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Keeping It In Trim: Ballast and Great Lakes Shipping

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On the morning of July 24, 1915, hundreds of employees of the Western Electric Company and their families boarded the passenger steamship *Eastland* for a day trip to Michigan City, Indiana. Built in 1903, this twin screw, steel hulled steamship was considered a fast boat on her regular run. Yet throughout her service life, her design revealed a series of problems with stability. Additionally, changes such as more lifeboats in the aftermath of the *Titanic* disaster, repositioning of engines, and alterations to her upper cabins, made these built-in issues far worse. These failings would come to a disastrous head at the dock on the Chicago River. With over 2,500 passengers aboard, the ship heeled back and forth as the chief engineer struggled to control the ship's stability and failed. At 7:30 a.m., the *Eastland* heeled to port, coming to rest on the river bottom, trapping passengers inside the hull and throwing many more into the river. By the time rescue operations were completed, 844 passengers and crew had died in the worst human loss in the history of the Great Lakes.[1]

The aftermath of the *Eastland*'s capsizing revealed a host of errors and misjudgments throughout the life of the ship. Testimony at the trial of the ship's engineer, Joseph Erickson, the only person convicted after the disaster, described the extent of the poor stability and flaws in the ballast system. The trial also revealed the limited nature of regulatory agencies, the limits of professional designers, and the surprising lack of action to address known flaws in the *Eastland*'s stability and ballast system.[2]

Ballast is of particular interest on the Great Lakes since many ports are on shallow rivers with obstructions requiring vessels to adjust their depth

[1] "Capt. Pederson Doesn't Know Tragedy Cause," *Chicago Tribune*, July 25, 1915; "'Who Are You?' Thousands Ask at Huge Morgue as Kindred of Missing Seek Victims of Tragedy," *Chicago Tribune*, July 26, 1915; "Death Every Cicero Block," *Chicago Tribune*, July 26, 1915; Jay Bonansinga, *The Sinking of the Eastland: America's Forgotten Tragedy* (New York: Citadel Press, 2004), 68–82; George W. Hilton, *Eastland: Legacy of the Titanic* (Stanford: Stanford University Press, 1995), 95–112.

[2] *Investigation of Accident to the Steamer* Eastland*: Chicago, Ill., July 24 to August 5, 1915: Copy of Testimony and Report of Board of Inquiry Made to the Secretary of Commerce with Letters from the Secretary of Commerce to the President and to the Speaker of the House of Representatives, in relation thereto: also, Copy of Preliminary Report of the Committee of Supervising Inspectors of the Steamboat-Inspection Service, with letter from the Secretary of Commerce, in relation thereto* (Washington: Government Printing Office, 1916), testimony of Joseph Erickson, 1110–1115; Bonansinga, 218–224; Hilton, 181–182.

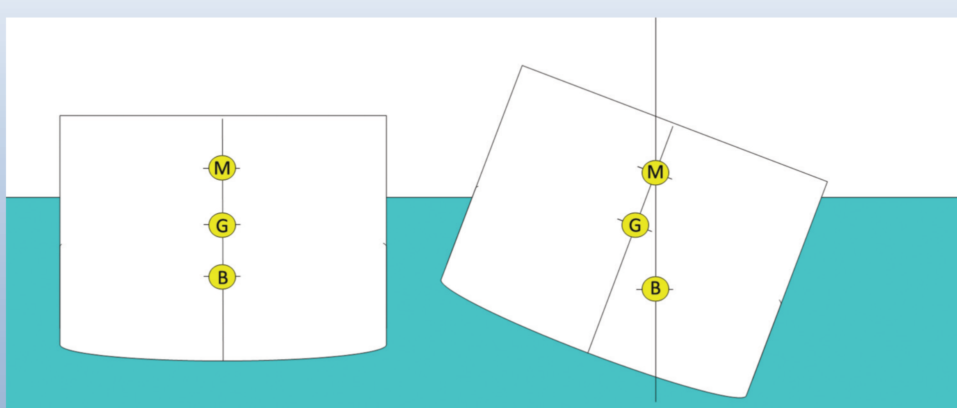
in the water by discharging ballast. Furthermore, ships utilize ballast, solid or liquid, to provide stability to a vessel's movement in the water and its response to wind and wave action on the hull. *Eastland*'s design took into account and incorporated the need for a ballast system due to its intended homeport from the start. That a supposedly modern, professionally designed ship would come to such an end while in port is in part what makes the tragedy so compelling. *Eastland*'s loss highlighted some of the problems associated with new methods, advancements in ship design, and failures to consider ballast and stability when making updates in ship structure. Though a story of heroism, tragedy, and poor judgment, the disaster is also one that shows the vital role that ballast plays in the operation of ships, both on the ocean and the Great Lakes. Far from being an unavoidable accident, the *Eastland* demonstrates the range of decisions that need to be made correctly to keep a ship "in good trim."

Ballast systems have undergone many changes in all types of navigation until the present day. In ancient times, as soon as ships venturing out on the sea or large lakes and rivers could be constructed, the need for ballast to provide stability has been recognized. From solid materials in the earliest ships to modern water-based systems, ballast serves as an integral part of vessel design and operation. Technical developments in these designs emerged in response to new commercial or environmental demands, advances in science, and the availability of new materials and energy sources. Though the earliest shipbuilders were professionals in a sense, these artisan-builders worked within a world of the "rule of thumb," where knowledge of hydrodynamics and stability were incompletely known; designs were based on some professional knowledge, intuition, trial and error; and risks were viewed as intrinsic to vessel operation. However, the design of ballast systems eventually came to be based on science-based understanding of the physics of ship stability and engineering principles, professionally taught at schools for naval architects and marine engineers. Though not as acutely dramatic as a ship rolling over, environmental disasters that resulted from the transport of organisms on solid ballast and in ballast water have highlighted the newest demand in the design of ballast systems: reducing the number of organisms associated with ballast when ballast is discarded or discharged to adjust for cargo or water depth. Reflecting these different technical demands and capabilities, we identify three successive but overlapping eras of ballast design: "rule of thumb," professionalism, and preventing the transport of invasive organisms. This article, and the associated exhibit first displayed in 2017 at the National Museum of the Great Lakes, traces the development of ballast systems through these three eras, culminating with current developments in the prevention of invasive species from entering the Great Lakes via ballast.

Ballast: What It is and Where It Comes From

Every ship requires some form of ballast to aid in the stability of its movements through a body of water. This additional weight within the hull provides for the ability to adjust the depth of the bow and stern (trim) and the amount of list from side to side (heel) of a ship. A design must possess the ability to stand straight on calm water without the need for additional weight at the bottom of the hull as a simple matter of fact. A design that capsizes or heels significantly is a grave design flaw even before the addition of ballast. The use of materials to increase weight within the hull allows for the correction of minor faults to stability, to enhance stability with or without cargo, and to improve seakeeping qualities during a variety of conditions.[3]

The type and design of a ship helps to dictate the placement and type of ballast used. For sailing ships, ballast adjusts stability, but also provides additional weight to help counteract the amount of heel by a ship when underway. Typically solid materials provided both permanent and adjustable ballast to address different cargos being carried. Steamships, particularly with the advent of iron and steel hulls, relied upon water for ballast with the amount managed by a series of pumps and tanks located throughout the hull. For all ships, ballast helps a design address the core issue of its initial static stability and buoyancy, known as a vessel's metacentric height.



This drawing demonstrates the relative positions of the center of gravity (G), center of buoyancy (B), and metacenter (M) with the ship upright and the heeled over.
This drawing is based upon work by George William Herbert

[3] S.R. Bross, *Shipping Nomenclature* (New York: ALCOA Steamship Company, Inc., 1952), 15.

