ELECTRIC POWER RESEARCH INSTITUTE

EPRI JOURNAL

MARCH
1979

Creating the Electric Age

ROOTS OF INDUSTRIAL R&D

This issue of the *EPRI Journal,* which examines the growth of electrification and the roots of modern R&D, has been prepared to commemorate the invention of the incandescent lighting system by Thomas Alva Edison 100 years ago. It looks at this past century in the hope of enhancing our understanding of the roles of science and technology in society today and of their relationship to the human prospect.

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Objectives of the Issue

On the occasion of the 100th anniversary of Edison's invention of a practical electric lighting system, the editors of the *EPRI Journal* have reexamined some of the major episodes in the electrification of our society. This special issue is the result of that study.

It has been observed that Edison was not a solitary inventor of the old school but a "transitional figure who pointed the way toward the systematic research of the technological age." Thus, it seems appropriate for an Institute dedicated to systematic research and development to trace some of the roots of modern R&D from the Edison era. During this past century, in fact, R&D has been the armature on which the electric light and power industry has been shaped. Electrification has had an extraordinary effect on peoples' livelihood and ways of life. Consequently, these three threads—the impact of electrification on man and society, the growth of the electric industry, and the evolution of R&D—are interwoven in this issue commemorating Edison's achievement in 1879.

In the process of developing this special issue of the *EPRI Journal*, many members of EPRI's staff and other organizations interested in the evolution and impact of electrification have made contributions in planning, counsel, information, research, writing, editing, and production; credits and particular acknowledgements appear on the inside of the back cover. Here, we would like to acknowledge especially the invaluable guidance and advice of four eminent historians of science and technology, who served as special advisors to this project. They are: James E. Brittain, Associate Professor of the History of Science and Technology, Georgia Institute of Technology; Bernard Finn, Curator, Division of Electricity and Nuclear Energy, Smithsonian Institution; Thomas Parke Hughes, Professor of History of Technology, University of Pennsylvania; and Charles Süsskind, Professor of Engineering Science, University of California, Berkeley.

Although our advisors are not responsible for the final form and outlook of this issue, it was, in part, their recommendation that led us to deal only with selected, well-documented episodes in the history of electrification. Surprisingly, from an historian's perspective, there are many areas in this relatively recent past that have not been fully explored. Even the Edison period itself is only now coming under new intensive scholarly scrutiny and reassessment.

There is considerable known documentation that no one has had time to explore and study; and many electric companies, utilities, and others probably have in their archives material that would be of great interest to historians of electricity were it to become available. Partly to redress this situation—this lack or loss of significant historical material—the Institute of Electrical and Electronics Engineers recently decided to establish the Center for Electrical Engineering History to help stimulate a wider interest in, awareness of, and concern for the history of electrification. It is our hope that this issue of the *EPRI Journal* will help to foster such wider interest.

Nilo Lindgren
Guest Editor

EPRI JOURNAL

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The Preelectric World

A new force, which has been glimmering on the horizon for more than a century, is about to change radically the way people live and work.

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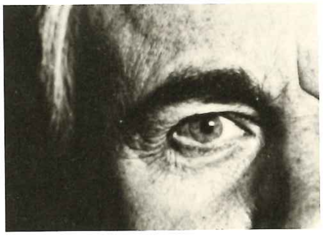

SEIZING THE MOMENT *Age of the Inventor-Entrepreneur*

A stubborn, driven, competitive man realizes the time is ripe; he senses the right trail, invents an entire electric lighting system, develops it, builds factories to produce it, and begins to market it to the world.

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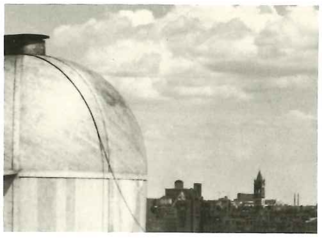

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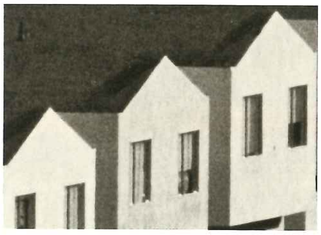

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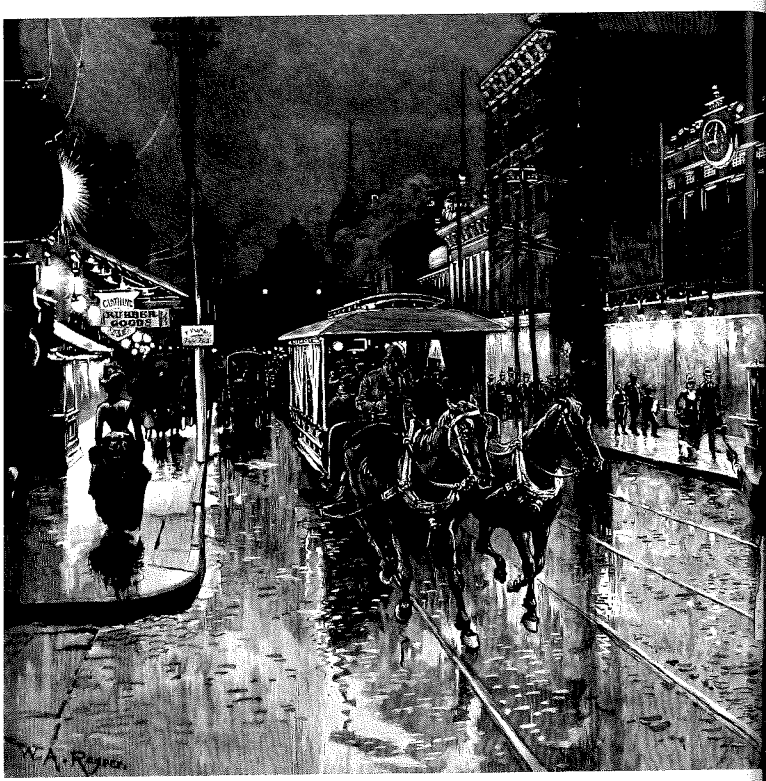
The Edison Heritage

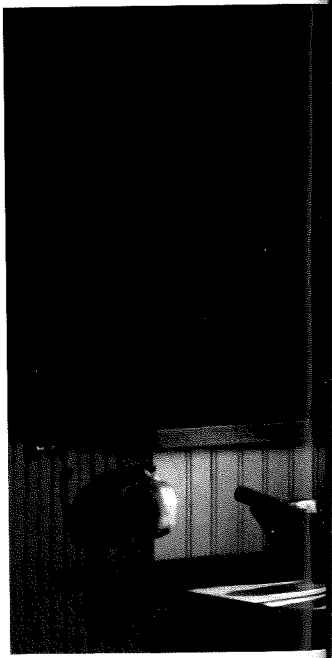
After a century of electrification, society appears to be crossing a new threshold of change perhaps as profound as that of the Edison era.

The Preelectric World

Our world began in the last quarter of the nineteenth century. It is almost no exaggeration to say that. With the invention of practical incandescent lighting, the dynamo, and the electric motor, man's ways of livelihood and means of life were irrevocably and massively transformed. The year 1879 marks the threshold. Thereafter, the juggernaut of worldwide electrification was irreversible.

Scarcely anything of the world before electrification has remained untouched: how things work, how and where work gets done, how people are transported, how food is cooked and served, how people keep in touch, the kinds of paintings they hang on



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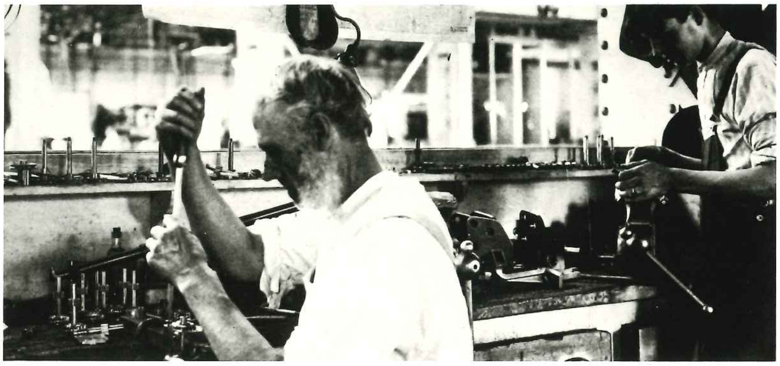
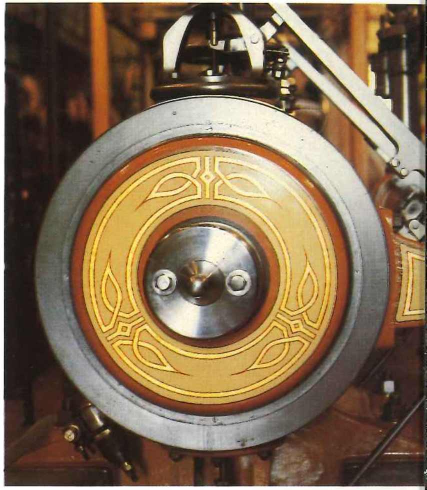
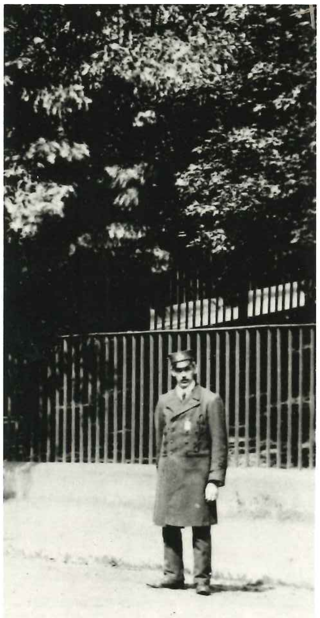
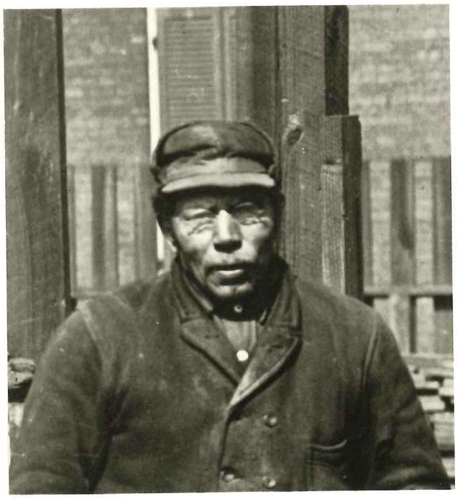
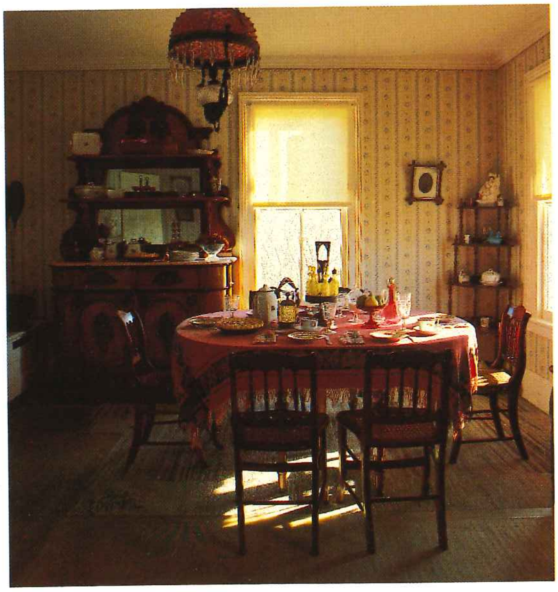


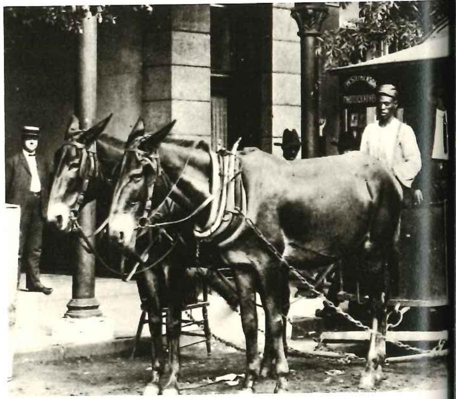


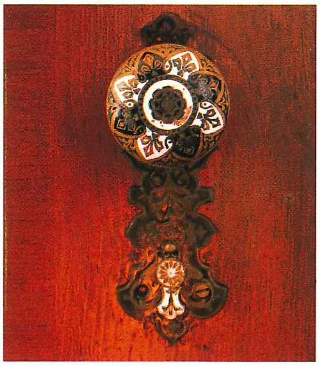



JAMAICA POND ICE CO.
2589 WASHINGTON ST.









their walls, what they see in the man-made world around them. The very smell of cities has been altered.

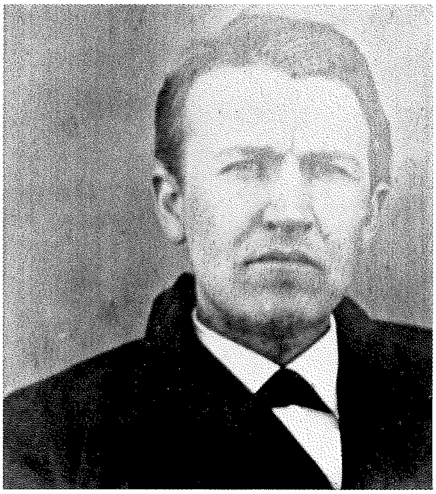
In some ways, one can imagine nineteenth-century preelectric cities as closer to the spirit of the cities of the Middle Ages—the alternations of night and day were more marked; many of the tools of the crafts and trades were recognizably ancient; and horses still pulled wagons in the streets. But their consciousness was closer to those cities of the twentieth century in their zest for technological innovation; optimism, commercialism, hurry, and pressure were in full stride.

Something was stirring—the people of the last quarter of the last century sensed themselves on the brink of something momentous. They knew they were about to undergo, or were already undergoing, a profound transition from one style of life to another. Only the form of the change was not yet clear.

Edison wasn't the first to be working on incandescent lighting; work began as early a
1802. However, by Edison's period, the time was ripe, and Edison seized the opportunit
What made the crucial difference in his success—as he boasted—was the fact that he ha
an organized group, an organized laboratory, better resources, and a powerful methodolog
His practical orientation also made a real difference. He analyzed the gas lighting industr
studied its strengths and weaknesses, its method of distribution, its customers, economic
—everything. Only after this study did he begin bending electricity to the solution of th
problem. From then on, the road to success was certain—at least in Edison's vision.

SEIZING THE MOMENT

Age of the Inventor-Entrepreneur



Edison, age 30

The breakthrough came late in 1879 in Edison's laboratory in Menlo Park, New Jersey. Sometime between the evening of October 21st and the evening of October 22d, Edison and a small group of his associates maintained a watch over a thread that burned undiminished hour after hour in a glass bulb from which most of the air had been removed. Although the records are conflicting, that long watch came to be known as the 40-hour vigil, during which the researchers of Menlo Park realized that after more than a year of agonizing efforts, of seemingly endless trials, and of a near-blind process of elimination they had crossed over the threshold to success in their cooperative quest.

The dim reddish light of the incandescent filament, as Edison had named it, seemed to them one of the most beautiful sights in the world. As it became clear that the fragile carbonized thread could survive, Edison concluded the experiment by turning the voltage higher and higher so that the light grew brighter and brighter until suddenly it burned out. As Matthew Josephson depicts the scene in his classic biography of Edison, the men broke into cheers, and Edison announced, "If it can burn that number of hours, I know I can make it burn a hundred."

It was a mere nothing, a fragile glass bulb, a carbonized piece of ordinary sewing thread, two pieces of platinum, and a sealed vacuum—not a perfect vacuum, but the very best achievable at that time. Yet this bare nothingness became the most breathtaking and elegant solution to one of the most perplexing problems of that period—namely, how to make a solid material luminous without burning it up. The incandescent light was the key to a system of domestic electric lighting that was to displace gas illumination.

Microscopic examination of the carbon filament revealed that the carbon had changed in character while it burned. It had become harder, more durable, more resistive, and more stable in its behavior, thus obviating the need for various regulatory devices that Edison had thought might be necessary. The solution, for the incandescent light at least, looked simpler and cleaner than they could have hoped for. Through earlier trials in the late summer and early fall of 1879, Edison and his men had come to realize that carbon could serve as the high-resistance element they had been seeking and that the key to success could lie in the development of an extremely high vacuum. In an authoritative article on the invention, Francis Upton, Edison's mathematician, attributed the success to advances in vacuum technology. Had vacuum technology been sufficiently advanced, preceding decades of experiments with enclosed incandescent lights and evacuated bulbs by other inventors might conceivably have succeeded.

However, there were many other factors that contributed to Edison's success at that moment. One, absent from many other inventors and researchers, was the irrational persistence, the lust for success that was Edison's special demon and made him appear a near-wizard in many people's eyes.

As Josephson observes, "Edison himself never wavered in his assertion that he was not a wizard or a genius—in fact, he despised the designation. When an acquaintance once referred to his 'Godlike genius,' Edison snorted, 'Godlike nothing! Sticking to it is the genius! Any other bright-minded fellow can accomplish just as much . . . if he will stick like hell and remember nothing that's any good works by itself just to please you. You got to make the damn thing work'."

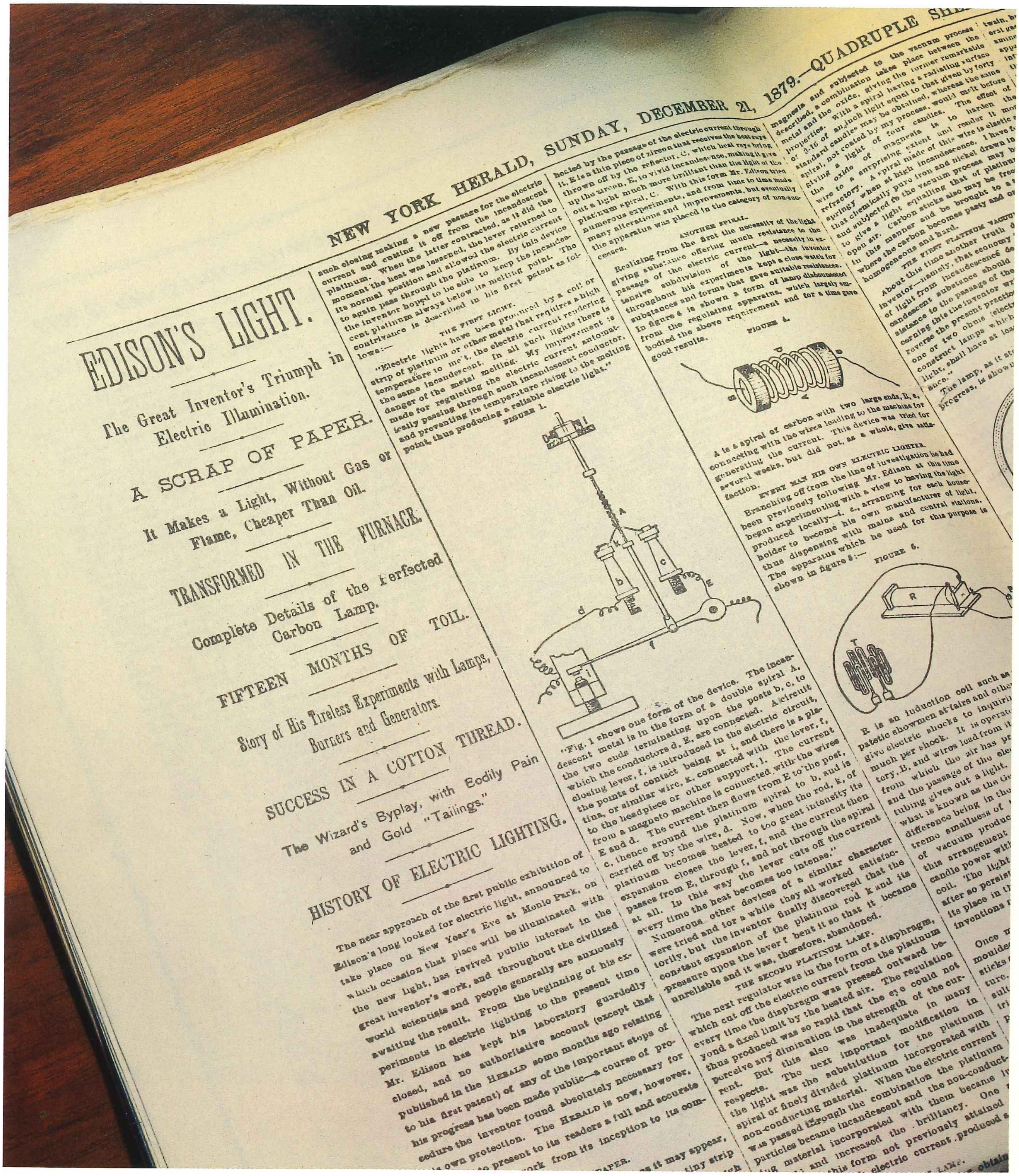
That persistence and overweening ambition had seen Edison and his crew—Batchelor, Kruesi, Upton, Jehl, Boehm, and others—through countless obstacles and had drawn their combined inventiveness and skills to extraordinary lengths. From the time Edison seriously started his pursuit of the incandescent light in September 1878, his "invention factory" had made thousands of trials in the Menlo Park laboratory, using uncounted numbers of materials for filaments and leads, and had designed and invented numerous elements—generators, regulators, wiring methods, insulation materials—that would be needed in a practical system of domestic lighting.

