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Replication, re-placing and naval science in comparative context, *c.*1868–1904†

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Abstract. The test tank broadly embodied the late nineteenth-century endeavour to 'use science' in industry, but the meaning given to the tank differed depending on the experienced communities that made it part of their experimental and engineering practices. This paper explores the local politics surrounding three tanks: William Froude's test tank located on his private estate in Torquay (1870), the Denny tank in Dumbarton (1884) and the University of Michigan test tank (1903). The similarities and peculiarities of test tank use and interpretation identified in this paper reveal the complexities of naval science and contribute to the shaping of an alternative model of replication. This model places the emphasis on actors at sites of replication that renegotiated the meaning of the original Froude tank, and re-placed the local values and conditions which made it a functional instrument of scientific investigation.

> All the European [test tank] stations are modelled on the station at Haslar; [yet] each station had its own individuality which I will try to throw into relief, avoiding tedious repetitions or comparisons.[1]

In 1906, Cecil Peabody, professor of naval architecture at the Massachusetts Institute of Technology, presented the American Society of Naval Architects and Marine Engineers some observations of European test tanks. His research for the paper entailed personal visits to European test tanks, beginning with the Admiralty Experimental Station at Haslar on the Solent, Hampshire. During his visit there, Peabody remarked on the tank's 'practical adaptation of the means to the end'. He also noted the 'simplicity of manner and scientific enthusiasm' of Edmund Froude, who directed the test tank facility after his father's death in 1879.[2]

The first test tank, design by William Froude, consisted of a waterway approximately three hundred feet long, a railway, hauling engine and carriage to propel ship models,

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[1] Cecil H. Peabody, 'Personal impressions of ship-model towing stations', *Transactions of the Society of Naval Architects and Marine Engineers* (1906) 14, pp. 43–51, 46.

[2] Peabody, op. cit. (1), p. 43.

automatic measuring and plotting instruments and model-making equipment. Froude, an Oxford-trained mathematician and gentleman of science, undertook this work on the test tank in the 1870s on behalf of the British Admiralty to investigate ship resistance. Froude's work successfully demonstrated that the behaviour of twelve-foot models in a tank accurately represented the way that ships behaved at sea.[3] By 1887, the Admiralty had relocated Froude's tank to its own experimental station at Haslar.

Instrument systems like the test tank constituted an attempt to bring scientific theory and mechanical experiments together within the shipbuilding industry. The first tank represented one such successful connection between the Admiralty and Froude's research into hydrodynamics and ship efficiency. The second tank, a replica built by William Denny & Brothers at their Leven shipyard on the Clyde (1884), belonged to the same general enterprise, but embodied a very different dynamic between experimentation and industry. Peabody claimed that the Denny tank 'enabled the firm to take a leading role in the solution of certain problems in naval architecture such as very high speeds for paddle-boats and the installation of steam turbines'.[4] Via the tank, Denny helped demonstrate the motive power of Charles Parsons's marine steam turbines that defied the usual methods of dynamometric measurement. Peabody reported that the test tank afforded the Dennys a commercial advantage over other shipbuilders, as their tank provided precise speed and horsepower forecasting.[5]

Beyond Britain, Peabody judged tanks in Bremerhaven (operated by the North German Lloyd SS Company) and St Petersburg. He also praised a decision made in 1904 at the University of Michigan to position a tank at the centre of its technical training and Great Lake shipbuilding relations. Peabody hoped that his employer (MIT) would follow Michigan's strategy. At each of these sites, actors replicated Froude's tests and incorporated the tank into naval science practices. How this replication took place is by no means straightforward, as the local practice of naval science and understanding of the test tank differed from site to site. To examine this problem, it is necessary to take our understanding of replication in new directions, and explore what happens beyond the core concern of calibration.

Decentralizing replication through comparative analysis

Replication resides at the conceptual core of science and technology studies. It is an invaluable tool for analysing how actors made matters of fact and distributed the material culture of experiments. The replication of an experiment from one site to another also demonstrates how scientific practices and the knowledge derived from them became 'placeless' (or 'universal'). Replication separates the experiment from the conditions of its local origins, such as the experimenter's status, instruments and site of

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[3] For nineteenth-century hydrodynamics and experiment see Ben Marsden, 'The administration of the "engineering science" of naval architecture at the British Association for the Advancement of Science, 1831–1872', *Yearbook of European Administrative History* (2008) 20, pp. 67–94.

[4] Peabody, op. cit. (1), p. 46.

[5] Peabody, op. cit. (1), p. 47.

experiment. The 'placeless' quality of post-replication science and engineering presents a problem for the sociology of scientific knowledge. Adi Ophir and Steven Shapin posited it thus in 1991:

> How is it, if knowledge is indeed local, that certain forms of it appear global in domain of application? Is the global – or even the widely distributed – character of, for example, much scientific and mathematical knowledge an illusion? If it is the case that some knowledge spreads from one context to many, how is that spread achieved, and what is the cause of its movement?[6]

Confronted with this obstacle, historians of science have traced the replication of experimental materials and practices outward from their original site. Noteworthy examples include Harry Collins's account of the TEA-laser and experimenters' regress, and Steven Shapin and Simon Schaffer's analysis of the air pump in seventeenth-century experiments.[7]

The process of replication in particular presents challenges; as Peter Galison wrote, 'An instrument made in one spot is often difficult to replicate in another without the bodily transport of things and people. Paper instructions are not enough.'[8] Galison's model for understanding replication examines how scientific knowledge and practices were 'delocalised' as practitioners (theorists, experimenters and engineers, among others) met in trading zones where meaning 'hesitantly, partially, and nonetheless efficaciously' travelled.[9] In contrast, Schaffer consolidates this replication with the sociology of scientific knowledge through a model in which multiple contexts 'distribute instruments and values which make the world fit for science'.[10] In both approaches to replication, Galison and Schaffer assign agency primarily to actors at the centre of the replication process, those who either delocalize the experiment or duplicate the context in which it takes place.

An alternative, decentralized model of replication assigns greater agency to actors at the site of replication. To make this argument, it is first necessary to note that existing scholarship on replication remains largely connected to questions of calibration and standardization. The decentralized model of replication described in this article is more concerned with the activities of actors beyond the calibration of the test tank. Methodologically, this argument addresses the broader question of how knowledge travels, and is less concerned with how experimental practices are standardized. The

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[6] Adi Ophir and Steven Shapin, 'The place of knowledge: a methodological survey', *Science in Context* (1991) 1, pp. 1–16, 15–16.

[7] H.M. Collins, *Changing Order: Replication and Induction in Scientific Practice*, Chicago: Chicago University Press, 1985, pp. 79–112; Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle and the Experimental Life*, Princeton: Princeton University Press, 1985, pp. 225–272, 226–27.

[8] Peter Galison, 'Material culture, theoretical culture, and delocalization', in John Krige and Dominique Pestre (eds.), *Companion to Science in the Twentieth Century*, London: Routledge, 2003, pp. 669–682, 675–676.

