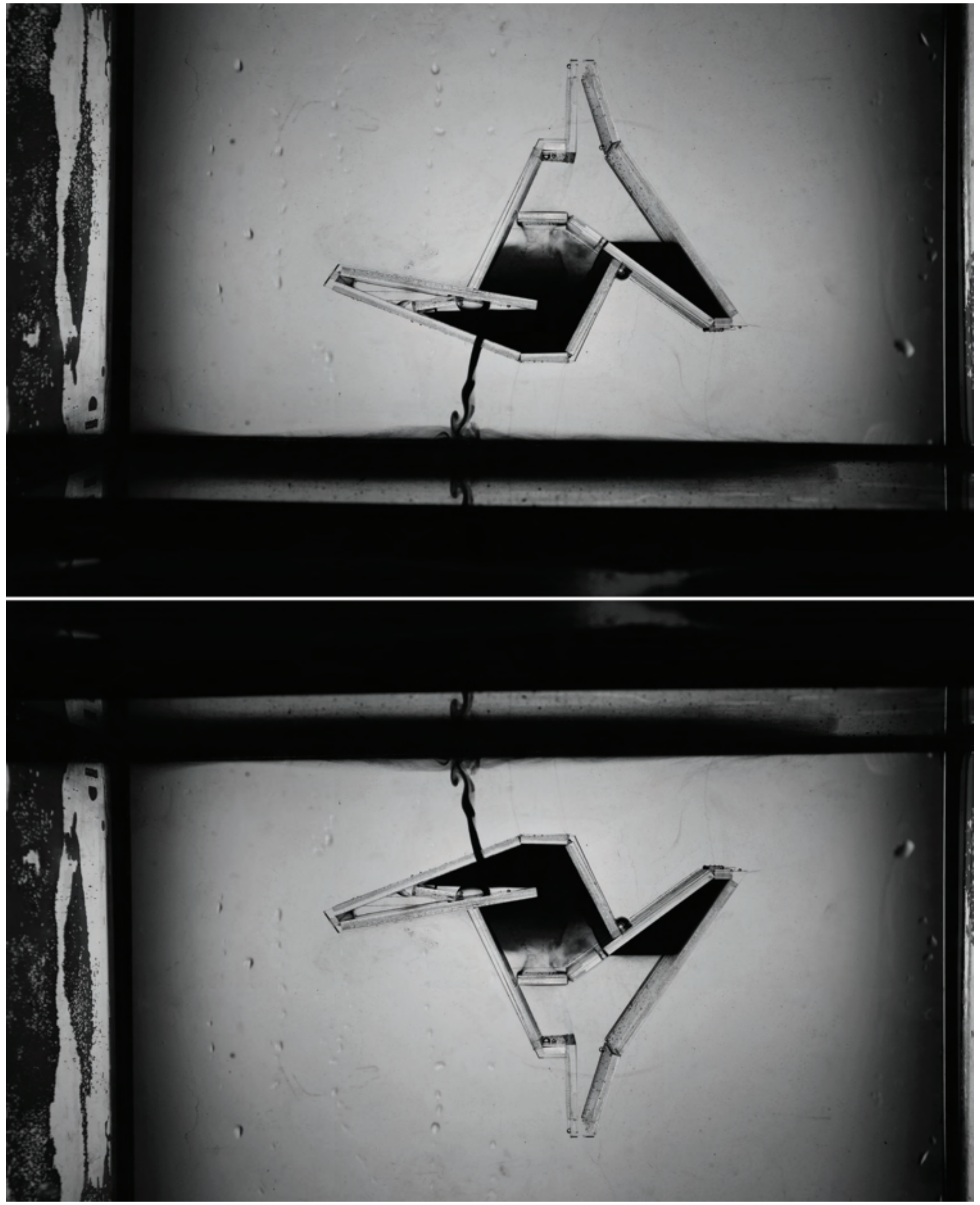
5.17

5.18 Photograph of FB2 model D after model has drained. The model sits inert within the tank, the figures of the model receding from view. The resultant architecture is in equilibrium with its environment.



5.18

5.19 Photograph of FB2 model E flow visualisation study. The high-contrast image dramatically captures buoyancy-driven flows through a space subdivided into three horizontal levels and out a single outlet at the base.



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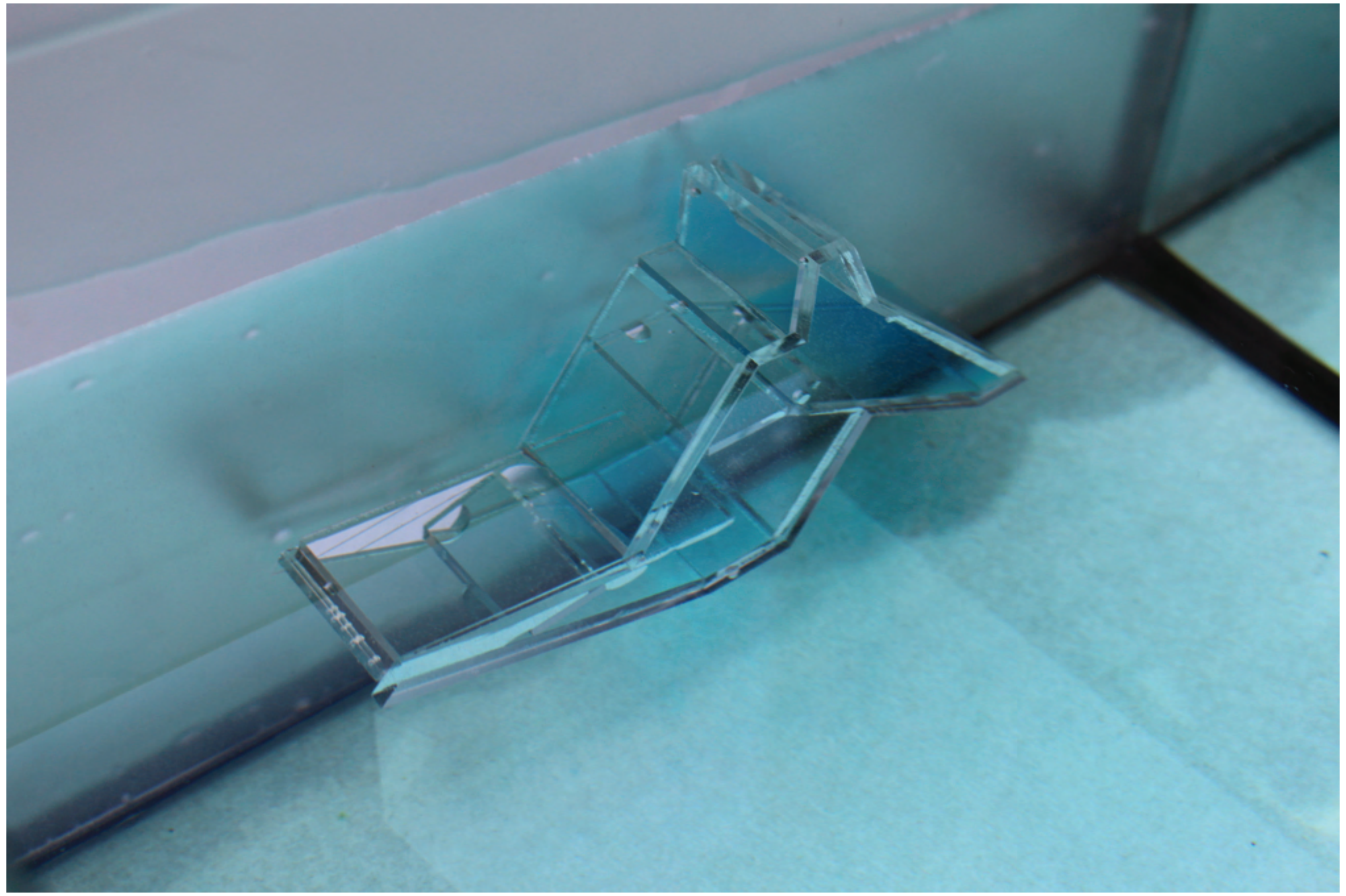
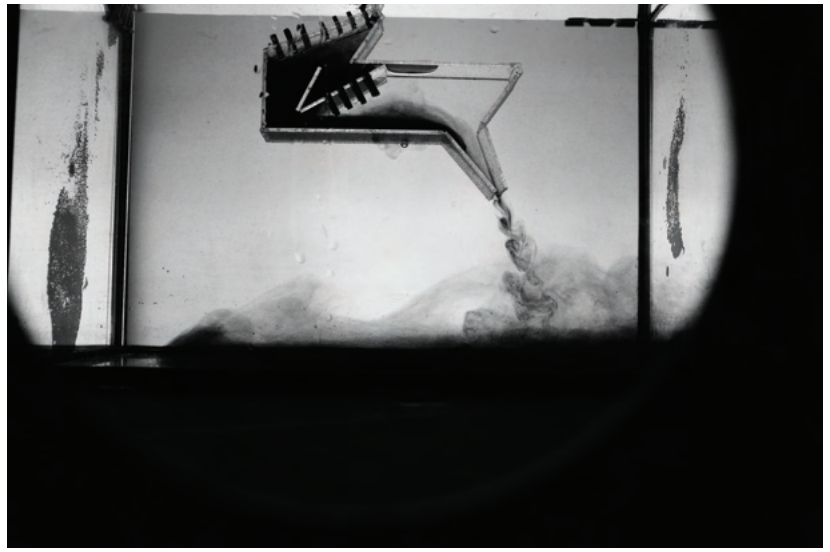


