HEAT & COLD

MASTERING THE GREAT INDOORS

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HEAT & COLD

MASTERING THE GREAT INDOORS

A SELECTIVE HISTORY OF HEATING,
VENTILATION, AIR-CONDITIONING AND REFRIGERATION
FROM THE ANCIENTS TO THE 1930S

BARRY DONALDSON & BERNARD NAGENGAST
WITH AN INTRODUCTORY ESSAY BY GERSHON MECKLER

AMERICAN SOCIETY OF HEATING, REFRIGERATING
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SCIENTIFIC ROOTS OF HVAC&R

GERSHON MECKLER, P.E.

At least 750,000 years ago, our ancestor *Homo erectus* knelt in a cave and applied his wits to building and sustaining a hearth fire. Thus began the long, slow, pre-science evolution of technology to provide indoor comfort: first heating, later cooling and ventilating.

Before modern science emerged in the late sixteenth and the seventeenth and eighteenth centuries, the evolution of heating and cooling technology—the accumulation of practical, useful knowledge or "know-how"—was a ponderous, iterative, trial-and-error process marked from time to time by leaps of inventive insight. Despite the methodological limitations, given human ingenuity the pre-science results were impressive, as the early chapters of this book attest.

Central heating in the large, public Roman baths of the first and second centuries A.D. is a fascinating example. The Romans knew a lot. But, as D. Lindberg points out, the word "know" is tricky; knowing *how* to do something is quite a different matter from knowing *why* the thing acts as it does.[1]

The two kinds of knowing—knowing how and knowing why—imply very different capabilities. Science provides the "why," the fundamental principles or laws of nature that enable us to understand the forces producing the result we see and to invent new applications that were not apparent from previous experience.

Without scientific understanding, technological progress is tied to practical experience and is limited to the "next steps" that are within mental reach based on past practice. *With* fundamental scientific understanding, those boundaries fall away and the realm of the possible expands dramatically.

This introduction outlines the major scientific advances that enabled the craft-based technology of the past to evolve into the science-based one of today. Without science-based technology, modern heating, ventilating, air-conditioning, and refrigerating (HVAC&R) systems would not be possible.

SCIENTIFIC UNDERPINNINGS OF HVAC&R

The scientific underpinnings of modern HVAC&R systems emerged from a brilliant stream of experimentation and discovery in the three hundred years between 1600 and 1900. Among the scientific building blocks were fundamental discoveries about gas laws governing the interactions of pressure, volume, and temperature; the nature of heat; and the laws of thermodynamics, that is, the dynamic relations among heat, work, and energy.

A remarkable characteristic of this period was the close ties and mutual stimulus between scientists and engineer-inventors. Historically this was a period of unprecedented symbiosis between science and technology.

Not only were there many personal, collegial, and student-teacher relationships between significant figures in science and technology—something else quite powerful was also at work. As D.S.L. Cardwell writes in *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age*:

> The development of machines like the steam-engine in the eighteenth century almost forced man to recognise the enormous power, the *puissance*, of heat, the grand moving-agent of the universe. The sight of a primitive steam-engine tirelessly pumping ton after ton of water out of a mine . . . did more for science than all the speculations of the philosophers about the nature of heat since the world began. . . . Thus a great scientific revolution was effected as a result of man's experiences of an enormously important technological development: the invention of the heat-engine.[2]

Steam engine technology has a special place in the HVAC&R lineage. It both spurred and demonstrated major advances in understanding heat and the relation of heat and work, ranging from Thomas Newcomen's use of atmospheric pressure (1712) and James Watt's introduction of a separate condenser (1777) to Sadi Carnot's seminal work in thermodynamics (1824), including the concept of the reversible engine.

Only after the new science of thermodynamics was fully formulated in the mid to late 1800s did a mature engineering science and modern HVAC&R systems become possible. Based, for the first time, on a fundamental understanding of the principles governing the interaction of heat, work, and energy, mathematical relationships were formulated and new analytic tools developed to make practical use of this knowledge. It became possible, increasingly, for inventors to develop smaller, much more efficient and practical equipment tailored to specific needs and for engineers to predict design performance with a high probability of success.