Edison had started with carbon for the burners, a material he had come to understand and appreciate in his work with telephones, but he had moved on to other materials. Then, after long efforts with platinum and as different experimental results began to fall together, he returned to carbon in July 1879 after reading about new experiments by Joseph Swan in England. Swan, who had abandoned incandescent experiments a decade earlier, had returned to the effort under the impetus of new and better vacuum equipment. It allowed him to keep a piece of carbon lit for several minutes in a vacuum. However, the crucial design decision that allowed Edison to outdistance Swan and others and that was a factor in later lawsuits on both sides of the Atlantic was Edison's development of a very fine, high-resistance filament that could be subjected to a constant voltage and that could carry a very small current, the opposite objective of other inventors.

On October 6th, using a new vacuum pump designed by Upton and another colleague, Edison's team discovered that they could create vacuums in which only one millionth of an atmosphere of air remained. About that same time, Charles Batchelor noted that silicon might be a good insulator for the platinum contacts; moreover, silicon was compatible with glass, thus reducing the problems of getting good seals on the vacuums. These and other factors lent a great air of anticipation and renewed intensity to their research efforts.

Yet, toward the end Edison had almost concluded that the incandescent light might indeed be an impossibility (he had set out to prove the case one way or the other), and he had begun to turn his thinking toward central stations to generate electric power for running motors, elevators, traction machines, sewing machines, and the like. At one point, when Edison was nearly overwhelmed by failures, when he was being derided in the press for his ridiculous claims, when his financial backers (including the giant J. P. Morgan) had become extremely skeptical and were trying to make him appear in New York for an accounting, he took to his bed. But supposedly after several days he rose refreshed and went back to the battle and soon was issuing typical announcements through the press that the electric light was an accomplished fact.

But Edison had made his boastful claims too often, and the financiers, the press, and the public remained skeptical. When Edison finally did make the breakthrough, there was still skepticism and derision. Only as visitors began to trickle out to Menlo Park in the latter weeks of 1879 to see the actual lights did doubt begin to be transformed into belief. Then, on December 21, 1879, the New York *Herald* printed its exclusive full-page account of Edison's spectacular success. By New Year's Eve, the news of Edison's invention had created such excitement that several thousand people went to Menlo Park by special trains and every other conveyance possible. The visitors were ecstatic at what they saw—lights strung up on poles around Menlo Park and the laboratory buildings aglow. It was reported that people found it difficult to tear their eyes away from those marvelous new electric lights.



Facsimile of the famous New York *Herald*'s exclusive story announcing Edison's success.

NEW YORK HERALD, SUNDAY, DECEMBER 21, 1879.—QUADRUPLE SHE

EDISON'S LIGHT.

The Great Inventor's Triumph in Electric Illumination.

A SCRAP OF PAPER.

It Makes a Light, Without Gas or Flame, Cheaper Than Oil.

TRANSFORMED IN THE FURNACE.

Complete Details of the Perfected Carbon Lamp.

FIFTEEN MONTHS OF TOIL.

Story of His Tireless Experiments with Lamps, Burners and Generators.

SUCCESS IN A COTTON THREAD.

The Wizard's Byplay, with Bodily Pain and Gold "Tailings."

HISTORY OF ELECTRIC LIGHTING.

The near approach of the first public exhibition of Edison's long looked for electric light, announced to take place on New Year's Eve at Menlo Park, on which occasion that place will be illuminated with the new light, has revived public interest in the great inventor's work, and throughout the civilized world scientists and people generally are anxiously awaiting the result. From the beginning of his experiments in electric lighting to the present time Mr. Edison has kept his laboratory guardedly closed, and no authoritative account (except that published in the HERALD some months ago relating to his first patent) of any of the important steps of his progress has been made public—a course of procedure the inventor found absolutely necessary for own protection. The HERALD is now, however, present to its readers a full and accurate ork from its inception to its com-

APER.

s it may appear,

tiny strip

such closing making a new passage for the electric current and cutting it off from the incandescent platinum. When the latter contracted, as it did the moment the heat was lessened, the lever returned to its normal position and allowed the electric current to again pass through the platinum. By this device the inventor hoped to be able to keep the incandescent platinum always below its melting point. The contrivance is described in his first patent as follows:—

THE FIRST LIGHT.

"Electric lights have been produced by a coil or strip of platinum or other metal that requires a high temperature to melt, the electric current rendering the same incandescent. In all such lights there is danger of the metal melting. My improvement is made for regulating the electric current automatically passing through such incandescent conductor and preventing its temperature rising to the melting point, thus producing a reliable electric light."

FIGURE 1.

"Fig. 1 shows one form of the device. The incandescent metal is in the form of a double spiral A, the two ends terminating upon the posts b, c, to which the conductors d, E, are connected. A circuit closing lever, f, is introduced in the electric circuit, the points of contact being at i, and there is a platina, or similar wire, k, connected with the lever, f, to the headpiece or other support, l. The current from a magneto machine is connected with the wires E and d. The current then flows from E to the post, c, thence around the platinum spiral to b, and is carried off by the wire, d. Now, when the rod, k, of platinum becomes heated to too great intensity its expansion closes the lever, f, and the current then passes from E, through f, and not through the spiral at all. In this way the lever cuts off the current every time the heat becomes too intense."

Numerous other devices of a similar character were tried and for a while they all worked satisfactorily, but the inventor finally discovered that the constant expansion of the platinum rod k and its pressure upon the lever f bent it so that it became unreliable and it was, therefore, abandoned.

THE SECOND PLATINUM LAMP.

The next regulator was in the form of a diaphragm, which cut off the electric current from the platinum every time the diaphragm was pressed outward beyond a fixed limit by the heated air. The regulation thus produced was so rapid that the eye could not perceive any diminution in the strength of the current. But this also was inadequate in many respects. The next important modification for the light was the substitution for the platinum spiral of finely divided platinum incorporated with non-conducting material. When the electric current was passed through the combination the platinum particles became incandescent and the non-conducting material incorporated with them became lu and increased the brilliancy. One this form not previously attained electric current produced a

LAMP.

heated by the passage of the electric current through it. E is a thin piece of zircon that receives the heat rays thrown off by the reflector, C, which heat rays bring up the zircon, E, to vivid incandescence, making it give out a light much more brilliant than the light of the platinum spiral, C. With this form Mr. Edison tried numerous experiments, and from time to time made many alterations and improvements, but eventually the apparatus was placed in the category of non-successes.

ANOTHER SPIRAL.

Realizing from the first the necessity of the light giving substance offering much resistance to the passage of the electric current—a necessity in extensive subdivision of the light—the inventor throughout his experiments kept a close watch for substances and forms that gave suitable resistances. In figure 4 is shown a form of lamp disconnected from the regulating apparatus, which largely embodied the above requirement and for a time gave good results.

FIGURE 4.

A is a spiral of carbon with two large ends, B, c, connecting with the wires leading to the machine for generating the current. This device was tried for several weeks, but did not, as a whole, give satisfaction.

EVERY MAN HIS OWN ELECTRIC LIGHTER.

Branching off from the line of investigation he had been previously following Mr. Edison at this time began experimenting with a view to having the light produced locally—i. e., arranging for each householder to become his own manufacturer of light, thus dispensing with mains and central stations. The apparatus which he used for this purpose is shown in figure 5:—

FIGURE 5.

R is an induction coil such as patetic showmen at fairs and other give electric shocks to inquirin much per shock. It is operat tery, B, and wires lead from it from which the air has pr and the passage of the ele tubing gives out a light. what is known as the Ge difference being in the tremo smallness of of vacuum produc this arrangement candle power with coil. The light after so persist its place in th inventions r

Once m moulde sticks ture. sult tri

magnesia and subjected to the vacuum process described, a combination takes place between the metal and the oxide, giving the former remarkable properties. With a spiral having a radiating surface of 3-16 of an inch light equal to that given by forty standard candles may be obtained, whereas the same spiral, not coated by my process, would melt before giving a light of four candles. The effect of the oxide of magnesia is to harden the wire to a surprising extent and render it mor refractory. A spiral made of this wire is elastic springy when at high incandescence. I have f that chemically pure iron and nickel drawn in and subjected to the vacuum process may b to give a light equalling that of platinu open air. Carbon sticks also may be free in this manner and be brought to a where the carbon becomes pasty and o homogeneous and hard.

THE FIRST PLATINUM VACUU

About this time another truth d inventor—namely, that economy of light from incandescence de candescent substance should sistance to the passage of the cerning this the inventor wr reverse the present practic one or two ohms (electr construct lamps which light, shall have at lea ance."

The lamp, as it st progress, is shown

The process of invention and the factory system

A leading American historian of technology, Thomas Hughes, has called the factory system "the most impressive general concept explaining the Industrial Revolution." It is clear, in fact, that the use of inanimate motive power based on steam encouraged a division of labor that was translatable, through machinery, into a division of power.

The mechanization of production had been going on for more than 50 years before Andrew Ure, a British engineer, gave it definitive expression in *The Philosophy of Manufacture,* published in 1835. Ure's system called for the substitution of mechanical science for hand skill, the division of the productive process into basic mechanizable components, and the organization of those components into a steady repeatable process of assembly of desired products. (In his teens Edison had studied his work.)

Conceived in Britain, the factory system and the methods of mechanization took root in the United States, where shortage of labor, costliness of skilled labor, and abundance of raw materials all supported its adaptation and where there was little craft-based opposition to mechanization. By the 1860s the habits of mechanical analysis and synthesis became a prominent stimulus to American inventiveness. Meanwhile, in Germany (the other nation that would surpass Britain technologically by the close of the century) British factory techniques were imported and implemented. They were also incorporated into an educational system that helped develop the German technical institute system.

The factory system method of production, the arrangement of mechanized action to produce a desired output, may well have inspired the invention of organized invention. For instance, the work at Menlo Park used an orderly division of labor, although it wasn't steam-driven machinery that dictated the division. The "motive force" was Edison and Edison's vision that the system of electric light could be developed through a methodical process of trial and error. It was abetted by strong belief that the goal could be achieved through development of a high-resistance incandescent filament.

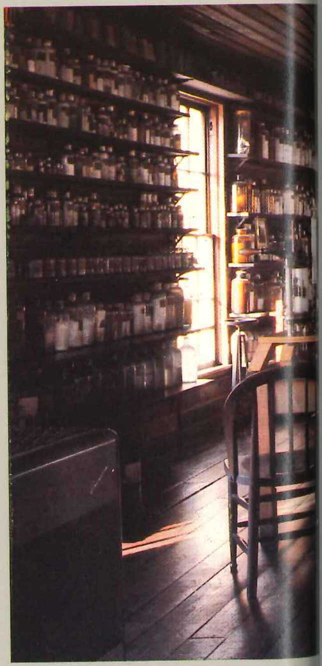
In order to realize the goal, Edison structured the work in the Menlo Park laboratory. Highly skilled workers performed tasks that compensated for the unavailability of basic theory or knowledge of the relevant structure or properties of materials. Hands and senses sought what theory might today predict, although a working background in physics and chemistry did influence many of the decisions.

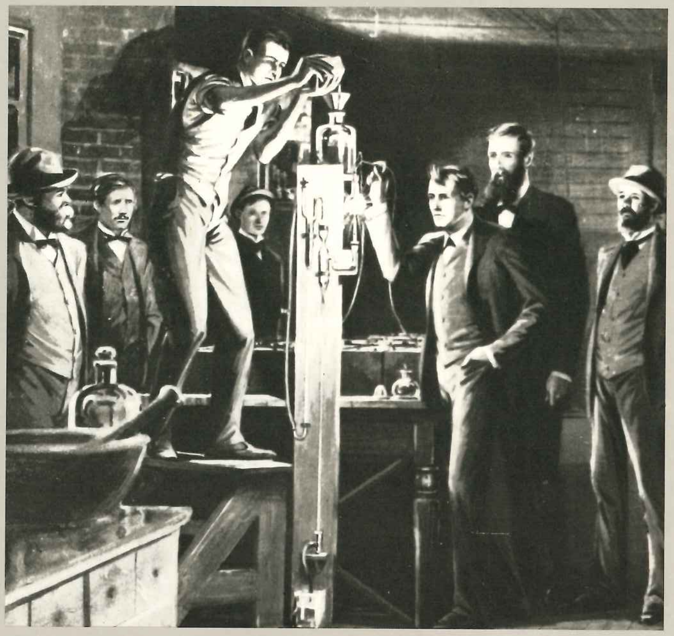
The workers carried out a disciplined attack; they used a standard procedure through most of their 4000 or so trials of potential filament materials. For each trial, Edison himself selected the raw materials to be tested and prepared a filament. Another man carbonized the filament; a third supplied hand-crafted copper and platinum elements; and a fourth blew a glass stem and inserted the copper and platinum wires. The chain continued. The carbonized filament was placed on the glass stem by one man; the stem and filament were enclosed in a glass bulb by another man. The next worker placed the bulb on a vacuum pump and evacuated the air. Then Edison heated the filament, removed the gases released by the heated metal, and forwarded the bulb for systematic observation and testing.

This concept of arranging a rational search procedure and persisting in it in trial after trial has been of lasting significance. So has the scale of Edison's research (prohibitive for inventors less credible to investors than Edison). The scale and the repeated procedure are just two suggestive resemblances between the factory method and Edison's method.

Today, research, development, and production have all evolved into highly specialized functions. They can be carried out in isolated environments under controlled conditions, whether in laboratory or factory. Certain aspects of both the scientific method and factory production rely on precise repetition to ensure reproducible results or standardized products.

In both, the identity of the individual carrying out the task is relatively unimportant; one might even assert that once an inventive process is organized, any competent worker can carry out the specified functions.

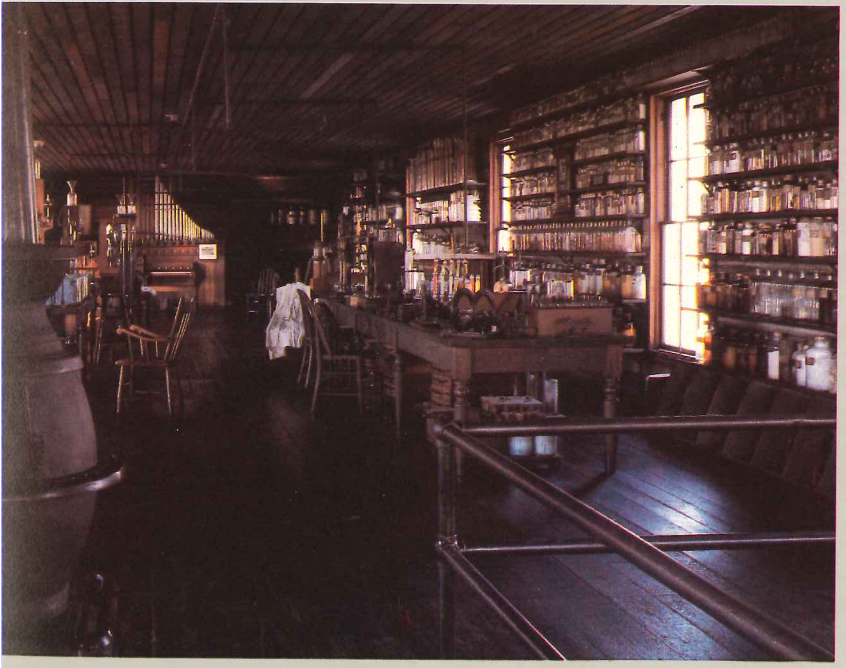


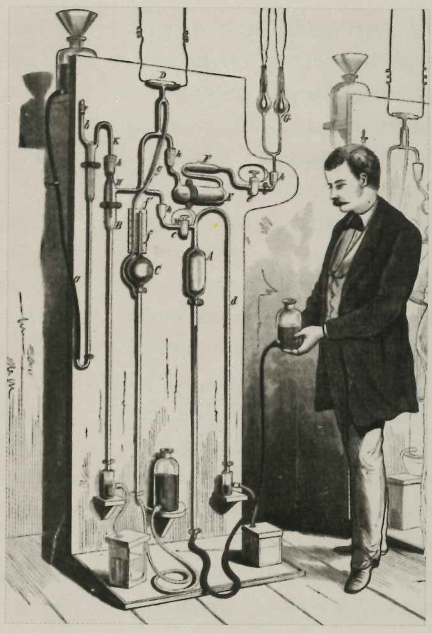


On the eve of the breakthrough, Edison and his olleagues prepare the incandescent lamp for testing: (from left) John Kruesi, Martin Force, Francis Jehl, (pouring mercury in the Sprengel vacuum pump), Ludwig Boehm, Edison (driving out occluded gases from the filament with electric current from a battery), Francis Upton, and Charles Batchelor.

e mercury pump for producing high vacuums was the crucial technology that made the incandescent light ssible. Wrote Upton, "Following the laws of discovery, it has been for some time a speculation of the riter that the wonderful perfection to which vacuums been brought pointed historically toward some direct connection between them and the electric lamp."

elow is Edison's Menlo Park laboratory as re-created at the Henry Ford Museum in Dearborn, Michigan.

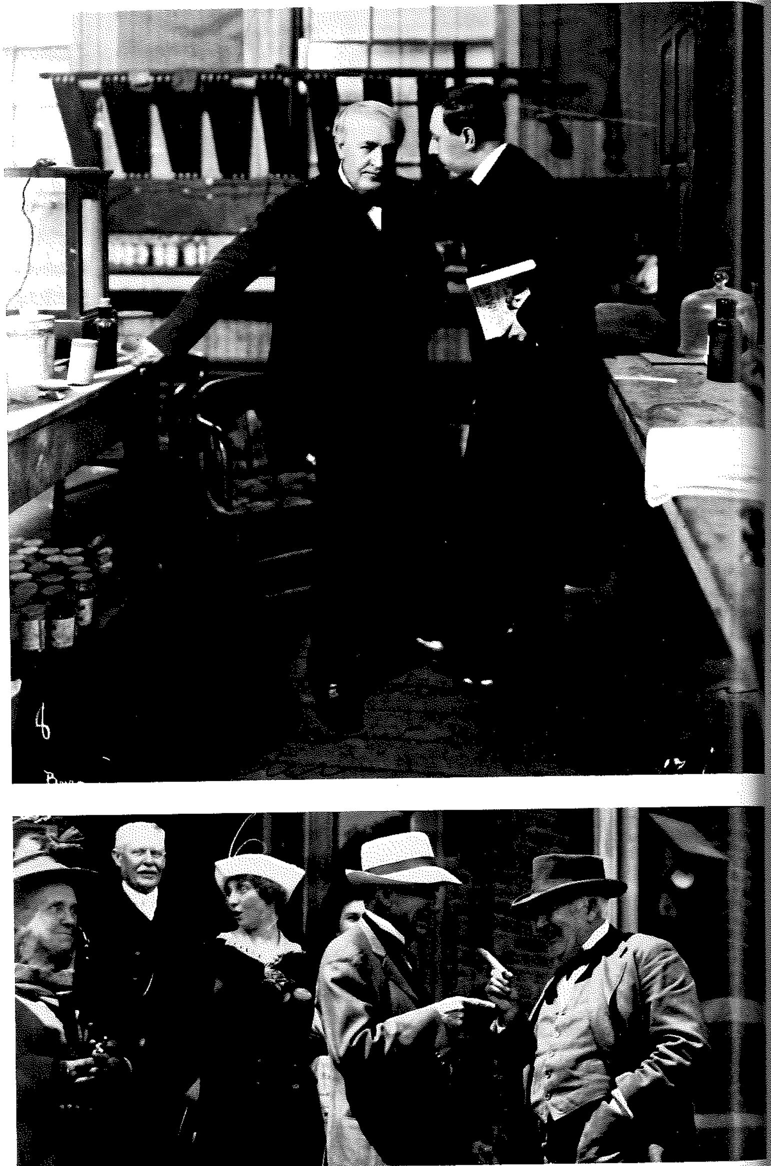




Growth of the legend

Around that moment of a century ago, many legends have been woven about the making of the magic light, about the laboratory in Menlo Park in which the problem was solved, and about the person of Edison—legends that Edison himself helped to foster. To enliven his first official biography, for instance, he evidently told his biographers (Dyer, Martin, and Meadowcroft) a lot of stories with little concern for accuracy, and that early biography became the source for many successive writers. So interwoven were fact and fiction that today they are still difficult to sort out. This might seem slightly amazing; after all, it all happened just a century ago. Extensive laboratory records and notebooks were kept by Edison and his colleagues; "authorized" and scholarly biographies, such as that by Josephson, have been written; and thousands of articles have been published. Yet, a new biography of Edison, written by Robert Conot, who spent many months in the enormous Edison archives in West Orange, New Jersey, raises many new questions regarding the established image of Edison, and a newly launched 10-year scholarly program based at Rutgers University promises fresh insights into this seminal figure of universal electrification.