[9] Galison, op. cit. (8), p. 680; *idem*, *Image and Logic: A Material Culture of Microphysics*, Chicago: Chicago University Press, 1997, pp. 803–844.

[10] Simon Schaffer, 'Late Victorian metrology and its instruments: a manufactory of ohms', in Robert Bud and Susan E. Cozzens (eds.), *Invisible Connections: Instruments, Institutions and Science*, Bellingham: SPIE Optical Engineering Press, 1991, pp. 23–49, 23.

focus of the decentralized model in relation to previous models invites a reconsideration of how actors manage replication.

What follows is a comparative analysis of the spaces and 'experienced communities' (that is to say, groups of laboratory investigators or engineering firms) where model experiments were made a key practice within naval science.[11] Taking the test tank as a case study, I focus on these categories to demonstrate how communities of experimenters understood the tank and integrated it into their work. This analysis identifies local conditions that existed at sites of replication and examines how they shaped and possibly enabled the re-placing of material culture and the replacing of cultural values. The results of this investigation reveal that actors at the centre (or initial site) could not work alone to delocalize the test tank or multiply the context of the tank's use. Replication, therefore, is treated here as a negotiation that takes places in the physical space of an 'experienced community', where local actors (who did not make the first instruments) replaced the meaning and context whereby the tank found form and function.[12]

The justifications and consequences for a comparative analysis of sites of science and their local contexts warrant some reflection. It is only through a comparative analysis that local conditions at sites of replication can be compared for similarity and difference. This is a heretofore overlooked area for research. Much of the history of science and technology – especially that which employs an ethnomethodology – is predicated on the principle that all knowledge, practice and achievement is local. The corollary is that local conditions help to explain science's inescapable social and spatial specificities. Placing the illusory truism – that the local is unique – aside, how can we take seriously the question of what makes the local unique, and understand how it shapes the transfer of scientific practices and material?

The proposed mode of analysis borrows heavily from cultural historians who experienced their own ethnographic turn towards microhistory and thick description and subsequently nuanced their analytical insights via comparative methodologies. This constituted a reconsideration of the nature of comparative historiography. The traditional methodological focus of comparative history consisted of treating case studies as 'equals', as utilized in economic and social history to compare structural patterns. This method was inadequately rigid as an analytical frame for cultural history. Cultural historians have thus tended to follow a 'relational' model of comparative history in which the comparative focus is shifted between case studies, and evidence from the other cases is used to 'make a particular point about that particular case'.[13] This type of framework adds analytical depth to the investigation of how local knowledge and

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[11] The phrase 'experienced communities' is used by Benedict Anderson to refer to the unique, local facets of life, work and ideology that bind a group of people in a place. See Benedict Anderson, *Imagined Communities: Reflection on the Origin and Spread of Nationalism*, London: Verso, 1983. Also see Michel de Certeau, *The Practice of Everyday Life* (tr. Steven F. Rendall), Berkeley: University of California Press, 1984, p. 16; David N. Livingstone, *Putting Science in Its Place: Geographies of Scientific Knowledge*, Chicago: University of Chicago Press, 2003, p. 12.

[12] For a fuller discussion of these issues see Robert E. Kohler, 'Lab history: reflections', *Isis* (2008) 99, pp. 761–768, 766–767.

[13] Jay Winter, 'The practices of metropolitan life in wartime', in Jay Winter and Jean-Louis Robert (eds.), *Capital Cities at War: Paris, London, Berlin 1914–1919, a Cultural History*, Cambridge: Cambridge

practices are distributed. A substantial contribution can be made to how we understand replication by identifying which epistemological, material, spatial, social and cultural values are transported during replication, and those that already exist at a new site of experiment through which the original experimental practices are adapted for new uses.

A secondary function of a comparative model is to frame historical questions in a broader, yet more focused, contextual setting. James Secord has persuasively argued that historians of science need to think more extensively and reflexively about how to frame their work, to avoid both methodological repetition and disciplinary isolation.[14] Historians of science have acknowledged the potential within comparative history to combat parochialism, yet the application of a comparative methodology has remained rooted to deconstructing histories of science reified within national boundaries.[15] Such histories can appear to be little more than a series of national case studies – rather than a comparative account of how a particular event or phenomenon has been experienced.[16] The appeal of comparative history to the historian of science should be, as Deborah Cohen notes of the discipline, its potential to distinguish contextual explanations from causal explanations by providing 'a counterfactual glimpse that illuminates a path not taken, policies not pursued, which serve to throw a wrench in overdetermined historical narratives'.[17] Yet historians of science have largely neglected comparative analysis as a tool to nuance the episodic focus that prevails in the discipline following its ethnographic turn.[18] It is with the aim of illustrating three very different appropriations of the test tank into the working practices of engineers and shipbuilders that this article employs a comparative mode. Only through assembling such a rich and varied picture of replication can this phenomenon be recast as something more than calibration and standardization.

A gentleman's tank

Early nineteenth-century shipbuilding was an industry of artisans suspicious of hydrodynamic theory and the value of experiment.[19] By the end of the century, shipbuilders formed a range of relationships with men of science, engineers and university professors.

University Press, 2007, pp. 1–19, 8–9. Also see Raymond Grew, 'The case for comparing histories', *American Historical Review* (1980) 85, pp. 763–788, 766.

[14] James A. Secord, 'Knowledge in transit', *Isis* (2004) 95, pp. 654–672, 659.

[15] Carola Sachse and Mark Walker, 'Introduction: a comparative perspective', *Osiris* (2005) 20, pp. 1–20, 10; Mark Walker, *Science and Ideology: A Comparative History*, London: Routledge, 2003; Roy Porter and Mikulás Teich (eds.), *The Scientific Revolution in National Context*, Cambridge: Cambridge University Press, 1992; Mark B. Adams (ed.), *The Wellborn Science: Eugenics in Germany, France, Brazil and Russia*, Oxford: Oxford University Press, 1990.

[16] Deborah Cohen, 'Comparative history: buyer beware', *Germany History Institute Bulletin* (2001) 29, pp. 24–26.

[17] Cohen, op. cit. (16), pp. 23–33, 28–29.

[18] Lorraine Daston and Peter Galison recently argued that there are 'developments that unfold on a temporal and geographic scale that can only be recognized at the local level once they have been spotted from a more global perspective'. See Daston and Galison, *Objectivity*, New York: Zone Books, 2007, p. 47.

[19] William Thiesen, *Industrializing American Shipbuilding: The Transformation of Ship Design and Construction, 1820–1920*, Gainesville: University of Florida Press, 2006.

The test tank deserves attention as one such site where this relationship was forged. William Froude's test tank was the first built and thus forms the basis for further comparative analysis.

In the 1860s, Froude resurrected models as objects that could be used in experimental enquiry and engineering research. A series of attempts beginning in the 1790s to use scaled-down ships to examine hydrodynamics failed to convince the scientific and shipbuilding communities of their utility. For example, Mark Beaufoy's model experiments for the eighteenth-century Society for the Improvement of Naval Architecture made little impact on the mentality and working practices of the Admiralty and private firms.[20] In this instance, model experiments represented a failure to join science and industry in a common project.