5.20

5.20 Photograph of FB2 model E after model has drained. The model sits, inert and immersed in the tank. The filling-box models leak both intentionally and unintentionally, unlike the hermetically sealed architectural ideals they sometimes represent.

5.21 Photograph of FB2 model B flow visualisation study. A steady plume drains from the base of the model into the agitated tank floor.



5.21

5.22 Photograph of FB2 model B flow visualisation study. As the model leaks, view shifts from the source of the leak to the destination of the leak, establishing dialogues with the wider atmospheric domain in which they are immersed.

5.22

Chapter 6 | Model environments

Designers often represent wind and other related environmental processes as a field of vectors akin to the wind barbs on a meteorological map. This representation of wind suggests a simultaneity and totality that is inconsistent with wind as a moving material system that is dispersed, variable, sensitive and fleeting. Like many complex environmental systems, wind does not reveal itself as a single, big exclamation suggested by the swirling arrows on a map, but instead as a series of episodic whispers learned subtly over time and through many scales of observation. Environmental models focus attention on these observations across many scales, from instrument to body to architecture to world.

The first chapter introduced historian of science D. Graham Burnett's distinctions between analogical and ontological models. Burnett probes the relation between a model and its target(s) by asking if their relationship is based simply on analogy or something more that starts to blur or merge meaning between model and world. Ultimately, Burnett suggests, it is the *oscillations* or the reconceptualisations that take place through design that make models productive as thinking tools about the wider world. Design oscillations are ways of knowing through actively shifting vantage point. Designers know this well; when something does not make sense from one vantage point, shift vantage points. If it does not make sense at one scale, look at it from another. If it does not make sense from up high, look down low. If a drawing does not suffice, make a model, or an experiment or an installation. When you are stuck, move around a little.

I learned this way of actively shifting vantage point when tracking wind on Limekiln Line. My attention oscillated from ground to sky, from the totality to the point, from the installation to the sketch, from the sketch to the survey. Each mode of working established dialogues between a synoptic measure – the quantitative – and a local measure – the material and experiential – which never entirely aligned. The installation raised questions that prompted further research featured in this book. How does wind behave as a moving material system? How might its registration and redirection shape and inform an approach to architecture? What is the relationship between a model of an environmental system and its referent at full scale? How does working with physical models reveal new ways of understanding the model, its associated architecture and the world? To grapple with these questions, I looked outward at the work of others and inward at my own model prototypes. I looked at the environmental apparatus as a totality, at the architectural models within the testing bed, at the architectural spaces in which the models operate, and at the methodologies the models enabled. I explored the dialogues between a model as a physical artefact and a model as a mental ideal.

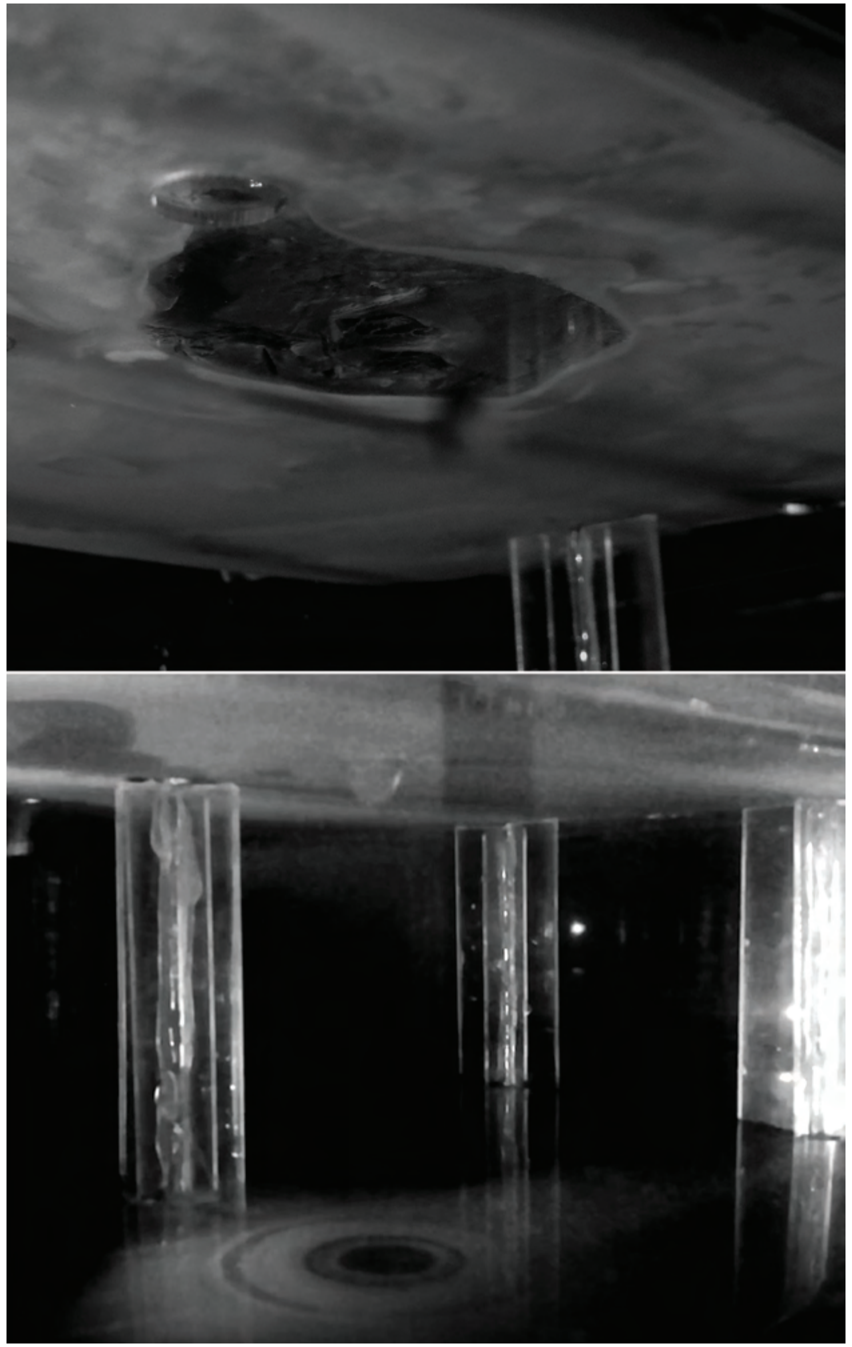
I completed *Wind Grid* nearly 12 years ago. I saw wind as experientially complex then. I also saw it as a renewable energy source and a mode of passive cooling, both of which were conducive to reducing fossil fuel dependencies. The full significance of our swirling, warming, increasingly volatile atmosphere and its shifting differentials and feedback loops on a planetary scale was lost on me.