The metacentric height is a calculation of three specific points within a hull: the center of gravity (G), the center of buoyancy below it, and then the metacenter (M) at a point above the waterline and G. When a hull heels to one side, the metacenter (M) remains above the center of buoyancy (B) depending on the degree of list. The metacentric height of a vessel (GM) measures the stability of a vessel against overturning. A higher metacentric height means that a vessel has a shorter period of roll that while safer, tends to be uncomfortable to passengers and crew despite its safety. A lower metacentric height produces a longer period of roll that while providing greater comfort is slower to return and if not carefully managed can cause a vessel to overturn under certain conditions. Modern ship designs attempt to balance between stability and comfort by adjusting a ship's center of gravity to raise and lower metacentric height as circumstances dictate. To do so requires a sophisticated ballast system of pipes, ballast tanks throughout the hull, and pumps to draw or expel water. One of the most challenging pieces of ship design, past and present, is the calculation and management of ballast to maintain proper stability within the complexity of fluid dynamics.[4]

From the earliest sailing vessels, ballast has been applied to enhance stability. The mathematical principles that explain the action of fluids on hulls remained unknown until Archimedes in his 250 B.C. treatise *On Floating Bodies* put forward his principle that, "Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object." The ability to calculate an object's buoyancy allowed for the ability to conceptualize larger and more sophisticated ship designs. Both the Greeks and Romans applied this knowledge to their own vessels, giving them an unparalleled reach throughout the ancient Mediterranean world and even into northern Europe and Africa. Two types of artifacts, the archaeological record of sunken ships and the piles of ballast left in ports, are evidence of their journeys.[5]

[4] Capt. Philip Brown, R.N., "Remarks on the Stowage of Ballast," in *Papers on Naval Architecture and Other Subjects Connected to Naval Science, Vol. III*, William Morgan and Augustin Crueze, eds., (London: Whittaker, Treacher, and Arnot, 1831), 423–425; Edward L. Attwood, *Theoretical Naval Architecture* (New York: Longmans, Green and Co., [1899] revised 1922), 90–105; A. Francescutto and A.D. Panaikolaou, "Buoyancy, stability, and subdivision: from Archimedes to SOLAS 2009 and the way ahead," in *Proceedings of the Institution of Mechanical Engineers — Journal of Engineering for the Maritime Environment*, 225 (February 2011), 19–22.

[5] Jonathan Adams and Johan Rönnby, eds., *Interpreting Shipwrecks: Maritime Archaeological Approaches* (Southampton: Highfield Press, 2013); E. Galili, V. Sussman, G. Stiebel, and B. Rosen, "A Hellenistic/Early Roman Shipwreck Assemblage off Ashkelon, Israel," *The International Journal of Nautical Archaeology* 39 (No.1, March 2010), 125–130; Federico Foerster Laures, "Roman Maritime Trades," *The International Journal of Nautical Archaeology* 15 (No.2, 1986), 166–167.

ERA 1, ANTIQUITY–1800S: SOLVING FOR STABILITY

Solid materials, the principal method of ballasting ships from antiquity until the nineteenth century, provided permanent and temporary weight as needed for maintaining stability. Cargo served as the main form of temporary ballast. Though it required careful loading and bracing, or positioning in the form of passengers, the distribution and weight of cargo would alter a vessel's sailing characteristics for each trip. If additional weight were needed when carrying a light cargo or no cargo at all, ships utilized a variety of materials to enhance their stability. Rocks, iron, gravel, sand, building debris, and other loose items, sometimes designed for easy handling, were loaded into a hull and removed as required.[6] Harbors possessed a ballast master who determined where this unneeded ballast could be dumped where it would not interfere with docks and channels. In some cases, the ballast was repurposed, increasing its utility as a source of revenue for shipmasters and as building materials for ports.[7] The archaeological record documented by discarded or repurposed solid ballast provides a window into the operation of ancient ships, the routes of mariners, and the mate-

Stone anchors from the Uluburun Shipwreck at the Bodrum Museum of Underwater Archaeology in Turkey. **Carrie Sowden photo**

[6] Lionel Casson, *Ships and Seamanship in The Ancient World* (Baltimore: The Johns Hopkins University Press, [1971] 1995), 173–175; Justin Leidwanger, "Two Late Roman Wrecks from Southern Cyprus," *The International Journal of Nautical Archaeology* 36 (No.2, September 2007), 308–316.

[7] Casson, 361–369; F. Peter Rose, "A Flint Ballast Station in New Rochelle, New York," *American Antiquity* 33 (No.2, April 1968), 240–243.

rial culture of ancient societies. The historical dates of these sites also helps to pinpoint the rise and decline of ports throughout the era when only limited written record remains.[8]

Well into the eighteenth and nineteenth centuries, ships continued to rely on solid ballast. Among the most recent and valuable of these dumping sites concerns the slave ports along the African coast. To counteract the fluctuating weight of slaves held within their hulls, captains relied upon iron bars for ballast. The amount of ballast found in shipwrecks helps to give a more precise sense of both the size of the ship and amounts of cargo, and to track both vessel origins and destinations. Vessel manifests also list the type of ballast used, giving clues for shipwrecks, ports, and dumping patterns. Iron ballast also could be traded and reused as a commodity to obtain additional slaves and cargo. Thus, ballast is a vital clue about both how vessels operated as a technological system and also its role within a cultural framework of exploration and exploitation.[9] The movement of Europeans to North America, enhanced navigational techniques including the calculation of longitude, and increased military conflicts, all significantly influenced innovation in ship design.[10]

The effort to push the limits of military ships demonstrated the limits of both vessel design and the ability to ensure these new ships were not actually dangerous. The *Mary Rose*, pride of the English fleet after its completion in 1512, underwent a significant overhaul during 1536, substantially changing her original plan. While under sail to intercept a French invasion force on July 19, 1545, the *Mary Rose* heeled sharply, took on water through her open gun ports and quickly sank, taking down most of her crew. While a definitive explanation for its loss remains elusive, historians generally agree that alterations to the ship during its refit left it susceptible to a greater amount of instability than its original design. The lack of

[8] John Peter Oleson, "The Technology of Roman Harbours," *The International Journal of Nautical Archaeology* 17 (No. 2, 1988), 147–157; Baruch Rosen and Ehud Galili, "Lead Use on Roman Ships and its Environmental Effects," *The International Journal of Nautical Archaeology* 36 (No. 2, September 2007), 300–307; Gregory F. Votruba, "Imported Building Materials of Sebastos Harbour, Israel," *The International Journal of Nautical Archaeology* 36 (No.2, September 2007), 325–335.

[9] Helene Cooper, "Grim History Traced in Sunken Ship Found Off South Africa," *New York Times*, May 31, 2015; Chapurukha M. Kusimba, "Archaeology of Slavery in East Africa," *The African Archaeological Review* 21 (No.2, June 2004), 59–88; David D. Moore and Corey Malcom, "Seventeenth-Century Vehicle of the Middle Passage: Archaeological and Historical Investigations on the 'Henrietta Marie' Shipwreck Site," *International Journal of Historical Archaeology* 12 (No.1, March 2008), 20–38; Nigel Sadler, "The 'Trouvadore' Project: The Search for a Slave Ship and its Cultural Importance," *International Journal of Historical Archaeology* 12 (No. 1, March 2008), 53–70; Jane Webster, "Slave Ships and Maritime Archaeology: An Overview," *International Journal of Historical Archaeology* 12 (No.1, March 2008), 6–19.

[10] James Peake, *Rudiments of Naval Architecture: or, an Exposition of the Elementary Principles of the Science and their Practical Application to Naval Construction* (London: J. Weale, 1849), 50–56.

understanding about its buoyancy, additional weight to the upper part of the ship, and *the lack of sufficient attention to ballast* [italics added for emphasis] resulted in a disaster.[11] Even more dramatic is the loss of the Swedish warship *Vasa* on August 10, 1628, on its maiden voyage. Though able to maintain its stability while at dock, placing the vessel under sail resulted in a catastrophic heel to port and an inability to return from the roll. Inquests at the time demonstrated that while no one would accept responsibility for the sinking of a brand new ship, many involved with *Vasa*'s construction were aware of its significant problems, yet took no action.[12] Though the *Mary Rose* and the *Vasa* illustrate two of the most serious losses, other lesser known ship sinkings were likely due to similar combinations of negligence and lack of specific technical knowledge.

