to be answered within days. What are the normal operating conditions for the part? How do we accelerate the corrosion mechanism and predict the lifetime of the part in the field? This problem sounds interesting and challenging from a materials standpoint but there is no time to set up a reasonable experiment.

Constant pressure exists on the manufacturing floor. Schedules for shipments must be made. New products must be released before the details of manufacturing can be worked out. A key learning point for me in moving from research and development (R&D) to manufacturing is the concept of manufacturability. As an R&D engineer, creating one or two or even a dozen working prototypes is sufficient. Yet the ability to make a consistent product over and over may have very different requirements. The key to manufacturability is process stability. It is critical to limit the variation in a process. Yet variation is a fact of life on the manufacturing floor. Different operators, different shifts, different technicians, even different engineers lead to variation. Also, variation occurs from incoming materials or from the upstream processes. These variations can result in low yield, inefficient operation of equipment, line stops, or poor reliability. It is enough to keep one awake at night—every night.

In many ways, the skills needed to be successful in manufacturing are the opposite of what we learn in graduate school. Decisions must be made quickly and often with an incomplete set of data. The language and concepts in manufacturing are not taught in a typical materials science program: just-in-time manufacturing, cycle time, statistical process control, self-directed work teams, assurance of supply, contingency plans, WIP, kanban*, ergonomic design, design for manufacturability, design for reliability, design for test, cost, absorption variance, and yield variance.

In other ways, skills I developed in acquiring a PhD degree have been useful in my other positions. Such skills as project management, literature searches, technical writing, and oral presentations are essential. The ability to approach a problem logically and lay out an action plan to resolve issues is critical. I have also found that the contacts I have made in the research community have provided valuable input when I have faced many different manufacturing problems. ☐

Suggested Resources

Robert H. Hays and Steve C. Wheelwright, *Restoring Our Competitive Edge, Competing through Manufacturing*, (John Wiley and Sons, New York, 1984).

Richard Schonberger, *World Class Manufacturing*, (Macmillan, New York, 1986).

Peter Senge, *The Fifth Discipline*, (Doubleday Books, Garden City, NY, 1994).

Eliyahu Goldratt and Jeff Cox, *The Goal*, (North River Pr., New York, 1992).

Gordon MacKenzie, *Orbiting the Giant Hairball, A Corporate Fool's Guide to Surviving with Grace*, (Penguin Putnam, New York, 1998).

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*Kanban is a Japanese term for a way to manage the production floor. It basically results in *a pull* of material through the process instead of *a push*. Usually kanbans are implemented with a card system or by limiting the space where work can be staged. Its real positive impact is that it is a simple system which stops material from piling up at a bottleneck process because it limits the amount of product that can be staged in front of any operation.

HISTORICAL NOTE

John Harrison's "Sea Clocks"

Despite centuries of experience navigating on the open seas, prospects for a safe journey were still grim in 1714. Whereas latitude, the distance (measured in degrees) north or south of the equator, was easily determined from astronomical observations, longitude (the distance in degrees east or west of some arbitrary meridian), yielded to no such easy solutions. Sailors relied on a method called "dead reckoning" whereby estimates of the ship's speed and the elapsed time at sea were combined with the captain's intuition to estimate longitudinal positions. Given that one degree of longitude equals 68 miles at the equator, even small errors in judgment proved to be disastrous: Sailors traveling through fog who thought they had 50 miles to go to reach the shore frequently found it sooner than they had hoped. Ships were running aground, lives and cargo were being lost, and something had to be done.

In 1714 merchants and sailors petitioned the British Parliament for a solution. The 1714 Act of Queen Anne established a top prize of £20,000 (the equivalent of millions of today's U.S. dollars) to anyone who could determine the longitude to the accuracy of half a degree on a routine 60-day voyage from England to the West Indies.

For several centuries the best scientific minds had wrestled with the dilemma of longitude determination. In its essence, it was a problem of timekeeping. Since the Earth rotates 15 degrees in an hour, two locations an hour apart by the Earth's rotation are separated by 15 degrees of longitude. Calculating a ship's longitudinal position at sea requires a knowledge of the time in two locations: that at the ship's current position, and at some arbitrary reference position of known longitude. Comparison of the time difference between the two locations yields the distance separating them.

Two possible solutions emerged: the astronomical and the mechanical. Astronomers such as Edmond Halley of the Royal Observatory at Greenwich strove to understand the clockwork of the heavens to the necessary precision, while artisans worked to solve the mechanical difficulties of keeping time on a rolling sea. No less an authority than Sir Isaac Newton expressed his skepticism that a mechanical solution would ever be found.

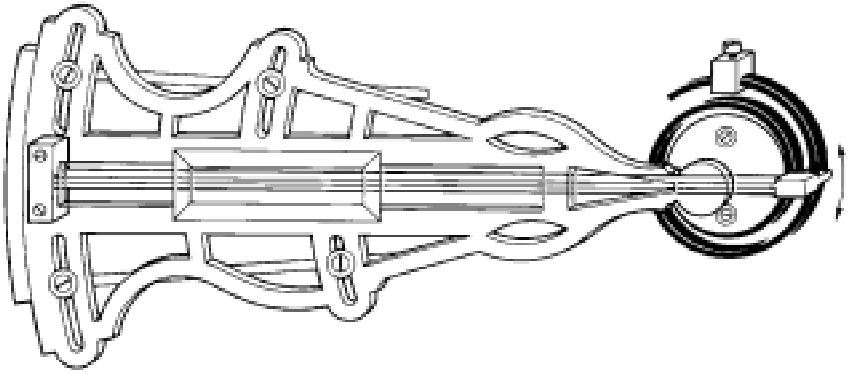
But John Harrison (1693–1776), a carpenter and clockmaker from the town of Barrow Upon Humber with little formal education, used a combination of mechanical skills and basic materials research to rise to the challenge. Realizing that he first had to understand and perfect timekeeping on land, which at that point was capable of an accuracy of only about a minute a day in the best clocks available, he set about analyzing and improving upon the current technology.