When I emerged from the PhD cocoon in which much of this research was completed three years ago, the air we breathe and the atmosphere we have anthropogenically altered were charged with renewed significance. Air – its movements, composition, meteorological and climatological properties, and its disproportionate impacts – has never been more consequential. Cultural historian Eva Horn reminds us that air, atmosphere, weather and climate – terms she intentionally uses interchangeably, much as I have throughout this book – remain in the background until their disruptions focus our attention. She notes:

> With pollution, changing weather patterns, extreme weather events, changes in local climates, water cycles, and other consequences of global warming, the silent, imperceptible background has come to the fore, demanding attention and concern – scientific, social, and political. It may well be that the only way to relate to a medium is from the vantage point of its disruption. (Horn 2018, 17)

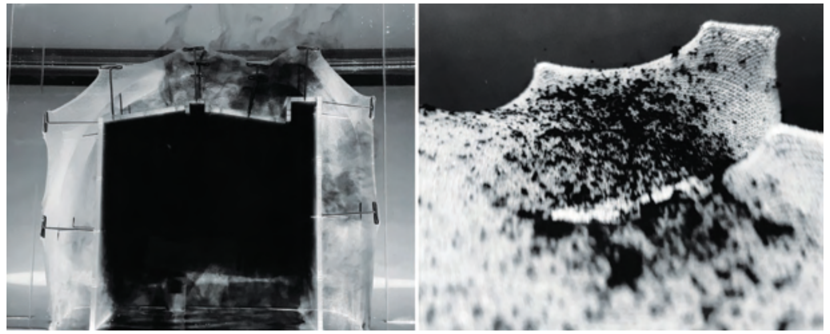
Our environments – that stuff in the *background* – is now in the foreground (Figure 6.1). Our awareness of the atmospheric environment is disrupted on three major fronts.

First, our altered atmosphere has resulted in climatological breakdown. The level of disruption to the chemical composition of the atmosphere and the impact this changing composition has had on both weather events and our changing climate is radically unprecedented. The 2021 IPCC (Intergovernmental Panel on Climate Change) offers a sober account. The air we breathe has the highest concentrations of the greenhouse gases largely responsible for altering the energy balance of the planet – carbon dioxide, methane and nitrous oxide – recorded in history. The gaseous bubble surrounding the Earth – our atmosphere – has been warming with each successive decade since 1850 (IPCC 2021). Weather patterns are changing, with increasing heatwaves and droughts, reduced cold waves, increased rain intensity and extreme weather events such as hurricanes and monsoons. The heating of the Earth's climate system has resulted in global mean sea level rises. Changes in these sea levels, ice melt and alterations to the ocean are 'irreversible for centuries to millennia' (IPCC 2021, 21). Each increase in temperature inaugurates feedback loops that accelerate further warming effects. Warming trends will continue, likely resulting in increases anywhere between



6.1

6.1 Photograph of Eilidh Sutherland's melting ice and plaster casts completed in the fourth-year *Tank Worlds: Hamilton Harbour* studio. In the model, slow, steady drips from the cast eerily marked the passage of time. Courtesy of Eilidh Sutherland, 2021.



6.2

6.2 Photograph of Hailey McGuire's model of an existing industrial building in Hamilton Harbour, Ontario, a federally designated area of environmental concern. The building, shrouded in a filtering mesh that intercepts pollutants and facilitates growth of climbing vegetation. In the model, the building both filters and breathes. Work was completed in the fourth-year *Tank Worlds: Hamilton Harbour* studio. Courtesy of Hailey McGuire, 2021.

1.0°C and 5.7°C, depending on future mitigation strategies. To put this change in perspective, the IPCC report notes with medium confidence that 'the last time global surface temperature was sustained at or above 2.5°C higher than 1850–1900 was over 3 million years ago' (IPCC 2021, 14).

Second, the COVID-19 pandemic which began in early 2020 has heightened our awareness of air as a medium of viral transmission. As described in Chapter 5, the idea that so-called *vitiated* air was a dangerous medium of disease and contaminants drove many improvements in building ventilation practices and public-health measures in the late nineteenth and early twentieth century. These improvements were so effective that concerns about airborne transmission of disease mostly lost traction in the public consciousness. COVID-19 has reignited our awareness of the air surrounding us while reinforcing the significance of the 'bubble' both as a small social grouping and as a sealed physical space of isolation and containment. Air exchange rates, air filtration standards and systems of building ventilation have renewed significance. This heightened awareness of our shared breathing has prompted profound recalibrations of how we gather, where we gather, how we occupy interior and exterior spaces and how we ventilate our buildings (Figure 6.2).

Finally, George Floyd's chilling final words, 'I can't breathe', in May 2020, galvanised the Black Lives Matter movement. Floyd was asphyxiated by Derek Chauvin, a Minneapolis police officer, rendered breathless, deprived of life-sustaining air. Floyd's murder ignited civil unrest not seen in the United States since the height of the 1960s civil rights movement, while also prompting a heightened awareness of the intersection between climate change and race. The term 'environmental racism' was coined in the 1980s in the United States to account for the disproportionate environmental impacts due to public policy, white flight and the proximity of hazardous industrial processes and waste management to racialised communities. The term applies much more expansively now to highlight resource distribution and access inequities globally as well as climate-change-induced refugee migration patterns. The air we breathe and the atmosphere we inhabit is not homogenous, but is in fact highly differentiated, impacting some much more gravely than others.

That world, *this world*, forms some of the targets of our environmental models today. This is a world of Greta-Thunberg-initiated climate activism and of professional and pedagogical crisis. It is a world marked by fear of the many cascading urgencies at unimaginable scales caused by imminent mean global warming temperature increases, substantiated by lengthy IPCC reports. It is a world of heightened awareness that we share the air we breathe, which is a medium of viral transmission. And it is a world of heightened awareness of environmental racism and the disproportionate impacts of the effects of contamination and climate change on marginalised and racialised populations.