Vessels on the Great Lakes, 1700–1880

Wooden sailing ships with solid ballast played a vital role on the Great Lakes from the start of European exploration. *Le Griffon*, the elusive Holy Grail of shipwrecks, established the utility and necessity of vessels larger than canoes on the vast expanses of the Lakes. Even though canoes continued to be a vital part of cargo movement between trading posts and military garrisons, sailing ships moved heavy cargo, transported supplies, and — when armed — ensured compliance with colonial authority.[13] The opening of the Erie Canal (1825) and Welland Canal (1829), along with the locks bypassing the rapids between Lakes Superior and Huron at Sault Ste. Marie (1798, for canoes and small boats, destroyed in the War of 1812, and rebuilt for ships in 1855) provided the impetus for a sailing ship more suited to the Great Lakes.[14]

Though economics served as a powerful driver for the evolution of ship design on the Great Lakes, navigational considerations were another im-

[11] *Narrative of the Loss of the* Mary Rose, *at Spithead, July 20, 1545*, (Surrey, England: Genesis Publications, 1983); Julie Gardiner and Michael Allen, eds., *Before the Mast: Life and Death on the* Mary Rose (Portsmouth: The *Mary Rose* Trust, 2005); Douglas McElvogue, *Tudor Warship* Mary Rose (Annapolis: Naval Institute Press, 2015), 56–71; Peter Marsden, *Sealed in Time: The Loss and Recovery of the* Mary Rose (Portsmouth: The *Mary Rose* Trust, 2003), 15–25.

[12] George S. Bass, "History Beneath the Sea," *Archaeology* 51 (No.6, November/December 1998), 48–53; Marika Hedin [Roger Tanner translator], Vasa: *The Story of a Swedish Warship* (Stockholm: The Vasa Museum, 2011), 12–24; Lucas Laursen, "*Vasa's* Curious Imbalance," *Archaeology* 65 (No.4, July/August 2012), 42–45.

[13] James Oliver Curwood, *The Great Lakes: The Vessels That Plough Them: Their Owners, Their Sailors, and Their Cargos* (New York: G.P. Putnam, 1909), 84, 111; James Cooke Mills, *Our Inland Seas: Their Shipping & Commerce for Three Centuries* (Chicago: A.C. McClurg & Co., 1910), 36–37, 43–45, 50–62; Hanumant Singh, Jonathan Adams, David Mindell, and Brendan Foley, "Imaging Underwater for Archaeology," *Journal of Field Archaeology* 27 (No.3, Autumn 2000), 319–328; Mark L. Thompson, *Graveyard of the Lakes* (Detroit: Wayne State University Press, 2000), 14–15, 315.

[14] Jeff Alexander, *Pandora's Locks: The Opening of the Great Lakes-St. Lawrence Seaway* (East Lansing: Michigan State University Press, 2009), 2–6.

portant consideration. Most ports on the Great Lakes are found at the mouths of rivers or their estuaries. Unlike the great ports of New York or Boston, most lake ports, particularly along the west coasts of Michigan and Ontario, experience a series of challenges. Where the river meets the lake, sandbars and other navigational hazards meant that deep-draft sailing ships ran the risk of running aground in these ever changing conditions. Often the rivers were narrow and relatively shallow, making it difficult for sailing ships to maneuver without the aid of a tug or lightering to lift a grounded ship off an obstruction. Accordingly, ships that reflected local conditions began to emerge from shipyards along the Lakes.

Drawing on a bluff-bowed, two-masted design with simple fore-and-aft rigging, and a shallow, rounded bottom, shipbuilders produced a vessel capable of moving through the obstacle course of Great Lakes harbors by the 1850s. The simple rigging permitted a sufficient speed yet also reduced the number of crewmen needed to handle the sails. At the same time, the flat bottom allowed for the creation of a stable hull and sharp ends meant ship-handling characteristics that reduced the need for assistance in constricted waterways. Like their counterparts on the high seas, these Great Lakes schooners relied on solid ballast, generally rock, stone, or similarly heavy materials easily off-loaded to make room for cargo in port or taken on to aid with stability.[15] Nearly every port had a dumping pile somewhere in the harbor and like those along the ocean, solid ballast dumps could be a valuable source of archaeological data.

Great Lakes schooners featured an innovative component to aid with stability. Ocean going vessels offset the force against their sails by ballast and hull design. The flat bottoms required for the Great Lakes significantly reduced that resistance and though offering a highly stable platform, it offered a heightened chance of capsizing while under sail. Pioneered during the American Revolution, yards on the Lakes introduced a retractable keel called a centerboard to this new schooner design. Housed in a watertight box along the keel of the boat, the centerboard could be extended in open waters for greater stability and then retracted as needed to cross a sandbar or other obstruction while entering a port. Though it took up valuable cargo space, the centerboard meant that schooners could strike a balance between harbor conditions, ballast, and stability.[16] Among the most famous

[15] Richard Henry Dana, Jr., *The Seaman's Friend: A Treatise on Practical Seamanship* (Mineola, NY: Dover Publications, Inc., [1879] 1997), 138–146. Dana discusses the duties of the chief mate responsible for the stowage of cargo and ballast, including freshening, or moving ballast in the hull.

[16] Theodore Karamanski, *Schooner Passage: Sailing Ships and the Lake Michigan Frontier* (Detroit: Wayne State University Press, 2000), 34–37.

of these schooners, the *Rouse Simmons* also had the distinction of having two centerboards for stability. Built in 1868, she spent most of her career operating in the lumber trade on Lake Michigan before sinking in December 1913 with a load of trees for the Chicago holiday market, forever marking her as "the Christmas Tree Ship."

While shipyards on the Lakes followed the professional skilled trade of the ocean, not every ship was constructed in a formal yard. An equal number of sailing vessels were constructed by men familiar with the design and construction of ships who would often then command them. This tradition of builder-owner-operator followed the tradition of "rule-of-thumb" construction and led to an additional innovation in the standard schooner design. The so-called "scow schooners" had far more blunted bows, even shallower draft, and very little aesthetic consideration compared to the finer lines of their contemporaries. Built to maximize cargo capacity for the minimum cost, scow schooners of 100 tons displacement were ubiquitous on the Great Lakes. Well into the 1880s, boats on the Great Lakes serviced a largely undeveloped area, requiring vessels to carry a broad range of cargos, rather than service a specialized cargo such as lumber, grain, or iron ore. This diversity also meant that a great many sailing ships belonged to small fleets, partnerships, or the captains who sailed them.[17]

END OF THE WOODEN SAILING SHIP AND SOLID BALLAST ERA

The final significant innovations in solid ballast systems occurred with the advent of clipper ships in the mid-nineteenth century. Built around long, lean wooden hulls, clipper ships running from North America and the British Isles to ports in China and Australia demanded a more sophisticated understanding of both hydrodynamics and the way ships respond to different conditions. Clipper ships were known for their record-breaking fast voyages across long ocean distances and had solid ballast systems designed for fast changes to facilitate this speed. For example, the *War Hawk*, built in 1855, had a deliberate arrangement of ballast stones of particular sizes for the hold of a given ship.[18]

[17] Karamanski, 37–42; Jay C. Martin, "The Grand Haven Rig: A Great Lakes Phenomenon," *American Neptune* 51 (No. 3, June 1991), 195–201.

[18] Glenn A. Knoblock, *The American Clipper Ship, 1845–1920: A Comprehensive History, with a Listing of Builders and Their Ships* (Jefferson, NC: McFarland, 2014), 52.

At almost the same time as the clipper ships achieved the pinnacle of sailing ship design, ships also began to be built with iron and steel hulls, and steam engines instead of sails began to be used for propulsion. Iron and steel construction permitted spaces within the hull to hold water as ballast, a far more flexible material than solid ballast that had to be moved, stowed, and adjusted by manual labor. The collier *John Bowes*, built in 1852 in the UK, was one of the earliest such ships and operated successfully for over 80 years.[19] *Persia*, the earliest steam-powered iron passenger liner, broke all previous speed records on her maiden trans-Atlantic voyage in 1856. The 1859-built *Great Eastern* caused a sensation when it went into service on the Atlantic. It had a double hull, screw propeller propulsion (albeit, with auxiliary paddle wheels and sails), steam-driven pumps, and exclusive use of water as ballast, but was so far ahead of its time that technical issues plagued its operation. Nevertheless, the design of the *Great Eastern* featured a host of innovations destined to become standard practice in metal vessel construction, including the double-bottom hull for water ballast to adjust the heel and trim of the giant vessel. Such ships could adjust their ballast water at different points of their voyages using mechanical pumps powered by steam instead of the crew's physical labor at a fixed point.