The evidence indicates that Edison, who had grown up in the Midwest when the telling of tall tales was an indigenous American art, was not loath to embellish the details of his own life. For instance, the famed 40-hour vigil may have been a transposition of a death watch that Edison and his colleagues actually conducted in 1879 between Friday, October 17th, and Sunday, October 19th, while they waited for news about Edison's nephew, who lay dying in Paris. Even Edison's famed ability to go without sleep is now disputed as more Edison theory than Edison fact. Said one familiar, "His genius for sleep equaled his genius for invention. He could go to sleep anywhere, anytime, on anything." And according to Conot, a colleague wrote to



Edison was a man of many sides, one being that of the practical jokester. On one occasion, when Edison was about to be interviewed, a colleague relates, "While th reporter was being ushered in, the Old Man disguised himself to resemble the heroic image of 'The Great Inventor, Thomas A. Edison' graven in the imagination of those who have no imagination. Suddenly gone were his natural boyishness of manner, his happy hooliganism. His features froze into immobility, he became statuesque . . . and his unblinking eyes assumed a faraway look like a circus lion thinking of the Nubian desert. He did not stir until the reporter tiptoed right up to him, then he slowly turned his head, as if reluctant to lose the vision of the Nubian desert." The next day the journalist wrote of the formidable "Wizard of Menlo Park On many other occasions, however, Edison was the irrepressible storyteller.

Edison after reading one of his early accounts, "You can invent history as easy as other things. Now that Mark Twain has retired as humorist you are in line of promotion."

The new studies, however, do not threaten to disturb his image as an American culture hero or diminish his achievements. They will undoubtedly verify his role in the introduction of universal electrification, and they may succeed in illuminating further his role in establishing an organized process of invention, which may be seen as one root of modern R&D. As Edison's colleague Francis Jehl said in observing how closely Edison worked with his collaborators, "Edison is in reality a collective noun and means the work of many men." Such an appraisal is much more consonant with modern R&D experience than with the legend of towering individual genius.

To appreciate the specific nature of Edison's achievements and inventive drive, one must step back into the post–Civil War era to look at the state of the art of the electric light, at the preelectric society, at the entire field of inventive activity, both in the United States and abroad, at Edison's earlier career and approach to invention, and at the gas illuminating industry. Even a brief look reveals why Edison became a legend in his own time. More important, it shows that Edison not only invented a system of electric lighting, but he was also the principal creator of a system of invention that has had as deep an effect on this past century as electrification itself. Alfred North Whitehead, among others, regards the Edison approach to the method of invention as the greatest invention of the nineteenth century.

What emerges is the picture of a man who was defiant of authority, stubborn in his own path, willing to borrow freely, unlettered in the traditional sense, uncredentialed, and caustic about theorists.

Early influences on Edison

It is probably impossible to determine all the forces and influences that turned the young Edison into a professional inventor, but it is likely that the Civil War and its aftermath helped to shape his direction and his character. Edison was in his teens during the war and became an itinerant telegrapher soon after. Although he had been fascinated with chemical and electrical experiments from early childhood, it was during his period as a telegrapher that he took his first steps toward becoming a full-time inventor.

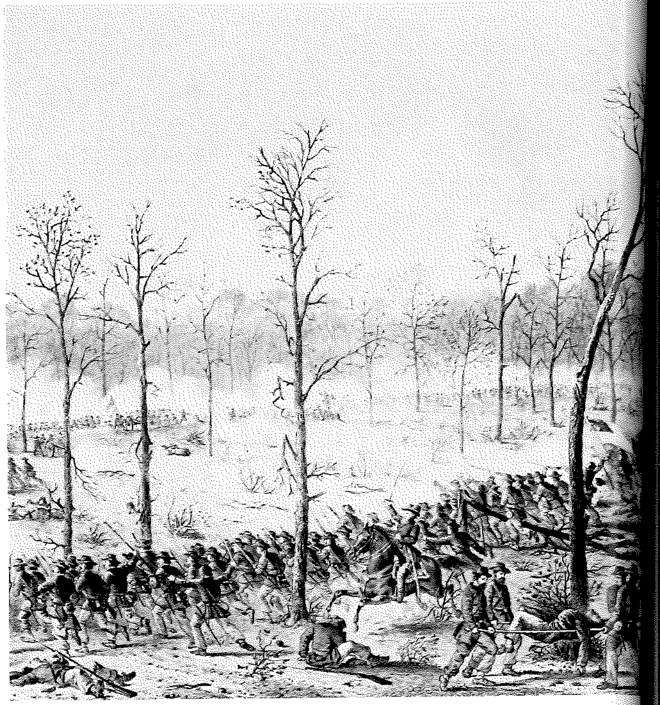
The Civil War precipitated profound changes, not only by its ferocity but also by its enhanced mechanization, and gave industrialization preeminence in America. In the two decades following the war, as if in preparation for electrification, industrialization gathered power and prestige. The freed blacks of the South and the immigrant laborers from Europe poured into the industrial basins of the North—Detroit, Cleveland, Chicago, Pittsburgh, New York. Thus, the old, nearly equal split of power between the planters and the traders was decisively altered. The traders—the capitalists and industrialists—were in charge, and the railroad and the telegraph rather than the horse, the canal, and the Mississippi steamboat were the emblems of change.

Inventions and inventors flourished in this period. The American conviction that each man was as good as the next spurred the mass production of former luxuries and transformed them into common household necessities. By 1865 mechanized apple peelers, knife cleaners, clothes wringers, and egg beaters, for instance, were found in many American homes.

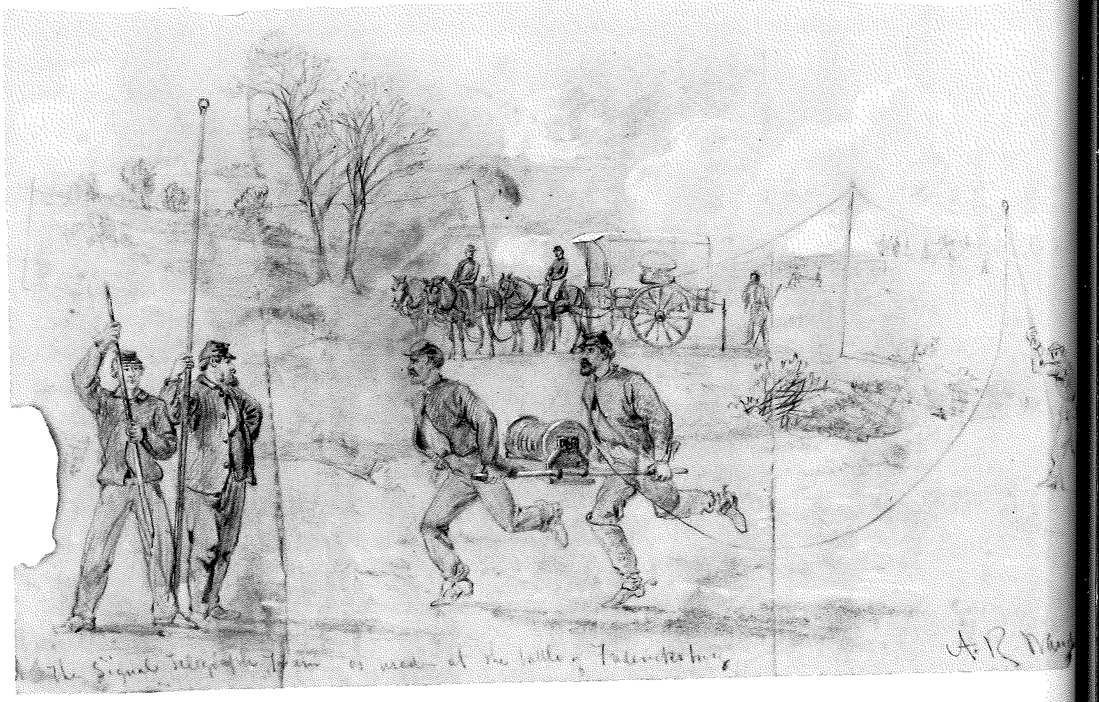
A long line of commercial inventors—Whitney (cotton gin, 1792), Fulton (steamboat, 1806), Hunt (safety pin, 1825), Colt (revolver, 1835), Morse (telegraph, 1844), Howe (sewing machine, 1846), Scholes (typewriter, 1867), and Hills (lawnmower, 1868)—had become American heroes and inspired young men to follow in their tracks. In the 1830s Alexis de Tocqueville had noted how Americans esteemed technologists: "Every new method," he wrote, "that leads by a shorter road to wealth, every machine that spares labor, every discovery that facilitates pleasures or augments them, seems [to Americans] to be the grandest effort of the human intellect." The prestige associated with practical inventions was in itself a powerful incentive to young men like Edison and many of his contemporaries.

In the post–Civil War period itinerant telegraphers like Edison possessed a craft and a skill that allowed them to work and drift wherever they would. They were a fraternity, were all in touch with one another, and could easily find a bed and a new post. They experimented and learned, sharpening their skill and making gradual improvements in the equipment. At an early age many of them acquired an understanding of electrical connectivity for the continent and with Europe via the trans-Atlantic cable (successfully laid in 1866). These young men probably also understood the meaning and significance of such connectivity and communication in the building of the nation. From railroad scheduling and business messages to Reuters and other international dispatches, the telegraphers were privy to the hour-by-hour workings of national enterprises. From telegraphy, Edison moved to improvements and inventions in stock tickers, which took him a step closer to grasping the central operations of finance and capitalist maneuver. It was undoubtedly a part of his training in becoming an entrepreneur with his own inventions.

Edison's conscious appreciation of the power of telegraphy came at the age of 14 when he was selling newspapers on the Grand Trunk Railroad, which ran between Port Huron and Detroit. It was April 1862, and the first accounts of the terrible Battle of Shiloh were coming in by telegraph. Seeing the awful newspaper headlines—60,000 reportedly killed and wounded—and the excitement in Detroit, Edison had the Detroit telegrapher wire ahead to all the stops so the news he was carrying could be chalked up on station notice boards. He ordered a thousand



Telegraphy and the Civil War figured strongly in Edison's early career. As a newsboy on the Grand Trunk Railway, he telegraphed ahead the news of the terrible Battle of Shiloh and, as a result, sold five times his normal complement of the Detroit *Free Press* when he arrived at the stations along the line. It was then, he was to relate later, that he realized the telegraph was a great invention. The war conscripted many telegraphers, and young civilian telegraphers like Edison found ready opportunities for employment. Of Edison's 1000-plus inventions, 150 were related to telegraphy, 389 to electric light and power.



copies of the *Free Press* (he normally took 200). At each stop he was met by large crowds anxious to read the news, and he raised the price of his papers from 5 cents to 10 cents to 15 cents to 25 cents. It was then, Edison later related, that he realized the telegraph was a great invention.

The story is most provocative. The young Edison saw the conjunction of several media carrying the same message—newspaper, train, chalkboard, telegraph—and he saw the commercial power of that conjunction. People grasped the message with greater vividness because it came through different media, at different levels, and therefore conveyed a greater sense of reality. For Edison, the lesson was never forgotten. In fact, a large proportion of Edison's inventions were related to communications media.

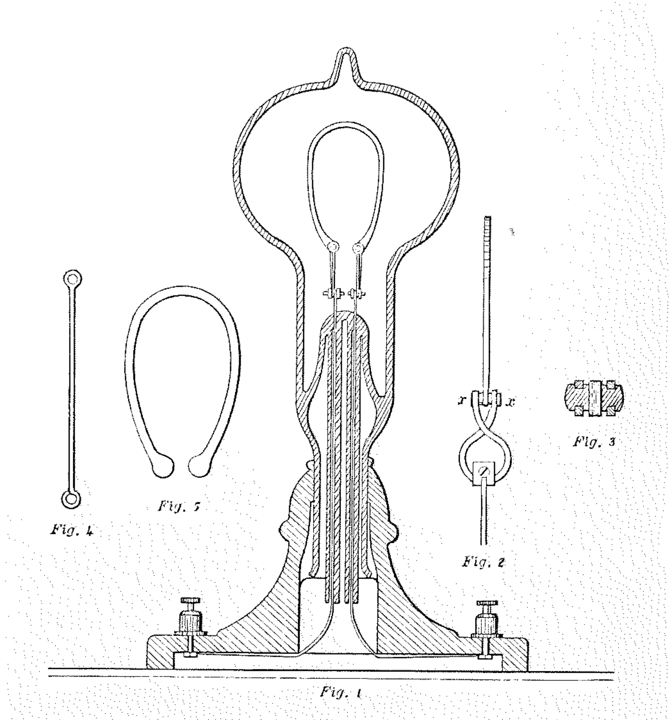
Building on earlier work

When Edison turned his attention to electric light in 1878, there was already a long history of developmental effort, and the field abounded in competitors. As early as 1802, the British chemist Sir Humphry Davy demonstrated the phenomenon of incandescence before the Royal Society in London. Using a stack of voltaic cells, he ran current through a platinum strip, causing it to turn white hot before the material eventually burned away. In fact, Volta's development of the first electric battery only two years earlier (1800) provided the basis for such experimentation. Following on Volta's work, Davy demonstrated the voltage arc light in 1808, which, with but few refinements, became the electric light for the better part of a century. By forcing an electric voltage to leap across a gap between two wire tips, he produced a brilliant arc of light five inches in length. Later experiments showed that carbon was the best material for such tips. It was possible to produce a fairly constant light, if the current was kept flowing and the distance between the tips was properly regulated.

Although they gradually came into practical use, arc lights suffered serious drawbacks. The tips gradually burned away (in anywhere from 2 to 10 hours) and had to be replaced. The lights required complicated regulating devices to maintain the length of the gap; they emitted noxious fumes and gave off such a brilliant, glaring light that they could only be used outside for street illumination or in very large indoor spaces, such as theaters and factories.

Early experiments in incandescent lighting fared less well. In 1845 a 24-year-old American named J. W. Starr obtained an English patent for a carbon incandescent light in vacuo (even though this may have been based on work by De Moleyns, who in 1841 used incandescent charcoal in an evacuated globe). But such early vacuums were not sufficient, and the insides of the glass bulbs became blackened from the interaction of the carbon and remaining oxygen. The first experiments with a bulb shaped like those we recognize today were those of M. J. Roberts in 1852, but his light proved ineffective.

Meanwhile, British inventor Joseph Swan, who was destined to rival Edison, had become interested in incandescent lighting after hearing a lecture by electric lighting pioneer W. E. Staite in 1845. Studying existing patent publications, Swan found Starr's description of his carbon light. He began a series of experiments, combining features of Starr's lamp and one designed by Staite. Swan deduced that thin, high-resistance burners would be better than thick ones—the thinner the strip, the greater the heat, the brighter the light, he reasoned—and he made various horseshoe-shaped burners of platinum, which has a higher resistance than carbon. Although he was in advance



Edison's patent application of December 8, 1879, for the paper carbon filament contains the following description: "Fig. 1 is a vertical section complete; Fig. 2 is a side view on large size of the clamping device; Fig. 3 is a section at the line *xx* in still large size; Fig. 4 is the wire forming one of the clamps before it is bent up to shape; Fig. 5 is the paper blank before it is carbonized."

Edison's career

Thomas Alva Edison was born in Milan, Ohio, of modest circumstances on February 11, 1847, and was largely schooled at home by his mother. By his tenth year he discovered a love for chemical and electrical experiments. He went to work selling newspapers on the railroad and then printed his own newspapers during his early teens, the years of the American Civil War. He devoured books, pursued his experiments, and occasionally got into trouble. Then, after an Horatio Alger–like rescue of a child, the child's father taught young Edison the Morse code and the elements of telegraphy, the first major industry to use electricity.

As a young man, he worked as an itinerant telegrapher in a number of cities—Fort Wayne, Cincinnati, Nashville, Memphis, Louisville. All the while, his experimenting went on. In 1868 he made his way to Boston, a city of busy experimental and intellectual activity, with the second highest per capita patent rate in the nation (in 1880 it was first). There he made his first patented invention, a telegraphic vote recorder, which he learned rather painfully was not something that politicians or anyone else much wanted. Thereafter, Edison considered the feasibility of profitable development before undertaking any sizable inventive effort.

By the time his vote recorder was rejected, he had seriously embarked upon a career of invention, buttressed by his reading of the works of the great English electrical experimenter and theorist, Michael Faraday. Edison repeated Faraday's experiments and evidently found a decisive role model in Faraday, whose early childhood and inclinations somewhat resembled his own. Faraday's dedication to experiment and to the facts that emerge from experiment reinforced Edison's empirical inclination. In Boston, Edison worked for a time in Charles Williams's shop, apparently a Mecca for many young would-be inventors, including Alexander Graham Bell, who invented the telephone in 1876.

Following his Boston experience, Edison's own course was much bolder and more determined. His experiments and his early patents were, like those of so many of his contemporaries, related to improvements and innovations in telegraphy, and he gained some notice and support. Although his work was not yet remarkably different from that of many other young inventors, he revealed an unusual mettle. He went on from invention to invention. Then, burdened by business debts, he moved to New York, the city that beckoned so many others from the small towns of America.

In the heart of New York's Wall Street he managed to fix a telegraphic gold indicator broken at a critical moment. As a result, Edison found himself with a well-paying job in the center of the financial operations of the day. From then on his work flowered; he gained more access to financial backers for his inventions; and his reputation grew. If one were writing about an artist, one might say that at this period he was beginning to find his own style. In October 1869 he set up perhaps the first electrical engineering consulting service in this country in partnership with Franklin Pope, who later became president of the American Institute of Electrical Engineers. He invented equipment improvements for the giant Western Union Telegraph Company (a company that employed many inventors). In his first year in New York he took out seven patents, and in due course he was being paid handsomely for his inventive work. He received $40,000, an incredible sum then, for a stock ticker improvement. In 1871, at age 24, holding orders worth $500,000, he opened a manufacturing plant in Newark, New Jersey. In 1872 he improved the system of the Automatic Telegraph Company.

In 1873 he went abroad for the first time, to England, again on a telegraphy mission. By that time, his reputation clearly allowed him to attract venture capital in whatever he undertook, and he had come to know the financial tycoons of the day. Ingenious and indefatigable, the young man produced invention upon invention, gradually expanding beyond telegraphy, but always commercially aimed. In 1874 it was the duplex and quadruplex telegraphs; in 1876, after Bell invented the telephone, it was an improved carbon

Edison's stockticker inventions proved to be his passport to becoming a full-time professional inventor.

transmitter telephone. While working on what he intended to be a telephone repeater device in 1877, he invented the phonograph, which astonished the world. And in 1878 (the same year in which a biography appeared describing him as a great inventor) he undertook the invention of the incandescent light, in which he succeeded in 1879 at age 32.

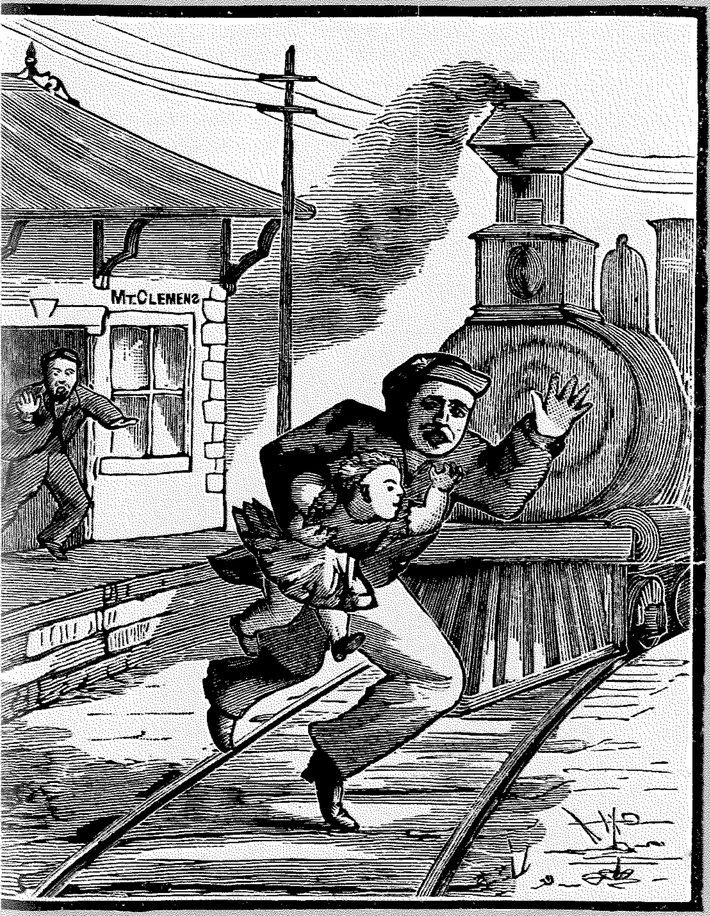
Almost simultaneously, he went on to invent and develop all the elements of an entire electric lighting system. In 1882 he built and installed the famous New York Pearl Street central station, which was the first step in the development of the electric utility now known as Consolidated Edison Company of New York. During this intense period of developing the electric light and support system with a team of inventive colleagues, craftsmen, lawyers, and manufacturing aides, his patent production was unmatched: 60 patents in 1880, 89 patents in 1881, 107 patents in 1882, most of which were connected with electric light systems. He founded manufacturing companies for dynamos, for underground conductors, for lights, for meters, for generators, and more.

In 1889 these companies consolidated as the Edison General Electric Company. During this period, European Edison Illuminating companies were licensed, and Edison emissaries traveled through America establishing electric lighting companies in cities and towns everywhere.