Modern engineering had arrived, with a major assist in the HVAC field from ASHRAE's forerunner, the American Society of Heating and Ventilating Engineers (ASHVE), and subsequently from ASHRAE. Established in 1894, ASHVE sought to raise standards in the field by incorporating applicable science and by using the experimental methods of science as a basis for drawing conclusions and formulating design rules. Chapter 9 tells ASHVE's story.

ROOTS OF CHANGE: 1550-1600

The scientific roots of HVAC&R reach directly to the first modern experimental scientist, Galileo Galilei, and to the early Greek science and mathematics that influenced him. Galileo began the long journey toward a science of heat with his invention, in 1592, of the first device to use the expansion principle to indicate changes in temperature.

Often called the first thermometer, Galileo's classroom air-and-water thermoscope was crude by today's standards. It was not portable, it was unsealed and therefore subject to changes in atmospheric pressure, and it did not incorporate markings to indicate gradations of temperature (it is thought that a separate scale was used). Nevertheless, the idea of measuring and comparing the intensity of heat at different times or different places represented an important conceptual leap.

The thermoscope aroused great interest and led, ultimately, to the ability to measure temperature or degree of heat with consistent, reproducible results based on a common scale. It would be 170 years, however, before Joseph Black drew a clear distinction between the concept of temperature—intensity or degree of heat—and that of heat quantity or heat capacity.

Galileo had been influenced profoundly, as had many of his contemporaries such as Kepler, by the rediscovery in Europe of early Greek science and mathematics. Among other works, that of the first applied mathematician, the brilliant Archimedes, excited great interest. The agent of rediscovery was the printing press, which, by the 1500s, made accessible to great numbers of people information previously available only to an elite few via painstakingly hand-copied manuscripts.

The classical concept of mathematics as a critical means to truth had a powerful impact in the intellectual environment of sixteenth- and seventeenth-century Europe. Something else from the ancient works also had an impact: ideas so rare that most scholars agree that "unlike technology or religion, science originated only once in history, in Greece . . . no other society independently developed a scientific mode of thought, and all later developments in science can be traced back to the Greeks."[3]

Implicit in the rediscovered works of Aristotle and others from the third to sixth centuries B.C. was the unprecedented attempt to understand and explain natural phenomena on their own terms, to satisfy curiosity, rather than to fit the tenets of particular myths or religions. Also implicit in Greek "natural philosophy" was the assumption that it is possible to discover and understand the physical reality of natural phenomena.[4]

These were stunning conceptual innovations. They were not, however, modern science. The key missing ingredient, which would not appear until the late sixteenth and the seventeenth centuries, was the methodical use of controlled experiments, empirical data gathering, and data analysis to confirm or disprove scientific assumptions—what we know as the experimental method.

Why, one can't avoid wondering, did the impressive early Greek work in exploring biology, physics, medicine, and mathematics not lead to greater scientific and technological progress in the classical world? After all, in addition to their theoretical work, the Greeks made an enormous number of concrete observations.[5] Furthermore, although the first-century inventor Hero of Alexandria did not understand the nature of compressed air, artificial vacuums, or steam, wind, and water power, he used them all in various small devices he developed.

The answer provides clues to the dynamics of later progress. These were among the reasons: (1) Thinkers of the time, including the "natural philosophers," were disdainful of manual labor, the domain of slaves and craftsmen, and did not regard applied science as a suitable occupation for the philosopher class. (2) There was little communication between the natural philosophers (scientists) and craftsmen (engineers of the time). The principal area in which technological development was encouraged was weaponry. (3) There was little motivation to increase production, since slaves managed to satisfy the material needs of those in authority.