Key members of the newly formed British Association for the Advancement of Science (BAAS) Section G (mechanical science) also utilized models in shipbuilding research. Members sought to demonstrate that scientific theory and analysis could potentially solve the problems of Victorian industries.[21] Glasgow professor of mechanical engineering W.J. Macquorn Rankine and the naval architect John Scott Russell, in particular, explored how hydrodynamic theories and experiments could resolve problems in ship design, such as hull resistance. Between 1838 and 1870, seven committees met to examine knowledge of hydrodynamics and commission a great number of small-scale experiments.[22] Leading members of the BAAS concluded that model experiments alone could not establish the behaviour of a ship at sea.[23] The Admiralty sought to avoid the cost of full-scale testing and the loss of ships from active service. A BAAS committee decided to revisit this issue in 1868, adamantly concluding that full-scale experiments were necessary to improve theoretical and practical knowledge of hydrodynamics and ship design. The committee also submitted a minority report by William Froude concerning a new programme of extensive and systematic model experiments.

Prior to 1868, Froude, a gentleman of private means, undertook a series of observations on models in the ponds and estuaries surrounding his father's Torquay parish parsonage. From these observations he produced a set of controversial ideas that contradicted many prevailing theories of hydrodynamics, such as Russell's wave line theory and the advantages of long ships for ship resistance.[24] Froude's work was initially rejected by the scientific and engineering authorities in Section G of the BAAS and the Institution of Naval Architects (INA). Not until the mid-1870s, when the Admiralty permitted Froude to undertake trials with HMS *Greyhound* and *Devastation* as part of

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[20] These model experiments are examined in detail in Simon Schaffer, 'Fish and ships: models in the age of reason', in Soraya de Chadarevian and Nick Hopwood (eds.), *Models: The Third Dimension of Science*, Stanford: Stanford University Press, 2004, pp. 71–105, 91–96.

[21] Jack Morrell and Arnold Thackray, *Gentlemen of Science: Early Years of the British Association for the Advancement of Science*, Oxford: Oxford University Press, 1981, pp. 259–260.

[22] Tom Wright, 'Ship hydrodynamics, 1710–1880', PhD thesis, Science Museum/University of Manchester Institute of Science and Technology, 1983, p. 97.

[23] W.J. Macquorn Rankine, 'Remarks on Mr Froude's theory on the rolling of ships', *Transactions of the Institution of Naval Architects* (1862) 3, pp. 22–45; John Scott Russell, 'Postscript to Mr Froude's remarks on rolling', *Transactions of the Institution of Naval Architects* (1863) 4, pp. 276–283.

[24] For these theories of ship resistance and their BAAS context see Marsden, op. cit. (3), pp. 67–94.

the ongoing uncertainty over ship resistance and stability in the wake of the loss of HMS *Captain*, could Froude establish the credibility of model testing. Froude undertook a series of experiments with the ships and proportional models, from which he demonstrated the accuracy of his practices in the test tank.[25]

In 1871, Froude secured Admiralty funds to build and operate the test tank required for his programme of model experiments (ending a BAAS rival request for full-scale experiments). Froude's correspondence with First Lord of the Admiralty Hugh Childers, on model testing, made little reference to the epistemological problems of hydrodynamics. Froude suggested that the test tank would tackle an extensive list of practical problems, including the trial-and-error method of much shipbuilding and the waste of coal resources to drive inefficient ships.[26] These arguments, which linked model experiments directly to notions of 'efficiency' and 'economy', convinced the political heads of the Admiralty to support Froude's tank experiments instead of the more expensive ship experiments proposed by the BAAS.

Froude's letters to the Admiralty also highlight his specific skills and credibility as an experimenter. '[T]hough there are probably many men of science whose qualifications would be found in various respects superior to my own', Froude admitted, 'I have . . . acquired a large stock of apposite knowledge and matured habits of experimental inquiry.'[27] He recognized the importance of demonstrating his knowledge of hydrodynamics and his experience as a skilled experimenter. Consequently, Froude requested that 'on the score alike of efficiency and economy the work should be trusted to myself at my residence here'. 'I have a good workshop in my own house', Froude continued; 'nowhere else could I approach it with the same mechanical advantages'.[28] The Admiralty did not object, which suggests either that they had no long-term plans for model testing or that they trusted Froude to undertake the work in private. Nor did the Admiralty object to Froude's demand for paid assistants and staff appointments, including his son Edmund Froude, G.S. Baker and a number of graduates of the newly created Royal School of Naval Architecture at Kensington. Until his death in 1879, Froude and his assistants systematically tested ship plans that the Admiralty sent and, with the Admiralty's permission, used the data to publish papers on hydrodynamics.

Froude's work for the Admiralty took the form of consultancy. The Admiralty initially left him to undertake his own work on resistance in tandem with the Admiralty Constructors Department. This changed during the public controversy surrounding the Navy's first mastless ship, HMS *Devastation*. Nathaniel Barnaby, chief constructor of the Navy, appealed to Froude to help dismiss concerns surrounding the ship's stability. Henry Marc Brunel, who assisted Froude in the test tank, conveyed the worries of the

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[25] *Copy of Reports of the Behaviour of H.M.S. 'Devastation' on her Passage from England to Malta*. London: HMSO, 1876; David K. Brown, 'William Froude and "the way of a ship in the sea"', *Reports and Transactions of the Devonshire Association for the Advancement of Science, Literature and the Arts* (1992) 124, pp. 207–231, esp. 216.

[26] William Froude to Hugh Childers, 11 December 1868, Admiralty papers, National Archive, London (subsequently ADM), 116/167.

[27] Froude to Childers, 11 December 1868, ADM 116/167.

[28] Froude to Childers, 11 December 1868, ADM 116/167.

Constructors Department to Froude: 'if they [the constructors] do not establish the position of this type of ship in the eyes of the general public, and of their own unscientific superiors, as a success', the mastless ship – together with the authority of naval science – would severely suffer.[29] Froude undertook model experiments, then full-scale experiments with the *Devastation* to demonstrate the ship's stability.[30] This example demonstrates that Froude controlled his site of experiment and role as consultant to the Board of Admiralty. He managed the site of experiment, and controlled access to it and how knowledge left it, in the form of reports to the Admiralty and scientific papers on the theory of ship resistance – he did not, however, have the authority to discuss specific ship data in public.

The spatial organization and values of the 'experienced community' in Froude's test tank suggest a number of issues for comparative reflection. Unlike previous proponents of model testing, Froude did not believe that research into hydrodynamics could be sustained for its own sake. The identity Froude sought for the test tank as a privileged site in the practice of shipbuilding depended on the premise that mechanical experiments could be useful for Admiralty shipbuilders. In addition to Froude's personal financial resources, his disinterest within the shipbuilding community, which included many commercial builders, also influenced Admiralty support. The literary editor James Spedding wrote to the Admiralty in support of his cousin's project:

> few have had better means than myself of knowing how perfectly disinterested a man he is – what an immense amount of patience, pain and ingenuity he will spend upon the thorough investigation of one of these problems, and how entirely he is moved therein by scientific curiosity, and the love of a perfect machine (ally [like] a ship), and a sense of the immorality of wasted force and unnecessary friction.[31]

Froude's identity as a disinterested experimenter, loosely associated (especially spatially) with the Admiralty, offers insight on the type of connection between science and shipbuilding built into the first test tank. To demonstrate these local specificities and their peculiarities to Froude's work in Torquay, it is necessary to compare them to other sites and contexts where the tank was replicated. The first site of comparison, the Leven shipyard of William Denny & Brothers, reveals significant shared values which may explain why Froude's test tank appealed to a Presbyterian family's shipbuilding firm – and how the test tank was re-placed into the Glasgow shipbuilding industry.