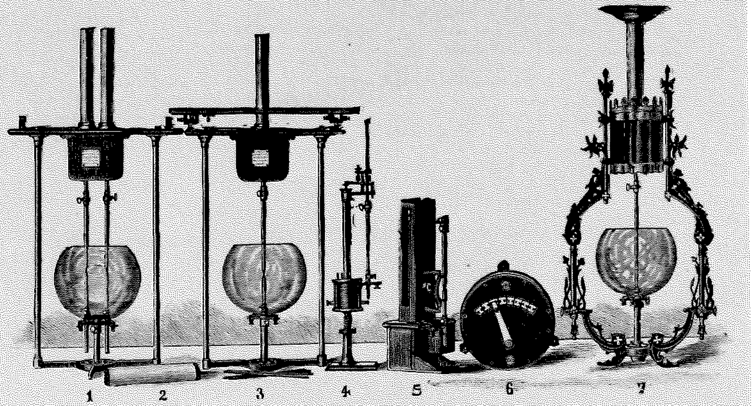
Although the peak of his great inventivity had been reached by 1884, he took out 1093 patents in his lifetime, more than any other individual ever. Scholars are now beginning to attempt to clarify how the ideas of Edison's colleagues contributed to this record, but it is clear that Edison was a major driving force in the great inventive period in the latter part of the last century and the beginning of this. As his authorized biographers F. L. Dyer, T. C. Martin, and W. H. Meadowcroft wrote in 1910, "It will be admitted that in Edison one deals with a central figure of the great age that saw the invention and introduction in practical form of the telegraph, the submarine cable, the telephone, the electric light, the electric railway, the electric trolley car, the storage battery, the electric motor, the phonograph, the wireless telegraph; and that the influence of these on the world's affairs has not been excelled at any time by that of any other corresponding advances in the arts and sciences."

Although the world has witnessed many more revolutionary scientific and technological advances since 1910, they take away nothing from this earlier Edison era. The style and the acceptance of R&D was set then.

Later in his career, Edison went on to invent methods of magnetic ore separation, improved portland cement, storage batteries, motion pictures, artificial rubber, and much more. He lived until 1931, witness to the tremendous growth of all forms of electrification and witness to the growth of his own legend. By the time of his death he had become a culture hero, deeply identified with the development of America itself.



A chance rescue by Edison led him into telegraphy, the foundation for his later work in electricity and communications. Horatio Alger, it is said, modeled some of his novels on Edison's escapades.



1. Double Lamp.—2. Carbons.—3. Single Lamp 4. Focusing Lamp.—5. Head-light Lamp.—6. Dial Attachment to Machine.—7. Ornamental Lamp.

BRUSH ELECTRIC LAMPS.

In America, Brush arc lights were being introduced commercially and were stirring widespread interest in the potential of electric lighting.

During July and August of 1878, on their western journey, George F. Barker (above) urged Edison to work on the electric light. They talked about the work of Jablochkoff and others.

In Paris, during that same summer, Paul Jablochkoff had illuminated a half mile of the Avenue de l'Opéra with arc lights and had set up interior lighting systems such as this (left) in the fashionable Morrish salon in the Hôtel Continental.

In San Francisco, in the summer of 1878, two arc lights powered by a Brush generator were installed in the courtyard of the elegant Palace Hotel. They illuminated a gala reception on September 20, 1879, for former-president Ulysses S. Grant at the conclusion of his world tour.

of other inventors, Swan was stymied by the lack of good methods for obtaining a vacuum, and in 1860 he discontinued his experiments. It was not until 1875 that Swan heard of the mercury vacuum pump, which had been invented by Herman Sprengel, and he resumed his experiments, using high vacuums and straight carbon burners. Thus, by 1878 these two inventors on either side of the Atlantic were moving neck and neck toward *the* invention. But two crucial distinctions would eventually separate Edison's and Swan's efforts. One was that Swan's burners, although small, were still relatively wide carbon strips, whereas Edison's filament was extremely small in cross section. The other was that Swan was concentrating on the incandescent light alone, whereas Edison started with a concept of an electric lighting system in which the light was but one piece.

In addition to the early work in incandescence, the electrical pioneers were pursuing an adequate means of generation for arc light systems. All the early lighting experiments had been hampered by the lack of effective generators for producing electricity. But in the 1860s significant improvements in generators began to be developed when it was found that steam power could be converted to electricity. By 1862 Michael Faraday, who was Edison's special hero, introduced an arc light in a British lighthouse. Thereafter, experiments with electric lights gained momentum both on the Continent and in the United States.

At the 1876 Philadelphia Exposition, which made the world really aware of the technological advances going on in America, Moses Farmer and William Wallace demonstrated an electric dynamo that ran three glaring arc lights. That dynamo light system inspired many young inventors to pursue the possibilities of electricity.

To the inventors and entrepreneurs (men like Charles F. Brush, Charles J. Van Depoele, Elihu Thomson, and others in America and Swan, Jablochkoff, Siemens, and others in Europe), it was becoming clear that electricity had a far greater practical future than in telegraphy alone. Both in the United States and abroad there was great public excitement as blazing arc lights came into use in streets, in large stores, and in factories. In Paris in 1877, for instance, the engineer Paul Jablochkoff was installing his new designs of arc lights, called electric candles, and by 1878 a half-mile length of the Avenue de l'Opéra was brilliantly lit. That was the news of the day when Edison—a latecomer to the lighting problem—decided he could find the solution before anyone else.

Edison steps into the ring

It was apparently on the long train ride after an unsuccessful experiment in Wyoming during the July 1878 total eclipse of the sun that Edison was drawn to the problem of a practical electric light. His companion on that trip, George F. Barker of the University of Pennsylvania, had become very excited with the possibilities of electric lighting, and he pressed Edison to turn his inventive capabilities to the problem. Edison, who had willingly accepted Barker's invitation to join the eclipse expedition, was at a turning point, at which he felt he needed to take up something new. He had scored major successes in telegraphy and telephony, and he had just invented the phonograph, which added to his renown. But problems with his hearing were making it increasingly difficult for him to work in these media. He needed a new kind of problem, a more visual one.

He had become intrigued by the problem of electric lighting, had performed some arc light experiments in 1877, and had even pasted reports of Jablochkoff's work in his notebooks. On his return from Wyoming his interest was further reinforced by papers sent him by his friend and longtime supporter, Grosvenor P. Lowrey, then counsel general to Western Union. These papers included news of the Paris Exposition and more on the Jablochkoff artificial lights, which had aroused great admiration in Europe.

With his interest growing and persuaded by the advice of Barker and Lowrey, Edison accompanied Barker to Ansonia, Connecticut, on September 8, 1878, to visit William Wallace's establishment and to see his arc light system. It consisted of eight arc lights of 500 candlepower each, run by an eight-horsepower dynamo that was a newer version of the dynamo shown at the 1876 Philadelphia Exposition.

Seeing the Wallace system, Edison seems to have had an immediate insight into what could be done and to have determined on the spot the character of his own campaign. He even announced ungraciously to his host, "I believe I can best you in making the electric light. I do not think you are working in the right direction."

After leaving Ansonia, Edison began, as he said, his "usual course of collecting data" and making numerous calculations. He was soon to report, "I saw for the first time everything in practical operation. I saw the thing had not gone so far but that I had a chance. I saw that what had been done had never been made practically useful. The intense light had not been subdivided so that it could be brought into private houses. In all electric lights theretofore obtained, the intensity of the light was very great and the quantity [of units] very low. I came home and made experiments two nights in succession. I discovered the necessary secret, so simple that a bootblack might understand it. It suddenly came to me, like the secret of the speaking phonograph. It was real and no phantom . . . the subdivision of light is all right." That intuition escaped those authorities of electricity who had denied the possibility of subdivision of light. According to Josephson, "The leading electricians, physicists, and experts of the period had been studying the subject for more than a quarter of a century and, with but one known exception, had proved mathematically and by close reasoning that the subdivision of the electric light, as it was then termed, was practically beyond attain-

Edison's contemporaries

Edison was not alone in his drive to exploit electricity in useful ways; he belonged to a generation of young inventors, all of whom were active at that time, all of whom would come to know and compete with one another. Their work was based on the theoretical work of Faraday and others, who in the 1820s to the 1840s created a body of theory and experimental findings that was ripe for exploitation in the practical realm by the last quarter of the nineteenth century.

At age 28 Charles F. Brush, supported by the Cleveland Telegraph Supply Company, developed an arc lamp system and dynamo in 1876. He went on to invent a series arc lamp with a regulating shunt coil, which made possible the commercial introduction of arc lighting from central stations.

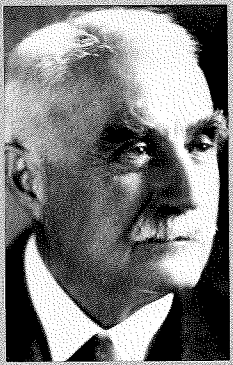
Charles J. Van Depoele, a Belgian immigrant, used his cabinet-making skills to establish a prosperous wood-carving business in Chicago in 1869 when he was only 23. Then he used his business to support his experimental work in electric arc lights. By 1879 he had installed arc lighting systems in Chicago and Detroit. He set up a company, Van Depoele Electric Manufacturing, which developed motors for electric streetcars.

Frank J. Sprague, a transplant from England, pioneered electric streetcar propulsion and electrically driven elevators. For a time he worked with Edison. He came to be seen as the father of horizontal and vertical electric transportation systems, both of importance in the growth of American cities. He held patents on electric trolley systems as early as 1882.

Elihu Thomson experimented with electricity as a child, later became a professor of chemistry and mechanics, lectured on electricity at the Franklin Institute in Philadelphia, and developed methods for measuring the efficiency of early dynamos. Stimulated by Brush's work, he designed and built his own arc light systems, left teaching, and launched a long and vigorous career in invention and development. He was initially supported by a small manufacturing company in New Britain, Connecticut (the American Electric Works), an enterprise that led to the formation of the Thomson-Houston Company, which engaged in electrical equipment development and manufacture. Through various mergers in the 1880s—with Brush, with Van Depoele, and with the Bentley-Knight Electric Railway Company, and others—Thomson-Houston became a major root of the General Electric Company.

To these and many other inventors growing up in the post–Civil War period, it was clear that electricity had a great practical future. Collectively, such individual inventor-entrepreneurs in America—as well as Paul Jablochkoff in Paris, Joseph W. Swan in England, Z. T. Gramme in Belgium, and C. W. Siemens in Germany—were at the forefront of a movement that transformed electricity into a practical force. Realizing that electricity would one day light up the world, they invented and developed the first generation of electrical systems. Among them they developed lights, dynamos, wiring methods, meters, motors, switches, methods of electric traction for streetcars and trains, transmission and distribution methods, transformers, insulators—in short, the basic alphabet and vocabulary for an electrified civilization, the foundations for the giant industrial and utility operations of today.

Brush

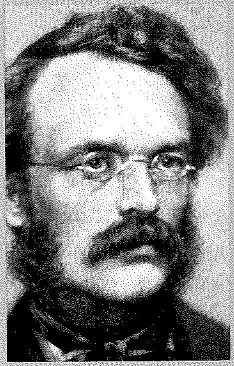


Van Depoele

Sprague

Thomson

Jablochkoff



Siemens

ment." They were thinking in terms of the large currents that were delivered for arc lights and of the existing dynamos that delivered a high and constant current. If that current were to be fed to a number of lights in the same circuit, then the light emitted by each would indeed diminish as the number of lights increased.

Edison's answer, which he realized quite early, was what has become popularly known in our day as a systems solution. Most would-be inventors were focusing their efforts on the bulbs and, as with arc lights, believed they would be drawing high currents and would need something like the existing dynamos to generate that current. Edison deduced that the filaments of the lights should be highly resistant, drawing only a small current; that the dynamo would have to be redesigned to supply a high, constant voltage and a varying current, depending upon the total number of lamps being supplied; and that the lamps should be hooked up in parallel, or ladder-type, circuits, so if any lamp were turned off or burned out, the remainder would be unaffected. All that was needed, then, was to invent the light, the keystone of the whole system, within the context of these specifications. No one else was taking such a systems approach. Any home electrician today recognizes these as obvious facts, but they were not so obvious in 1878.

This systems solution simultaneously answered another problem that would have been raised by the high-current systems—namely, that there would not have been enough copper in the world to have supplied the distribution lines. The constant-voltage, low-current system reduced the necessary copper dramatically and made the vision a practical reality. Another aspect of the total-system problem was the development of an economical method of feeding current throughout a wide customer area. It was solved in 1883 by a method analogous to the gas distribution system and became known as the three-wire system.

Even when Edison had reached his goal in the closing months of 1879 and created a world sensation, his competitors were still slow to grasp the full significance of his very thin, high-resistance filament. They understood it later, however, and they copied it. And understandably, Swan in England, who in 1869 had worked with carbonized paper filaments, claimed prior rights. Later litigation established that the invention—with its unique, extremely thin filament—was Edison's. Given the sensational character of the incandescent light itself, what was obscured for a long time was Edison's systems approach to the problems of invention and implementation.

The Edison methodology

The laborious search for the right filament material, the thousands of experiments, the countless theories that Edison and his colleagues at Menlo Park painstakingly explored, and the 40-hour vigil have been much romanticized over the years. It was clearly hard work, requiring incredible patience, persistence, and endurance. And it is clear from all accounts that Edison had the kind of indomitable spirit that kept his experimenters going.

Just as important was the fact that Edison threw the resources of his colleagues and his laboratory into a broad, methodical attack. In just four years of intense activity, Edison and his team succeeded in solving the key problems of incandescence, and in a seven-point program they developed the components of an entire system. According to Josephson the goals of Edison's systems engineering program included the development of (1) the parallel circuit, (2) the durable, high-resistance light, (3) the improved dynamo, (4) the underground conductor network, (5) the devices for maintaining constant voltage, (6) safety fuses and insulating materials, and (7) light sockets with on-off switches. Every one of these elements had to be invented and then, through careful trial and error, developed into practical, commercial, reproducible components.

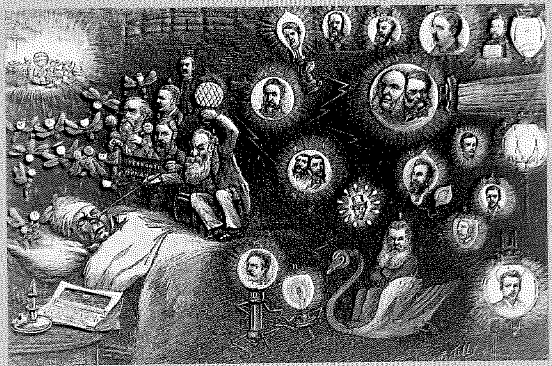
From the time Edison began his work on the electric light problem in 1878 to his construction, development, and commercialization of an electric lighting system in 1882 was a lapse of only four years. In that time Edison and his group did everything—from invention to development, from financing to manufacture, to marketing surveys, to operating a functioning utility that served customers in a square-mile area (the First District) in the heart of New York City.

Pearl Street and after

Edison's predominance in the first era of incandescent lighting comes not only from his invention of an entire lighting system but also from his ability to follow through. He improved on his basic inventions and was entrepreneur, industrialist, and capitalist in the development of individual or isolated generating systems, as well as initiator of a host of manufacturing enterprises to supply the necessary equipment, including lamp production facilities. The vision of all this must have been with Edison from the very beginning of his work on the light itself. In an interview with a reporter from the New York *Sun* on October 25, 1878, just a few weeks after his visit to William Wallace, Edison laid out a scheme for a central station for electric lighting in New York, which would supply a myriad of household lights over a network of lines. According to Edison, the model for the system was that of the central gashouse and its distributing system, of gas mains running to smaller branch pipes and leading into many dwelling places. Just four years after Edison's 1878 prediction, the famous Pearl Street Station in New York became the first central station for supplying incandescent lighting.

Even during his work on the incandescent problem, Edison was moving on other fronts as well. Almost simultaneously with the 40-hour vigil, the *Scientific American* of October 18, 1879, was carrying an article by Francis Upton on the "long-legged Mary Ann," the special

Edison's target: the gas illuminating industry



A British cartoonist's view of a gas manufacturer's nightmare at the time when many inventors in many countries were working feverishly to develop commercially practical electric lights.

The gas era began in England in 1792 when Thomas Murdock discovered how to distill gas from coal and to pipe it into his home for lighting burners. Very soon thereafter, various methods of producing gas were developed. Gas began to supplant candles and oil lamps, which had changed little since ancient times. By the early 1800s, when electricity was a mere infant, gas lighting was making strong headway, especially in urban areas.

The need for street lighting had been a chronic urban problem, and gas lighting was a boon. Municipal governments were the initial customers for gas company products and hastened the expansion of gas lighting into factories and homes. Older cities like Baltimore and Philadelphia had employed some gas lights as early as 1807, and New York began experiments with gas lights in City Hall Park in 1812. Thereafter, gas lighting and gas utilities grew at a rapid pace in many cities.

Since Charles F. Brush's success in 1878, electric arc lights had gradually made inroads in the gas street-lighting market. But except for large railway stations or factories, the glare of arc lights prevented them from competing with gas indoors.

But Edison was on a different track. One entry in his notebook read, "Object: Edison to effect exact imitation of all done by gas, so as to replace lighting by gas by lighting by electricity. To improve the illumination to such an extent as to meet all requirements of natural, artificial, and commercial conditions."

That the gas companies were the clear target of Edison's efforts with electric light is evident in the authoritative article written in 1880 by his assistant Francis Upton for *Scribner's* magazine: "The crowning discovery of Mr. Edison—the electric light for domestic use—is at last a scientific and practical success. A mistaken idea has been afloat that this new light was intended to be a rival of the sun, rather than what it really is—a rival of gas. The generator of the electricity is simpler than a gas generator, and the wires for its distribution are more manageable than are gas mains and pipes. The light is equal to gas in brightness and whiter in color; it is enclosed and, consequently, perfectly steady; it gives off no appreciable heat; it consumes no oxygen; it yields up no noxious gases, and, finally, it costs less than gas." Even the first crude incandescent electric lighting systems were far superior to gas lighting in nearly all respects. Incandescent bulbs, according to an 1882 account, diffused the light, making reading a "delight" while gas lighting made it "irksome."

Many authors quote the sharp drop in gas company stocks when Edison first advertised his electrical system and leave the impression that the companies slid into bankruptcy, but this was not the case. Through consolidations they could control the price of their product better than the struggling electric firms. As late as 1908, the cost of gas lighting per hour was 28 cents compared with electricity's 55 cents. Moreover, as the establishment, the gas firms retained their rights to dig up streets for laying mains. In 1880 New York City alone had 860 miles of gas mains in public streets; that total rose to 1300 miles in 1899. Although the electric light gradually forced gaslight vendors out of interior lighting into street lighting, the market for gaslights still appeared strong enough even in New York to attract new operations like the Equitable Gas Light Company in 1884 and the Standard Gas Light Company sometime later.

Although the gas companies appeared confident that electric light would never challenge the price of gas, they did not assume an idle stance toward innovation. Even in earlier years, some firms improved their systems. For instance, in 1870 the Mutual Gas Light Company increased the candlepower of gas by enriching coal gas with naphtha. A more radical breakthrough came in 1876 when the French engineer Tessie de Motey developed a method of producing hydrogen gas admired for its brilliant white glow. Although the method required two mains, one for oxygen gas and one for hydrogen, companies eager for an edge installed them. Another company equipped its wrought iron gas mains with screw joints to lessen leakage.

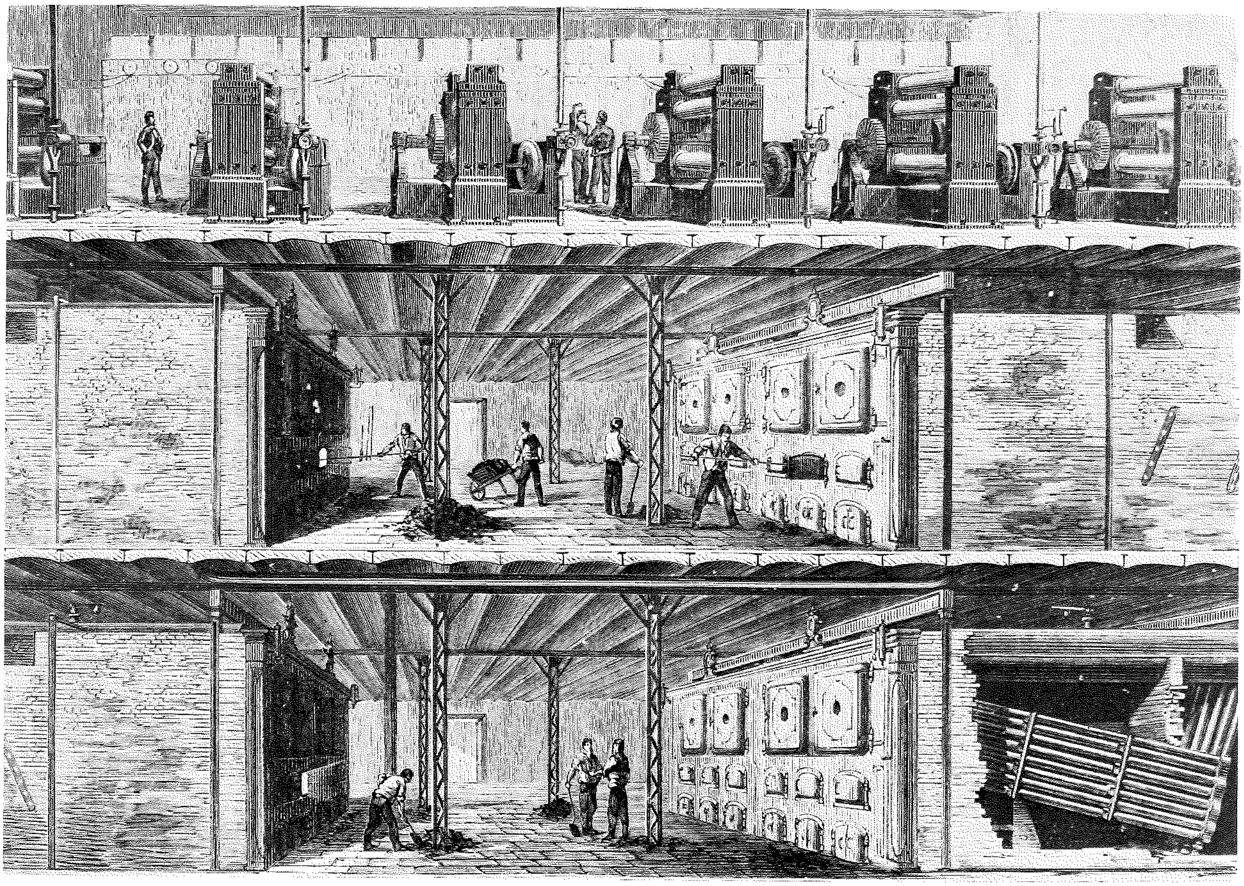
With the advent of the gas range, gas lighting companies added to their list of salable conveniences and services that included street and home lighting, heating, and power derived from gasoline engines.

