Notes on the Origins and Evolution of the Subject of Heat Transfer

"We are picking fruit from an orchard that we have been cultivating for a long time, more than we are cultivating next year's orchard. It is easy to let the heart go out of our work when we do this. We are at our best when we mix abstract and applied thinking..."

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Joseph Black died quietly in his chair on November 26, 1799, with a cup of tea balanced in his lap. Five years earlier, Antoine Lavoisier's head had been publicly removed by the French Revolutionary Tribunal. These two men defined our understanding of heat phenomena on the eve of the 19th century.*

The Turn of a Century

Lavoisier was a key person in replacing the concept of heat as *phlogiston* with the idea of *caloric*. Phlogiston was thought to be a component of matter that was liberated or consumed in chemical reactions. It was sometimes called the "matter of fire." Caloric was an invisible, elastic fluid that could neither be created nor destroyed. It was not a component, but an *occupant*, of matter that flowed from any hot body to neighboring cold bodies. Caloric was the first really useful tool for describing *heat transfer* processes.

Black, on the other hand, provided us with the concepts—and the first measurements—of specific and latent heats. Although his colleague, Cleghorn, had codified the rules governing the behavior of caloric, Black himself did not embrace a theory of heat. He took a restrained operational view of heat phenomena. He was a keen observer—disinclined to extend his claims beyond what he knew with certainty.

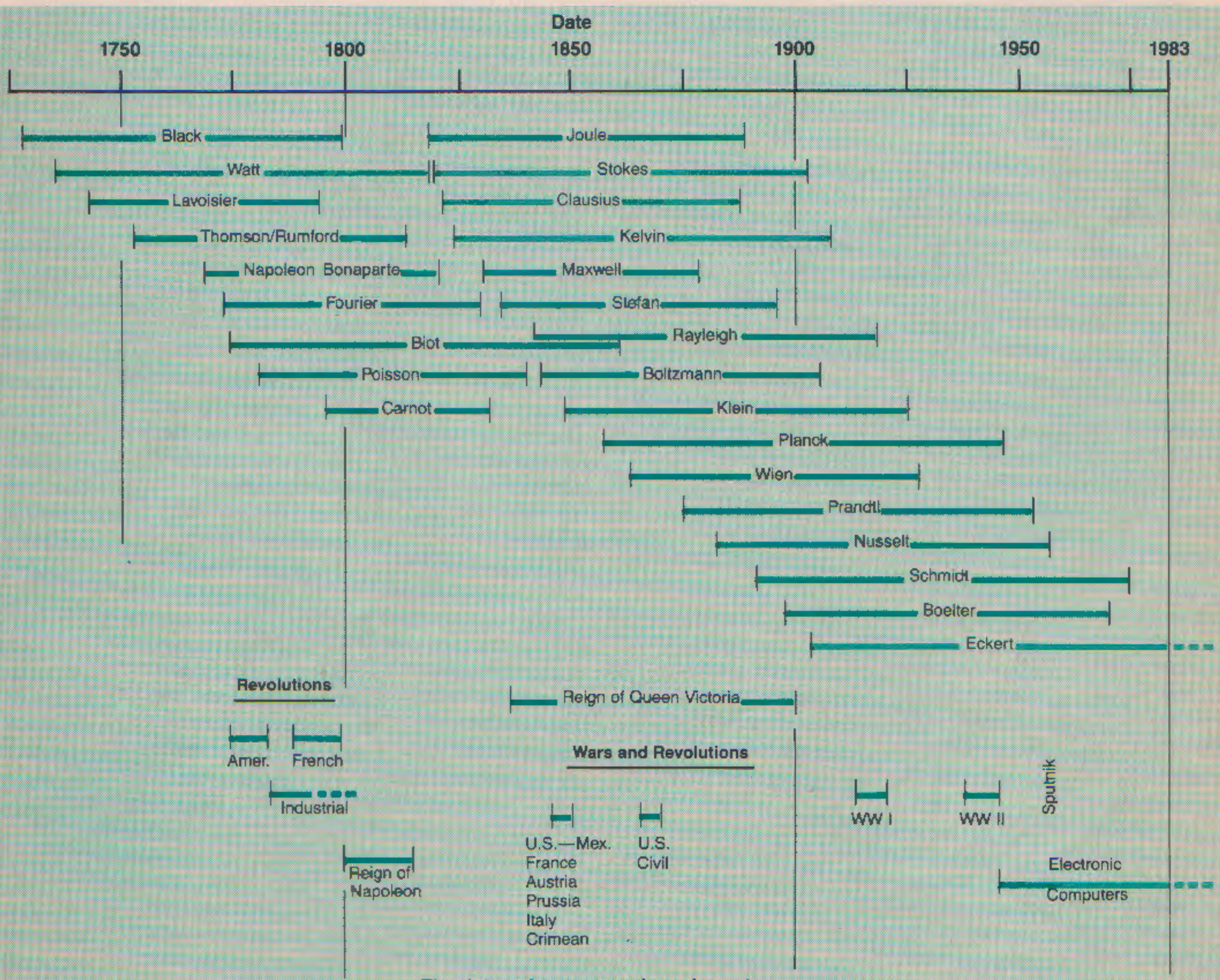
Black's lecture notes on the "General Effects of Heat" were published posthumously in 1803 by a former student, John Robison, who edited them heavily. The notes reveal several things at once: Robison's adulation of Black, the rising concern that educated people had in 1800 for learning about heat, Black's own clear-headedness, and the peculiar closeness of the technical/scientific community at that time. Robison dedicated the work to James Watt who had long been both his, and Black's, personal friend. (He attributed Watt's invention of the separate condenser to Black's tutelage in Glasgow. Watt privately muttered that this was not at all the case. The underlying ideas were, he felt, his own.)