As for Hero's devices, it seems clear they were intended to amuse or impress but not to serve productive ends. As J. Lindsay points out, "no attempt was made to combine the inventive faculty, so evident in a range of thinkers from Ktesibios to Heron [Hero], with such possibilities as were present in the existing technological level, especially in metallurgy."[6]

Contrast this situation with the dynamic, changing economic and social conditions in Europe from the sixteenth through nineteenth centuries. Early in this period, the new medium of printed books contributed greatly to intellectual ferment and cross-communication between scientists and engineer-inventors. Reaching a wide audience for the first time were such works as Georgius Agricola's *De Re Metallica* (1556), a study of state-of-the-art technology in mining and metallurgy, including ventilation in mines, and Francis Bacon's *The Advancement of Learning* (1605).

Bacon's influence was incalculable. He articulated the scientific method that was to revolutionize human understanding and spark an explosion of useful technology. As the sixteenth century gave way to the seventeenth, the concept of verifying scientific theories by independent measurement was not yet part of the culture in Great Britain, Europe, or anywhere else.

Bacon was an impassioned advocate of rational experimentation to uncover the fundamental laws of nature:

> He felt sure that he knew the right method [of inquiry], and that, if only this could be . . . applied on a large enough scale, there was no limit to the possible growth of human knowledge and human power over nature. . . . [This] was not in

> the least obvious at the time; it was, on the contrary, a most remarkable feat of insight and an act of rational faith in the face of present appearances and past experience.
>
> What was wrong with the methods in use up to Bacon's time? . . . In the first place [in Bacon's view], there was an almost complete divorce between theory, observation and experiment, and practical application. [Furthermore, too often,] . . . scientists decided all questions, not by investigating the observable facts, but by appealing to the infallible authority of Aristotle.[7]

Bacon's view that "theory must hence-forward learn from craft practices, and vice versa" had a lasting impact, influencing, for example, the activities and deliberations of the Royal Society of London, established in 1660, as well as the French Académie des Sciences.[8] From the 1640s on, there was a group at Oxford University, which included Robert Boyle and which evolved into the Royal Society, that was dedicated to Bacon's experimental method.

INDISPENSABLE INSTRUMENTS: 1600-1660

Two instruments invented in this period, the barometer and the air or vacuum pump, aroused great interest and stimulated both scientific and technological advances of enormous significance to the future of HVAC&R. S. Lilley provides insight into an even more fundamental significance of these and other seventeenth-century scientific instruments (thermometer, telescope, microscope, etc.). Noting that instruments designed specifically for scientific purposes were used in this period on a "big scale for the first time in all history" and "opened up vast new fields of discovery," he observes:

> [Their use] did more than merely lead to new discoveries. It played a major part in establishing the *experimental method*—the method that characterizes modern science. Without special instruments . . . [experiments] don't really get you very far—not far enough to show clearly that experiment is a better method than the old method of just thinking about things. Then, when the new instruments came along, experiment produced such remarkable results that it only took a few decades to demonstrate that the experimental method is better than any other.[9]

By the seventeenth century, water pumps—ordinary suction pumps—were fairly common. At the same time, the mining industry was expanding, mines were growing deeper, and problems with water standing in mines had focused attention on how pumps could be improved and on related scientific issues.

Evangelista Torricelli, a student of Galileo, shared Galileo's curiosity about why ordinary lift pumps could not raise water more than about 32 feet above its external level. Torricelli suspected that pressure from the external air—atmospheric pressure—played a role.

In 1643 he devised a new instrument, the mercury barometer, to test his theory about how high mercury could be raised by a vacuum. His predictions, based on the relative weights of mercury and water and the effects of external air pressure, proved accurate, and he correctly attributed day-to-day variations to changes in atmospheric pressure.

Torricelli's experiments, carried out with assistance from Viviani, another student of Galileo, demonstrated both atmospheric pressure and the existence of a vacuum—a proposition much in doubt at the time. Torricelli died soon after, and it took confirmatory work by Blaise Pascal and further work by Otto von Guericke to convince the many skeptics that a vacuum could indeed exist.

Meanwhile, another major invention was just around the corner. It would lead directly to Robert Boyle's historic work on the physical properties of gases and the importance of air to respiration and combustion. The inventor was Otto von Guericke.