Yet the gas industry could not overcome the fundamental drawbacks to its product in all but heating and cooking. Nausea from leaks and smoke from gas burners were normal conditions, which the companies never satisfactorily eliminated. The severe limits on the distance central gas works could pipe gas and the minimum amount of gas needed to produce a lamp were barriers the gas companies never crossed. And after the electrical entrepreneurs made basic improvements in lightning arresters and insulation, thus reducing the damages of electrical shocks, the risk/benefit ratio tilted markedly in favor of electricity.

generator designed for the incandescent lighting system, which had a much higher efficiency than existing dynamos. Edison named it the Faradic machine in honor of Michael Faraday. Although the machine seemed to be a radical departure from existing designs, historian Thomas P. Hughes, in an incisive monograph on Edison, notes, "Upton brought to Edison and the design thorough knowledge of the well-made Siemens arc-lighting generator, and Upton also drew upon the analysis of generator characteristics made by the brilliant British engineer and scientist John Hopkinson." The same Hopkinson served as an advisor when the English Edison Electric Light Company was organized to build and operate the Holborn Viaduct central station in London, the British counterpart of the Pearl Street Station.

Pearl Street Station actually began to supply electricity to the lamps in the First District on September 4, 1882. From that time until January 2, 1890, the station supplied electricity to its customers with only one three-hour interruption, thereby establishing a standard for reliability in the utility industry. In his study of Edison's career and methodology, Hughes concludes, "In the first decade of its existence, the Edison direct-current, low-voltage, central-station system, introduced at Holborn Viaduct and at Pearl Street, spread throughout the United States and the world. The acceptance of an American system offered convincing additional evidence of the rising technological power of the United States."

Central systems grew much more slowly than Edison had hoped. In fact, electric lighting coexisted with gas lighting for many years, and the stimulus from the competition actually led to improvements and innovations in gas lights.



Thomas Edison's first practical central station, located in two buildings at 255–257 Pearl Street in lower Manhattan, was put into operation on September 4, 1882. The "jumbo" dynamos shown on the upper floor supplied electricity for customers in New York's First District.

The electric lighting industry would not have a million customers until a few years into the twentieth century.

Seeds of universal electrification

The atmosphere of Edison's headquarters at the Edison Electric Illuminating Company of New York (the direct predecessor of Consolidated Edison Company of New York) during the period when he was masterminding these activities was frantic. Edison was everywhere at once, organizing companies to manufacture electrical components, doing public relations work with New York aldermen to get permits to lay underground mains, working at inventions and improvements on electrical components at Menlo Park, working in the trenches as the mains were being laid, solving insulation and interconnection problems, and raising capital for the multipronged but integrated enterprises being founded.

The Edison Machine Works in New York built the generators, including the famous Jumbo named for P. T. Barnum's great elephant; the Edison Electric Tube Company manufactured the underground conductors; the Edison Lamp Works in Menlo Park began mass-producing the lamps; and the Bergmann Company in New York manufactured electrical fixtures and other elements. All these and some others merged later in 1890 to become the Edison General Electric Company, and then in 1892, in a further merger with Thomson-Houston companies, became the General Electric Company we know today.

Edison's skills and leadership extended also into the exploitation of media and market research. For example, soon after initiating his program, Edison launched a shrewd media campaign designed to shake the gas lighting companies and, more pointedly, to stimulate financiers to support his research. Perhaps it was not the first case of the conjunction of financial capital and technological innovation, of industrialists and entrepreneurs sponsoring an invention that was yet to be made, but it is certainly the most publicized one. It was to herald a way of sponsoring R&D that has become standard and accepted.

Edison's market research was also a solid model for the kinds of planning that many modern corporations undertake. On launching his efforts in electric light, he made a thorough investigation of gas illumination. He collected a large library and made actual observations of gas jet distribution in New York City. He made calculations of every aspect of gas economics and point by point made comparisons with what he might expect of electric lighting systems. These calculations more clearly defined the constraints his lighting system would have to meet. An expert from the gas industry, whom Edison hired as a consultant, reported later that he had never met anyone who knew as much about gas as Edison.

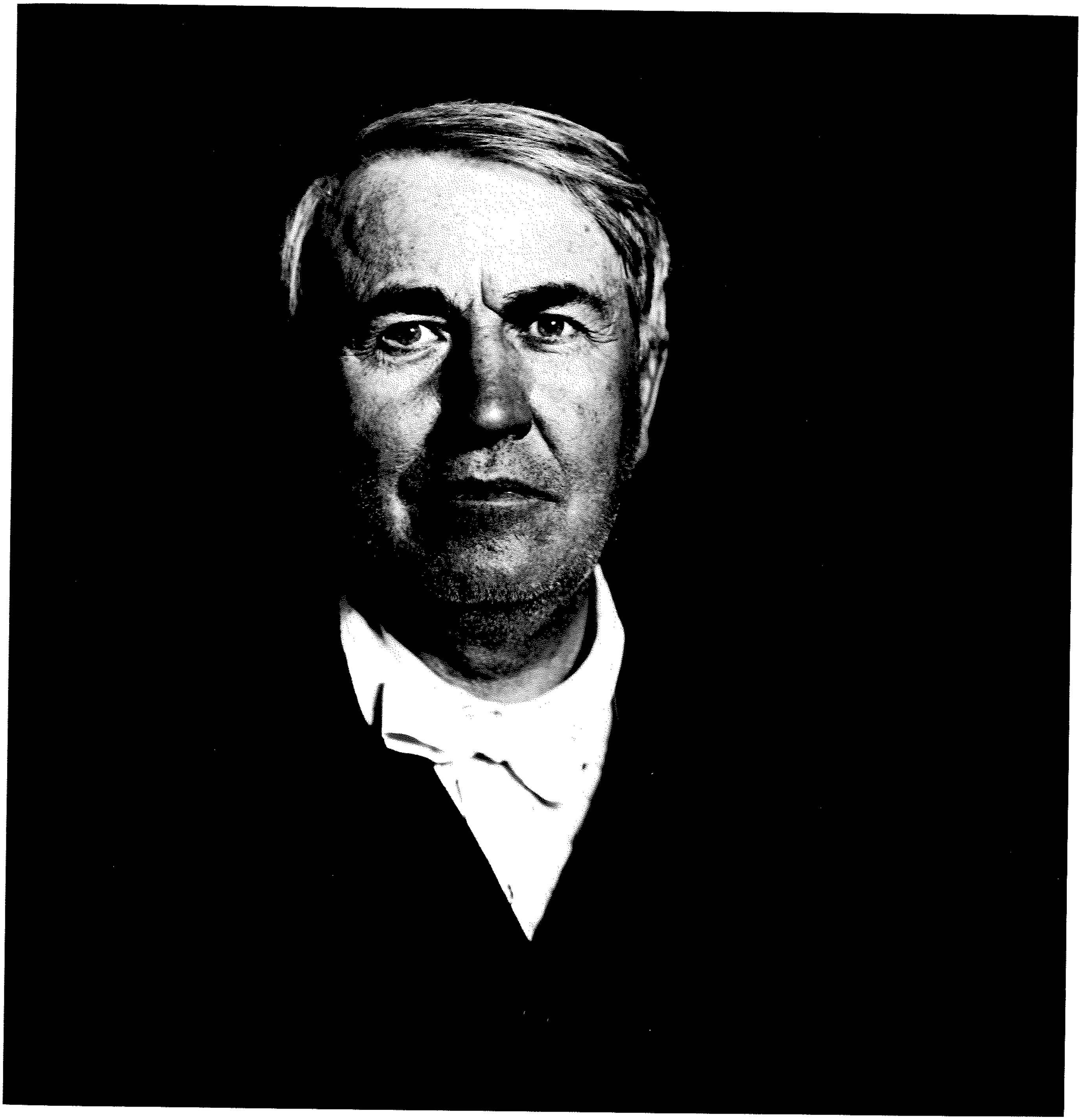
Later, when Edison pushed forward with his first central electric generating station in New York City, he took equal care in his business strategy. "I got an insurance map of New York," he recounted, "in which every elevator shaft and boiler and housetop and firewall was set down and studied it carefully. Then I laid out a district and figured out an idea of the central station to feed that part of the town. . . . I worked on a system, and soon knew where every hatchway and bulkhead door in the district I had marked was and what every man paid for his gas. How did I know? Simplest thing in the world. I hired a man to start in every day about two o'clock and walk around through the district, noting the number of gas lights burning in the various premises; then at three o'clock he went around again and made more notes, and at four o'clock, and up to every other hour to two or three o'clock in the morning. In that way it was easy enough to figure out the gas consumption of every tenant and of the whole district."

The choice of the First District was equally shrewd. It was bounded by Wall Street, Spruce Street, Ferry Street, Nassau Street, and the East River and included a residential area as well as factories, thus in Edison's original thinking, "evening up the daytime and nighttime loads" (although initially power was not to be supplied during the daytime). "Even more important," according to one description, "the First District included the financial capital of the nation, the Stock Exchange and the great banking houses, as well as the offices of some of the city's most influential newspapers. When the light went on in the First District, the bankers, brokers, and editors would be the first to sing their praises."

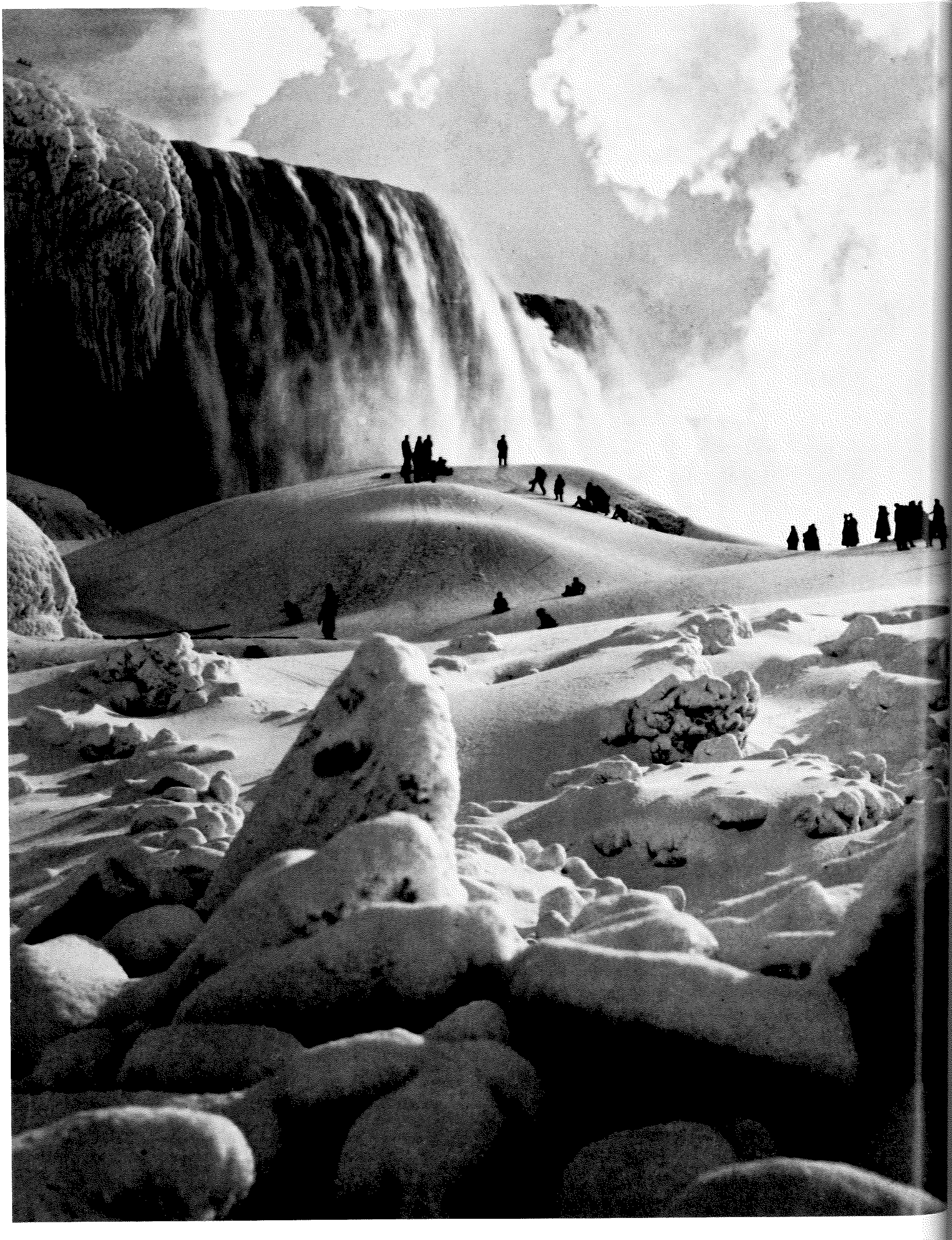
An appraisal

What we see in the Edison era are two major and related events: the birth of organized R&D that depends largely on a team approach to problem solving and the birth of the electric utility industry (although in the Edison period it was still part of electrical manufacturing). That first event, which has been viewed as the most significant invention of the nineteenth century, was certainly not one of Edison's goals; for him it was but the means to an end. That end, widespread electrification, was Edison's conscious goal from the very beginning of his entry into the electric light contest. He aimed for it and succeeded.

One cannot go so far as to claim that Edison alone was responsible for originating the organized R&D approach; there were other laboratories for research preceding his. Yet his eminence (and popularity) in the field of invention went a long way in creating a climate of acceptance for organized R&D. The very idea that people could organize resources in order to invent was really a revolutionary social idea that began to be accepted seriously in the Edison era. Edison's many successes gave credence to the idea and tended to take the mystique out of invention. Edison's insistence that invention was 1% inspiration and 99% perspiration was to have a lasting and profound effect. It lent support to the idea that technology could do anything. This idea has been a dominant factor in the twentieth century.



The determined inventor-entrepreneurs set into motion the age of electricity, but once the path seemed clear they were besieged by competitors on every hand. After his initial successes with dc systems, Edison was confronted with a new form of electric power system based on ac, a form he refused to countenance. Many, many years later, he would admit, "I was wrong."



The imagination of the United States and Canada and of the world was captured in the late nineteenth century by the great challenge to transform Niagara's "white coal" power into electric power. In its day it was a project of gigantic proportion—of technology, of finance, and of organization. The achievement represented what was then the ultimate in the state of the art of electrical machinery design and construction. It selected the best of components wherever they might be found and shaped them for this particular project. It was also the watershed for the technical debates over the use of ac and polyphase machinery versus the dc system established by Edison. Niagara was a victory of man over nature, a victory of financial organization, a victory for long-distance transmission, and a victory of ac over dc.

HARNESSING A MONUMENT

The Power of Niagara

Power development in the vicinity of Niagara Falls began in earnest during the latter part of the eighteenth century; yet harnessing more than a fraction of the area's potential remained an elusive goal until 1895. The problem was the very abundance of power and the limited amounts of land close to the falls. Waterwheels with mechanical linkages for power transmission constrained the scale and locale of power consumption. Small industries were able to cluster along the upper portion of the river, diverting water through loop canals and using a small head (vertical drop) as the means to drive a flour or grist mill, a forge hammer, or a sawmill.

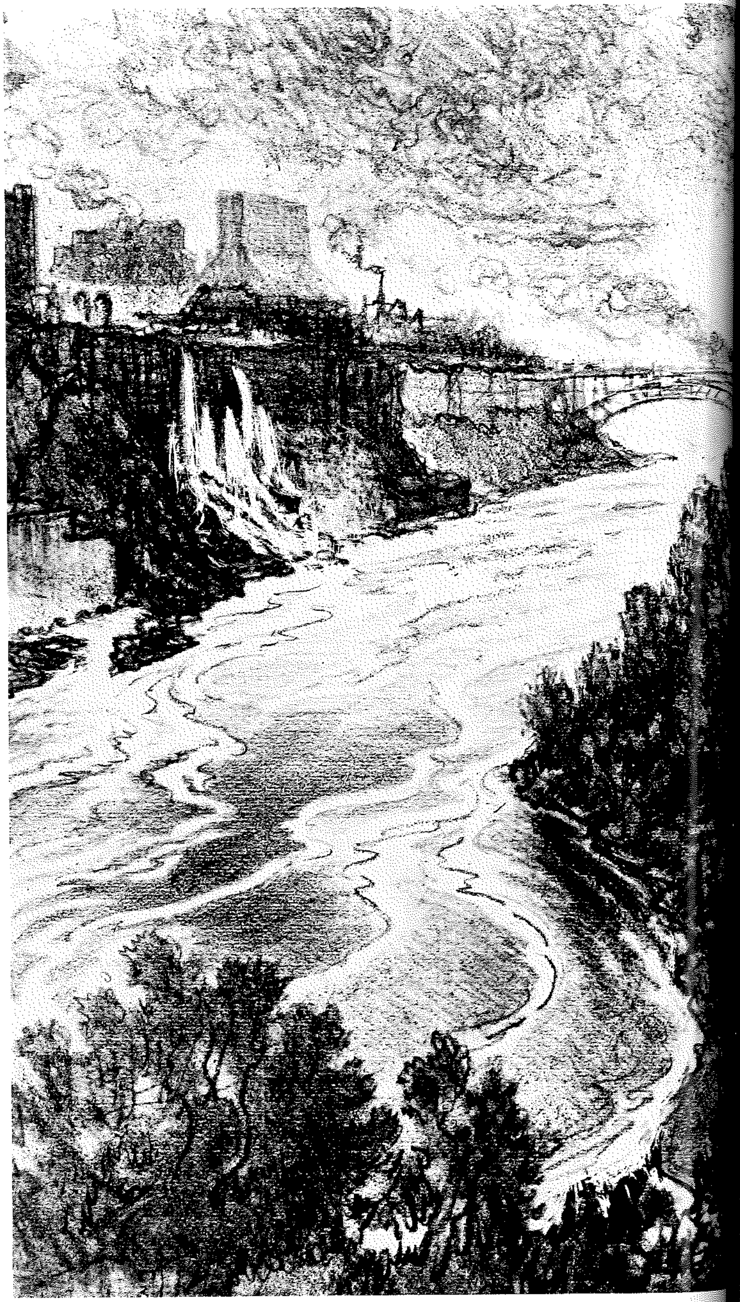
Large-scale consumption of power would have to wait for a means to transmit power to areas remote from the falls or for a means of highly concentrated industrial consumption. Central to all later schemes of grand development was the use of a canal connecting the upper and lower portions of the river. Since the Niagara River makes an immediate right-angle turn below the falls, such a canal would, in effect, form the hypotenuse of a right triangle, and the limited amounts of land within this triangle became premium.

The first serious effort at industrial development of the area was made after the opening of the Erie Canal in 1825. The canal provided a direct waterway between New York City and the western frontier and allowed commercial traffic to bypass the difficult portage around Niagara Falls. The Niagara portage route was then under the control of Augustus Porter, and with his business facing ruin, Porter turned his energies toward industrial development. He issued an invitation to eastern capitalists and manufacturers to exploit the power of Niagara Falls. Response was slight, for industry was preoccupied with the canal terminus and the fervor of the boomtown of Buffalo, 22 miles to the west. A similar lack of interest answered Porter's second call, over 20 years later, for venture capital with which to construct a power canal at Niagara.

By 1850 there was a growing awareness of Niagara's advantages: an unprecedented evenness of flow due to the massive reservoirs that fed the falls, the proximity of emerging population centers, and a recently calculated power potential of 6 million horsepower. The cost of excavation remained the great stumbling block; the land available for manufacturing sites was simply too limited to justify underwriting the project on the basis of power sales.

Nevertheless, over the next three decades a series of entrepreneurial organizations rose and fell, each attempting to construct the power canal first envisioned by Augustus Porter. Even when a surface canal finally was brought to the high bank downriver from the falls, manufacturing development languished, and it was not until 1875 that use of the hydraulic canal was first made by a flour mill. This mill used a head of only 25 feet, a safe limit for the waterwheels then in operation, yet amounting to less than one-eighth the potential energy of the falling water from the upper to the lower river levels.