A shipbuilder's tank

The shipbuilding community received Froude's work for the Admiralty with a great deal of ambivalence. There was no immediate replication of the test tank by commercial shipbuilders. Those shipbuilders interested in Froude's work took the optimistic view that the Admiralty would make available the data Froude produced so that they could, if

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[29] Henry Marc Brunel to Froude, 14 July 1873, Henry Marc Brunel papers, Bristol University, Special Collections, Letter Book 14.

[30] [Lords of the Admiralty], *Design of Ships of War: Copy of the Instructions Given by the Admiralty to the Committee on Designs for Ships of War*, London: HMSO, 1871, p. xi.

[31] James Spedding to Childers, 2 April 1869, ADM 116/167.

they wished, use it in their designs. The shipbuilding community did not envisage that the Admiralty might guard against making specific test tank data available to the nation.[32] The only nineteenth-century commercial shipbuilder to build a tank of their own was the Clyde-based William Denny & Brothers (1884). The next British commercial test tank was not built until 1903.[33] To appreciate why the Dennys replicated Froude's test tank technology and made it part of their engineering practice, it is necessary to first assess the company's connections with Froude, its cultural values and its sympathies toward the use of scientific practices in shipbuilding.

Established in 1844, William Denny & Brothers of Dumbarton formed part of a lively and competitive community of shipbuilders and marine engineers on the Clyde.[34] William Denny (1847–1887), grandson of the William Denny who formed the company, led the firm through the 1870s and 1880s. Denny was an extraordinarily energetic and socially conscious shipbuilder, noted for 'a marvellously productive mind' and 'manly self-reliance'.[35] He advocated applying what he described broadly as 'science': a 'progressive' attitude toward the conscious and moral use of mental faculties, in everyday work.[36] Denny was a Calvinist and worked in the same religious and engineering community where William Thomson assembled his notions of energy dissipation in physics and engineering.[37]

Denny's reforming work in the shipyard focused on the '*application of science and of experimental investigations* to the construction and propulsion of ships' and the 'mechanical progress' of the shipbuilding process (Denny financially rewarded employees with prize money for mechanisms and suggestions that refined shipbuilding practices in the yard).[38] The most significant example of this work was Denny's practice of 'progressive trials' on the measured mile. Traditionally, engineers calculated the relationship

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[32] The project to establish a test tank at the National Physical Laboratory (1911) was pursued after the Admiralty's repeated refusal to INA shipbuilders. The NPL did not wish to finance a tank for the shipbuilding industry, and so it was only established after Alfred Yarrow agreed to pay for the tank in full. [J.H. Biles], 'Introductory proceedings', *Transactions of the Institution of Naval Architects* (1902) 44, p. xl; 'The opening of the National Experimental Tank at the National Physical Laboratory', *Nature* (13 July 1911) 87, pp. 57–58.

[33] Sidney Pollard and Paul Robertson, *The British Shipbuilding Industry, 1870–1914*, Cambridge, MA: Harvard University Press, 1979, pp. 133–134.

[34] For Victorian shipbuilding on the Clyde see Crosbie Smith and Anne Scott, '"Trust in providence": building confidence into the Cunard line of steamers', *Technology and Culture* (2007) 48, pp. 471–496. For the Dennys see William Denny & Brothers, *Denny, Dumbarton, 1844–1950*, Edinburgh: McLagan & Cumming, 1950.

[35] John Ward, 'Memoir of the late William Denny, F.R.S.E., President of the Institution', *Transactions of the Institution of Engineers and Shipbuilders in Scotland* (1887) 30, pp. 257–258.

[36] A.B. Bruce, *The Life of William Denny. Shipbuilder, Dumbarton*, London: Hodder & Stoughton, 1889, pp. 40–42, 59–70.

[37] Bruce, op. cit. (36), p. 70; Crosbie Smith and M. Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin*, Cambridge: Cambridge University Press, 1989, pp. 24, 730.

[38] Italics in the original. William H. White, [a memoir of William Denny], May 1888, quoted in Bruce, op. cit. (36), p. 227; Ward, op. cit. (35), pp. 269–270; William Denny to Froude, 17 February 1873, in Bruce, op. cit. (36), p. 141. Dennys were not alone in seeking to apply science to the shipbuilding industry, but the majority of other Clyde-based shipbuilders tended to focus on the thermodynamics of steam engines rather than on the hydrodynamics of hull shapes. See Ben Marsden and Crosbie Smith, *Engineering Empires: A Cultural History of Technology in Nineteenth-Century Britain*, Basingstoke: Palgrave Macmillan, 2005, pp. 107–128.

between engine power and speed from a single run at high speed on a measured mile. They used this result and the 'Admiralty formula' (that engine horsepower varied as the cube of ship speed) to establish the relationship at different intervals. Denny remained unconvinced that a single run provided enough data to ascertain the power–speed relationship. In 1870, he instituted 'progressive trials' in which his ships were tested on the measured mile at various levels of horsepower to ascertain the relationship with speed (but not yet hull form, which Froude was investigating). Denny empirically demonstrated that the 'Admiralty formula' was inaccurate, and significantly produced a curve of power and speed for his ships.

Denny's curve of power and speed interested Froude. Both shared the view that Rankine, who had offered an alternative general formula of ship resistance, was 'very unintelligible to practical men', and that his 'overmathematical and algebraic' solution to the problems of ship resistance was an undesirable basis for establishing a science of ship design.[39] In public, Denny praised Froude's work:

> We are . . . only [now] entering upon the investigation of speeds, and are very far from the theorising stage. Mr Froude has clearly expressed this opinion; and I regard him, in the discovery of the relations existing between the speeds and resistances of larger and smaller models and of models and steamers, as having added the only solid bit of science worthy of the name to the subject for many years. And we are very fortunate in having such a man as Mr Froude to lead the scientific and purely experimental side of speed investigation. Unpossessed of crotchets, unbiased by theories, unfaltering in his desire for plain and simple truth, ready to take up and investigate every suggestion.[40]

In private, Denny told Froude, 'Without compliment and with only truth I can say you have made my views on design.'[41] These public and private statements demonstrate that Denny shared Froude's perspective on the function of rigorous testing in shipbuilding.