The main problems with the existing clocks of the time were the need for lubricants to minimize friction and the thermal expansion of the metal pendulum rod altering the length, and hence the period, of the pendulum's swing. The primitive lubricants of the time (mostly animal fats) changed viscosity with variations in temperature, which alternately slowed down or sped up the internal mechanisms through changes in friction. Eventually, the lubricant dried out, making periodic cleaning a necessity. Harrison the carpenter used his intimate knowledge of wood types to select a naturally greasy variety called *lignum vitae* as the primary material for his gears and bushings. With careful attention to his craft, for the first time the need for lubrication was eliminated.

The period of a pendulum is directly proportional to the square root of its length. A slight change in length due to temperature fluctuations would alter the period to an unacceptable degree if one were aiming for the tolerances specified in Queen Anne's Act. Harrison, no metallurgist, borrowed the expertise and samples available from the foundries of London, and began performing basic experiments in the thermal expansion of metals.

For temperature control, Harrison reports that he "prepared a Convenience on the outside Wall of my House, where the Sun at 1 or 2 o'clock makes it very warm." Relying on cold winter mornings and hot summer afternoons, he hung the samples of metals he was comparing—steel, iron, brass of various compositions, silver, and copper—and measured their lengths as the temperature varied. He used the data obtained in this manner to develop his first major innovation, the "gridiron" pendulum. Constructed of four rods of brass layered between five rods of steel, the complementary thermal properties of the two metals kept the pendulum at a constant length despite temperature fluctuations. With this innovation Harrison's land-based clocks were losing only a second per month by 1730.

For his first "sea clock," dubbed H.1 by historians, Harrison retained the wooden gears but rejected the gridiron pendulum since its motion would constantly be disrupted by the rocking of a ship. Instead, Harrison devised a double-balance mechanism whereby two rods with brass balls at each end were connected by helical springs so that the motion of one balance was offset by an opposite motion of the other, thus stabilizing the oscillator. Three rectangular gridiron devices were connected by levers to the balance springs to alter their effective lengths and compensate for temperature changes. Given a trial run on a seven-day voyage between England and Lisbon in May of 1736, H.1 registered an average error of three seconds in 24 hours, which should have been good enough to claim at least part of the prize. However, Harrison, the perfectionist, already had improvements in mind, and he turned down a proposed test on the West Indies run that was stipulated in the act of 1714.



Detail of the bimetallic strip of John Harrison's sea clock labeled H3. Illustration by David Penney, Copyright.

In H.2, the second sea clock, Harrison replaced the wooden gears with brass ones that were precisely machined and polished to minimize friction. In combination with anti-friction bearings and bushings he managed to craft the first all-metal clock that did not require lubrication. However, by the time H.2 was finished, he had ideas for improvements, and it was never given a test at sea.

For H.3, completed in 1757, Harrison substituted two massive circular balances for the double-balance, and replaced the helical balance springs with a thin, coiled balance spring. Thermal expansion effects were more pronounced since the thin metal spring responded much more quickly to temperature changes than the more massive rods used in the gridiron devices. To solve this dilemma he developed his greatest innovation, and one that remains with us to this day as a component of thermostats: the bimetallic strip.

Returning to his research data on thermal expansion of metals, Harrison constructed the bimetallic strip by riveting together two thin strips of steel and brass. One end of this strip was fixed in a metal frame having somewhat the shape of a violin; at the other end two pins slid along and held the flat sides of the coiled balance spring. As the temperature changed, the bimetallic strip flexed due to the differing thermal expansion coefficients of the steel and brass, and the pins moved to a different position along the balance spring, effectively shortening or lengthening it. Thus expansion and contraction of the balance spring were compensated by the bimetallic strip, which maintained it at a constant length (see Figure).

With this last innovation Harrison had perfected the art of timekeeping to a sufficient degree to claim his prize. However, it was not H.3 that finally brought him the reward, but an oversized pocket watch dubbed H.4 that used the principles developed in his previous efforts. During a voyage begun in October 1761 from England to Jamaica aboard the HMS *Deptford*, H.4 lost only five seconds over 81 days at sea. In 1765, having fought many political battles, the 72-year-old Harrison collected £10,000—only half of what he deserved—for solving the problem of finding the longitude at sea. As a tribute to his genius, Harrison's sea clocks were restored to working condition in the 20th century, and continue to keep time today at the National Maritime Museum at Greenwich.

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FOR FURTHER READING: D. Sobel, *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time* (Penguin Books, New York, 1995); W.J.H. Andrewes, ed., *The Quest for Longitude: The Proceedings of the Longitude Symposium, Harvard University, Cambridge, Massachusetts, November 4–6, 1993* (Collection of Historical Scientific Instruments, Harvard University, Cambridge, Massachusetts, 1996); and H. Quill, *John Harrison: The Man Who Found Longitude* (Humanities Press Inc., New York, 1966).