The ability to capture the full head of Niagara had to await improvements in the turbine design. These came rapidly. Turbines were first built of wood, then wood and sheet iron, and still later, bronze and steel. By 1881 another flour mill was operating under a 50-foot head, followed by still another using water under a head of 80 feet. The paper industry followed suit, and by 1882 the Cliff Paper Mill was operating under a head of 120 feet. These same turbines ushered in the hydroelectric age to the Niagara region. They operated an arc light machine owned by Brush Electric Light and Power Company, which provided 16 lamps for the streets and stores of the village of Niagara Falls.



Drawing by Joseph Pennell shows the despoiling of Niagara by industries arou the falls that led to an intensive movement to restore its natural beauty. Almost inadvertently, the way was opened for the esthetically clean exploitation of Niag power by centralized electricity generation.

"Free Niagara"

By the end of the Civil War, the conflicting appeals of Niagara Falls had set pragmatic and esthetic values of the American people on a collision course. With the access of railroads, tourists were flocking to the scenic wonder only to find their view increasingly blocked by the cluster of industry along the prime shoreland above and below the falls, to find the waters diverted and the landscape despoiled. Foreboding about the rapidly approaching ruin of the characteristic scenery of Niagara appeared in print as early as 1869. Over the next decade, this concern escalated into a public movement to "rid the spot of every touch of commercialism . . . to set it apart so that all nations and peoples might come together and behold the scene unmolested." And "Free Niagara" became the slogan of the day. The state legislature responded in 1879 by asking the commissioners of the state survey to look into the matter. They reported, "There is no American soil from which the falls can be contemplated except at the pleasure of a private owner and under such conditions as he may choose to impose, none upon which the most outrageous caprices of taste may not be indulged or the most offensive interpolations forced upon the landscape."

At the behest of Lord Dufferin, Governor General of Canada, the creation of an international park was set in motion in 1879, and on July 15, 1885, 75,000 people gathered at the dedication ceremonies of the New York State Niagara Reservation. A mile-long stretch of the most choice industrial land was to be absorbed into parkland, and the demolition of roughly 150 buildings began. For the 166,000 visitors to Niagara Falls in 1887, "The revelations of impressive scenery hidden by commercial obstructions for more than one generation created surprise and admiration."

Scaling up

The Niagara Reservation suddenly absorbed the prime industrial lands and heightened all the preexisting problems of power development. Any power canal would have to be fed from further upstream and would have to discharge further downstream, thereby extending the distance and escalating construction costs. Financing, already the source of earlier failures, looked momentarily bleak. However, this environmental obstacle merely served as a prod to a larger vision, to an escalation of power development on an unprecedented scale, so that distant as well as local markets might be served from a single, central station.

None of this was apparent in 1886 when Thomas Evershed put forth the first proposal for large-scale power development at Niagara Falls. Evershed, a civil engineer formerly employed on the Erie Canal, had played a leading role in the establishment of the Niagara Reservation and was determined to prove that large-scale development was possible without destroying the beauty of the falls. His concept called for 12 canals carrying water to a large number of vertical shafts that, in turn, dumped into a single discharge tunnel pitched downward so as to strike the river below the falls. These shafts were to be the wheel pits for 238 turbines, each of 500 horsepower. Mills and factories would be spread along the 12 canals and, in aggregate, would consume 119,000 horsepower. This was a bold and dramatic development scheme in an age when a few hundred horsepower was the norm.

The Evershed scheme stirred the interests of business leaders in Buffalo, who in 1886 incorporated and went about the United States and England discussing the project in an attempt to raise capital. Although the excavation costs for the multiple canals and shafts of the Evershed scheme eventually proved prohibitive, the local group finally brought the potential of Niagara Falls to the world and succeeded in furthering the two-market vision: local consumption plus the transfer of bulk power to Buffalo, which at that time was a city of 250,000 people.

In the summer of 1890 representatives of the leading investment banking houses in the United States, including J. P. Morgan and William Vanderbilt, met with the directors of the local organization. Morgan hesitated and then said, "Well, there is Adams, if you can get him, I'll join you." Edward Dean Adams, a banker who sat on the board of Edison General Electric Company, accepted their offer and in 1890 was made head of the Cataract Construction Company, the financial agent overseeing the engineering. With Adams in charge, the dominance of the financiers in innovation and planning was firmly established. And with the resources of Morgan and Vanderbilt behind the project, the historical obstacle of insufficient capital was finally surmounted.

Currents of advice

Cataract officials had essentially purchased (for $483,000) the Evershed plan and the options for land and right-of-way. But Adams was disconcerted with the plan's inherent decentralization and gravitated toward a commitment to have a central generating station built at the falls and linked by bulk power transport to Buffalo. He sought the advice of prominent engineers, scientists, and inventors and found no consensus. Electric power with incidental lighting, rather than the converse, was the new condition posed by Niagara, and nothing in then-current engineering practice even approached the magnitude of power development envisioned. Moreover, the state of the art in electrical engineering was in a stage of rapid evolution and was seemingly confused.

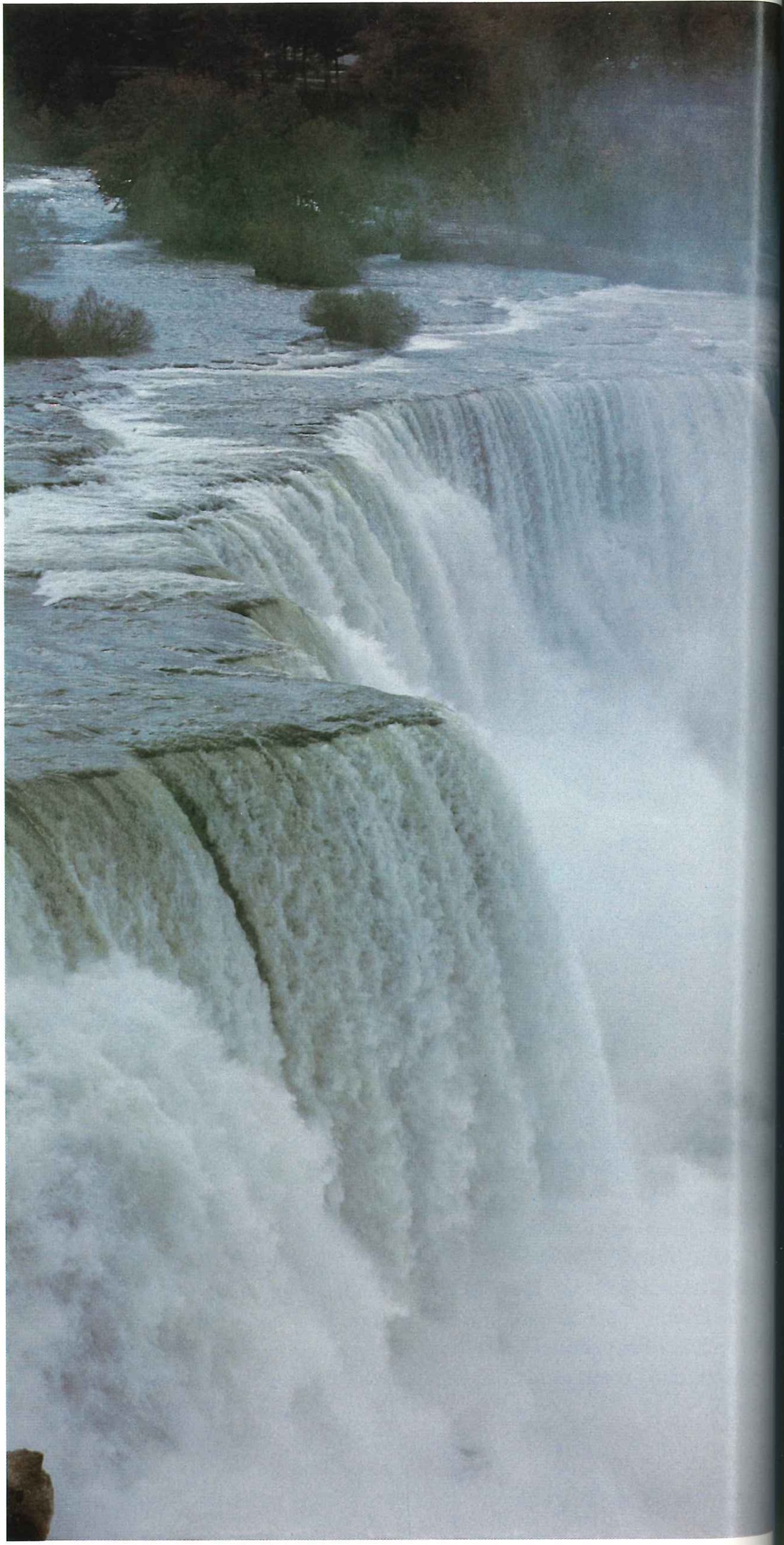
Edison was among the first consulted (in 1889). He recommended a central tunnel with rope or cable transmission to dynamos on the surface and dc transmission to Buffalo. Frank Sprague, the father of electric traction, doubted the commercial feasibility of any such electric transmission, and Westinghouse, for com-

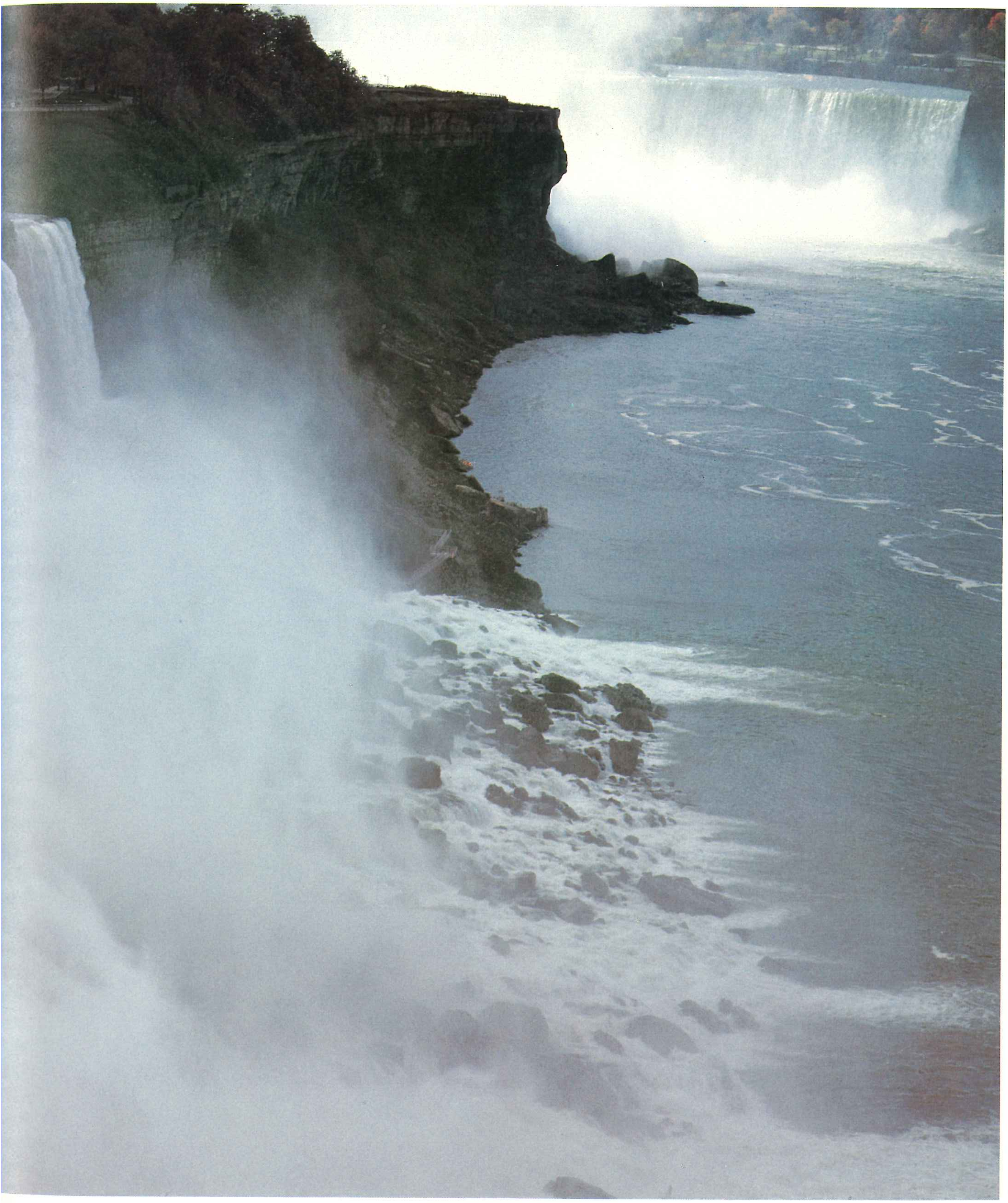
Whence the thunder

A gathering cloud rolls up and over northern Minnesota, compresses in the chill, and lets its vapors drop. One raindrop among the many is cleaved upon a small stone, splashing separately off the western and eastern faces. Striking the ground, one part is carried off in a stream bound for the Mississippi, down to New Orleans and into the Gulf; the other part trickles off toward Newfoundland. To the east of the stone lies one of the great drainage basins of the North American continent, a vast aquatic land created from some 30 inches of rainfall descending every year over a quarter of a million square miles, a land of streams in constant converging movement, a land of rivers so swollen as to pool into small and massive reservoirs in the glacial depressions that pocket their path to the sea, a land of lakes and Great Lakes.

For every three raindrops plunging into the western extremities of Lake Superior, only one travels full course to the sea. Superior, the largest freshwater body in the world, descends some 21 feet, forcing its way into the deep horseshoe-shaped pool known jointly as Lakes Michigan and Huron. This body, in turn, pushes out at the southern extremity of Huron through the concourse known as the Detroit River and cascades nine imperceptible feet into the shallow holding tank of Lake Erie. From here—at 572 feet above sea level and only 30 feet below the elevation of Lake Superior—the flow spreads out toward the Northeast, then necks down, lifts up, and spills over the northern bank, rushing into the Niagara River. For 20 miles this concourse of descent to Lake Ontario gradually accelerates, the currents of the milewide river growing swift. Then, the gentle incline down which the inland seas have been rolling for a thousand miles begins to give way, pitching forward and propelling the waters into a turbulent race through 51 foaming feet of vertical descent to the brink of the Niagara cataract. And then it drops a 3600-foot curtain of thunder.

"The great cataract is the embodiment of power. In every second, unceasingly, 270,000 cubic feet of water leap from a cliff 160 feet high, and the continuous blow they strike makes the earth tremble."
H. B. Gilbert 1895





mercial reasons, recommended transmission by compressed air, which could be used directly in existing steam engines. Perplexed, Adams sailed to Europe to sound out the Swiss, French, and British experts.

After touring European hydro sites for several months, he decided the best tactic for eliciting technical advice was to sponsor a design competition. The International Niagara Commission was thus established in London in 1890 with Lord Kelvin (Sir William Thomson) as chairman; 28 firms in Europe and the United States were asked to submit proposals based on the idea of a single central station. Escher Wyss of Zurich, Switzerland, received a first prize for hydraulic turbines, but there were no first prizes in the category of transmission. Methods proposed for the latter varied: seven for electric, four for pneumatic, two for hydraulic, and one for wire rope.
nificantly, only two proposals were m
for ac transmission, and only one
polyphase by George Forbes, a Bri
engineer who significantly influenced
ultimate decision some three years la

The effect of the commission was
bring the scheme before the entire wo
to speed the coalescence of world en
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Beginnings of engineering education

Educational reform—a movement that became a major impetus in the growth of science and engineering in the United States—swept through the universities in the post–Civil War period and installed the sciences in a place nearly equal to the humanities and to theology. A new generation of college presidents encouraged science. Outstanding among them were Charles William Eliot at Harvard, Noah Porter at Yale, and James B. Angell at Michigan.

Johns Hopkins, a university founded in Baltimore in 1876, became especially influential. It was headed by Daniel Coit Gilman, who set as its goal the encouragement of research. To his faculty, Gilman attracted Henry A. Rowland, one of America's first eminent electrical scientists, Lord Kelvin (as a visiting professor), and Charles Saunders Peirce, who laid the groundwork for pragmatism and did profound work in logic.

The first four-year program in electrical engineering in this country was offered at MIT in 1882, the same year Edison's first central stations opened and one year after the international system of electrical measurement was standardized. In 1883 Cornell University started a program that was soon internationally recognized for its dynamo laboratory, where tests were performed on commercial and experimental equipment. The MIT and Cornell programs laid the general foundation for programs offered at other institutions in the following years.

The university/science reform movement had two interesting consequences for R&D. It directly stimulated interest in science and indirectly helped push science into industry. The movement arose out of the great hunger for science that prevailed in the Victorian era. But this stimulation in the universities had an ironic twist. Except at Johns Hopkins, it tended to encourage the teaching of science and to discourage actual research on the part of science faculties. Thus, those who yearned to do actual research became increasingly frustrated. By the end of the nineteenth century, the dilemma led many scientists of caliber to consider pursuing science within the industrial context.

In the early 1880s electrical engineers were graduates of other branches of engineering, physics, or mathematics; were entrepreneurs; or were practical technicians who had worked in telegraphy, telephony, arc lighting or machinery construction. By the mid-1880s the industrial applications of electricity were seen to have broad potential, and specific programs were established in universities. As the trend within the industry began to grow, electrical engineering programs increased in number and size. By the early 1890s they were the chief suppliers of electrical engineers, although many of the earlier electrical engineers held important positions well into the twentieth century.

Four who led the second

Within a few years after the
Edison's Pearl Street Station
system developers began to
the limitations of direct-curre
tems. Because dc is restricted
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serve a distance of less than
Thus a large city serviced by
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mission, to initiate the construction of the central tunnel, and to pave the way for negotiations with Swiss firms for designs of 5000-horsepower turbines. But the commission failed to determine the state of the art in the rapidly emerging polyphase systems (at that time alternating currents in multiple phases were called polyphase). Lord Kelvin was heavily biased toward dc, and the two leading proponents of polyphase, Westinghouse and Maschinenfabrik Oerlikon of Zurich did not bother to submit bids. Said Westinghouse, "These people are trying to get $100,000 worth of information for a prize of $3000. When they are ready to do business, we will submit a plan and bid for the work." When the commission finished its work in the fall of 1891, no definitive system had yet emerged. Nevertheless, design invitations for a central electric station were extended to six firms, three in the United States and three in Switzerland.

Decision for ac

Meanwhile, a rapid succession of polyphase installations began to catch the attention of Adams and his advisors. Westinghouse had transmitted hydroelectric ac power at 3300 volts over the 13 miles from Willamette Falls to Portland, Oregon, in 1891.

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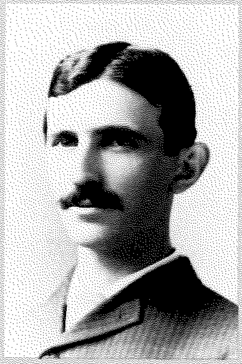
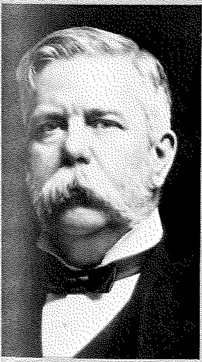
Tesla





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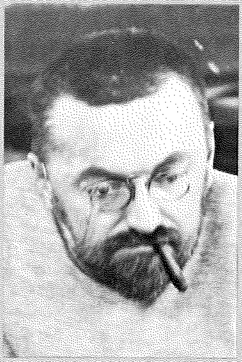


Steinmetz

1914), an intrepid inventor-entrepreneur, perceived the economic and technical significance of ac and unswervingly persisted in bringing such systems into practical reality; and Charles P. Steinmetz (1865–1923), more than anyone else, made the greater complexities of ac systems understandable.

Backed by Westinghouse, who had bought the British patents on the Gaulard and Gibbs transformer, William Stanley significantly improved their design and, by connecting them in parallel, demonstrated their feasibility. This demonstration persuaded Westinghouse to proceed with the marketing of ac systems.

In 1882, while working in Budapest, engineer Nikola Tesla, in a sudden flash of insight, conceived the operations of rotating magnetic fields, the concept of the ac induction motor, and the basic concepts of polyphase systems of ac generation and distribution. But failing to find support for the development of his concepts in Europe, he immigrated to the United States, where, in 1888, he took out patents on ac polyphase systems, complete with motors, generators, and transformers—inventions that have undergone no really basic change since. Westinghouse bought these patents and sponsored years of work on their development.

George Westinghouse, just two years younger than Edison, was himself a prolific inventor-entrepreneur, acquiring more than 400 patents in his lifetime. He had built his reputation early with his invention of the air brake in 1869. But it was not until 1881 that Westinghouse became commercially involved with electricity. His understanding of the commercial potential of ac systems led him to push hard the developments that revolutionized the electric power and light industry. By 1891 his company—the Westinghouse Electric Company, formed in 1886—installed the nation's first single-phase power transmission system at Telluride, Colorado, the first polyphase system in Chicago in 1893, and then—at the turning point for the entire industry—much of the Niagara facility, completed in 1895.