What can architecture's model environments do for this world? What models as ideals should we aspire to for our environmental futures? What terms of reference might we take from environmental models to help us make sense of the triple threat of the climate crisis, the global pandemic and environmental injustice? Case studies profiled in this book told stories about moments in time while drawing out connections to current practices. What additional insights might these historical moments tell us about designing at a time of environmental breakdown?

This concluding chapter sketches three terms of reference latent in case study models that might be of value when discussing environmental concerns today. The first model draws from Marey's wind tunnel explorations and is marked by ideas of *resistance*. The second draws from the Olgyays' thermoheliodon and reflects on the significance of *diminution*. The third, based on Reid's convection experiments, is defined by *buoyancy*. In all three cases, the term model is understood as an idealisation, rather than a scale artefact, of the relationship between architecture, environment and the wider world. These three terms start to reconcile thinking about air, the atmosphere, weather or climate in terms that are scientifically substantiated while also being culturally situated.

This chapter includes photographs of speculative tank-world models completed by students in a series of design studios and theory seminars that I taught at the University of Edinburgh and Carleton University in Ottawa, Canada. Tanks of water offer spaces of speculation about immersion in atmospheric and hydrological environments, engaging with questions of scale, time and materiality. They combine traditions of engineering experimentation within tanks of water to test principles of building ventilation, such as the filling-box technique, with theoretical notions of 'worlding', or the design of microcosms to enable wider speculations and stories about possible futures. Together, writing and visual material reinforce the role that creative practice plays in constructing imaginative possibilities of what might be in the world.

Resistance

Marey's wind tunnels marked a shift in his working methods from visualising objects in motion to visualising the medium through which motion takes place. Objects of resistance – both literally and conceptually – they revealed, through their streamlines and vortices, how objects placed within the testing bed accelerated and dampened air movement. Model wing profiles at times created pockets of shelter, moments of stillness. Lines of moving smoke through the tunnel revealed how air resisted total containment and how sensitive air was to disruption. Air resisted being drawn as discrete lines over time, instead rendering itself as a delicate thread always near disruption.

The wind tunnels play a curious role in Marey's career. In some ways, the entirely inanimate wind tunnel seemed a logical conclusion to a lifetime spent studying the mechanics of flight. No longer bound to working within the limits and contingencies set by the movement patterns of the living subjects of his experiments, Marey could fully subsume his investigation to the controlled laboratory environment. Yet the workings of wind tunnels evaded his grasp, and he abandoned the research early on, providing little by way of written theorisation or reflection. Marey felt that his empirical working methods were insufficient for fully understanding the complex interactions between smoke streams and obstacles. He wrote that his 'insufficient knowledge of mathematics prohibits me from leaving the experimental field. Sometimes I am even quite embarrassed by my inability to interpret certain experimental results like those of the smoke fillets in the experiments that I have spoken to you about. They proceed very slowly' (Marey in Braun 1992, 214). He lost enthusiasm for the wind tunnel experiments shortly after completing the final version, likely due to a combination of ill health and theoretical limitations. The wind tunnels were objects of cognitive resistance much as the scales and scope of atmospheric alteration today resist comprehension.

What characteristics might define an architecture of resistance, either physically or conceptually? An architecture of resistance creates intentional disturbance. It is not an aeronautical, streamlined architecture. It is not shaped to deflect things subtly. Obstacles in and on buildings are in fact productive; they drive flow, essential for purging and directing air movement. The componentry of architecture – the walls, roofs, apertures, fins and louvres – speed air up and move it through. Building up resistance through architecture entails conceiving of buildings as being composed of calibratable components that can be adjusted to operate as obstacles. This architecture is an instrument for making turbulence.

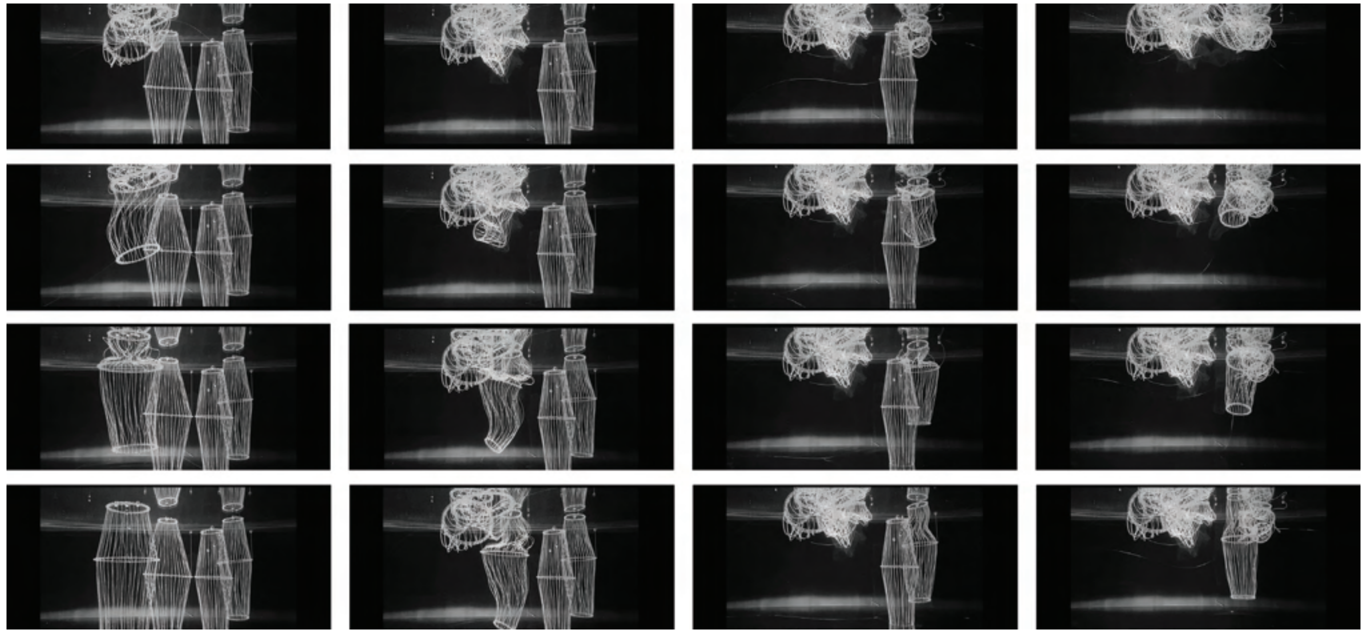
An architecture of resistance is subversive, operating in ways that counter prevailing expectations and resisting conventions of expediency or of comfort. Like many modes of design, working with environmental models can be tedious and time-consuming (Figure 6.3). They do not promise expedited solutions. If digital simulations are often predicated on the promise of expediency, environmental models are predicated on the opposite. They slow down more than they speed up. In this slowing down, they also attune awareness and focus attention on details, on the gaps, on the dialogues between components; they focus our attention on what could be.