The closeness of the intellectual community comes home to us in one of the magnificent ironies of the new century. In 1805, the widow Lavoisier was remarried to the first modern opponent of the caloric theory, Count Rumford. Rumford was a product of the 18th century who fairly hurtled into the 19th. While he was far from being the greatest scientific luminary of the time, his life tells us much about how things were changing, and about how the scientific study of heat was starting to turn into the technical study of heat transmission.

Rumford was born Benjamin Thompson in Woburn, Mass., outside of Boston, in 1753. His catch-as-catch-can education was partially achieved in the study-group system advocated by Benjamin Franklin. It was a kind of backwoods reflection of the 18th century "Enlightenment"—that mounting intellectual revolution that eventually led to populist upheavals of all sorts. The first of these revolutions occurred in the American Colonies shortly after Thompson had gone to Concord, N.H. (which had previously been named Rumford), as its new 18-year-old schoolmaster. Within a year he married the 33-year-old widow of Concord's wealthiest citizen, and thereafter became seriously involved in spying on revolutionaries for the English governor. In 1776 he had to flee to England, deserting his wife and new daughter, Sara.

During the next quarter century, revolution engulfed France and then continental Europe. Only England escaped real violence, for its revolution of the lot of the common man was industrial rather than political, and surely more significant in its effects. When Napoleon declared himself emperor of France in 1804 the revo-

*Sources of biographical information are given in the "Readings" at the end of the article.



The dates of some people and events

lutions were finished and the world was a very different place.

Thompson moved about this changing Europe with Byzantine guile. He was a master of exaggeration, parlaying every minor success into a major accomplishment. He immediately established himself on the right hand of the English Secretary to the Colonies. He raised a regiment and returned to fight the Americans briefly in North Carolina (against Marion's Raiders) and in Long Island. He became a Fellow of the Royal Society for his fairly straightforward studies of ballistics and gun powder. He worked with the British Navy on signal systems and ship design. In 1783 he left England and took up the post of aide to the Elector of Bavaria. In this position his efforts produced a record of really solid accomplishment that won him the title of Count in 1792. For his new title he took the name of his old town of Rumford, N.H.