In 1875, Denny supplied Froude with data from his progressive trials on the steamship *Merkara*. Denny and Froude set out to reproduce the trials with models. Because this endeavour technically constituted commercial work, Froude needed Admiralty permission before sharing his findings first with Denny, and then with the INA in 1876 and 1877.[42] Granted permission, this research demonstrated that the relationship between effective and indicated horsepower in steamships could be calculated from model experiments. Froude publicly praised his collaborator:

> it is to Mr Denny's honour that, finding the so-called constants were invariably variable and inconsistent, he determined of himself to strike out a new line and find out by trial what is fact, instead of contenting himself with assuming what ought to be, the relation between indicated horse-power and speed.[43]

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[39] Denny to Froude, 17 February 1873, in Bruce, op. cit. (36), p. 141.

[40] William Denny, 'The difficulties of speed calculations', *Transactions of the Institution of Engineers and Shipbuilders in Scotland* (1875) 18, quoted in Bruce, op. cit. (36), p. 144.

[41] Denny to Froude, 14 August 1878, quoted in Bruce, op. cit. (36), p. 196.

[42] William Froude, 'On the ratio of indicated to effective horse-power as elucidated by Mr Denny's M.M. trials at varied speeds', *Transactions of the Institution of Naval Architects* (1876) 17, pp. 167–181; William Froude, 'On experiments upon the effect produced on the wave-making resistance of ships by length of parallel middle body', *Transactions of the Institution of Naval Architects* (1877) 18, pp. 77–97.

[43] Froude, 'Indicated to effective horse-power', quoted in Bruce, op. cit. (36), pp. 149–150.

As early as 1873, Denny expressed interest in the mechanical procedures of model testing. '[T]he very description of your experiments', Denny wrote, 'makes me desirous to see your method of carrying them out'.[44] Denny intended to replicate the test tank. In the early 1880s, the Dennys purchased the land surrounding their Leven works and expanded their shipbuilding yard. Denny convinced his father Peter Denny, then company director, to construct a test tank as part of the expansion. Convinced that model testing provided a firm basis for experimentally deriving the ratio of effective to indicated horsepower and the most efficient hull shape for attaining certain speeds, Denny approached Edmund Froude to help replicate the test tank.

Froude shared with Denny the diagrams and schematics for the tank; instruments to automatically measure speed, force and resistance; and samples of the ruled paper that Froude designed for use with the instruments.[45] Correspondence between the Leven shipyard and Froude's test tank reveals numerous visits of technicians who exchanged specifications and verbal explanations regarding the design and operations of the tank.[46] Froude also facilitated the appointment of Frank Purvis, one of his assistants in the Torquay tank, to Leven. Purvis effectively brought the Denny tank into operation. He also used his connection with Froude to help Denny secure the employment of two other technicians from the Torquay tank, Mumford and Parker, who took charge of the tank's day-to-day operation.[47]

Upon cursory analysis, there are many similarities in how Denny and Froude approached the application of science and rigorous tests to engineering problems. Working within different experienced communities, Froude and Denny shared a common interest in utilizing scientific investigations to uncover the abstract and inaccurate guidelines offered by hydrodynamic theory. Significant distinctions become apparent, however, regarding how test tank experiments would be made part of the experienced community's practices. Denny strongly dismissed a proposal to build a public tank for shipbuilders on the Clyde:

> for over and above the elements of jealousy and distrust which would be pretty sure to enter into its use, there is the difficulty that unless each individual can command, not only the special item of information he requires, but practically the resultant of all the information obtained in the tank, the single item of information is of very little use to him. In this respect an experimental tank entirely differs from a chain-testing house . . .[48]

Froude operated his test tank, at a distance from the Admiralty, to examine long-standing problems in hydrodynamics and to provide Admiralty naval architects with a site of experiment upon request. Denny, in contrast, believed that the test tank could function as a link between experiment and industry only if it was directly connected to those who designed and built ships. Thus Denny placed his tank between the drawing

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[44] Denny to Froude, 17 February 1873, quoted in Bruce, op. cit. (36), p. 141.

[45] Frank Purvis to R.E. Froude, 8 June 1881, quoted in an appendix in P.A. Watts, 'The inception of the Denny Tank', MA thesis, University of Strathclyde, p. 82.

[46] This correspondence is presented in Watts, op. cit. (45). The location of the originals is unclear.

[47] Denny to R.E. Froude, 26 January 1884, quoted in Watts, op. cit. (45), p. 95.

[48] Quoted in Bruce, op. cit. (36), p. 203.

office and the stocks. When Cecil Peabody made his study of European test tanks for the Society of Naval Architects and Marine Engineers, a Denny employee 'expressed the opinion to the writer that every important yard would do well to have its own tank, and said that even with their large amount of accumulated information they kept the tank busy and would give work to another tank if they had it.'[49]

Materially, the Denny tank almost entirely replicated the first tank, differing only in its length. The peculiarities between how Froude and Denny used their tanks must be explained through the renegotiated meaning of test tank experiments assembled in Leven. Denny described the tank as part of an integrated engineering project:

> In the drawing-office we are gradually embracing the whole bulk of our subject, and from detailed and exact analysis we are gradually rising to the power of a wide and rapid synthesis. At least, this is our general goal; and it comes in sight. A quick and all-round approximation of any new proposal is the only platform from which a professional man can safely start; and it, again, can only be the outcome of years of laborious investigation, and observation, and experiment. The bulk of our brother-ship-builders, and I suspect pretty nearly all your men, don't yet understand the meaning of this. They will not likely ever accept it on reasonable grounds, but only through the teaching of their commercial books. These are their gospels, and they certainly hold their faith with more fervour than we should hold better belief.[50]

This spatial arrangement and integration of the test tank with other shipyard operations reflected Denny's mentality that science was not to serve industry so much as industry ought to become scientific – a distinct contrast to the type of relationship between experiment and shipbuilding that Froude established with the Admiralty's dockyards.

Ostensibly, on some level, the test tank meant something similar to Froude and Denny. It offered a mechanical means to determine experimentally connections between power, speed and resistance that were previously unconfirmed. Certain practices, like the application of science to shipbuilding, existed at both sites, albeit differently construed. Froude believed that scientific enquiry through mechanical experiment was the strongest way to objectively produce knowledge of ship resistance. While Denny agreed, he envisioned the application of science in terms of improving how his workforce operated. Denny understood the role of experiment and the benefits of the test tank through the localized context of industrial improvement and efficiency in a competitive shipbuilding community. Thus the process of model testing did not differ, but the context in which it found form and meaning had been replaced through the process of replication – reflecting the dynamic between experiment and industry that existed in Dennys' shipyard.

Dennys' building of the test tank distinguished their attitude to experimental practices from that of their Clyde competitors. It also helped shape their identity as 'the most scientific firm of shipbuilders and engineers in the country' – praise from William J. Pirrie, chairman of Harland & Wolff, during the firm's experiments with Edmund Froude on the hull of Charles Parsons's experimental turbine ship *Turbinia*.[51] Dennys actively sought this connection with the test tank and the work of William Froude,

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[49] Peabody, op. cit. (1), p. 47.

[50] Bruce, op. cit. (36), p. 205.