On the Great Lakes, one of the earliest iron commercial ships with steam power and a water ballast system was the *Onoko*, built in 1882. Like the famous *Great Eastern* iron steamship of the Atlantic Ocean, the early *Onoko* retained sails "just in case;" however, later refitting of the *Onoko* omitted the sails. The *Onoko* ran aground and sank in Lake Superior in 1915.[20]

Era 2, 1800s–1900s: Engineering Steel Ships for Water Ballast Systems

The ability to produce iron in large quantities offered shipbuilders the opportunity to utilize a newer and more durable material for vessel hulls. At the same time, metal hulls demanded a new level of technical skill from

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[19] "North of England," *The Engineer* (89, 2 March 1900), 239. http://www.gracesguide.co.uk/images/1/16/Er19000302.pdf. Retrieved 26 April 2013; Joe F. Clarke, *Building Ships on the North East Coast.* (Whitley Bay: Bewick Press, 1997), 120–121, 134–5; Fred M. Walker, *Ships and Shipbuilders: Pioneers of Design and Construction.*(Barnsley, UK: Seaforth Publishing, 2010): 118–120, 239. Regarding the *John Bowes*, the author notes the need to solve ballast problems with special tanks.

[20] *Onoko*: Minnesota Historical Society. Lake Superior Shipwrecks. *Onoko.* http://www.mnhs.org/places/nationalregister/shipwrecks/onoko/onoko.php. Accessed on August 24, 2016. The first iron-hulled vessel on the Great Lakes was the paddle frigate *U.S.S. Michigan* launched on December 5, 1843. For a full discussion of that vessel see Bradley A. Rodgers, *Guardian of the Great Lakes: The U.S. Paddle Frigate* Michigan (Ann Arbor: University of Michigan Press, 1996), 22–24.

The *Onoko*, one of the earliest (1882) iron hull, steam-powered, water-ballasted ships on the Great Lakes. Collection of Great Lakes Historical Society — National Museum of the Great Lakes

builders and far greater cost in construction. While the huge size of the *Great Eastern* showed the great capacity of iron ships and the benefits of double-hull construction, the technical issues that plagued its operation indicated a need to analyze and improve ship design on a less ad hoc basis. Fortunately, with the advent of iron and steel ships, naval architecture and the movement of ships in water furthered scientific study and mathematical models to produce new designs.[21]

Iron and later steel offered a host of advantages over wood construction. Navy powers came to realize the inherent advantages to a hull armored in iron and steel plates. The experience of the American Civil War and its clash of "ironclads" demonstrated those advantages along with the shortcomings of new technology. An additional factor came from the use of

[21] George S. Emmerson, *The Greatest Iron Ship: S.S. Great Eastern* (North Pomfret, Vermont: David & Charles, 1980), 5–27; Edward J. Reed, *Shipbuilding in Iron and Steel: A Practical Treatise* (London: Murray, 1869); James Reynolds, *Reynolds's View, Section, Plan, and Description of the* Great Eastern *Steam Ship: Building at Millwall for the Eastern Steam Navigation Company* (London: J. Reynolds, 1856).

propellers instead of sidewheels for propulsion. The powerful engine required to turn the driveshaft created enormous stresses on the hull and the vibrations along the equipment frequently damaged wooden hulls. The greater rigidity of iron and steel-plated hulls allowed for a greater overall length and depth without the sagging (bow and stern higher than the midsection) or hogging (midsection higher than the bow or stern) that came with wooden ships beyond a certain length.[22] Finally, particularly in Europe, the decline in the availability of inexpensive sources of wood for shipbuilding meant that metal-hulled vessels gained a significant cost advantage unlike on the Great Lakes where wood was still plentiful.[23]

Legislation supporting the increased awareness of stability and overloading issues led to the 1870s introduction of the Plimsoll line, named for its British proponent and member of Parliament (MP), Samuel Plimsoll. The Plimsoll system is a set of lines that designate the maximum loading for each type of ship, based on its stability characteristics, and depending on ship's dimensions, type of cargo, season, and the water densities encountered in port and at sea.[24] This type of specific calculation demonstrated the expansion of knowledge regarding vessel stability since the start of the nineteenth century and, while imperfect, meant that owners and builders faced stiff challenges to adopt new methods and to defend them when disasters due to overloading or inadequate ballast occurred, as in the case of the *Eastland*.

Throughout the late nineteenth and early twentieth centuries, builders increasingly drew on a body of standardized engineering principles. Like their counterparts in civil and mechanical engineering, this helped to address the complex issues posed by larger and more powerful ships. In the United States, programs in naval architecture and marine engineering at institutions such as Cornell University (1892), the University of Michigan (1899), and the Massachusetts Institute of Technology (1901) began to train a new generation of practitioners. Additionally, the formation of

[22] James Dickie, "Overhead Cranes, Staging, and Riveter-Carrying Appliances in the Shipyard," *Transactions: The Society of Naval Architects and Marine Engineers* 7 (1899), 190–192.

[23] Washington I. Babcock, "System of Work in a Great Lake Shipyard," *Transactions: The Society of Naval Architects and Marine Engineers* 7 (1899), 173–188; John F. Nichols, "The Development of Marine Engineering," in *Historical Transactions, 1893–1943* (New York: The Society of Naval Architects and Marine Engineers, 1945), 425–427; Thomas R. Heinrich, *Ships for the Seven Seas: Philadelphia Shipbuilding in the Age of Industrial Capitalism* (Baltimore: Johns Hopkins University Press, 1997), 20–30.

[24] Samuel Plimsoll, *Our Seamen. An Appeal* (London, Virtue & Co., 1873), 79–88; David Masters, "Mr. Samuel Plimsoll...his mark," *The Compass: A Magazine of the Sea* (June 1972), 16–20; Richard Jimenez, "The Evolution of the Load Line," *Surveyor* (May 1976), 7–13. National Ocean Service, "What is a Plimsoll line?" accessed at http://oceanservice.noaa.gov/facts/plimsoll-line.html.

professional societies such as the American Society of Naval Engineers in 1888 and the Society of Naval Architects and Marine Engineers (SNAME) in 1893, brought together academics and professionals in the field to exchange ideas and consider the changes to their profession. Their ideas received broader readership through publications such as the *Transactions* of the SNAME and other technical periodicals that gave specialists and practitioners alike access to new ideas. These efforts contributed to the rapid decline of the owner-builder-operator model, particularly on the Great Lakes. This came not only from the increasingly complex construction of the vessels, but also the far greater cost and skill required for constructing metal-hulled vessels.[25]

Ballasting and stability systems became more complex to address the demands of these new designs. With water now the preferred ballast, a series of tanks at the bow, stern, and on both sides of the hull gave the crew an unparalleled ability to adjust the heel and trim of a vessel. To move ballast within these tanks required a complex system of piping, valves, intake manifolds, and electric and steam-powered pumps. Though incredibly complex, the methods to judge precise measurements often consisted of a simple plumb line. Despite the critical importance for steel ships of measuring metacentric height and other components of vessel stability, vessels often relied on one-time calculations or incomplete tests to gauge their stability.[26] In the United States, the Steamboat Inspection Service was charged in the late nineteenth century to examine and approve steam boilers after a series of explosions and other mishaps. However, even this attempt at regulation left a variety of gaps, still relying on vessel owners to ensure the safety and integrity of their designs under the concept that sinking ships benefitted no one.