Rumford's instincts for political intrigue and his aspirations to scientific respectability might better have been placed in the courts and salons of 18th-century France, but his place in history was gained by his 19th-century genius for social reform and thermal systems development. He was an elitist, determined to make the poor useful and happy by attending to their basic needs. He set up poorhouses and public works programs in Munich, and then concerned himself with the elemental problems of food, warmth, and light in these institutions. His accomplishments included:

- countless designs and innovations in stoves, ovens, and lighting systems, and in their cleanliness and fuel economy.
- his famous cannon-boring experiments, which led him to conclude about heat: "Anything which any insulated (system) can continue to furnish without limitation cannot possibly be a material substance and it appears to me extremely difficult, if not impossible, to form any distinct idea of any thing, capable of being excited and communicated in the manner the heat was excited and communicated in these experiments, except it be motion."
- a set of experiments that led him to assert that the most important element in an insulating material was the entrapped air pockets that it contained; and other experiments that showed how important convective currents were in the transmission of heat through fluids.
- the creation of the enormous "peoples park" called the English Garden, which remains the beautiful centerpiece of Munich today.

Black lived long enough to quote "Sir Benjamin Thompson's" results side by side with those of Cleghorn. He was quite clear in observing that the transmission of heat must be, in some sense, the transmission of a mode of motion. He was also clear on another point that Rumford/Thompson had failed to understand—namely, that cold was not an opposite quantity to heat, but rather the mere lack of it.

No one in 1800 quite understood that heat and work were interchangeable, unless it was Rumford, and he failed to emphasize the enormous significance of the fact. It was generally recognized that heat was related to work and friction, but the idea that caloric could not be created stopped most people from looking for a direct equivalence between heat and work. Rumford showed that by doing work one could create heat indefinitely, but he did not advance a numerical equivalence. However, subsequent students were able to infer a rough value from his data.

One other extremely important product of 18th-century revolution was 19th-century education. Between his return to England in 1799, and 1802, Rumford's chief efforts went to forming the Royal Institution of Great Britain. He had meant to form a school for educating the lower classes in technology, although it rather quickly reverted to a higher social stratum. The French Revolutionary government had also formed an Ecole Polytechnique in 1795. Both institutions had a great deal to say about heat transfer, but during its first 30 years the Ecole Polytechnique set the very foundations of the subject.

The French

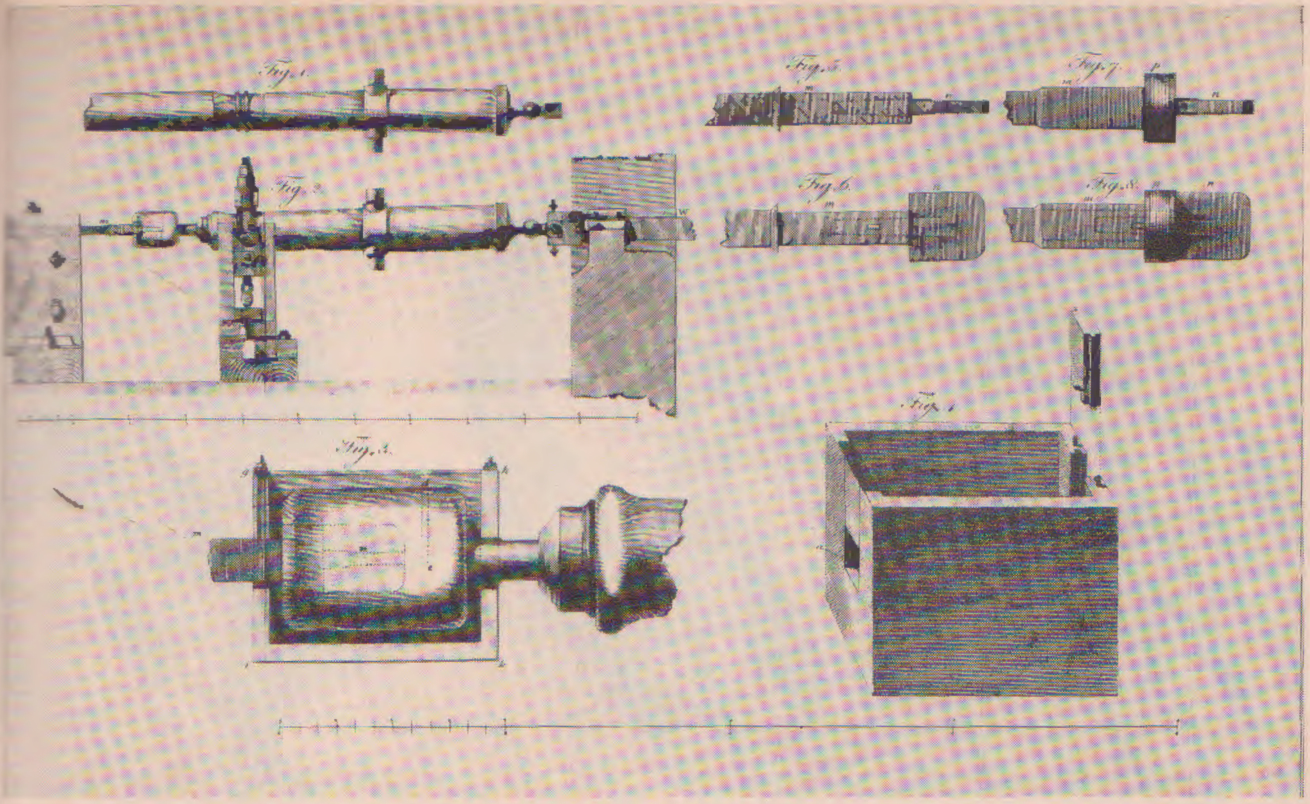
Napoleon was a strong supporter of the Ecole Polytechnique and when he invaded Egypt at the turn of the century he included a young professor of mathematics from the school in his entourage, Joseph Fourier, who held several administrative posts in the campaign. Fourier began working on the problem of heat flow while he was in Egypt, and continued when he returned to Grenoble in 1802 as Prefect of the region of Isère. By 1803 he had failed in his attempts to describe conduction among a series of connected elements. (This is what we do more successfully on the computer, today). He might have done no more, but in 1804, Joseph Biot suggested another approach.