> [Von Guericke] was remarkable for an emphasis on experiment, which was something new in Germany; and he was among those who prepared the way for the rise of experimental science in northern Europe.[10]

Controversies about the vacuum prompted von Guericke to develop a new kind of pump, one that would suck air out of a vessel. Von Guericke completed his air vacuum pump in 1645, two years after the invention of the barometer, and performed experiments related primarily to the force of atmospheric pressure.

Von Guericke later dramatized both the tremendous power of atmospheric pressure and the vacuum phenomenon in a much-talked-about demonstration. (He fitted together two hollow bronze hemispheres, evacuated the air between them, and then showed that two teams of eight horses each, straining in opposite directions, could not pull the hemispheres apart.)

Robert Boyle took the basics of von Guericke's air pump and created an instrument capable of much broader scientific investigation. He constructed it so that he "could put various objects into the receiver—as he called the vessel from which the air was pumped out—and see how they were affected by being deprived of air."[11]

PIONEERING THE GAS LAWS

Robert Boyle is one of the giants of science. Experiments of 1658-1659 using his new air vacuum pump, reported in "New Experiments Physico-Mechanicall Touching the Spring of the Air and its Effects" (1660), were stunning in their immediate, obvious implications. Beyond that, they led to his assertion, two years later, of what came to be known as Boyle's Law and was later accepted as a fundamental principle of thermodynamics: At a given temperature, the pressure and volume of a gas are inversely proportional, that is, volume decreases when pressure increases and vice versa.

Boyle's were the first experiments on the physical properties of gases. More than 100 years later (1787), Jacques Charles stated the role of temperature or thermal expansion in the pressure-volume-temperature relationship. In what came to be known as Charles' Law, he discovered that if he heated a gas while keeping the pressure constant, the change in volume was proportional to the change in temperature. Joseph Gay-Lussac independently discovered this relationship in 1802.

These two gas laws, Boyle's Law and Charles' Law, have since been combined as follows:

> The volume of a gas varies directly with its temperature and inversely with its pressure.[12]

Boyle's Law is also known, in some parts of the world, as Mariotte's Law. Edme Mariotte conducted exeriments with apparatus just like Boyle's,[13] and in 1676 he stated the same law, emphasizing that temperature must be kept constant for the law to be valid.[14]

Following significant progress from the 1750s through the 1770s in identifying constituents of air, in 1801 John Dalton formulated his theory of partial pressures, known as Dalton's Law: The total pressure of a mixture of gases is the sum of the pressures of its constituent gases. Stated another way, "each component of a mixture of gases in a given region produces the same pressure as if it occupied the region by itself."[15]

OXYGEN AND RESPIRATION

Robert Boyle's experiments in 1658-1659 with his air vacuum pump demonstrated, among other things, which phenomena required air and which did not. For example, deprived of air in his "receiver," animals died and fires were extinguished. Without air around it, a watch continued to run but its ticking could no longer be heard. Boyle showed that heat and light can travel through a vacuum, but the transmission of sound and magnetic attraction require the presence of air. With these experiments, Boyle sowed the seeds of future inquiry in many scientific fields.

Having shown that both respiration and combustion require some (not all) of the air, Boyle came close to discovering oxygen. His research assistant and instrument maker, Robert Hooke, who himself became a respected scientist, advanced this aspect of Boyle's work by identifying the air required by both respiration and combustion as the same part or type of air.[16]

In the 1750s Joseph Black isolated "fixed air" (carbon dioxide), and in the 1770s Joseph Priestley demonstrated that fixed air "would not support combustion and that mice soon died when placed in it, but that both the respirability of the gas and its ability to support combustion were improved by growing a plant in it."[17]

Priestley isolated "dephlogisticated air" (later recognized as oxygen) in 1774 and observed that "a candle burnt in this air with a remarkably vigorous flame. . . ."[18] He found that a mouse placed in the dephlogisticated air could survive "at least twice as long as a mouse placed in an equal amount of ordinary air."[19] He did not realize he was dealing with a distinct constituent of air, but instead thought of it as "pure" air.