[51] Discussion following Charles Parsons, 'The application of the compound steam turbine to the purpose of marine propulsion', *Transactions of the Institution of Naval Architects* (1897) 38, pp. 232–242, esp. 307.

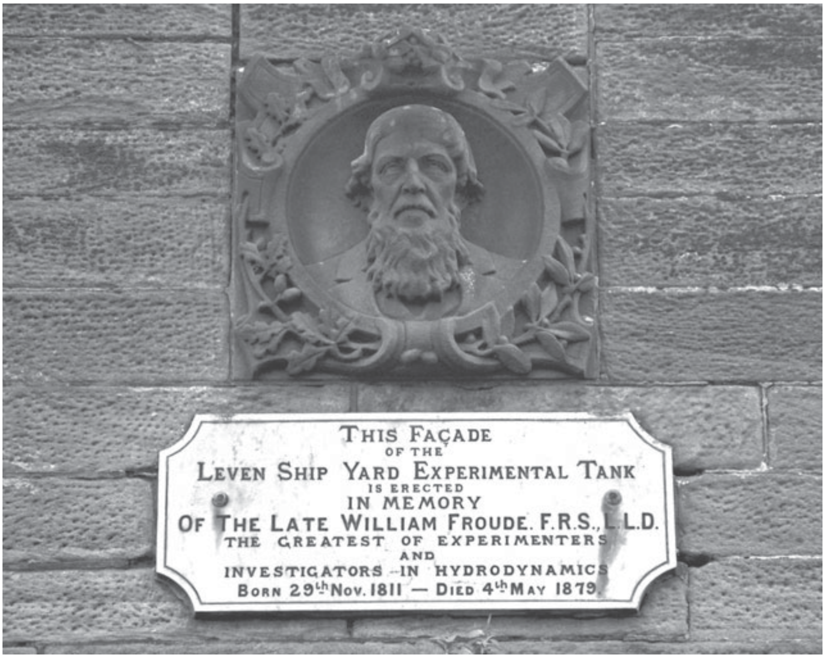

Figure 1. Façade erected outside the Denny test tank, Dumbarton, to honour William Froude (photo courtesy of Jim Bavin).

deriving credibility from the connection. Thus transforming the meaning of the test tank on one level did not negate forming strong bonds between test tank sites. Visual evidence of this appeared with the literal inscription of William Froude's legacy onto the Leven shipyard (Figure 1). In 1882 Denny asked Edmund Froude's permission to place the following dedication on the outside of the test tank building: 'This façade of the Leven Ship Yard Experimental Tank is erected in memory of William Froude F.R.S., L.L.D. the greatest of Experimenters and Investigators in Hydrodynamics'. Denny also requested a large photograph of Froude be hung inside the tank building.[52]

A professor's tank

Another dynamic between experiment and industry is evident in my third case study, a university tank. When Cecil Peabody visited the Denny tank on his European tour he was struck by how many of the technicians supported building an 'open' tank 'not hampered by government secrecy or trade jealousy, at which scientific problems could be investigated'.[53] The open tank arrangement interested academic scientists and engineers who worked on hydrodynamics. The first university to express interest in the test tank was Glasgow, where Philip Jenkins, the second holder of the Elder Chair in Naval

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[52] William Denny to R.E. Froude, 17 July 1882, quoted in an appendix in Watts, op. cit. (45), p. 86.
[53] Peabody, op. cit. (1), p. 47.

Architecture (established in 1883), advocated that academic research in an ‘open tank’ was ‘in the interest of the shipbuilders on the Clyde’.[54] From the late 1880s, Jenkins and his assistants, John Biles and Herbert Sadler, expressed their interest in model experiments, but to no end.

Geographically and socially less connected with either Froude's or Denny's tanks, the first university test tank was built at the University of Michigan, Ann Arbor. The Michigan tank formed part of the engineering department and programme. The engineering faculty at Michigan dates to 1852, making it one of the oldest in the United States. Engineering was not a large department at Ann Arbor, a campus dominated by its classical scholars. The engineering programme grew at Michigan during the 1880s as the university took advantage of an 1879 Congressional initiative to incentivize the teaching of marine engineering and naval science. Before then, American naval architects, including David Taylor, who operated a government test tank in Washington, DC, received training at either the Royal School of Naval Architecture in Greenwich or at Glasgow.[55] The 1879 legislation relocated talented engineers working in the US Navy's engine rooms, draught offices and dockyards to the country's leading universities. In 1881, Mortimer Cooley (Figure 2), who had trained in engineering at the Naval College at Annapolis, Maryland, and advanced through the engineering ranks of the Navy, arrived in Ann Arbor on special detachment.[56] Four years later, he retired his commission and was appointed professor of mechanical engineering.

Cooley played a key role in establishing the Michigan engineering programme. By 1903 and after, over seven hundred students entered the programme each year. To accommodate the growing number of engineering students Cooley campaigned for the construction of a new engineering building fitted with mechanical and electrical laboratories, including a test tank. Cooley was familiar with Froude's work with the test tank. He asked his naval colleagues to suggest texts on hydrodynamics prior to teaching. W. Webster from the United States Bureau of Steam Engineering explained, ‘In “[W.H.] White's Manual of Naval Architecture” 1877, you will find *all of Froude's ideas and papers* very ably and fully set forth and clearly discussed. Evidently the book you *want* and *need*.’[57] By reading Froude's papers Cooley began to understand a test tank's operation in theory but not its functional practice. He had no means to appreciate the significance of Froude's test tank as instrumental in the design of Admiralty warships.

Cooley's correspondence at this time shows no sign of interaction with either Froude, the Dennys or Taylor in Washington. This presents an interesting comparison to Denny's process of replication where technicians were imported from Torquay and the

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[54] Ward, op. cit. (35), pp. 276–277.

[55] In 1896 the British Admiralty excluded international students from attending the Royal School of Naval Architecture, extending the need for American programmes to teach naval architecture. William M. McBride, ‘The “greatest patron of science”? The Navy–academic alliance and U. S. naval research, 1896–1923’, *Journal of Military History* (1992) 56, pp. 7–34, 14–15.

[56] Mortimer E. Cooley (with the assistance of Vivien B. Keatley), *Scientific Blacksmith*, Ann Arbor: Arno Press, 1972 (first published 1947), p. 43.

[57] W. Webster to Cooley, 15 August 1881, Mortimer E. Cooley Papers, Bentley Historical Library, University of Michigan (subsequently CP), Box 1, original emphasis.

Figure 2. Mortimer Cooley, Professor of Mechanical Engineering at the University of Michigan. Mortimer E. Cooley Papers, Bentley Historical Library, University of Michigan, Box 66.