Biot recognized that the problem should reduce to a second order linear partial differential equation; but he failed to write the equation, and he did not see that one had to impose independent boundary conditions on it. Fourier appears to have been reenergized by Biot's insight. He returned to the problem and by 1805 produced an 80-page manuscript that included the differential equation:

$$(\text{constant})\ \nabla^2 T = \frac{\partial T}{\partial t} + hT$$

The problem with this equation is that it includes the heat convection effect, hT, which, we realize today, must be administered as a boundary condition.

Fourier became aware of this weakness and emended it during the next two years. His biographer, I. Grattan-Guinness, has observed that "in making this correction Fourier achieved his master stroke, the great inspiration from which not only do all his mathematical successes spring, but also the whole approach to 'modern' mathematical physics." Fourier submitted a new 234-page manuscript to the Institut de France in Paris in 1807. In it he did something more important than determining how to formulate the laws governing the flow of heat in a solid. He did something beyond updating Bernoulli's trigonometric series to solve the equation. He actually provided us with the strategies that would be basic to the entire field of continuum mechanics, of which heat conduction and convection are a major part. These are the identification of field differential equations and boundary conditions, the technique of separation of variables, and the idea of representing solutions in the form of series of arbitrary functions.



Museum model of Rumford's (Thompson's) cannon-boring experiment

His paper actually suffered years of delay before it was finally published in 1822 in the form of a monograph, and in 1824 and 1826 as a lengthy two-part article in the memoirs of the French Academy. These were years during which he fought serious resistance offered by such famous people as Poisson and Lagrange. In retrospect we can probably claim that the very process of dispute and argument not only honed Fourier's work, but served to extend and intensify its influence. By the time it finally appeared in the Academy memoirs, for example, C.L.M.H. Navier and S.D. Poisson were also completing the formulations of viscous fluid field equations that would eventually be needed to predict heat convection as well.

Victorian Science

We might ask what sort of bedfellows science and technology really are. Few of us doubt that science serves technology and that technology provides grist for the mills of science. Still, the greatness of English technology in the late 18th and early 19th centuries seems not to have been accompanied by great English science. The greatness of French science in particular seems to have been accompanied by a peculiar disinterest in adopting the "English revolution" during this time.