Antoine Lavoisier is credited with the discovery of oxygen. Lavoisier is also considered the founder of modern chemistry. Within two decades (1770-1790), his work and influence overthrew the well-entrenched phlogiston doctrine and replaced it with the oxygen theory of combustion, helped effect a total reform in chemistry's nomenclature, and established the modern concept of an element.[20]

Lavoisier had studied combustion and calcination and by 1772 had concluded, contrary to accepted theory, that phosphorus and sulphur "combined with air when burnt and that their weight was increased by this combination with air."[21] His finding contradicted the general belief that combustion released "phlogiston," thought to be a kind of subtle fire material that escaped from burning substances.

Learning of Priestley's work in 1774, Lavoisier concluded that metals also combine with air on calcination. Based on further experiments, he established in 1777 that Priestley's "dephlogisticated air" is one part of the air and that this part—which he named oxygen—is absorbed during combustion, calcination, and respiration.

Lavoisier also showed that respiration converts oxygen into fixed air (carbon dioxide). Subsequently, he and Pierre Laplace, using the ice calorimeter they had developed, demonstrated similarities between respiration and combustion.

Chapter 3 explores the increased focus on ventilation stimulated by Lavoisier's and related findings, and chapter 7 describes the nineteenth-century evolution of ventilation standards. Work done by Max von Pettenkofer in 1862 led to the use of air's carbon dioxide level as one general indicator of ventilation adequacy.

SCIENCE OF HEAT TO CARNOT

In the fifth century B.C., the Sicilian Empedocles formulated a theory involving heat, which, as expanded by Aristotle in the following century, remained influential for some two thousand years. According to Empedocles, all things were made up of four basic elements or "roots"—fire, earth, water, and air; varying the proportions of the elements produced different substances.[22]

As reformulated by Aristotle, the theory appeared to explain a wide range of observed phenomena, which accounts for its longevity. Aristotle emphasized the idea of transformation. Associated with the four basic elements were four primary qualities: dry, wet, cold, and hot.

> Earth was dry and cold, water was cold and moist, air was moist and hot, and fire was hot and dry. One element could, in principle, be converted into any other by the addition and removal of the appropriate qualities. Every substance on earth was composed of combinations of the four elements, and changes which we now call chemical were explained by an alteration in the proportions of the four elements.[23]

Although several seventeenth- and eighteenth-century scientists believed that heat is a kind of motion rather than a substance, the "caloric" or material theory dominated eighteenth-century beliefs about heat and was not overthrown until the 1840s. "Caloric was conceived as a kind of all-pervading, imponderable, highly elastic fluid the particles of which were attracted by matter and repelled by one another."[24] Caloric, it was thought, flowed from hotter bodies to adjacent colder ones.

Progress in understanding heat continued despite the material theory's dominance, thanks to scientific experimentation and the new instruments. In 1701, for example, based on a series of thermometric experiments, Isaac Newton stated what came to be known as Newton's law of cooling. In order to extend the temperature scale and determine high temperatures by extrapolation, Newton found that a solid's rate of cooling is proportional to the temperature difference between the hot body and its surroundings.

Science Applied to Heating Technology

Scientific principles and the scientific method were applied to heating technology in a significant way for the first time in Nicolas Gauger's 1713 work, *La Mechanique du Feu*. In this regard his book was a turning point in the long journey from the hearth fire of *Homo erectus* to modern heating.

Based on a series of floor-to-ceiling thermometer readings, Gauger determined that hot air rises and is replaced by colder air. He used this principle and others—such as Newton's hypothesis that "heat radiates and reflects just like light"[25]—to develop numerous fireplace innovations to increase warmth and eliminate smoke.

Gauger's work unquestionably stimulated Benjamin Franklin and others to attempt to advance the scientific design of fireplaces and stoves, as described in chapter 4. However, as I.B. Cohen points out, there was a limit to how successful these efforts could be during the 1700s, since the phenomenon of convection was not yet fully understood. "Only after the later [scientific] work of Rumford [1797] could truly efficient stoves or fireplaces be designed."[26]

Early Kinetic Theory

Daniel Bernoulli quantified an early version of the dynamic, kinetic theory of heat in his famous *Hydrodynamica*, published in 1738. His was not a kinetic theory in the modern sense,[27] but his work was "far in advance of the times." He dispensed with "fire particles" and "subtle fluids"[28] and considered oscillations and collisions of constituent atoms or particles.