Charles P. Steinmetz, the German-born mathematician and a political refugee of the Bismarck years, was the first true theoretician of ac systems. With his mathematical formulations, his textbooks, his teachings, and his research with the General Electric Company, which he joined in 1892, he became the architect of theory for a generation ready to embrace the practical making and building of universal electrical systems. By simplifying ac theory, by his analysis of hysteresis (a phenomenon causing energy dissipation in transformer cores), and by his teaching within the industrial environment, his influence became important in transformer- and motor-design developments, and he established an imitable style for the "pure" scientist within the industrial context that prevails to this day.

The transmission of 30 kV ac power over a distance of 110 miles at 77% efficiency took place in the same year in Germany and probably had more impact than the Oregon and other American installations. The young Oerlikon engineer responsible for the German feat, C. E. L. Brown, had so impressed Adams and Forbes (now an advisor) that he was invited to establish a firm at Niagara. Brown declined and started his own firm, Brown-Boveri, one of the major contenders for the Niagara contract. Finally, the impressive demonstration of Westinghouse's comprehensive two-phase system at the Chicago World's Fair of 1893 enhanced the case for ac.

Although the successful ac installations only presented in miniature what was proposed for Niagara, they were sufficient to swing the balance in favor of the newer current.

Lord Kelvin, whose work Maxwell had drawn upon for his electromagnetic theory and whose mirror galvanometer had made trans-Atlantic telegraphy possible, sent an eleventh-hour cable: "Trust you avoid gigantic mistake of alternating current." Despite this advice, Cataract decided in favor of ac in the spring of 1893.

It remained only to let the contract. The designs by the Swiss manufacturers were eliminated on the basis of patent considerations, transportation costs, and U.S. patriotism, and the contract decision came down to a battle between General Electric's three-phase, 40-cycle system and Westinghouse's two-phase, 30-cycle system. The three principal advisors preferred the Westinghouse plan, but Cataract officials rejected both. They felt the Westinghouse plan was incompatible with the turbines already contracted. Forbes took it on to redesign the generator and chose 16⅔ cycles per second and 20,000 volts, even though this would produce a noticeable flickering in incandescent lights. The Westinghouse engineers reacted strongly, and a compromise was reached on 25 cycles per second and 2200 volts. This became the standard for electric power for many years.

In the fall of 1893 Westinghouse received the contract for the first three generators. General Electric was awarded contracts for the transformers, the transmission line to Buffalo, and the substation. Although the generator contract was seen as a victory for ac over dc and for Westinghouse over General Electric, the policy of encouraging competition tended to even things out. By 1905, of the twenty-one generators in the two Niagara Falls powerhouses, ten were from Westinghouse and eleven were from General Electric.

Market turnaround

The first two Niagara generators went into service in August 1895, and a year later the transmission line to Buffalo was opened. The two-market vision on which the financial success of Niagara hydroelectric development was based became a reality. Yet technical events, unforeseen only a few years earlier, turned the market around.

The availability of cheap power at Niagara transformed Charles Hall's process for manufacturing aluminum into an economic enterprise, and the first customer was Pittsburgh Reduction Company. The Carborundum Company (which had been formed by one of Edison's former associates, E. G. Acheson) followed suit, and within a few years Niagara became a center for electrochemical and electrometallurgical processes. By 1897 two-thirds of the power was being consumed locally.

For years, long-distance transmission to Buffalo was the weakest part of the system. Continuity of service was a significant factor in market penetration, yet the system was troubled by inadequate lightning protection, insulation, and switching.

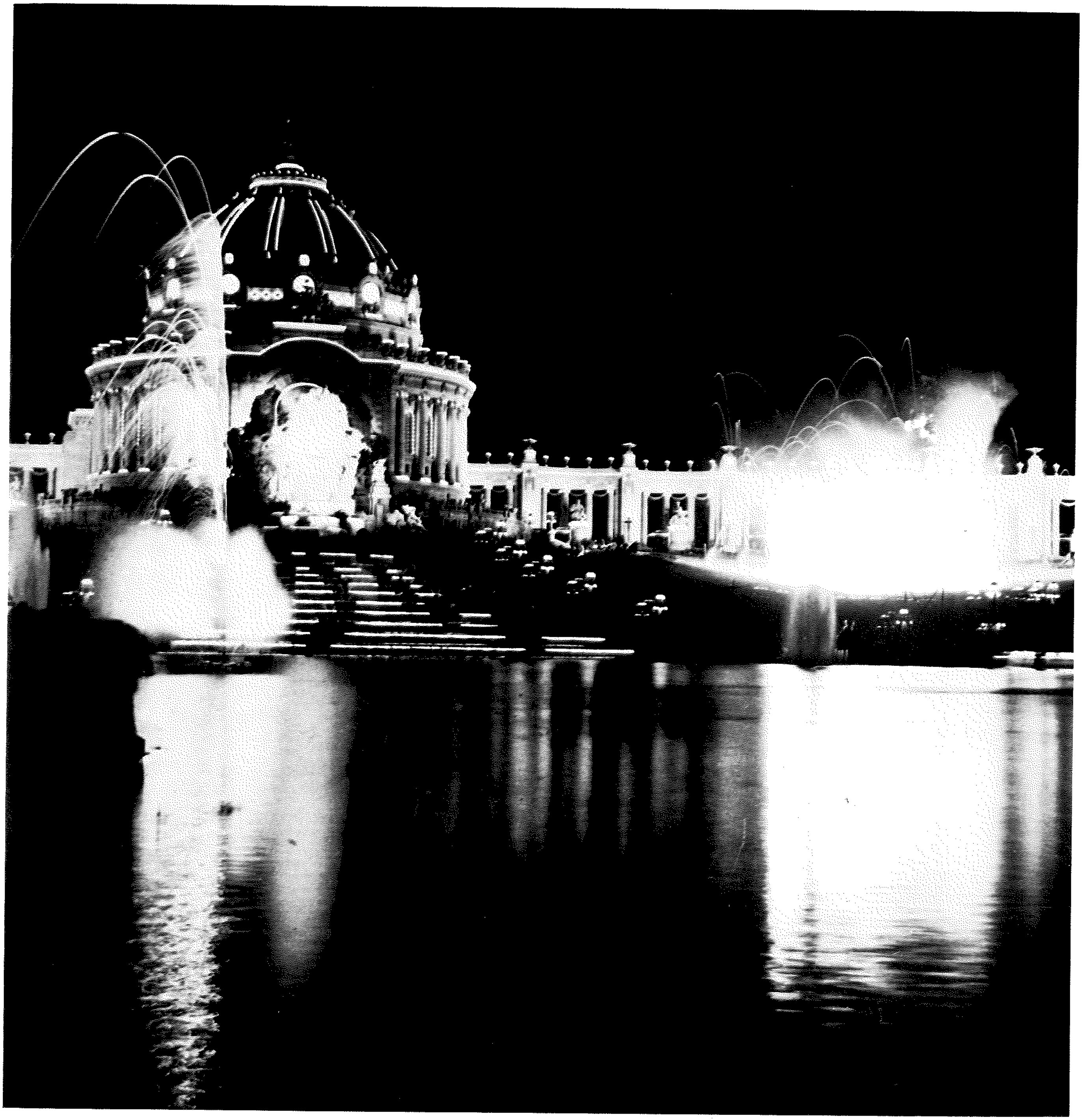
Never before had a power project so captured the world's imagination, and never before had the skills and ideas of so many gifted technologists been so carefully, cleverly, and quickly integrated. At Niagara the capability to harness the power of falling water was multiplied almost astronomically by its transformation into electric power. And the necessary linkage between such a concentrated source and a large, dispersed market proved to be long-distance ac transmission. As George Forbes was to appraise the development in 1897, "The greatest step, it seems, which has been taken in the distribution of electricity since the period when electric lighting took such a start in 1878 was the use of alternating currents with induction apparatus, which was simply achieved by the most indefatigable industry and plucky perseverance against the opinions of everybody who seemed to be capable of giving an opinion."

Significance of Niagara

In the Niagara period, central station electric power took on enormous proportions and set the stage for the universal electrification of the twentieth century. Coming a little more than a decade after Edison's Pearl Street Station, the project integrated the proliferating developments in the electrical sciences in Europe and America, developments that had outpaced and momentarily eclipsed Edison's work.

Unlike the Edison period when the inventor-entrepreneurs were in the lead, the principal organizing force behind Niagara was the financial consortium. It drew together international research efforts and cross-fertilized the somewhat isolated European and American developments, effectively creating a laboratory without walls.

The ac revolution that began in Europe was quickly assimilated into American practice and put into large-scale use for the first time at Niagara. Practical use of ac for long-distance transmission proved to be the key that unlocked the highly concentrated power of Niagara Falls. With the dc central stations of the Edison era, power distribution was limited to a few square miles, but with the Niagara project the geographical constraint on distribution (and therefore central station capacity) was removed at last.



The sheer excitement that people experienced over electric light at the turn of the century was expressed through great light displays like that of the Louisiana Purchase Exposition in 1904. But the universal adventure with electric light and power was just beginning, and new and more efficient ways of producing it became the focus of intensely competitive research in the new century.

In the seventeenth century Francis Bacon, intent on ways of releasing man's inventive powers, foresaw the cooperative approach that became the trademark of twentieth-century industrial science. Despite the conviction of Bacon and subsequent thinkers that science could be of practical value, it was not until the nineteenth century that fruitful alliances began forming between science and technology and between theory and practice. Then at the end of the last century, a whole set of conditions emerged that prepared the ground for the seeding and growth of industrial R&D laboratories. A twentieth-century phenomenon, the pioneering electric R&D laboratories in which scientists and engineers worked as equal partners, scored significant successes, both in science and in industrial applications. These early laboratories became the models for other industries.

CROSSING THE THRESHOLD

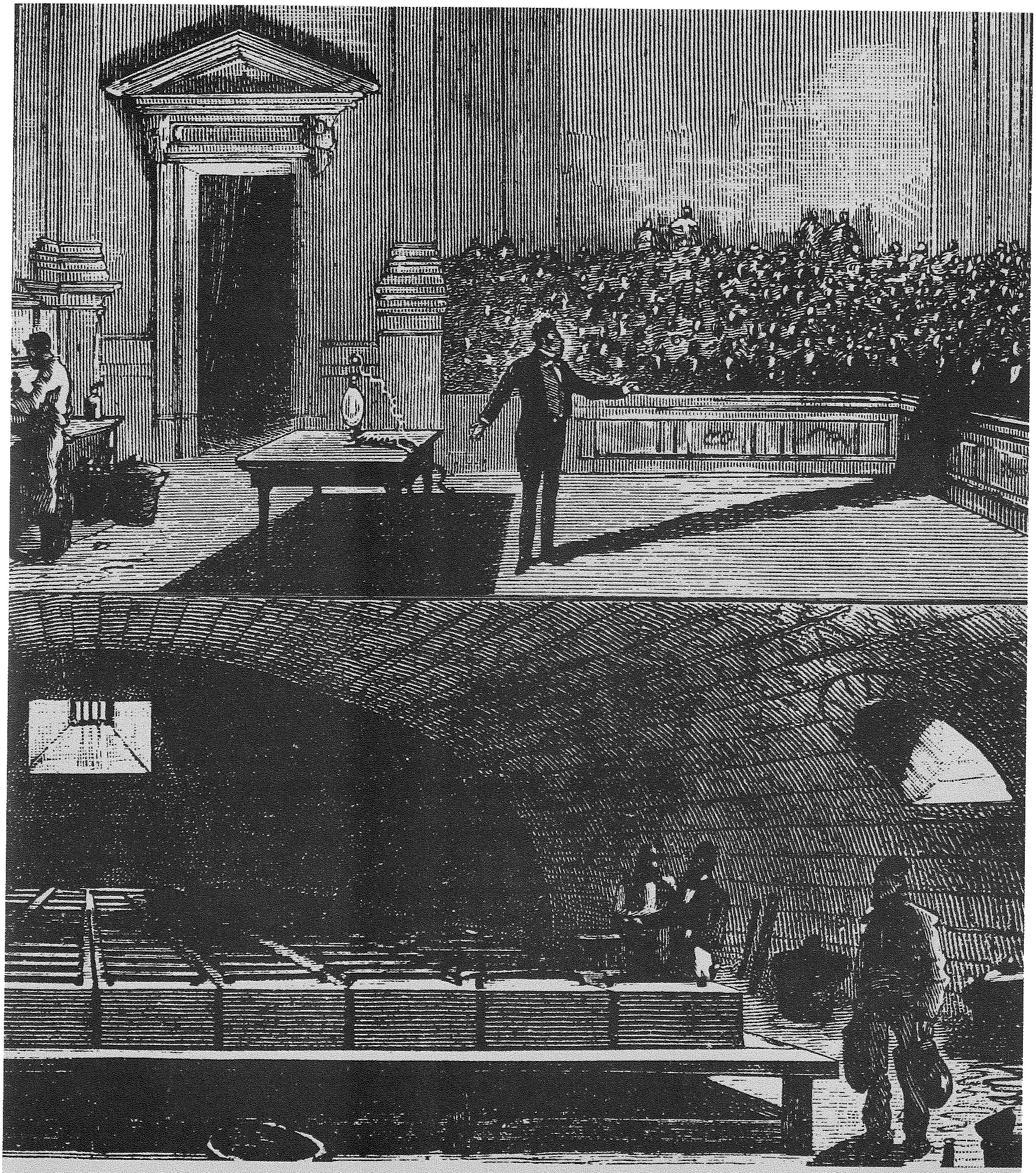
Industrial R&D

By the turn of the century, many significant changes in the American scene had given a new complexion to the electrical arts. Edison, still active as an inventor-entrepreneur, had turned his back on the electric light and power industry to develop a durable and improved storage battery for electric automobiles, which he saw as the wave of the future. At the same time, a new breed of men—trained in science and in engineering—were beginning to come into the electrical industry, at first slowly and then in increasing numbers. It was not merely their specialized training that was important; an emerging combination of conditions in industry and business attracted them.

Electrical research in the late 1700s. Animal electricity is postulated by the Italian physiologist, Luigi Galvani.

The legacy

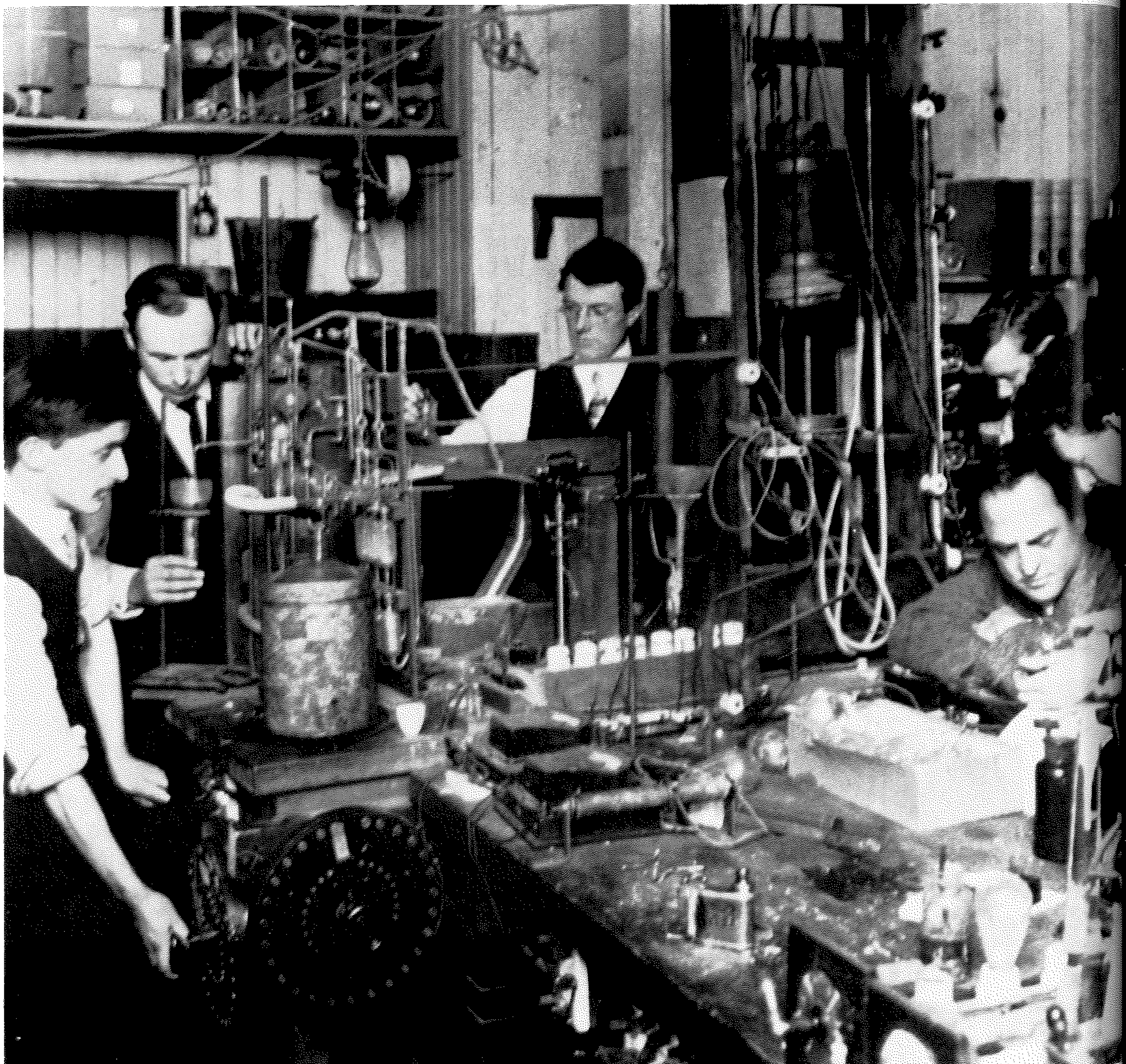
There are fundamental differences between the scientific and engineering laboratories of the nineteenth century and those of the twentieth. In large measure science and technology were separate activities in the nineteenth century. Only when theory and practice began to come together did the industrial laboratory begin to take on a recognizably modern shape. Of course, there had been vital connections between science and technology throughout history, but only in the nineteenth century did such connections develop in any programmed fashion, and then only in certain fields and in different countries at different times. For instance, the conjunction of science (es-



With a massive battery of 2000 voltaic cells, British scientist Humphry Davy demonstrated the first electric arc light before the Royal Society in 1808. It was the birth of the search for a practical electric light.

pecially chemistry) and agriculture started in Germany in the 1830s and eventually led to an agricultural revolution based on systematic scientific research. The convergence of thermodynamics (the science) and steam engine development (the practice) was largely achieved in Great Britain in the 1850s and 1860s. The convergence of organic chemistry (the science) and the synthetic dye industry (the practice) came about largely in Germany in the 1860s and 1870s. And the convergence of the electrical sciences (especially electromagnetic theory) and the electric light and power industry came about in the United States and in Europe in the 1880s and 1890s. In general, after such convergence, practical advances tended to move hand in hand with the scientific theo

Not only were science and technolo separate activities, laboratory and dev opment facilities were also separate un well into the nineteenth century. Ve early seventeenth- and eighteenth-centu laboratories in Europe and Great Brita were often in the homes of gentlem philosophers, who had little contact w



With the emergence of industrial R&D laboratories in the early twentieth century, a more organized, teamwork approach to special problems began to mature.

practical developments. Important research laboratories developed in university and other institutional settings in the nineteenth century, but they were also generally removed from practice. Some examples were the Royal Institution in London, presided over by Sir Humphry Davy and later by his former assistant, Michael Faraday; the Cavendish Laboratory at Cambridge University, first presided over by James Clerk Maxwell; and Hermann von Helmholtz's Physico-Technical Institute in Berlin, where in 1888 his student Heinrich Hertz discovered radio waves. (This discovery provided important support for Maxwell's electromagnetic theories, first proposed in the 1860s.)

In America, laboratory development was much the same. Like other natural philosophers, Benjamin Franklin worked alone while making practical inventions like the stove and lightning rod (1749). There were important experiments in the 1830s on electric motors by Joseph Henry, but unlike the inventor-entrepreneurs, he disdained turning them into practical devices. Later, as head of the Smithsonian Institution he also tended to sponsor small, theoretical projects rather than applications. Various federal agencies, such as the U.S. Geological Survey, the Coast Survey, the Naval Observatory, the Department of Agriculture, the National Academy of Sciences, began making some connections between pure science and practical problems after the Civil War, but such connections were generally not condoned by Congress. Some research went on in various universities, but it was very limited until 1876, when Johns Hopkins University in Baltimore was founded with the announced intention of making research a central activity. Meanwhile, the laboratories of the inventor-entrepreneurs—Edison, Thomson, Westinghouse, Stanley, and others—largely focused on practical problems. Although these individualistic inventors sometimes drew on the advice of scientific consultants, they did not usually form lasting associations.

It has been argued that Edison's laboratory was an important prototype for the organized R&D laboratories of the modern era. But Edison's laboratory was a nineteenth-century phenomenon in the sense that the inventor and his scientific associates were not equal partners in their endeavors. Although they used science whenever they could and scoured the literature, their research was based more on trial-and-error methods than on scientific theory.