The English plunged ahead building greater and grander heat engines "by-guess-and-by-God," while the Frenchman Sadi Carnot contemplated heat engines in the abstract. In 1824, Carnot developed the notion of the second law of thermodynamics using the caloric theory of heat, yet he prefaced his work with the words "Everyone knows that heat can produce *motion.*" Twenty-three years later, James Prescott Joule, who was educated privately—outside of the English scientific academies—completed the task that Rumford had begun. He confirmed that the converse was true by measuring (within a fraction of a percent) exactly how much heat a foot-pound of work would yield.

The year was 1847, the world was on the brink of widespread wars and upheavals once more, and the English had already started to gain scientific ascendancy where the French had left off. Joule put in place the last foundation stone upon which the new subject of thermodynamics would be erected by Kelvin and Clausius. The English science that followed in the stable Victorian period was remarkable in its vitality and much of it was basic to the science of heat transfer. It was centered upon Cambridge University.

The first new stars of English mathematical physics were Lord Kelvin and the Irishman, George Stokes. Stokes spent his life at Cambridge and his contributions to fluid mechanics poured forth from 1841 until 1901. One of his earliest contributions was an independent, and more modern, formulation of the "Navier-Stokes" equations. By the late 1850s there appeared in this group one of the great geniuses of all time, James Clerk Maxwell.

Maxwell set the foundations of the kinetic theory of gases in the 1860s. It was a time when many—maybe most—scientists and engineers still thought of heat as caloric, and Maxwell provided a succinct and precise description of the mechanism of heat propagation in gases. By predicting how energy was passed from molecule to molecule during collisions, he showed us what it

really meant to call heat a mode of motion. He published a textbook titled *Theory of Heat* in 1871, the same year he accepted the chair of experimental physics at the Cavendish Laboratory at Cambridge. When he died of cancer eight years later he was only 47 years of age.

Maxwell was succeeded at the Cavendish Laboratory by John Wm. Strutt—better known to us as Lord Rayleigh. He held the chair until 1884 and then moved to the Royal Institution of Great Britain, which Rumford had founded over 80 years earlier. From the viewpoint of the field of heat transfer, Rayleigh (like Stokes) did a vast amount of the preparatory fluid mechanics that would soon serve all areas of heat convection.

The English science of the late 19th century was soon joined by powerful German and Austrian contributions and by the American engineer J. Willard Gibbs, who was an entire scientific movement in himself. The moody Austrian, Ludwig Boltzmann, finished what Maxwell had begun. Beginning in the 1870s he advanced the kinetic theory of gases to the point at which it rationalized equilibrium thermodynamics completely and provided a far more powerful capability for predicting transport phenomena than Maxwell had reached.