Bernoulli pioneered kinetic theory in 1738, but it would be one hundred years before the material theory of heat was abandoned and the mechanical theory accepted. As Cardwell suggests, "Only with the establishment of the doctrine of the *conservation of energy* in the mid-nineteenth century could the dynamical theory come into its own."[29]

Latent Heat and Heat Capacity

Joseph Black is a key figure in the science of heat. Black had been a student of William Cullen, who in 1755 wrote of producing ice by evaporation under high vacuum. In advances that were indispensable to future progress in heat studies, Black distinguished between temperature and quantity of heat and, between 1757 and 1762, defined the concepts of *heat capacity* and *latent heat*.

Building on the work of Hermann Boerhaave and Daniel Fahrenheit, Black discovered that the capacity of substances to absorb heat varies according to the substance. This work eventually led to use of the concept of *specific heat capacity*, i.e., the amount of heat required to raise the temperature of one pound of a substance by one degree Fahrenheit (or one gram by one degree centigrade).

Black discovered that a boiling liquid absorbs a large quantity of heat without having its temperature raised and that the heat can be recovered from the steam. He determined that the unrecovered heat existed in "some sort of inactive or *latent* state," and he called it the "*latent heat of vaporization*."[30] Similarly, heat absorbed when a solid melts was called the *latent heat of fusion*.

Within two decades, Joseph Lavoisier and Pierre de Laplace had developed their ice calorimeter to measure heat flow. Devised for Lavoisier's combustion experiments, the calorimeter measured heat quantity by determining how much ice the heat would melt.

Heat as Motion

As the eighteenth century drew to a close, the material theory of heat—the belief that heat is a substance—reigned virtually unchallenged. What accounted for its staying power, despite the fact that Newton, Boyle, Bernoulli, and others had favored the "heat is motion" idea? Cardwell explains:

> The merits of the theory were considerable, for it provided a very convincing explanation of the process of thermal expansion in solids, liquids and gases; it accounted for the latent heats of fusion and of vaporisation and it harmonised very well with the phenomenon of compressive heating or expansive cooling of a gas—indeed the picture of material heat being squeezed out of a gas was a particularly persuasive one.[31]

In 1798, Benjamin Thompson—Count Rumford—dealt the first blow to the material theory and laid the initial groundwork for later acceptance of the dynamic or kinetic theory of heat as motion. The American-born Rumford was a highly ambitious adventurer, scientist, and inventor who won titles and important posts in both London and Munich, eventually marrying the prominent widow of Antoine Lavoisier in Paris.

While supervising cannon boring at a Munich arsenal, Rumford was struck by the tremendous amount of heat generated by the process. He devised an experiment, famous in the annals of heat studies, in which he duplicated the boring of a cannon inside a box filled with water. The intentionally dull borer was connected to a lathe turned by two horses.

Rumford demonstrated that friction from boring could bring the water to a boil within two and one-half hours and that there appeared to be no limit to the amount of heat that could be generated this way. This result was inconsistent with the idea of heat as substance, he maintained:

> It appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of anything capable of being excited and communicated in the manner the Heat was excited and communicated in these experiments, except it be MOTION.[32]

He buttressed his hypothesis with experiments demonstrating that heat is weightless.[33] He weighed a block of ice before and after it had melted. Rumford found that, although a considerable amount of latent heat had entered the ice as it melted, there had been practically no change in weight.

Rumford's heat-related discoveries and inventions were remarkably wide-ranging. He discovered convective currents in liquids and examined their role in oceans. He made the "fruitful suggestion that radiant heat is propagated by undulations in an aether and is therefore of the same nature as light."[34] He made the significant discovery that the shinier a surface was, the more slowly it cooled.[35]