The *Eastland* disaster in 1915 stimulated awareness of the importance of ballast systems for ship stability. Though technically inspected and found acceptable, neither inspectors nor, most critically, her owners took into account the vast number of alterations to her original design and demanded increasingly careful management of her ballast. That system followed a poor design that took water in only on one side to her ballast tanks

[25] *Laws Governing Marine Inspection, 1890–1916* (Washington: U.S. Government Printing Office, 1938); Frederick G. Fasssett, *The Shipbuilding Business in the United States of America* (New York: Society of Naval Architects and Marine Engineers, 1948), 2–35; Ralph D. Williams, *The Honorable Peter White: A Biographical Sketch of the Lake Superior Iron Country* (Cleveland; The Penton Press, 1907), 155–160; Heinrich, 85.

[26] Albert E. Seaton, *A Manual of Marine Engineering: Comprising the Designing, Construction, and Working of Marine Machinery, 14th ed.* (London: C. Griffin & Co., 1899), 342–349; David Arnott, "Rules and Regulation for Freeboard," *Transactions: The Society of Naval Architects and Marine Engineers,* 28 (1920), 121–151; Matej David, "Vessels and Ballast Water," in *Global Maritime Transport and Ballast Water Management,* Matej David and Stephen Gollasch, eds. (New York: Springer, 2015), 15–19.

The *Eastland* on her side shortly after she heeled over in July 1915.

and utilized the same manifold to discharge it on the opposite site, limiting the speed with which changes could be made. The lack of baffles, or obstructions to limit water sloshing back and forth within partially empty ballast tanks, also critically impacted stability. Akin to running with a large pan of water, called the "free-surface effect," the free movement of water from port to starboard and vice-versa amplified the difficulties *Eastland* experienced with stability from her initial construction. This dependency on ballast in a primarily passenger and general freight vessel should have indicated that stability issues must be addressed, but they were not.

Changes during the next dozen years, including reworked cabins that added tons of weight, additional lifeboats in response to regulations mandating boats for all following the *Titanic*'s sinking, and a concrete-covered deck in her kitchens for convenience, significantly compromised her stability. The inquests after the disaster read as an echo to the *Vasa* nearly three centuries earlier as *Eastland*'s problems were laid bare with the sheer amount of knowledge about them and the decisions not to address them. While owners preferred to not have regulations placed upon them, their actions demonstrated a jarring inability to make independent decisions to insure the safety of both vessel and passengers.[27]

[27] Testimony in *Investigation of Accident to the Steamer "Eastland,"* 182–184, 735–746, 1111–1112; Hilton, 191–194; Joel Stone, *Floating Palaces of the Great Lakes: A History of Passenger Steamships on the Inland Seas* (Ann Arbor: University of Michigan, 2015), 213–214.

In addition to the need for better designs and management to avoid disasters like the *Eastland*, the demands of the rapidly growing Great Lakes bulk freight business required new designs and larger ships to be economically viable. Dense bulk cargos such as iron ore, limestone, and coal had become mainstays of the Great Lakes bulk fleet and the wooden ships hauling these cargos began to prove inadequate by the 1890s. As with their ocean counterparts, builders began to utilize iron and steel in their construction. Among the earliest highly engineered steel ships were the whalebacks built by Captain Alexander McDougall. A distinct departure from more conventional steel ships that took their basic design cues from earlier wooden ships, whalebacks followed the rounded bottom, straight-sided concept and altered it with a rounded deck. This semi-conical hull required careful ballasting and meant that unlike its contemporaries, whalebacks had ballast systems integrated into their hulls from the start to go with their double-bottoms. With their uncluttered main decks and steel construction, they helped pave the way for the full conversion of the bulk freight fleet to steel by the early 1900s despite the ready access to lumber across the region.[28]

The increasing length and depth of bulk freighters also pushed a new set of changes to the Great Lakes. Though the second ship locks at Sault Ste. Marie, Michigan, initially opened in 1855, they proved inadequate by the 1880s and were continually lengthened and expanded to allow larger vessels to travel between the iron ranges of Lake Superior and the steel and coal ports of the lower lakes. Traditionally, ships conformed to the limitations of harbors and sandbars, but with new, highly specialized systems of cargo movement, transportation companies pushed for direct involvement of the U.S. federal government in removing obstacles. Congress usually viewed the various Rivers and Harbors Acts as a type of pork barrel project for districts, but in this case, the passage of the July 13, 1892, Act transformed the Lakes. No longer satisfied with piecemeal projects for dredging and improvements, this Act mandated the creation of a waterway with a minimal 20-foot depth linking Chicago, Buffalo, and Duluth. Concurrently, harbors and ports would also need to meet this mandate along with improved an-

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[28] Hull #112, *Charles W. Wetmore,* Hull #135 *John B. Trevor*, Hull #212, *City of Everett*, Blueprints and Miscellaneous Drawings, American Ship Building Company and Predecessors, GLMS-75, Historical Collections of the Great Lakes, Bowling Green State University; Frank E. Kirby and A.P. Rankin, "The Bulk Freighter of the Great Lakes," *The Marine Review* 41 (August 1911), 285–287; W. Bruce Bowlus, *Iron Ore Transport on the Great Lakes: The Development of a Delivery System to Feed American Industry* (Jefferson, NC: McFarland & Company, Inc., Publishers, 2010), 145–153; Richard Wright, *Freshwater Whales: A History of the American Ship Building Company and Its Predecessors* (Kent, Ohio: The Kent State University Press, 1969), 50–54.

chorages, lighthouses, and numerous other navigational aids.[29] These improvements, in turn, fueled the rapid growth of the shipbuilding industry and the creation of an integrated network for moving bulk cargos across the Lakes to ports containing specialized equipment reliant on vessels specifically designed to haul these cargos.[30] As vertical integration of the steel industry took hold through mergers and consolidations, the era of the owner-operator of vessels passed as fleets of sophisticated steel ships took on the task of this ballet of bulk freight. The maintenance of this vast system also changed from a purely local matter to one addressed by the federal government in cooperation with the shipping fleets and their powerful associations, the Dominion Marine Association (Canada) and the Lake Carriers' Association (United States), along with regulatory functions for ship design. The formation of the modern United States Coast Guard continued the limited nature of its regulatory mission in the face of opposition from the associations. It would demonstrate its limitations in the years to come.

Even today, when significant parts of steel production and shipbuilding have moved abroad, the Great Lakes is populated with several hundred bulk cargo vessels that carry coal, iron ore, limestone, grains, salt, and other bulk products from port-to-port. Vessels that traverse the Lakes from Lake Ontario to Lake Superior must meet the limitations of the Seawaymax-size of 750 feet imposed by the 800-foot long locks of the Welland Canal; however, the largest bulk cargo ships on the Great Lakes are the 1,000-foot ships that were built in the period of 1976–1981 and remain in service today. These ships, such as the *Indiana Harbor*, are able to traverse the Soo Locks between Lake Superior and Lakes Michigan/Huron. The 13 1,000-foot bulk cargo carriers carry about 70,000 tons of cargo, balanced or offset during loading or unloading with water ballast that can be pumped at volumes of up to 60,000 gallons per minute. The Great Lakes are also the destination of numerous ocean-going freighters coming from ports in coastal North America, Europe, and somewhat less frequently from Africa, South America and Asia. Constrained by the St. Lawrence Seaway Seawaymax-size and designed to withstand both ocean and lake conditions, these ships are generally limited to about 20,000 tons of cargo and pump ballast at slower rates

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[29] Laurent, 10–17; Samuel H. Williamson, "The Growth of the Great Lakes as a Major Transportation Resource, 1870–1911," *Research in Economic History* 2 (, 175–186; Wright, 4.

[30] Marie McPhedran, *Cargos on the Great Lakes* (Indianapolis: The Bobbs-Merrill Company, Inc., 1952), 121–130; Alex Roland, W. Jeffrey Bolster, Alexander Keyssar, *The Way of the Ship: America's Maritime History Reenvisioned, 1600–2000* (Hoboken, N.J.: John Wiley & Sons, 2008), 207.