Figure 3. The test tank in the new engineering building at the University of Michigan. Cooley Papers, Bentley Historical Library, University of Michigan, Box 66.

local context in which the test tank found operational form and meaning was replaced as the tank was re-placed into the Leven shipyard's experienced community. The Michigan tank, in contrast, negotiated replication through a limited set of instructions and descriptions. Construction of the Michigan tank was orchestrated by Cooley, but led by the Glasgow-born and -educated professor of naval architecture and marine engineering Herbert Sadler, who joined the engineering faculty in 1900. Sadler undertook the final design and direction of the tank (Figure 3), consulting Edmund Froude to resolve technical problems, and thus serving as a trading zone between Michigan, Glasgow and Haslar.[58]

The Michigan test tank, which Cooley referred to as 'a professors' swimming tank, in which ship models may be tested', was initially three hundred feet in length.[59] The Michigan tank used the same measuring and plotting instruments that Froude designed in the 1870s, which consisted of pens attached to dynamometers and regulating clocks that automatically made marks on lined paper fed from a drum that indicated the speed

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[58] Herbert C. Sadler, 'The experimental tank at the University of Michigan', *Transactions of the Society of Naval Architects and Marine Engineers* (1906) 14, pp. 51–63, 62.

[59] Cooley to Charles C. Cook, 28 January 1902, CP, Box 10.

and resistance of the model. The Michigan tank also used wax paraffin models, following Froude's practice rather than Taylor's practice in the Washington tank that, for climate reasons, used wood.

Michigan's geographical distance from Britain, together with the lack of correspondence between Michigan and other test tank sites, suggests that the prime movers in this replication were at Michigan. What cultural values and practices did Cooley share with actors in other sites of naval science? Cooley's engineering syllabus displays a connection with the North British network of engineers and physicists.[60] Cooley taught steam engineering with the use of Rankine's textbook on thermodynamics, which he used at Annapolis. Rankine's books were widely recognized in America as the leading texts for teaching thermodynamics and mechanics to college students – although not easily readable. 'If I had my way about it I would "shoot" Rankine altogether', Cooley's former naval colleague Asa W. Matten complained. His books were 'in too condensed and vague a form for the average student'.[61] Cooley nevertheless showed great deference to the authority of North British energy physics and Glasgow engineering. Cooley wrote to DeVolson Wood, professor of engineering at the Stevens Institute of Technology, regarding the first two laws of thermodynamics, 'that my mother was an old fashioned Methodist and my wife a good Baptist, and that I took the two laws on faith'.[62]

Cooley also developed links with professional engineers in a style similar to Rankine and William Thomson in Glasgow. He did this by relating the engineering department's work 'as closely as possible to local needs' and offering the services of the engineering department to test equipment and standardize engineering practices.[63] Cooley believed that engineers ultimately worked outside laboratories: 'students learn exacting research methods in the laboratory, but they do not learn much else'. It was vital, Cooley believed, that his colleagues stay attuned to engineering practices: 'an engineering teacher should practice his profession for much the same reason that a surgeon needs to continue to operate, not simply to lecture on how to operate'.[64] The engineering context in which Cooley operated resembles the model of engineering science assembled by Rankine and others in Glasgow.[65] These similarities may help explain why the local conditions at Michigan made it possible to re-place the test tank there.

The similarities between Cooley's engineering science and Glasgow engineering science also help explain Herbert Sadler's appointment in 1900 to the newly created chair in naval architecture and marine engineering. With the help of the US Navy, Cooley searched for a candidate with the suitable academic rigour, engineering experience and attitude toward the preparation of graduates for careers in local industry. Unable to find such a candidate in America, Cooley was impressed by the praise given to

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[60] For the North British network see Crosbie Smith, *The Science of Energy: A Cultural History of Energy Physics in Victorian Britain*, Chicago: Chicago University Press, 1998.

[61] Asa W. Matten to Cooley, 24 August 1881, CP, Box 1.

[62] Cooley, op. cit. (56), pp. 89–90.

[63] Cooley, op. cit. (56), pp. 109–10.

[64] Cooley, op. cit. (56), p. 118.

[65] Ben Marsden, 'Engineering science in Glasgow: economy, efficiency and measurement as prime movers in the differentiation of an academic discipline', *BJHS* (1992) 25, pp. 319–346.

the staff at Glasgow University. Jenkins since retired the Elder Chair in Naval Architecture, succeeded by John Biles. Holden A. Evans of the US Naval Yard, Norfolk, Virginia informed Cooley that Biles's assistant, Sadler, 'has had considerable experience for a young man in yard work, has had the technical education necessary, and in addition, has had actual experience of teaching at the University of Glasgow'.[66] In 1900, the University of Michigan appointed Sadler professor of naval architecture and marine engineering.

Sadler was eager to include 'practical shipbuilding' in his lectures, which he thought would be 'of great interest and value to the students' and aid Cooley in establishing firm links with shipbuilders and marine engineers. Sadler informed Cooley that in Glasgow the practical branch of shipbuilding topics was not associated with university teaching, but with technical-school education.[67] Sadler's attitude to practical education was evidently compatible with Cooley's, who believed, 'Experienced professional engineers contribute a knowledge of the method of translating engineering theory into actual practice'. Cooley 'wanted excellent professional men to head departments', and Sadler seemed to offer this in union with his experimental skills.[68] Sadler also offered Cooley a deep understanding of British naval architecture and testing practices, evidenced by the following lecture synopsis he sent in 1900:

> Early theories: wave making, eddy making and surface friction: stream line theory: Froude's experiments: model experiments: laws of comparison of ship and model: effect of form and length upon resistance: progressive trial trips and data obtained therefrom: Ratio of E[ffective]. H[orse]. P[ower]. to I[ndicated]. H[orse]. P[ower]. Coefficients of performance: Application of results of trial trips for determining the I.H.P. for a new vessel.[69]

Sadler evidently had a good grasp of the theoretical elements of hydrodynamics, experience of working in a community with industrial engineers and, most importantly, familiarity with Froude's model experiments and Denny's progressive ship trials on the ratios of effective and indicated horsepower.

Similarities between Michigan and Glasgow engineering science were clearly present, but based on deeper local peculiarities. These contrasts point to a process of renegotiating the meaning of the tank and re-placing it into a distinctly different local context – mirroring the process which took place in Denny's Leven shipyard. For example, Cooley was committed to a harmonious relationship between science and engineering practices, which appears to mirror Denny's view that scientific ways of working made his workforce efficient and led to advantages in industrial competition. Cooley's conception of this dynamics, however, was shaped and practised through his role as an educator and his background as a naval engineer.

Cooley asserted, 'Such institutions as the University of Michigan … are substantially auxiliary military training schools, and contribute in no small degree to the military

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[66] Holden A. Evans to Cooley, 9 June 1900, CP, Box 8.

[67] Sadler to Cooley, 10 July 1900, CP, Box 8.

[68] Cooley, op. cit. (56), p. 118.

[69] Sadler to Cooley, 10 July 1900, CP, Box 8.

strength of the country.'[70] He suggested that while experiments undertaken in Taylor's tank in Washington had to be kept secret (just as they did in Froude's tank), 'the results of tests conducted here would of course be available, and in time the ship-building industry of the country should profit thereby'.[71] The Michigan test tank was significant to the work of the engineering department in training engineers to take a role in local industries and contribute to national industrial and economic strength.