An architecture of resistance might create pockets of stillness, moments of calm, drawing insights from the model miniature in their approach to temporality. The slowing of time is a defining quality of miniatures in cultural theory. In an accelerated world, slowing down is an act of resistance. Literary theorist Susan Stewart's *On Longing: Narratives of the Miniature, the Gigantic, the Souvenir, the Collection* (1992) explores the significance of scale and the exaggerative effects of the miniature on narration. She argues that miniatures, through distillation, offer a heightened didactic focus; they have the capacity, through exaggeration, to make the mundane fantastic or strange. The miniature offers an image of an intricate orderly world. She suggests that miniatures have their own temporal logic:

> The miniature … skews the time and space relations of the everyday lifeworld, and as an object consumed, the miniature finds its 'use value' transformed into the infinite time of revery … the miniature [has the capacity] to create an 'other' time, a type of transcendent time which negates change and the flux of lived reality.
>
> (1992, 65)

An architecture of resistance focuses our attention on the long now.

An architecture of resistance might make us feel uncomfortable. It might consider that thermal comforts codified by psychometric charts and enabled by HVAC systems are tied to deep social inequities. Much of the world does not have access to such comforts, and the mechanical systems that enable this narrow bandwidth of thermal conditions to occur are profligate energy-consumers. Thermal variability, thermal delight and thermal asymmetry are all terms of reference that suggest that variations in the thermal environment can be desirable, pleasurable even. But an architecture of resistance might work harder, pushing to expand these limits even further. Daniel Barber reflects on the inevitability of



6.3

6.3 Video stills of Hailey McGuire's netting models completed in the fourth-year *Tank Worlds: Hamilton Harbour* studio. The nets are cast into the harbour near existing overflow outlets, acting as infrastructure for bioremediation. The nets are tedious, carefully constructed, cast and eventually retrieved, requiring maintenance over time. Courtesy of Hailey McGuire, 2021.

thermal *discomfort* and what design 'after comfort' might entail, noting that

> Comfort, like capital, is unevenly distributed – not everyone gets to have the same amount … As the climate crisis renders global asymmetries more extreme, rethinking comfort will force us to critically think through these asymmetries. Who decides who gets to be comfortable? What are the technological, industrial, political and affective contours of asserting such agency?
> (Barber 2019, 46)

Barber invites architects to design buildings in a way that resists outdated standards and conventions of conditioning buildings which are incompatible with dwindling resources and their inequitable patterns of distribution.

Diminution

The Olgyays' thermoheliodon was an ambitious analogue to their bioclimatic design process. It attempted to reconcile given exterior climate conditions with desirable interior thermal comfort expectations. The thermoheliodon represented two competing notions of building environmental management – one predicated on variability and the other on total control. It raised complex questions about the construction of environments in general and of a building's role in mediating these constructions.

In photographs of the thermoheliodon, the architectural model of the *Phoenix Balanced House* is strikingly diminutive. It recedes from view, overshadowed by the supporting componentry required to simulate its meteorological surroundings. In some ways, this diminution reflects a shift in focus of the Olgyays' work, from that of the design of buildings to the design of methodologies. It also reflects broader turns in the development of models of building-science experimentation, particularly of sundials and heliodons at the time, as the site of operation of these models shifted from outside using the 'real' sun to inside using an 'electrical' sun. The machining of the electrical sun increasingly took visual precedence over its effects on the architectural model. A comparison between the Olgyays' Stühmer Chocolate Factory Model and the thermoheliodon presses this point even further still. Not only has architecture receded, the operator of the model has also been cast outside the bounds of the hemispherical dome containing it. Rather than view this diminution as a loss, what might be gained by this change in stature?

The thermoheliodon suggests an architecture of *diminution*. It is both a totality and a distillation, and a reminder of architecture's increasing diminution in relation to the complex climatological forces at play upon it. As a codification of a complex multi-valent sustainable design methodology, the thermoheliodon is a prescient reminder that as the variables of environmental consideration expand, there is risk that the architectural response dampens under the weight of reconciling these often-competing demands.

Just like the thermoheliodon, an architecture of diminution *miniaturises the gigantic*. Susan Stewart suggests that miniatures had value during the Victorian era, when they were used as devices for explaining the world. The model miniature makes the often mundane fantastic; it is marked by containment; it focuses on detail and craft; it is an object of revery, slowing down time. The gigantic, on the other hand, is without limits; it is overwhelming, immersive, infinite and disorderly. Unmanageable and distant, the gigantic is beyond human cognitive and physical grasp, reinforcing dualisms such as the conceit of human and nature as distinct. We understand now that humans are agents of large-scale environmental destruction, disrupting Victorian-era understandings of humans as being diminished recipients of the incomprehensible forces of nature. Climate change has collapsed the perceived distance between us and the 'gigantic' climatological systems once seen as being beyond our cognitive and physical reach (Figure 6.4). We have become, according to Ghosn and Jazairy, 'geographic leviathans' (2017, 271).

6.4

6.4 Photograph of Charles-Étienne Déry's project, *Disruptive Vitrines*, completed in the *Miniaturising the Gigantic* thesis seminar. The model nests three radically divergent scales of observation: the 1:1 scale of the tank, the 1:20,000 scale of the Canadian ecoregion, and a more conventional architectural scale model of a single regional icon. Courtesy of Charles-Étienne Déry, 2021.

An architecture of diminution learns from the tank of water as a site of architectural speculation. The tank objectifies the aerial (as watery) domain to make it a more accessible subject of speculation (Figures 6.5). The tank contains that which appears limitless and gives weight and material presence to that which appears without. The tank is an aquarium, an object of enchantment and curiosity that collapses distinction between the incommensurate scales of real-world degradation and scale world design exploration. Rania Ghosn and El Hadi Jazairy's reflections on the aquarium as both an object of design speculation and a device for telling stories about 'environmental externalities' situates tank-world models as artefacts of speculation about post-natural histories.

> In general, complex systems are difficult to fathom, and the issue of climate change is particularly challenging because its effects involve vast scales of both time and space. Furthermore, an ocean is large, difficult to see all at once in its depths and extents, and it requires a vast representational machine to comprehend. Its sheer size is overwhelming. What is the affective agency of a cabinet of natural history in a postnatural world and within this ocean of uncertainties? If environmental issues are unrepresentable in their scale, their ubiquity, and their duration, then perhaps miniatures of the Earth can present such scientific concerns to the senses.
> (Ghosn and Jazairy 2017, 273)

6.5

6.5 Photograph of Laura Haylock, Calum Rennie and Katie Sidwell's filling-tank studies of hydrological infrastructure in the Blue Lagoon, Iceland (midground), and Bath, UK (foreground). The models collapse scales of observation, from that of the building, immersed within the tank, to that of the infrastructure operating at the territorial scale. Work was completed in the Master of Architecture studio, *The Streamlines, Vortices and Plumes of the Blue Lagoon and Bath*, co-taught with Simone Ferracina. Courtesy of Laura Haylock, Calum Rennie, Katie Sidwell, 2019.

The aquarium brings together these two aesthetic experiences of miniaturising the gigantic into a single artefact, resituating the infinite in relation to the manageable scales of body, while at the same time offering an imaginative portal to a vast territory of exploration. The tank is a physical construction that enables speculation about environmental reconstruction across scales (Figures 6.6 and 6.7).

An architecture of diminution is one that can hold opposing, often conflicting views about our place in the world. We are all implicated in vast environmental entanglements. We are agents of environmental disruptions at the planetary scale yet feel insignificant and lacking agency as individuals. We are both gigantic and miniature. For a diminutive architecture to be small in its footprints, it must position itself in relation to a set of systems and values that are vast, complicated and expansive.