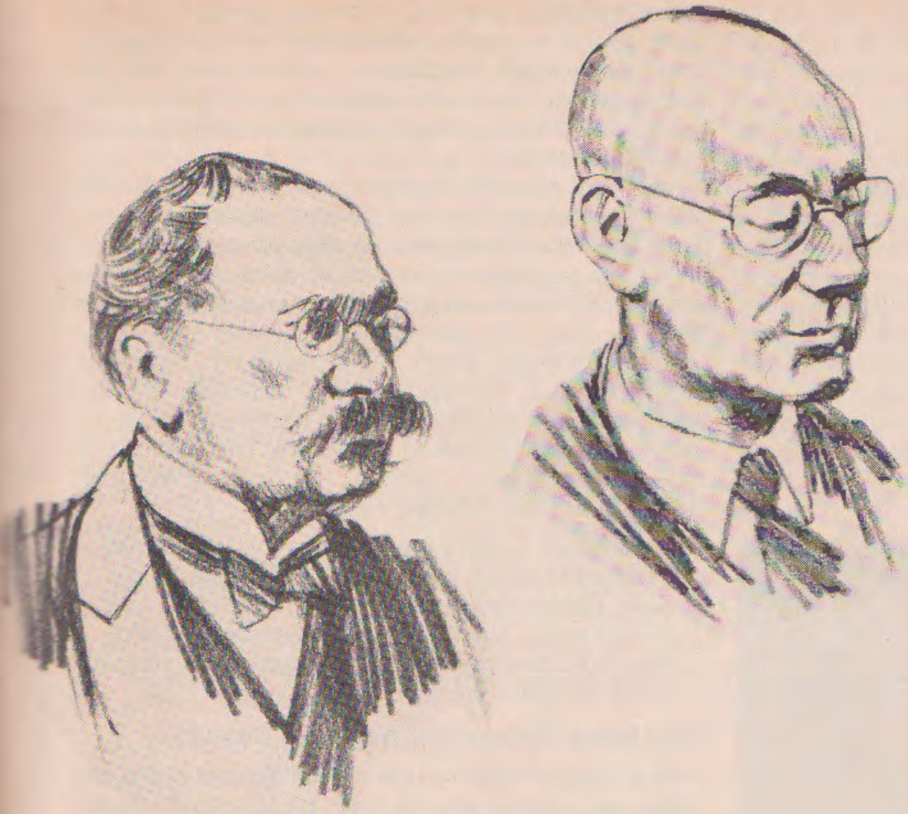
In 1884 Boltzmann turned his attention to the subject of thermal radiation, which had been attracting increasing attention since G. Kirchhoff showed the relation between emittance and absorbtance, in 1860. By 1879, another Austrian, Josef Stefan, had shown experimentally that the heat *radiated* from a hot, thermally black object, should rise with the fourth power of its absolute temperature. Boltzmann used a very clever heat-engine argument to prove that this was exactly true. The Stefan-Boltzmann law, of course, tells us nothing about the distribution of emitted energy in wavelength, but in 1889 the German physicists O. Lummer and E. Pringsheim produced measurements of this distribution, which were well defined and fairly screamed for theoretical interpretation.

The German physicist Willy Wien provided an imperfectly rationalized distribution law in 1896. It involved experimental constants and it slightly underpredicted the energy carried by the longer wavelengths. Lord Rayleigh attacked the problem next, and in 1900 showed how to obtain the distribution using classical statistical mechanics. His prediction was one of the grand failures of Victorian science. It bore no resemblance to the experimental data at any *but* the longest wavelengths, yet it was a perfectly correct use of the by then well-established Boltzmann statistics.

Max Planck's explanation of radiation followed a year later. He discovered, almost by accident, that if he assumed radiant energy could only occupy discrete energy levels, then the classical prediction could be made to work perfectly. It took another three decades for scientists to make sense of Planck's insight and to establish our modern concepts of quantum mechanics. By then, however, the subject of heat transfer had finally separated itself from physics and gained a life of its own.

From Science to Technology

Those of us whose primary identification is with the subject of heat transfer today see ourselves more as technologists than as scientists. Many of us feel a closer kinship with *making* and *doing* than we do with merely *observing* and *describing*, even when we are largely involved in investigating phenomena. Yet all of the char-



From left to right:

Benjamin Thompson

Baron Jean Baptiste Joseph Fourier

Josef Stefan

Leo Graetz

Max Jakob

acters we have mentioned, except Watt and Rumford, are primarily identifiable as scientists.

Heat transfer became an identifiable discipline—call it a technology, or a separate body of science—after enough practical problems arose to demand it. The first of these problems was that of heating or cooling the fluid flowing in a pipe. This problem was first treated in 1885 by Leo Graetz who showed how to set the problem up using the viscous flow equations. Of course the question of treating turbulent flow was not on Graetz's horizon.

Osborne Reynolds had only published his observations of the laminar-to-turbulent transition of pipe flow two years earlier and the world was far from dealing with the subject. Reynolds's studies of turbulence, condensation, and other complex phenomena that demand attention in an industrial world, were the work of an engineer. It is significant that the original apparatus with which he first demonstrated the laminar-turbulent transition in 1880 is *still in use* in an undergraduate experiment in the mechanical engineering department at the University of Manchester.

Another wind had risen in the middle of the 19th century, namely, the institution of purposeful research aimed at inventing the machines and products of industry. Boulton and Watt would not have considered setting up their own research division at the turn of the 19th century, but 50 years later such institutions became commonplace. Thomas A. Edison's famous laboratory, started in the 1870s, was typical of these. We trace the first industrial R&D laboratory to the one set up in 1825 by the German chemist Justus von Liebig, and it is out of this concept that the Germans evolved, and for many decades led, the field of technical heat transfer.