The *Indiana Harbor*, a 1,000-foot bulk cargo carrier on the Great Lakes, owned by American Steamship Company. Various ballast treatment and verification systems have been tested on this ship. Photo by Ken Newhams, of Duluth Shipping News

of only about 2,500 gallons per minute.[31] Among the newest such ships is the *Federal Caribou*, built in 2016. These ships demonstrate the modern era's expertise in naval architecture and the match of proper ballast system operations to enable large freighters to traverse the Great Lakes and for ocean-going ships to enter and carry ballast water throughout the Great Lakes system.

Because of the sophisticated, highly engineered designs of ships today, and the safety regulations for those designs enforced by the U.S. Coast Guard, very few ballast-related disasters have occurred on the Great Lakes since the *Eastland* disaster. Ships have been lost in the Great Lakes, of course, but the causes since 1915 are all listed as groundings, storms, fires and collisions.[32] Unfortunately, the same cannot be said globally. As recently as 2012, greed and ballast mismanagement were responsible for the death of over 250 secondary school children in the rollover accident in South Korea of *Sewol*.[33] The *Sewol*'s original design allowed it to carry about 2,000 tons of cargo, but

[31] Noel L. Bassett, James D. Sharrow, Allister Patterson, Capt. Ivan Lantz. (2012) "Great Lakes / Ocean-Going Vessels: Issues and Concerns." Slides, dated March 2, 2012. Accessed at: http://www.greatlakes-seaway.com/en/pdf/Bassett_Sharrow_Great_Lakes_Ocean_Vessels_Issues_Concerns.pdf.

[32] Dave Swayze, (2001) The Great Lakes Shipwreck File: Total Losses of Great Lakes Ships 1679–1999. http://www.boatnerd.com/swayze/shipwreck/ and confirmed by checking internet-available records of individual wrecks when this general database lacks details.

[33] "Greed Was Biggest Culprit in Ferry Disaster". *Chosun Ilbo*. 6 May 2014. Retrieved 6 May 2014.

after an illegal modification that made the ship top-heavy, naval authorities approved a limit of 1,000 tons of cargo provided that 2,000 tons of ballast was used. On the day of the sinking, the ship was loaded with more than 2,000 tons of cargo and less than 800 tons of ballast (some sources say less than 600 tons). Certainly, mismanagement of ballast was a contributing factor in the heeling over of the *Sewol*, as the crew pumped ballast out prior to the fateful voyage in order to accommodate more cargo.

Era 3, 1900s–present: Protecting the Environment from Invasive Species

As already briefly outlined, beginning in the 1800s and continuing in the 1900s, direct water connections that could be traversed by ships between the Great Lakes and several river systems were constructed. While enhancing commerce, these systems of dredged channels, canals, locks, and other navigational aids affected the size and ballasting of ships. Also, because the intake, transport, and discharge of ballast carried with it non-native organisms and pathogens on or in both solid and liquid ballasts, these transportation paths also caused harm to Great Lakes environments and to the ships' destinations due to the transport of invasive organisms. Beginning in the 1900s, when the harm that such organisms created was first recognized, modifications and additions to ballast systems and ballast operations have become part of the engineering challenge of designing ballast systems.

The problem of ship-borne transport of invasive organisms began as soon as ships gained the ability to access the Lakes from the Atlantic and inland waters beginning in the early nineteenth century and continuing throughout the late nineteenth and early twentieth centuries. Though the St. Lawrence River serves as the drain for the Great Lakes, it is also a formidable natural barrier for ships attempting to enter from the Atlantic Ocean. Fast currents, multiple islands and channels, and numerous rapids, such as the Lachine Rapids near Montreal, prevented the easy transit of cargo ships west from Quebec City. Despite the growing demand for ocean access by interior settlers, it was not until the 1820s that efforts in Canada overcame limited funds and technical challenges to commence constructing a sophisticated network of canals and locks and other navigational aids throughout the river system. Once the St. Lawrence was fully connected navigationally to Lake Ontario, the ability to transport interior agricultural and raw materials directly to the coast made the investment very profitable.

Similarly, to overcome the barrier of Niagara Falls, which still blocked access to the upper Great Lakes, construction in Canada began in 1824 by a chartered company of the Province of Upper Canada on a series of 40 locks to lift ships up to Lake Erie. Combined with additions throughout the 1830s, the network made the Great Lakes fully connected to the Atlantic through the St. Lawrence River. The route's popularity prompted a second and third set of expansions of the locks and canals connecting Lake Erie to Lake Ontario during the 1840s and 1880s, deepening the canals and reducing the number of locks by half. Construction of the Fourth Welland Canal starting in 1913 enlarged the maximum vessel length that the locks could handle from 250 feet up to 730 feet[34]; however, until the construction of the St. Lawrence Seaway in the 1950s, full size bulk carriers were confined to the Great Lakes and were unable to travel through the St. Lawrence to the ocean.

On the American side, construction began in 1817 of a 340-mile long network of locks, canals, and aqueducts across New York State. Connecting the Hudson River at Albany to Lake Erie at Buffalo, the Erie Canal bypassed the Canadian system and provided direct access to New York City and European ports. A technological marvel, the Erie Canal trained generations of practical engineers in how to overcome natural obstacles in their path. Though aqueducts appeared revolutionary, their builders drew upon techniques the Romans had relied upon centuries earlier. However, the scale of the endeavor is what truly captured the imagination of the nation and drew international observers to examine how it had been accomplished.[35]

No other city gained more from the connections to the global market than Chicago, which leaped in population from 4,000 in 1840 to over 100,000 in 1860. Though it fronted Lake Michigan, city leaders also desired a connection through Illinois to the Mississippi River to enhance the reach of their city and opened the Illinois and Michigan Canal in 1848. The economic vitality of the link proved so strong that in 1900, the Chicago Sanitary and Ship Canal replaced its predecessor and linked to the Illinois Waterway, creating an even more sophisticated water route that allowed for larger tug and barge operations to reach Chicago. The system also permitted water diversion from Lake Michigan if needed to keep the system operating during periods of drought. The result was an impressive network stretching

[34] Hugh G.J. Aitken, *The Welland Canal Company: A Study in Canadian Enterprise* (Cambridge: Harvard University Press, 1954), 57–76; John N. Jackson, *The Welland Canals and Their Communities: Engineering, Industrial, and Urban Transformation* (Toronto: University of Toronto Press, 1997), 270–290; Roberta M. Styran and Robert R. Taylor, *This Great National Object: Building the Nineteenth-Century Welland Canals* (Montreal; Ithaca [NY]: McGill-Queen's University Press, 2012), 195–223.

[35] John Peter Oleson, *Greek and Roman Mechanical Water-Lifting Devices: The History of a Technology* (Toronto: University of Toronto Press, 1984), 65–98; Carol Sheriff, *The Artificial River: The Erie Canal and the Paradox of Progress, 1817–1862* (New York: Hill and Wang, 1996), 19–30.

throughout the interior of North America, integrating agricultural and industrial production into a rapidly expanding national and global market.[36]

Removing the natural barriers between the Great Lakes and the ocean, the Hudson River watershed, and the Mississippi watershed, also allowed for an influx of new biological immigrants and rapid dispersion of internal migrants. Indeed, possibly the first symbolic influx of such organisms came in the ceremonial "wedding of the waters" when Buffalo's Judge Samuel Wilkeson, who would later become mayor, poured water from a keg of Atlantic Ocean water that had been carried by river and canal on board the *Seneca Chief* from New York City to Lake Erie to mark the completion of the Erie Canal.[37] The growth of cities and heavy use of the waterways also turned them into conduits of disease organisms and invasive species. During the 1830s and 1840s, a series of cholera epidemics spread through the United States from population migration, but also from contaminated water. Both of the Chicago waterways were utilized as methods of removing domestic and industrial waste from the city's drinking water supply in Lake Michigan. Reversing the flow of water away from the lake meant that communities further inland experienced disease and pollution far beyond their own contribution.