An architecture of diminution starts to reconcile our insignificance amidst the magnitude of the impacts, accelerations and scales of climate change and environmental injustice. It is an architecture that keeps its many footprints – and *there are many* – small to redistribute resources. An architecture of diminution takes seriously its own limits, consolidating and compressing its spaces, its material palette and its internal consumptions. It is a more nimble, less heroic, architecture, supporting many uses simultaneously, to eliminate redundancies. At the same time, it makes the inscriptions of more expansive processes, such as water or solar cycles, or waste-processing streams or labour practices, evident through material choices, siting, orientation or construction method.

Buoyancy

Reid's test tube experiments revealed the mechanics underpinning the process of convection within a hermetically sealed vessel, a distillation of the processes driving his natural ventilation schemes at the scale of buildings. Reid's convection experiments were objects of *buoyancy*. Small didactic experiments, they reflected an approach to working materially as a means of making complex phenomena apparent. And in their simplicity, they enabled speculation about how a small physical experiment could be understood as a model of architecture as a series of interconnected vessels that expand and contract in response to thermodynamic processes. Reid's work was predicated on thermal differentials, on the property of buoyant air to float up and away and be displaced by lower, cooler air.

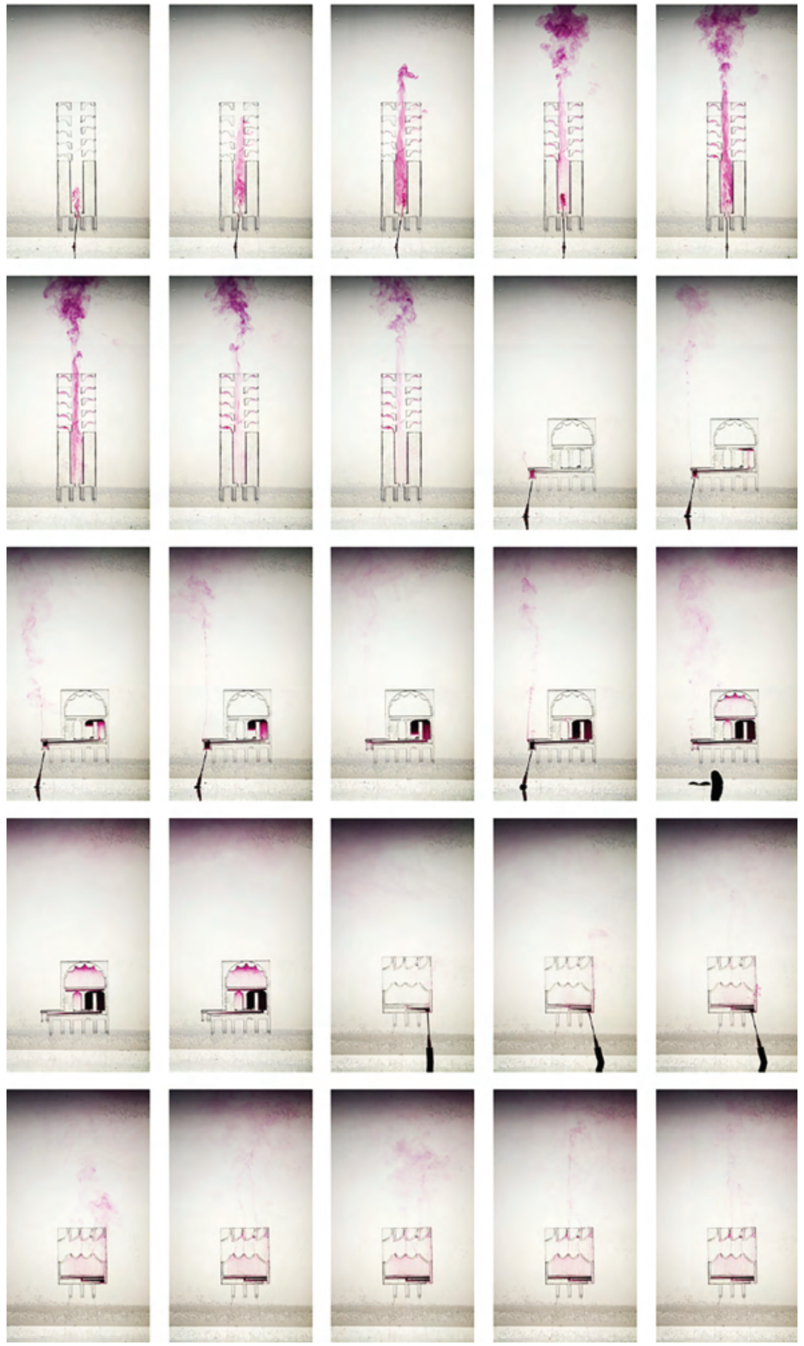
Chapter 5 outlined that an architecture of buoyancy uses naturally occurring processes as the primary determinants of a building's form. It is architecture as a tubular apparatus, a series of interconnected chambers designed to enable the flow of fresh air or heat or the passage of light. It is an architecture moulded by the Earth's inhalations and exhalations. An architecture of buoyancy is an architecture of differentials marked by towers reaching skyward and basement plenums reaching outwards, by inlets and outlets, perforations, filters, baffles, cowls and chimneys.

An architecture of buoyancy works analogously between air and water, and by association, between the atmosphere and the ocean. Air behaves like water, and the atmosphere as a totality shares characteristics with that of the ocean. In *Illustrations*

6.6 Video still of Laura Haylock's buoyancy model for a communal kitchen, part of an adaptive reuse project for the Balance Street social housing development in Bath, UK. The project incorporates a biofuel adaptation of the existing CHP system while also proposing a series of thermal commons heated with existing thermal springs. Courtesy of Laura Haylock, 2019.

6.6

6.7 Video stills of Laura Haylock's buoyancy models of three architectural elements for the adaptive reuse of the Balance Street social housing development in Bath. (top) An existing CHP chimney is adapted to divert heat to its perimeter to aid clothes drying. (middle) A new communal kitchen/ bake house directs heat generated below to a common room above. (bottom) A new thermal bath with draped ceiling that diverts steam to a greenhouse space above. Courtesy of Laura Haylock, 2019.



6.7

of the Theory and Practice of Ventilation, David Boswell Reid noted,

> The human frame and all other objects there, are subjected to the pressure of the superincumbent atmosphere in the same manner as a diver at the bottom of the sea is subjected to the weight of the column of water above him. We live at the bottom of an aerial ocean … The aerial ocean or atmosphere is subjected to currents, and its height to fluctuations, in the same manner as the waters of the globe.
>
> (1844, 142)

The currents in Reid's atmosphere are meteorological and reductive. Reid's characterisation of the atmosphere is marked by fluctuations and currents, but it is largely compositionally homogenous.