The tank held a prominent place in the new engineering building which served as the entrance to the south-east quarter (engineering quarter) of the campus. This was not, however, spatially intentional. Although the design of the engineering building accommodated a test tank, the space was not made for it. Sadler's 1906 paper to the Society of Naval Architects and Marine Engineers described how the final design of the tank took shape out of the architecture of the first-floor hydraulic laboratory that required a length of over three hundred feet and a reservoir. The internal space of the engineering building was, in fact, resistant to the replication of the test tank, meaning that the design had to fit to the space:

> It was part of the new Engineering Building, and as I pointed out to the Board of Regents, we have practically the tank already completed when we had the foundation wall on the one side and the heavy wall on the other for carrying the roof; it simply meant a little more excavation and we should have an experimental tank. We got the tank in that way, and had to conform to the general design of the building, rather than to the experimental tank alone.[72]

The peculiar circumstances in which the building of the Michigan tank took place reveal another local source of agency that disrupted the replication of the test tank. In the case of the engineering building's architecture, the test tank was literally embedded into another, greater, enterprise.

Given the test tank's location on the ground floor, where it spanned an entire wing, it would be evident to anyone entering the building. Because the new engineering building also served as the entrance to the engineering campus, with an archway in the building, anyone entering the campus from the south-east would pass through the space. The final architecture of the engineering building reflected Cooley's desire that experiments and laboratories be placed at the centre of the university engineer's training for industrial work. The building, when constructed, was the largest and one of the 'finest' on the campus.[73] Cooley's interpretation of the tank and the building was echoed by Charles Denison, professor of stereotomy, who wrote that it resembled the 'largely enhanced and newer conception of the engineer's position', and would be instrumental in teaching scientific practices and practical skills in preparation for the engineer's social and economic function.[74]

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[70] Mortimer Cooley, 'The New Engineering Buildings, University of Michigan', *Journal of the American Society of Naval Engineers* (1903) 15, pp. 908–918, 918.

[71] Cooley, op. cit. (70), p. 913.

[72] Sadler, op. cit. (58), pp. 51, 56.

[73] Cooley, 'New Engineering Buildings', pp. 911–912.

[74] Charles Denison, 'The new engineering building for the University of Michigan', 1902, CP, Box 48.

Conclusion: replication or re-placing the local

This study treated three distinct yet connected sites of naval science through a comparative framework in order to shed light on how replication took place in the late nineteenth-century science–industry nexus. It explored the individuality of the tank at each site by examining the meaning of test tank experiments imposed by experienced communities and their spatial organization of the tank. This analysis thus demonstrated the diverse range of issues and processes through which social groups forged a relationship between science and shipbuilding at the end of the nineteenth century, including, but not limited to, the criticism of algebraic theories of ship resistance, the economic use of coal, the development of a scientific workforce, prosperity in a competitive industry, the strengthening of the national economy and the preparation of engineers for their future roles in society. The comparative mode provided a means to establish that a distinctly localized relationship between the experimenter – a gentleman of science, a shipbuilder or a university professor – the test tank and the context of its use existed at each site of naval science.

Comparative analysis focused on the local construction of knowledge and objects provides a corrective to the assumption of difference that pervades scholarship in the history of science and technology. Comparing the conditions, values, practices, spaces, institutions and attitudes in play at different sites of replication emphasizes what was peculiar or singular to specific sites of science. The comparative model can also reveal similarities, the presence of more general attitudes, nurtured across distance by social networks of scientists and engineers. This comparative methodology is important to developing new approaches to replication, and contesting the problem against which our understanding of replication has been developed: how is local knowledge made universal without losing its authority? This question did not seem to concern the actors discussed in this article. Neither Denny nor Cooley expressed anxieties regarding whether the test tank was an authoritative way to understand hydrodynamics, or if it would be functional when re-created in a new location. The transatlantic community of naval architects and marine engineers placed their trust in Froude's test tank prior to replication. This emergence of a decentralized network of experimenters, engineers and sites of authority is not without parallels in late nineteenth-century science and engineering. Graeme Gooday has contested the 'universalization of quantitative knowledge' in laboratory history with an account of the continuing localized 'measurement practices' and 'bonds of "trust" between practitioners' that persisted in electrical engineering.[75] In both studies, authority and agency are not centralized, but decentralized. The implication for replication is that the original site of experiment has a limited function in shaping the replicated site.

Studies of replication, from Collins's TEA laser to Shapin and Schaffer's air pump, recognize that instruments and written instructions – the 'algorithmic recipe for proper replication of an experiment' – are not enough to replicate experimental practices with

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[75] Graeme J.N. Gooday, *The Morals of Measurement: Accuracy, Irony, and Trust in Late Victorian Electrical Practice*, Cambridge: Cambridge University Press, 2004, pp. 16–23.

success.[76] The analysis here does not contest this: the bodily transportation of tacit knowledge was important in making the Denny and Michigan tanks operational. The issue that has arisen from this case study is that the actors who replicated the test tank had their own reasons for replication that were embedded in their specific working contexts – the significance of which not only brings a centralized model of replication into question, but suggests that a broader perspective needs to be taken on what is and is not being replicated.

Similarities in local attitudes, common social networks and cultural connections influence replication. Denny's close relationship with and advocacy of Froude's work, for instance, proved vital to the creation of the Leven test tank. Similarly, the harmonious relationship between science and engineering practices advocated by Cooley in Michigan resembled the engineering science of Rankine and Thomson, key interlocutors for Froude and Denny. This commonality became essential for the successful replication of the test tank over an expansive geography. Comparative analysis also reveals that commonalities between social groups may be rooted in very different local peculiarities. The relationship between science and engineering practices embodied in the Michigan tank, for example, also represented the university's particular function as an auxiliary military training school, the engineering department's continued growth as a support to local industry and the training of engineers for work outside the laboratory. Thus Cooley replicated (re-placed) the test tank from Britain to America, but the particular attributes of Michigan and its communal values and concerns locally pre-dated the test tank's entrance to the university and influenced its reception.

The successful replication of the test tank did not solely depend on the tank's being delocalized (Galison) or on duplication of the context in which it took meaning (Schaffer). The comparative analysis of sites where test tank replication took place reveals the pre-existence of key cultural commonalities that influenced and potentially enabled replication, but also distinct peculiarities and differences that were fundamental to how replicated test tanks took on new meanings. Identifying and following these commonalities and peculiarities through a comparative analysis demonstrates the test tank's interpretative flexibility. It shows that while the material components of the test tank were re-placed into new sites, those actors who desired its replication for their ongoing work replaced its meaning. To that end, this article has traced the substantial yet underexamined role of actors at the site of replication. These actors determine how replication takes place, hold agency to interpret and give meaning to experiments and, most importantly, integrate them with pre-existing scientific and institutional practices. The decision to replicate the test tank belonged to Denny and Cooley, not Froude. Although Denny and Cooley began without the tacit knowledge necessary to accomplish the replication, they integrated the test tank into their work and actively interpreted the tank through their cultural values (thereby replacing the identity Froude gave it originally). Through this human interpretative process, the tank's identity transformed from one determined by a gentleman, a shipbuilder, a professor; all, of course, residents of a particular local community.

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[76] Collins, op. cit. (7), p. 143.