The presence of both the St. Lawrence River canals and the tributaries to the Erie Canal meant that Lake Ontario would experience a great increase in the incursions of non-native species. Sea lampreys, anadromous fish able to live and spawn in fresh and salt water, likely traveled through the Erie Canal to appear in Lake Ontario during the 1830s. Similarly, the alewife entered Lake Ontario by the 1870s, possibly through the canals connecting the St. Lawrence to the Atlantic. Both species remained largely isolated from the four upper lakes by the presence of Niagara Falls and a quirk to the first two Welland Canals. Since the locks did not provide a continual flow of water from Lake Erie to Ontario, designers had used a nearby river as a booster to the water flow, meaning that ships coming upstream were not lifted by water from the lake.[38] The construction of the much larger

[36] T.Q. Ashburn, "Transportation on Inland Waterways," *Transactions: The Society of Naval Architects and Marine Engineers* 33 (1925), 67–73; Lorien Foote, "Bring the Sea to Us: The Chicago Sanitary and Ship Canal and the Industrialization of the Midwest, 1885–1929," *Journal of Illinois History* 2 (No.1, 1999), 39–56; John M. Lamb, "The Illinois and Michigan Canal and Other Illinois Inland Waterways," *Nautical Research Journal* 24 (No.2, Summer 1978), 75–80; Harold L. Platt, "Chicago, The Great Lakes, and the Origins of Federal Urban Environmental Policy," *Journal of the Gilded Age & Progressive Era* 1 (No.1, April 2002), 122–153; Ronald S. Vasile, "Cholera, Counterfeiters, and the California Gold Rush: Passenger Travel on the Illinois & Michigan Canal, 1848–1852," *Journal of Illinois History* 7 (No.2, 2004), 125–154.

[37] Historical marker in Buffalo, NY: http://www.hmdb.org/Photos3/311/Photo311805o.jpg

[38] Alexander, 25–35; Styran and Taylor, 173–181.

third and fourth canals not only gave larger vessels access to Lake Ontario, but eliminated the final barrier to the upper lakes. Sea lamprey devastated the largest Great Lakes fish species during the early twentieth century. Alewives took the place of these larger fish in the ecosystem and vastly expanded their numbers. Lacking significant predators and entering into a relatively young ecosystem meant disaster to the vibrant fisheries of the region. Efforts to control the lamprey population began in the 1930s, with the alewife receiving the same attention during the 1950s and 1960s.

The desire to increase access and to eliminate the small locks of the St. Lawrence River had long been a dream in both the United States and Canada. Multiple groups had backed plans to create a larger system to permit ships to travel continuously from Montreal to Duluth, in order to eliminate the need to transfer bulk cargos across transportation platforms thereby achieving immense potential savings in shipping costs. After World War II, a series of bilateral agreements initiated the start of construction of the new St. Lawrence Seaway in 1954. Designed in an era that prized massive engineering projects including the Interstate Highway System and the Space Race, the Seaway extended 370 miles and cost over $3 billion dollars (in 2016 dollars), most of it paid by the Canadian government. Coupled with the earlier Welland Canal, the goal of seamless transportation from ocean to the Great Lakes was fully achieved by the opening of the St. Lawrence Seaway in 1959.[39]

Despite the knowledge of the damage being wrought by sea lamprey and alewife introduction and the millions being spent to control these species by government agencies, the St. Lawrence Seaway reflected none of those concerns. For centuries, ballast-carrying ships had introduced new types of plants, insects and aquatic species throughout their routes. Water ballast had extended not only the reach of maritime commerce, but the size and scale of the vessels conducting that trade. By the 1950s, a series of aquatic species had taken hold in European ports, brought from Central Asia and African ports by water ballasted ships.[40] Though Lake Ontario had experienced the bulk of these incursions, the opening of the Seaway removed even the mildest of barriers to species capable of living both in salt and fresh water. Furthermore, ships from freshwater ports worldwide could harbor freshwater organisms in their ballast until possible discharge in the

[39] Clara Ingram Judson, *St. Lawrence Seaway* (Chicago: Follett Publishing Company, 1959), 93–103.

[40] James T. Carlton, "The Impact of Commerce and Maritime Biodiversity," *The Brown Journal of World Affair* 16 (No.2, Spring 2010), 131–142.

aquatic environments of the Great Lakes, which often provided them amenable nutrients, temperature and water chemistry but lacked their natural predators. By the 1980s, an influx of invasive species swept into the Great Lakes, most notably zebra and quagga mussels, the Eurasian ruffe, and the round goby. Instead of a slow spread throughout the Lakes, introduction took place across the region, primarily focused on the major ports. Today invasive species are a major factor within the Great Lakes and on other inland bodies of water, brought primarily by the discharge of ballast water.[41] The rate of influx of non-native organisms into the Great Lakes via ballast water has been estimated at about one to two non-native species per year between the years 1900 and 2000 and at least 65% of non-native introductions since the opening of the St. Lawrence Seaway.[42]

Preventing organisms from being introduced into new habitats worldwide presents a series of engineering challenges. Ballast water is difficult to treat for several reasons. The first factor is the large volume of water requiring treatment in each tank. Ships carry massive amounts of water, with ocean-going ships that enter the Great Lakes holding up to 3.2 million gallons of ballast water per trip. An additional issue is how to clean the muddy sludge at the bottom of ballast tanks that are divided by multiple baffles to prevent the free-surface effect of water that proved deadly to the *Eastland*.[43] In the sediment, different types of organisms can survive for transmission to a new environment. According to a Canadian government study, "ocean freighters entering the Great Lakes fully loaded with cargo carried an average of 157 metric tons of sediment."[44] The dense material protects the aquatic life because chemicals and other treatments are unable to penetrate. Moreover, sediments add weight and take space that shippers need to ship goods, and the fewer goods they can fit on their ship, the less money they make per trip. Indeed, the St. Lawrence Seaway has proven a disappointment as traffic never reached projected levels and the unanticipated simultaneous development of containerized maritime transportation eliminated the need to travel so far inland with smaller ships.

Even as regulators and shipping companies came to realize the extent to which harmful non-native organisms had been carried in ballast water into the Great Lakes via the St. Lawrence Seaway and other canals since the

[41] Alexander, 55–62, 153–165; Peter Annin, *The Great Lakes Water Wars* (Washington: Island Press, 2006).

[42] A. Ricciardi, "Patterns of invasion in the Laurentian Great Lakes in relation to changes in vector activity," *Diversity and Distributions* (12, 2006): 425–433.

[43] Hilton, 255–259.

[44] Alexander, 299.

1800s, implementing protective ballast handling methods has proven a difficult technical and commercial challenge. One way of removing and poisoning many organisms in freshwater ballast is to exchange the freshwater ballast for sea water while at sea, called "ballast water exchange." While most ships can conduct such operations, engineering aspects that need to be taken into account include over-pressurization of tanks, bending or rigidity of tank structures, and both stability and maneuverability issues when ballast tanks are less full than required or weather conditions are unfavorable.[45] Furthermore, since many invasive organisms can survive in sediments and others can adapt to changes in salinity, international, U.S. and Canadian organizations have proposed that methods of treating ballast water to virtually eliminate the discharge of all live organisms should be adopted. The International Maritime Organization (IMO) made four requirements for any potential treatment method in an attempt to find a balance in the cost-benefit analysis. Treatment systems had to be safe for crews, safe for the environment, provide reasonable affordability, and meet discharge standards not fully crafted until late in 2008.[46] Even within the Great Lakes Compact, finding a common regulatory standard was difficult, with the Michigan state legislature stepping in and banning ocean ships from discharging water into Michigan waters unless the ship was equipped with a state-approved treatment system. More recently, the IMO's Ballast Water Convention (BWC) was finally ratified by enough countries with sufficient gross tonnage on September 8, 2016, and will go into force one year later.[47] This treaty mandates ballast water management systems, including exchange and treatment, to reduce the number of viable organisms discharged when ballast is released.