Technical Heat Transfer

At the turn of the 20th century the highly influential pure mathematician Felix Klein observed that there was an increasing gulf between industrial and academic research. He used his considerable influence to create a series of technical institutes at Göttingen University with the purpose of reuniting the studies of mathematics and technology.

The young Ludwig Prandtl was given a chair at one of these institutes in 1904. He immediately presented his celebrated paper on the boundary layer and articulated this idea during the next generation with such students as H. Blasius and Theodore von Kármán.

Wilhelm Nusselt also emerged as a technical force during these years. His seminal paper on convective heat transfer, published in 1915, actually had its antecedent in an earlier, 1909, paper. The dates are interesting because Nusselt used dimensional analysis to prove things about natural convection that analysts were still rediscovering in the 1960s (e.g., that the Grashof number is the product of two independent dimensionless groups). Since the basic discussions of dimensional analysis by Rayleigh and Buckingham did not appear until 1914 and 1915 we must presume that Nusselt did his work quite independently. In 1916, Nusselt's basic paper on film condensation appeared.

Nusselt only had a temporary appointment at Dresden University at the time. His more famous tenure in the theoretical mechanics chair at Munich did not begin until 1925 and lasted until Ernst Schmidt followed him in 1952. Both Schmidt, whose early contributions almost eclipsed those of Nusselt, and Nusselt himself, had begun at Munich as graduate students.

The creative power and scope of the early work of these people was really remarkable. German contributions in convection, conduction, radiation, and heat exchanger design continued through the 1920s almost as though World War I and the disastrous postwar period had not happened.

Any bright moment must eventually wane, but this one did not just wane. Hitler had clearly trumpeted his intentions, and two months after he took power in 1933, he began the systematic removal of Jews and "political unreliables" from universities and other state institutions. Good people—both Jews and Gentiles—were driven out or left of their own accord. What remained of the once mighty German technical-scientific establishment had been weakened and dispirited for an entire generation.

Max Jakob also trained in Munich, left Germany in 1936, and settled in Chicago. His heat transfer text, published in 1949, includes these words:

> In particular [I] allow ample space for the German literature of the 25 years before Hitler. Since, obviously, German science has doomed itself for a long time to come, knowledge of the German language among students will decrease accordingly, and the earlier literature will not be accessible.

Ernst Kraft Wilhelm Nusselt's application photo for BASF, 1916. (Photo provided by Nusselt's student, G. Lück.)

The United States—The Next Half Century

Heat transfer work in the United States during the 1930s and 1940s was focused strongly on industrial process problems. A number of very able chemical engineers—such people as Alan Colburn and William H. McAdams—characterized this movement. They were strongly interested in the development and correlation of good *data*, and less interested in methods of analysis than the Germans were. McAdams's *Heat Transmission* book, published in 1933, shaped American thinking and teaching for three decades.

Yet during this period, and even before German scientists were displaced onto our shores in great numbers, a window was opened in this country through which the advanced German literature could make its entry. In the summer of 1932, H.A. Johnson and V.H. Cherry retreated to a cabin in California's Santa Cruz mountains. There they developed an extensive revision of a set of instructional notes that L.M.K. Boelter had written for the heat transfer course at Berkeley. Boelter and his group read the German literature and textbooks of the time and were involved with developing their own synthesis of the material. R.C. Martinelli joined Berkeley in time to contribute to the 1941 version of the notes.

When the smoke of World War II had cleared, the notes had wrought their influence in training a major set of the heat transfer luminaries of our generation. They have also been strongly reflected in every significant American textbook that has appeared in the last 30 years.

Berkeley and Max Jakob were not the only major ports of entry for the German expertise. Another very influential person has been E.R.G. Eckert. Eckert, who had studied with Ernst Schmidt, came to Wright-Patterson Air Force Base from Germany just after WW II. There he met a Berkeley student, R.M. Drake, Jr., who first encouraged, and later contributed to, the 1946, 1950, and 1959 editions of Eckert's English book. It, and Jakob's book, were the first modern U.S. heat transfer texts.