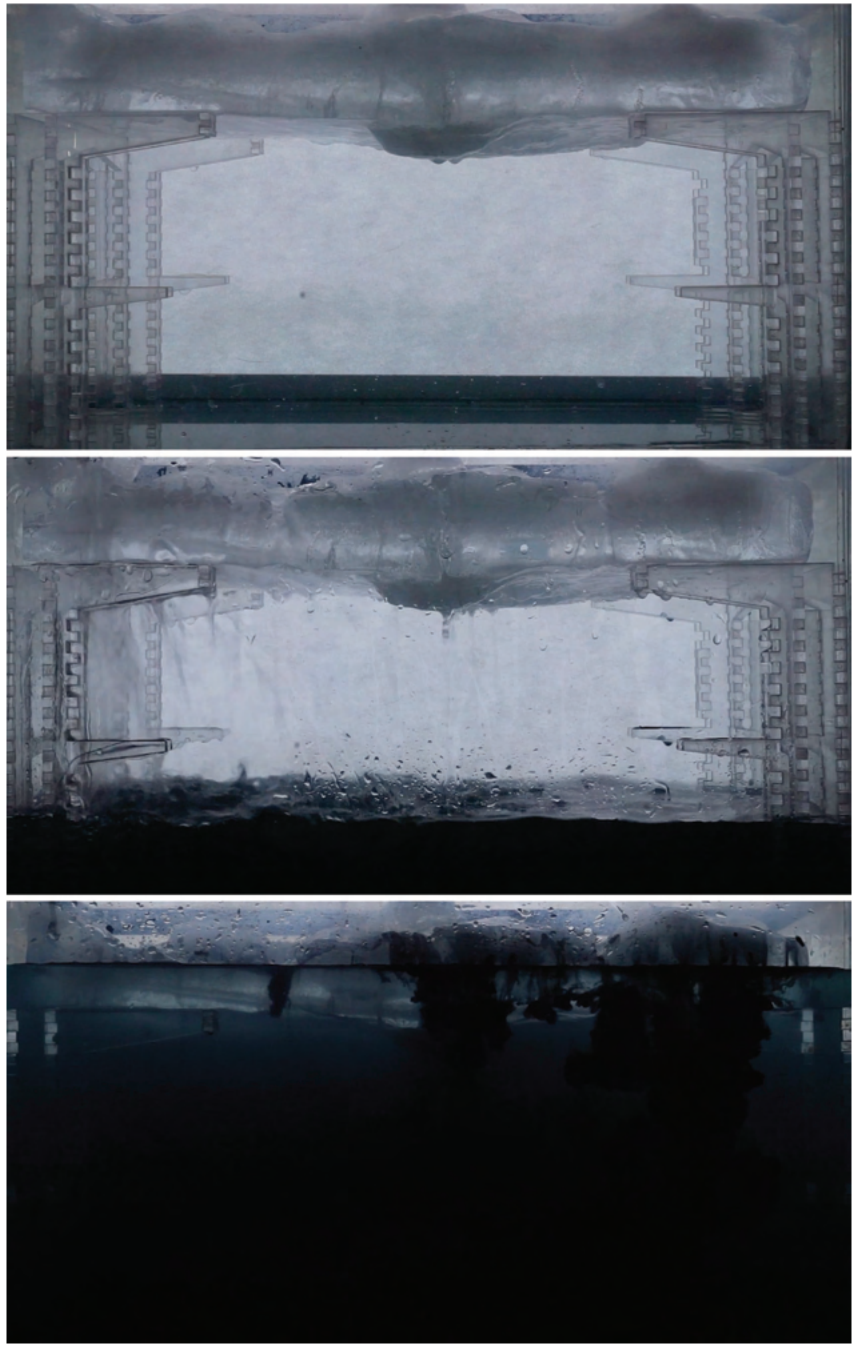
Visual artist Tomás Saraceno, whose aerial sculptures raise ethical questions about atmospheric inequities, challenges the idea that this atmospheric ocean is undifferentiated and largely invisible. Saraceno notes instead that it is in fact stratified, highly differentiated and increasingly a luxury for the privileged few:

> Though we live submerged at the bottom of an ocean of air, this ocean is not uniform for all its populace. Access to clean air is stratified across racial, socioeconomic, and geopolitical lines, with air quality varying even between neighborhoods. For those who must suffer for others' pollution, the air is no longer even invisible; instead a yellow sky hangs over many of the world's major cities, particularly in the Global South. Invisibility and what it allows – the ability to not have to think about the air one breathes – is a luxury afforded to only a few: localities that are themselves white in colour.
>
> (Saraceno 2020, 33–4)

Fundamentally, buoyancy induces stratification, and this stratification aligns with deep inequities (Figure 6.8). Amy Balkin's 2016 *The Atmosphere: A Guide* elaborates on several such atmospheric inequities, ranging from wind current transport of pollutants from industrial production in the US, China and Europe to the Arctic, to the occurrence of atmospheric brown clouds (ABCs) composed of soot and sulphates which cyclically cover parts of Asia, southern Africa and the Amazon basin. The politics of atmospheric inequity also apply to constructed interiors – the climate-controlled bubbles that are accessible to a privileged few who are buffered from the threat of discomfort. To think of architecture in buoyant terms prompts us to unravel these inequities and to design, as Barber suggests, for *discomfort* (2019).

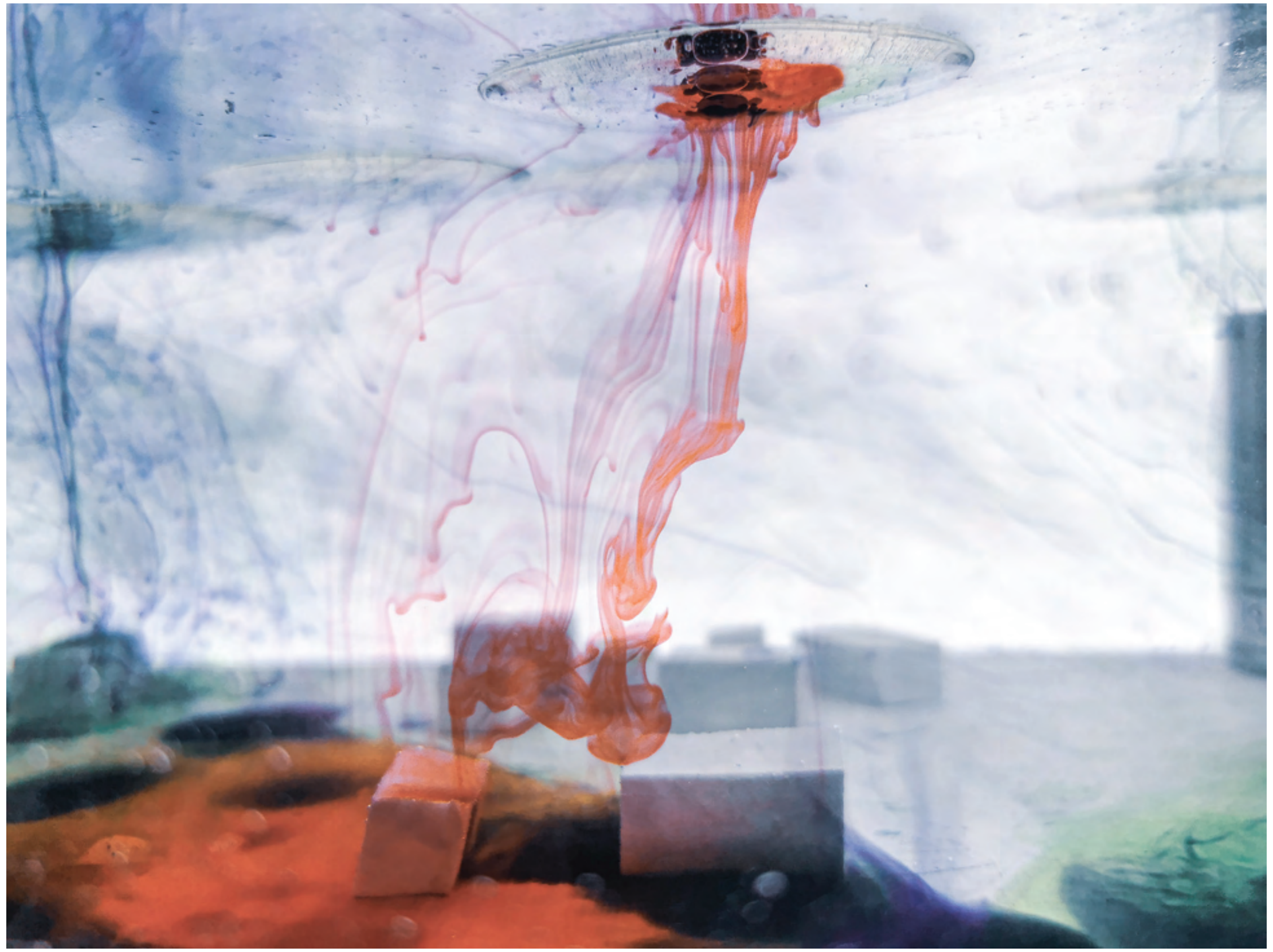
To be buoyant is also to stay afloat amidst disturbance. Eva Horn's essay 'Air as Medium' makes the case for understanding climate less as a scientific and more as a cultural endeavour. One way of doing so, she suggests, is through heightening our awareness of its disruptions, which are culturally registered more so than static, background conditions. Another way of situating climate as a cultural condition, she suggests, is by honing an aesthetic sensibility, or an *aesthesis* of air by:

> exploring it in all its sensory qualities – from its (in)visibility and its tactile states (e.g., temperature, humidity, movement), to its



6.8

6.8 Video stills from Charlotte Egan, Damiano Perrella and Sarah Van Alstyne's tank-model study exploring the capacity for salt water to erode ice, etching new topographies and infiltrating the water column below. Over the course of the video, ice melts, the tank fills, saline plumes contaminate the water and the ice breaks. Eventually, water in the tank sits in a state of visible stratification. Work was completed in the fourth-year design studio, *Tank World: Port Hope*. Port Hope is the site of the largest remediation project in Canada involving the removal of soil and silt contaminated by uranium tailings from conversion facilities that have been located adjacent to the harbour since 1930. Courtesy of Charlotte Egan, Damiano Perrella, Sarah Van Alstyne, 2022.



6.9

6.9 **Photograph of Joel Tremblay's kaleidoscopic exploration of weather events and their associated microclimates of ice fishing huts on Callander Bay in Lake Nipissing, Ontario, completed in the *Miniaturising the Gigantic* thesis seminar. The atmosphere is often described in oceanic terms. Tank-world models translate air into water and radically rescale the atmospheric domain into a contained space for design exploration.** Courtesy of Joel Tremblay, 2019.

inner dynamics (e.g., winds, drafts, updraft, density) and maybe even the affective qualities of certain weather conditions. It would entail a sense of place and season, of the natural, urban, and social atmospheres in which we are situated. An aesthesis of air means bringing air (back) to the foreground of our perception as both object and condition of perception.

(Horn 2018, 23)

Many of the projects featured in Chapter 5 begin to do just that.

Ultimately, Horn suggests, 'perhaps the most radical way of developing an aesthesis of air is through art' (2018, 23). Environmental models are not art per se, but they are physical artefacts that enable creative speculation (Figure 6.9). They draw from techniques in engineering, and they have the capacity to reveal technological principles. They have qualities that make them like instruments or like infrastructure or like architecture or like art. Ultimately, however, they are architectural models, and as such they are distilled objects of reverie that enable creative speculation about what might be. They are creative acts. They invoke wonder and possibility, acting as agents of creative speculation. They have the capacity to hone a technical and aesthetic awareness of the atmospheric domain in a way that can, as Horn notes, inaugurate changing reconceptualisations of the world. The role that contemporary architectural models play in *world-building* is particularly salient in this regard. When reflecting on this specific attribute, Christian Hubert, author of a pivotal essay in Peter Eisenman's 1976 *Idea as Model* exhibition catalogue, retrospectively written in 1981, notes:

> Most models today are more concerned with the future than was the case when I wrote my essay in 1981 … Future-oriented models are reflexive, in the sense of creating feedback loops that change perceptions of reality, and in that sense they are meant to change reality itself. They move beyond representation with the goal of setting out possible worlds.
>
> (Hubert 2021, 16)

This book began with a chapter titled 'Environmental models' and it concludes with this chapter titled 'Model environments'. These bookends reflect a shift in how the term model has been used in the book. The book began with a focus on models as scale artefacts, as conventions of architectural representation. Environmental models are architectural models that build on traditions of engineering experimentation. They are *not drawings*, capitalising on the messy material status that once made them undesirable. They are slow and imprecise unlike the promise of their digital counterparts. They resist extreme tolerances; they leak where they should not.

As writing progressed, the term model referred increasingly to categorical types. Two models of environmental architecture were explored in Chapter 4 – those that mediate versus those that resist their exterior surroundings. These two strategies of environmental building control smoothed over differences to find commonalities. One model was a filter; the other was a bubble. A third model was added in Chapter 5 – that of architecture formed by thermodynamic processes. The book concludes by considering models as mental ideals, as projections of what could be or should be in the world. These model environments – that of resistance, diminution and buoyancy – draw from insights embedded within each case study model. They are thought experiments. They establish conversations about the world as it is and that which could be.

As our ideals take physical form, their meanings oscillate depending on the orientation and vantage point from which we view them. Buildings become instruments. Instruments become models. Models become worlds. Physical artefacts become mental ideals. Environmental models enable us to surface ourselves and view the world from a new, distanced vantage point. We live immersed within this 'ocean of the element air'. It has material attributes. We are agents that alter its composition. Rather than feel as if we are engulfed by or drowning within it, environmental models shift the weight of this ocean to a distanced, contained object. Some distance is valuable, for to design in this moment of crisis, *we too must remain buoyant*.

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Index

DESIGN RESEARCH IN ARCHITECTURE

‘This ground-breaking book provides new insights and approaches to how models establish dialogues with those aspects of the world being modelled. In an era of climate emergency, understanding how environmental models can open up novel, effective trajectories for architecture is more critical than ever before. Architecture’s Model Environments presents an original and compelling argument for what we design, how, where and why.’ – Nick Dunn, Lancaster University

Seen through the distilling lens of the architectural model, Architecture’s Model Environments is a novel and far-reaching exploration of the many dialogues buildings have with their environmental surroundings. Expanding on histories of building technology, the book sheds new light on how physical models conventionally understood as engineering experimentation devices enable architectural design speculation.

The book begins with a catalogue of ten original model prototypes – of wind tunnels, water tables and filling boxes – and is the first of its kind to establish an architectural approach to fabricating such environmental models. Subsequent chapters feature three precedent models that have been largely overlooked within the wider oeuvres of their authors: French polymath Étienne-Jules Marey’s 1900–2 wind tunnels, Hungarian-American architects Victor and Aladár Olgyay’s 1955–63 thermoheliodon, and Scottish chemist and building ventilation expert David Boswell ‘The Ventilator’ Reid’s 1844 test tube convection experiments.

Moving between historic moments and the present day, between case studies and original prototypes, the book reveals the potent ability for models, as both physical artefacts and mental ideals, to reflect prevailing cultural views about the world and to even reshape those views. Fundamentally, Architecture’s Model Environments illustrates how environmental models reveal design insights across scales from the seam (that leaks) to the body (that feels) to the building (that mediates) to the world (that immerses).

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