Treatment systems vary in terms of effectiveness, cost, ease of implementation, and regulatory requirements. Five major methods have received the bulk of attention. The first involves the use of a biocide, chlorine bleach most commonly, in the ballast tanks and then the use of small pumps to circulate it through the various spaces of the ballast system. The biocide is then neutralized and emptied into open waters where it disperses. A second system has seawater pumped into the ballast tanks and heated using the

[45] American Bureau of Shipping, "Ballast Water Exchange." (Houston: American Bureau of Shipping, 2010), 84. accessed at https://www.eagle.org/eagleExternalPortalWEB/ShowProperty/BEA%20Repository/Rules&Guides/Current/171_BallastWaterExch/Guide.

[46] Alexander, 137–151.

[47] International Maritime Organization, "International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM)," http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Control-and-Management-of-Ships'-Ballast-Water-and-Sediments-(BWM).aspx Accessed September 22, 2016.

freshwater that cools the engines. The heated water then kills organisms in the ballast water regardless of the inaccessible components of the hull. Filtration of the ballast water as it is both taken in and expelled comprises a third solution. Organisms are prevented from entering the ballast system and in some systems are then strained again upon the emptying of the tanks. An addition to this system is the use of UV light to kill any organisms that enter the ballast system despite the filtration system, or in place of the filtration system. A final treatment system has ships flush their ballast tanks while at sea, neutralizing aquatic species that live in low-saline environments, and removing others through the discharge and exchange of water at sea.[48] Altogether, over 50 treatment systems were approved or in development as recently as 2014.[49] Several of the most recently built ocean-going ships on the Great Lakes have been constructed with ballast water treatment systems included in the design, like the *Trinityborg* built in 2013, with a Hyde GUARDIAN UV and filtration system, and Fednav Limited's *Federal Caribou* built in 2016, which features a chlorine and filtration-based treatment system representative of the environmental protection era of ballast water technology.[50]

The IMO-BWC regulations limit the number organisms allowed for discharge in several size classes. For example, fewer than ten live organism per mL can be released for organisms with minimal cross-sectional dimensions of 10–50 µm.[51] Direct verification that a treatment system is actually achieving these targeted reductions in live organisms is a time-consuming, labor intensive process that must be performed quickly on freshly collected samples and requires the focused and simultaneous work of expert microscopists. Therefore, a part of the technology development in this area has

[48] National Research Council, *Stemming the Tide: Controlling Introductions of Nonindigenous Species by Ships' Ballast Water* (Washington, D.C.: National Academy Press, 1996); Kyle H. Landis-Marinello, "Noontime Dumping: Why States Have Broad Discretion to Regulate Onboard Treatments of Ballast Water," *Michigan Law Review* 106 (No.1, October 2007), 135–168; A. Whitman Miller, Mark S. Minton, and Gregory M. Ruiz, "Geographic Limitations and Regional Differences in Ships' Ballast Water Management to Reduce Marine Invasions in the Contiguous United States," *BioScience* 61 (No.11, November 2011), 880–887; Joaquin J. Blanco and Adrian T. Fernandes, eds., *Invasive Species: Threats, Ecological Impact, and Control Methods* (New York: Nova Science Publishers, 2012); Gilles Wuyts, ed., *Ballast Water and Invasive Species: Management and Treatment Efficacies* (New York: Nova Science Publishers, 2013).

[49] American Bureau of Shipping (2014) Ballast Water Treatment Advisory 2014, accessed at http://ww2.eagle.org/content/dam/eagle/publications/2014/BWTAdvisory14312rev3.pdf.

[50] *Trinityborg* design information from a personal communication from Mark Riggio of Hyde Marine, September 22, 2016; Fednav Corporation, "Fednav Welcomes New Ship Featuring Innovative Ballast System at Port of Indiana," http://www.fednav.com/en/media/fednav-welcomes-new-ship-featuring-innovative-ballast-system-port-indiana Accessed September 22, 2016.

[51] American Bureau of Shipping (2014) Ballast Water Treatment Advisory 2014, accessed at http://ww2.eagle.org/content/dam/eagle/publications/2014/BWTAdvisory14312rev3.pdf.

Federal Caribou, built by Fednav Limited, represents a new class of Great Lakes "salties" designed to include a ballast treatment system. The BallastAce treatment system by JFE Engineering is based on chlorine and filtration. Photo © Joanne N. Crack

been to develop automated systems to either verify the IMO quantitative standards or to develop a correlated or indicative measurement system, to enable warnings to be given if a correlated measurement is clearly much higher than might be associated with the standard (gross "non-compliance"). One such system is the AFIDD system being developed by the Ram Laboratory at Wayne State University. Based on the production of a fluorescent product by live organisms, AFIDD is designed to respond to yield detectable signals for virtually any type of microscopic organism and to do so automatically and with the capability of remote control of testing and analysis.[52] Another proposed method depends on the ability of DNA-binding chemicals to enter dead cells, not live ones, and then its presence or absence is detected by DNA amplification methods.[53] Other indicative detection systems have focused on detecting viable algae by analyzing chlorophyll fluorescence.[54] Several tests of these methods have been done with temporary installations of interim or approved treatment systems installed on various ships, including the *Indiana Harbor*. Among other vessels in which treat-

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[52]AC Akram AC, Noman S, Moniri-Javid R, Gizicki JP, Reed EA, Singh S &, Basu AS, Banno F, Fujimoto M, Ram JL. "Development of an Automated Ballast Water Treatment Verification System Utilizing Fluorescein Diacetate Hydrolysis as a Measure of Treatment Efficacy." *Water Research* (70, 2015): 404–413. http://dx.doi.org/10.1016/j.watres.2014.12.009.

[53] American Bureau of Shipping, "Ballast Water Exchange." (Houston: American Bureau of Shipping, 2010), 84. accessed at https://www.eagle.org/eagleExternalPortalWEB/ShowProperty/BEA%20Repository/Rules&Guides/Current/171_BallastWaterExch/Guide.

ment systems have been installed and subjected to critical verification tests is the *Ranger III*, a ship that is used to transport both cargo and passengers to and from the Isle Royale National Park.

Fortunately, the good news is that since the implementation in 2006 of Canadian regulations requiring vessels to flush their ballast, the number of new aquatic invaders has dropped significantly. Each of these systems faces technical challenges or expensive retrofitting procedures, along with the necessity of verifying their use and continued maintenance. Since the start of efforts to reduce the number of invasive species began in the 1990s, the number of new aquatic species introduced to the Lakes has been significantly reduced while the struggle to advance these efforts remains.

Conclusion

The movement of cargo around the world is more dependent on ships than at any other time in history. The transition to containers has significantly altered the transport of manufactured goods and created more efficient and secure ports at which foreign goods can enter this country. So, too, has the spread of invasive organisms and increased pollution produced by these massive ships followed in their wake. The creation of flags of convenience in countries unable to provide any regulatory structure enhances the problems brought by these vessels. Along with this, the necessities of vessel design, and especially stability, continue to challenge the global shipping industry. Much as in the past, the ability to regulate and produce ships both of sound structure and responsive to environmental conditions remains a challenge. However, the flow of information regarding invasive species in particular has started to draw a larger amount of attention both on the high seas and on the Great Lakes. The issue of invasive species no longer is an unheard of subject when considering toxic algae blooms on Lake Erie and the damage done to the sport fishing industry. The distinctive world of the Great Lakes environment remains under threat in the present day. Though fewer passenger ships ply the waters of the inland seas, our increased understanding in ship design and ballast function and the active role of the U.S. Coast Guard and Canadian and state authorities in enforcing regulations, means that passengers can voyage across the Lakes without the threat of instability nor the type of mismanagement that led to

[54] Fujimoto M, Moyerbrailean GA, S Noman S, JP Gizicki, ML Ram, PA Green, JL Ram, (2014) "Application of Ion Torrent sequencing to the assessment of the effect of alkali ballast water treatment on microbial community diversity." *PLOS ONE* (9, September 15, 2014).

death tolls like 1915 *Eastland* and the 2012 *Sewol* ballast-related disasters. Moreover, ships like the *Indiana Harbor*, *Federal Caribou*, and the *Ranger III* have been leading the way in developing and implementing new technologies that will enable ballast systems to do less harm to the environment than at present. The expansion of our understanding in ship design has made the Lakes a safer place for those who work at sea and the organisms that inhabit them. ⚓

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