The 1930s and 40s were rather fallow years for the subject of heat transfer. The world was preoccupied with the short-term problems of arming and fighting. But after the Korean War an American version of German technical heat transfer burst out, armed with new tools: The most important of these was surely the electronic computer. The hot wire anemometer and other electronic instrumentation also changed the character of experimental investigation significantly. Berkeley and MIT, which had been strong during the fallow period, remained so. Now several new centers arose. For example:

- Boelter moved to UCLA in 1944 and brought with him both able people and radical theories of engineering education. Consequently the school enjoyed a long history of major contributions to heat transfer in the United States.
- Eckert moved to the University of Minnesota in 1951 and established a powerful heat transfer laboratory.
- The Analytical Section at the NACA Lewis research center (subsequently renamed NASA) was probably our strongest focus of heat transfer and fluid mechanics research during the 1950s and 60s. It was virtually dismantled by the government during the aerospace cutbacks that ushered in the 1970s.

The efforts of Americans during the 50s and 60s were directed at the existing problems of radiation, convection, and conduction. But a major new subject also arose during this time, namely, heat transfer with phase change. Work on phase-change problems has been strongly driven by industrial needs, but the field has remained undisciplined. That might give it greater vitality than the other areas, but it also robs it of academic respectability. Universities tend to teach the subject only on an *ad hoc* basis; an introductory text has yet to be written; and, since most of its major practitioners are still alive, none have yet been canonized by the profession.

Another manifestation of the American adoption of the subject of heat transfer was the formation in 1938 of the Heat Transfer Division of ASME, followed by the institution of both the *Journal of Heat Transfer* and the annual Heat Transfer Conferences in 1959. Prof. S. Peter Kezios has recently presented us with a history of the Division.

Of course heat transfer has become a strongly multinational pursuit since WW II. The International Heat Transfer Conferences (now repeating in a four-year cycle) were begun in 1951, and the *International Journal of Heat and Mass Transfer* was initiated in 1958. Many other international forums have been created subsequently.

Heat Transfer in the Late 20th Century

The major change in the field of heat transfer during the past decade was a great shift away from the development and refinement of the body of theory, and toward the pursuit of "mission-oriented" objectives. During the 1960s, many people were worried about a rising tendency to publish solutions to problems that didn't really exist. We have swung far in the opposite direction during the 1970s, and have achieved some very useful results.

Heat exchanger analysis was neglected during the 1960s, but during the 70s we vastly expanded the variety of design concepts and analytical methods in this area. The development of melting-freezing storage devices, of fluidized bed technology, of solar energy utilization schemes, of high-intensity heat transfer devices, of methods for computing turbulent boundary layer heat transfer, and of the analysis of heat transfer with phase change, all progressed strongly during the 1970s. Throughout all this, the computer has assumed a steadily rising role.

The change to a more practical set of mind was strongly motivated by various funding agencies that felt they had supported too much purposeless work in the late 50s and throughout the 60s. In many ways the change has been a breath of fresh air. On the other hand, we are picking fruit from an orchard that we have been cultivating for a long time, more than we are cultivating next year's orchard. It is easy to let the heart go out of our work when we do this. We are at our best when we mix abstract and applied thinking.

And the need for abstract thinking will still be with us as we close out the century. It will be driven by our relentless need to increase the *intensity* of heat transfer processes. We will need a better understanding of the thermodynamic issues involved with large temperature and concentration gradients, with metastable states, with coupled processes, and with reactions. More than anything, we will have to rewrite many of today's explanations of complex phenomena, because they are simply not accurate enough when heat fluxes reach the values to which we are pushing them.

There is a lesson to be learned from our history. It is that each major leap forward in the field has always occurred here or there, lingered for a generation, and then a new leap forward has occurred in another place. The United States has dominated heat transfer for 30 years. This does not mean that we must now cease to be strong contributors, but we well might wonder where, and in what form, the next major leap forward will occur. ME

Readings

Some of the larger sources for material in this article, and some additional material as well, are included for the reader who wishes to pursue these matters further.

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