People with strong scientific training who worked with Edison, like Nikola Tesla, were sometimes appalled by what they considered a lack of scientific rigor in Edison's methods. Said Tesla, with no little contempt, "If Edison had a needle to find in a haystack, he would proceed at once with the diligence of a bee to examine straw after straw until he found the object of his search. I was a sorry witness of such doings, knowing that a little theory and calculation would have saved him ninety percent of his labor." Yet, Edison's method led to the solution of the electric light problem, just as Tesla's theories of rotating magnetic fields later ushered in the world of ac machinery. Thus, each stood with a different stance at the threshold of the modern technological age.

To bring that age into being, to bring about the marriage of science and technology, and to evolve the industrial R&D laboratory that is at the core of modern enterprise would require three important elements. As Kendall Birr, who studied the pioneering industrial laboratories, states, "First, science had to develop to a point where there was no question about its usefulness to technology. Second, businessmen and those other people who made the basic decisions in economic life had to realize the importance of science to their economic welfare. Finally, some institutional arrangements had to be made for the conduct of industrial research."

In the electrical field, these requirements were being met in the latter part of the nineteenth century. As it happened, organized industrial research in the electrical field developed with the emergence of the modern business corporation. There was a strong symbiotic relationship between the two; one could almost assert that organized industrial laboratories could not have come to maturity without the structure of the modern corporation.

R&D in the modern corporation

Why the modern business corporation should have become such an important sponsor of organized industrial R&D can be traced through the experiences of the early electrical manufacturers. Although it was initially supported by other businesses, electrical development and manufacturing soon acquired its own distinctive characteristics, based on the need to produce a wide range of specialized products and components, each of which had to survive in a competitive field. Almost from the beginning, the production of lamps, switches, cables, generators, motors, and the like depended on the coordination of new skills within special constraints. It led fairly rapidly to specialized company divisions, each responsible for advancing components that had to function compatibly in the larger systems being set up by the operating utilities. Thus, such companies tended to outstrip the control of individual owner-entrepreneurs, who had to rely increasingly on the delegation of authority and on a hierarchy of command.

But the solution to one problem—the production of many specialized pieces by specialized divisions—led to another problem: intensified competition. It became quite clear in the last decade of the nineteenth century that research was acting as a unique force—research necessitated further research in order for a corporation to stay alive, and costs escalated. It became difficult for any one division to support its future-oriented research needs. Thus, larger corporations were being induced to establish research groups as a separate function, while engineering associates continued to support diverse functions, such as manufacturing, product development, and sales.

In addition, the new corporations were distributing their products in a national market, not local or regional markets as they had in the nineteenth century. Electrical system components were being sold—in both standard and custom form—from coast to coast. Thus, there was potentially a huge increase in profits, which would help cushion research investments. The value of manufactured electrical goods, in fact, was nearly 17 times as great in 1914 as in 1889 (from $19 million to $335 million).

The influence of patent laws

Patents were also stimulating change. As Leonard S. Reich describes it, "Beginning in the 1890s, the use of patents to control markets by often circuitous routes became possible as a result of judicial interpretations of patent rights. Until that time, a patent had to be used to have standing in court. Thus, if a company acquired the rights to several patents on one type of device, the courts held that only those patents relating to the device as actually produced could be enforced. Under these conditions, a company which undertook extensive research and development could see much of its work appropriated by others and have no recourse. In 1896, however, a federal court ruled that patents were 'clearly within the constitutional provisions in respect to private property' and that the patent holder was 'neither bound to use the discovery himself nor permit others to use it.' While a federal court ruling in 1898 confused this issue somewhat, the Supreme Court strongly upheld the patent as a property right in 1908. Thus, the way was cleared for corporations to use patents for forays into new—and not necessarily related—market areas and as effective shields for their established commercial positions."

Prompted by intricate patent relationships, infringements, litigations, and deadlocks, the big three of the electrical manufacturers—Edison General Electric, Thomson-Houston, and Westinghouse—entered an era of merger and cross-licensing during the 1890s. At this time, financial pressures were nearly catastrophic because of the depression of 1893. The result of these maneuvers and negotiations was an all-out competitive war that stimulated the need for more R&D.

Manufacturers in conflict and merger

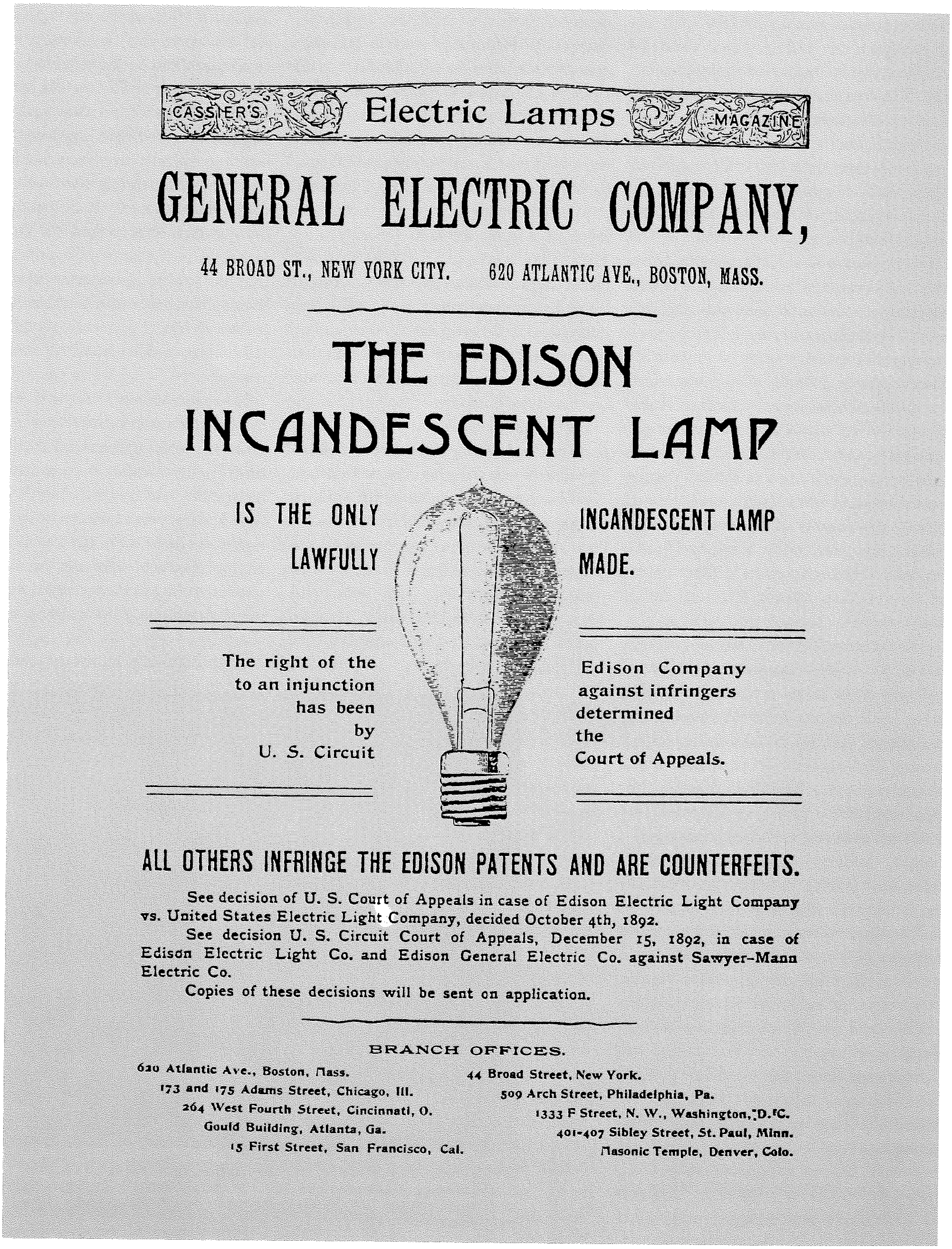
By 1890 the Edison General Electric Company and the Thomson-Houston Company were of nearly equal size and scope, and their growth was accelerating rapidly due to the introduction of practical electric streetcars in 1887–1888. These cars had created such a demand for new heavy electrical equipment that both companies were financially pressed to meet the demand, while avoiding further infringements upon one another's patents. These companies had learned a hard lesson about legal battles, especially in the lighting infringement contest—the so-called seven years' war over Edison's carbon filament lamp. That case, finally resolved in 1892, was a Pyrrhic victory for the Edison group. By the time other companies were forced to stop manufacturing and selling light bulbs, only two years remained on Edison's patents. The litigation had cost Edison's companies $2 million. Thomson-Houston's finances had been severely damaged, and Westinghouse, which was said to have been made almost insolvent, had to race to bring a new noninfringing lamp on the market in time to fulfill a contract for the lighting of the Chicago World's Fair of 1893.

Hemmed in by each other's patents and needing greater capital resources to meet the growing demand for their electrical equipment, Edison General Electric and Thomson-Houston decided to merge. The formation of General Electric Company on April 15, 1892, consolidated the patents of the two groups, increased their total industrial capability, and brought together two important groups of financial backers: Boston financiers, who had backed Thomson-Houston, and J. P. Morgan and his associates, who had backed Edison. It was also intended to bring into the same camp two highly inventive men, Thomas Edison and Elihu Thomson. However, Edison, apparently aggrieved that his name did not remain on the new company's standard, withdrew from the company's affairs, although he was on the board of directors and received a large stock holding. Charles A. Coffin, who had managed the business development of the fledgling Thomson-Houston Company, became the first president of General Electric and guided its growth until 1913. He presided over the period that saw the establishment, growth, and world distinction of General Electric's industrial research laboratory.

Separation of manufacturers and utilities

A second crucial patent challenge, confronted in 1896, was resolved in a different manner. That crisis came while most companies were still fighting the profound effects of the 1893 financial panic. General Electric weathered the economic depression, in part, by selling to a syndicate some of its assets in the form of claims against, and stocks and bonds of, local lighting and railway companies. The company had already sold some of its similar holdings in 1892 at the time of the merger. It should be noted that from the time that Edison and Thomson had established their enterprises, they had taken shares in local lighting companies in lieu of cash payment for electrical equipment. The fledgling utilities often could not afford central station facilities without such backing, and it was to the advantage (indeed, it was part of the strategy) of the electrical manufacturers to see the lighting companies established and prospering. However, it created a dangerous and unstable paper relationship that was shaken to the core by the 1893 financial panic.

Those events marked the separation of the lighting companies and their parent



CASSIER'S Electric Lamps MAGAZINE

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THE EDISON INCANDESCENT LAMP

IS THE ONLY INCANDESCENT LAMP
LAWFULLY MADE.

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has been determined
by the
U. S. Circuit Court of Appeals.

ALL OTHERS INFRINGE THE EDISON PATENTS AND ARE COUNTERFEITS.

See decision of U. S. Court of Appeals in case of Edison Electric Light Company vs. United States Electric Light Company, decided October 4th, 1892.

See decision U. S. Circuit Court of Appeals, December 15, 1892, in case of Edison Electric Light Co. and Edison General Electric Co. against Sawyer-Mann Electric Co.

Copies of these decisions will be sent on application.

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industries and established the pattern of independent utilities and vendor-suppliers that has prevailed to the present day. Thus, a specialization among industries—electrical operators and equipment manufacturers—was occurring at the same time that the modern corporation, with its specialized divisions and decentralization of responsibilities, was coming into being.

In addition to financial adversities, the two major contenders in the electrical equipment business—General Electric and Westinghouse—were rapidly becoming enmeshed in a patent deadlock. Thousands of patents in the electrical industry had been issued since the breakthrough of 1879, and each of the two giants held many patents, so that each was infringing—unwittingly or deliberately—on the other. General Electric held, among others, the patents of Thomson, Brush, Edison, Sprague, Van Depoele, and Bradley; and Westinghouse held the patents of Sawyer-Man, Maxim, Weston, Tesla, and Stanley.

The solution this time was not merger, but a cross-licensing agreement, whereby each could make products using the other's patents. As John W. Hammond, the early historian of General Electric, wrote, "This agreement insured freedom of action in the legal relations of the signatories for a period of 15 years. Instead of lessening commercial competition, it stimulated it, for both companies were now free to manufacture and sell in competition with each other all essential equipment required by their customers. The merit of each company's product governed the amount of trade and the range of prices which it could obtain—and neither of them controlled the market."

In this situation, the two major manufacturers were driven to produce new inventions in order to protect their very survival as corporations.

The first modern industrial laboratory

In addition to the patent struggles, a new challenge to the American electrical manufacturers appeared, this one from Europe. A new form of electric light that aroused anxieties in the leadership at General Electric—the Nernst lamp—was introduced in America by Westinghouse. The lamp featured a ceramic-type filament and was about 50% more efficient than the carbon filament lamp. The competitive challenge led to the establishment of a new research laboratory in 1901 to undertake improvements on existing lights. That laboratory brought trained scientists into the electrical industry and developed a new cutting edge for industrial research. It also signaled the end of the Edison carbon filament lamp and the Edison era.

For some time, it had been evident that the fund of scientific theory and insight into electrical phenomena that had been built up in the nineteenth century by men like Faraday, Henry, Maxwell, Heavyside, Rowland, and others was being mined out. General Electric's vice president, Edwin W. Rice, who had been with the company since its early Thomson-Houston roots, was aware of this situation and had begun to think seriously about hiring scientists to conduct new research. He was also apparently disturbed by the fact that some of his engineers were beginning to think that nothing radically new would develop in electrical engineering. Such an outlook did not necessarily bode well for an organization that staked its future on technical innovations in a product field that had proved to be intensely competitive. Although some of the guiding spirits of the electrical pioneering period, like Elihu Thomson, were still working, most were gone.

However, a new tone was being set in the electrical industry by men like Charles P. Steinmetz, who had become head engineer at General Electric in 1894 (at age 29), and by Benjamin G. Lamme, who had become chief engineer at Westinghouse in 1901 (at age 42). With their engineering achievements, based on an understanding of theory and the employment of complex mathematics, they were

British physicist Sir Joseph J. Thomson (center) on a visit to the General Electric Research Laboratory in 1923. His hosts, William D. Coolidge (right) and Irving Langmuir (left) show him a pliotron, a high-vacuum tube of the early electronics era.

building a greater respect for the use of science in industry. (In Europe, similar strides were being made by engineers in German General Electric [AEG] and other leading electrical firms.) Steinmetz and Lamme were also instructing new cadres of engineers within their organizations in the new complexities of electrical engineering. But these efforts were not enough to expand the frontiers of theory that would be required to open up new technical developments.

In some technical areas General Electric was strong. For instance, it was entering the turbine business. The turbine had been patented in England by Charles Parsons. (General Electric's approach to turbines was based on a new method devised by Charles G. Curtis. It was the beginning of the modern turbine-generator business.) But the company was being seriously challenged in its lamp business by innovations in the gas lighting industry, by a mercury vapor lamp being developed in America, and by lamp developments in Europe. A number of lamps had been developed in Germany, including a tantalum filament lamp by Siemens and Halske, but most worrisome was the Nernst lamp with its ceramic-type filament and great efficiency. General Electric's traditional rival, Westinghouse, had acquired the rights from AEG for distributing the Nernst lamp in the United States and was also supporting development of the vapor-type lamp.

One General Electric response to the threat was to initiate a search for new filament materials that would be equal to, or better than, those already available. That was the course adopted when Steinmetz proposed a new research laboratory, a proposal in which he was backed by the chief patent attorney, Albert G. Davis, and in which Thomson and Rice concurred.

The initiation of this industrial research laboratory constituted a classic case of defensive research, taken up to answer a utilitarian need and then going on to produce scientific results of high caliber. As historian George Wise has pointed out, there was initial agreement and some anxiety that it be understood by the scientists recruited that this "was to be a real scientific laboratory." Had the research laboratory not been successful in its first defensive mission, however, there is some doubt that it would have survived.

Science enters industry

At the turn of the century, very few industries in the United States supported continuing research activities. There was still a strong split between the scientific community and the applications-oriented engineering communities, as well as between scientists and the industrialists. The scientists questioned whether they should alter their original scientific aims by becoming permanently employed by an industry with commercial objectives. Although there were some notable examples of chemists working in the German and American chemical industries, the American electrical industrialists were still uncertain about how they were going to control or manage this unusual resource, how they would allow scientists to go about their science and still meet industrial, utilitarian objectives.

However, in some respects, the electrical industry was more ready to accept scientists than scientists were ready to accept industry. In 1900 the industry was still close to its origins and the revolutionary spirit of its founders, the inventor-entrepreneurs. Edison, who helped start the industry but who went back to his first love, inventing, was still a public figure, and Elihu Thomson continued to experiment in his laboratory and to act as consultant to General Electric. The industry—still new and raw in many respects—was accustomed to idiosyncratic and sometimes wild-spirited inventors. It had assimilated the highly individualistic Steinmetz with his socialist convictions, and it had listened to Tesla's mystic pronouncements. It had heard the contempt Edison heaped on scientists, but it also knew that he had hired scientists and had revered the scientist Michael Faraday.

The scientists themselves had other questions about the conditions and incentives they might find in the industrial setting. Reich's study of the early use of scientists by American industrialists argues that there was "a basic perception of science in the very restricted role of 'problem solver.' Used first on an ad hoc basis, scientists and the 'scientific method' of experimentation and testing had been institutionalized within a number of companies by the later years of the nineteenth century. However, there were always specific problems to be solved, and management usually dictated them to the chemist, physicist, or engineer in the laboratory. Most laboratories actually concentrated on testing and analyzing, eminently practical uses of science. Even those who went beyond testing tended to be directly goal oriented, which greatly restricted the scope of their research activities.

"The belief that science served best as an analytic tool and a problem solver limited the contribution that scientists could make to American industry. By delineating research programs along predetermined paths, it restricted technological development to preconceived goals, which usually took the form of improvement to existing types of technology."

In pursuing this argument, Reich states, "This same type of rigidity also existed at Edison's laboratory. While Edison's conceptions of new products did have revolutionary potential, once the creative act had been accomplished, work centered on meeting his preconceived goals. Certain discoveries made in the laboratory would have been extremely suggestive had Edison and his staff pursued them further. To be developed further, however, they had to be perceived in different technological frameworks, and Edison's development schemes did not provide the latitude." However, there is also considerable evidence that Edison did engage in free-ranging experimental play.

On the positive side for the scientists

R&D in World War I

Despite the success and growing recognition of industrial laboratories just prior to World War I, such as those at General Electric, AT&T, Kodak, and others, the American scientific community met resistance when it offered its services to the military establishment. It had to struggle to bring its knowledge to a rigid military and government system that was skeptical about what physicists might actually be able to do.

After World War I exploded in Europe, Edison urged the American government to begin mobilizing the country's scientists and engineers for the defense effort. He proposed the modeling of such an organization along the lines of Germany's engineering and science organization, of which he had become aware on a trip to Germany in 1911. Edison's proposal "for a mobilization of ingenuity" was well received by President Wilson.

Edison, then 69 and the white-haired patriarch of American inventors, was asked to head a distinguished group under what came to be called the Naval Consulting Board. That group included men of a more engineering or inventive cast than scientific. Among its distinguished members were Willis Whitney of General Electric, by then a well-known manager of industrial research, Leo H. Baekeland, the inventor of Bakelite (the first important plastic), Frank Sprague of electric traction fame, and Elmer Sperry, inventor of the gyrocompass, another of the old-timers. Although the board seemed to have a few token scientists, the standard of selection was Edison's "practical men who were accustomed to doing things, not talking about it."

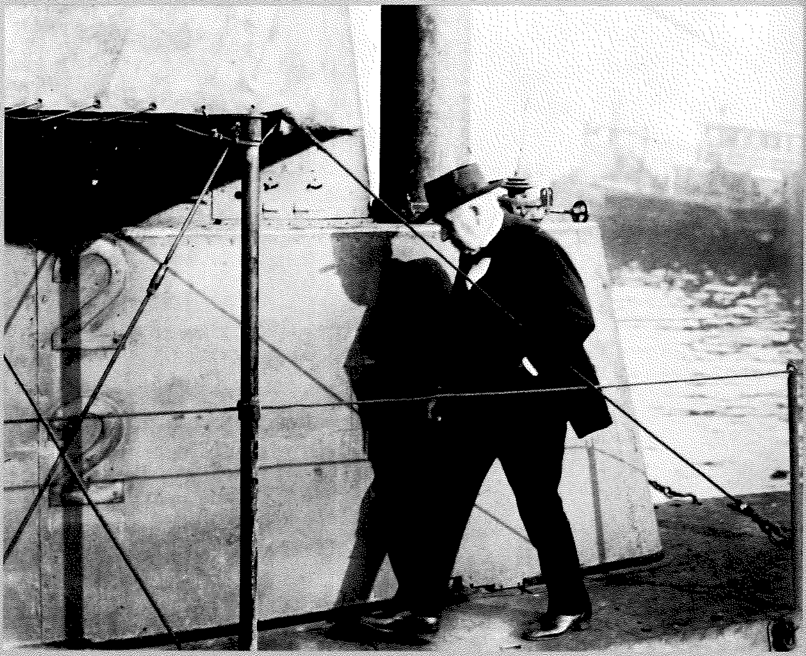
While the Naval Consulting Board was gearing up, Edison was widely quoted on his concept that it would be possible to build a submarine in two weeks from only a pile of scrap. He asked for ideas from America's citizens on ways of winning the war, and thousands of letters and suggestions poured in. By and large, Edison and his board discovered, they were worthless.

Another group of scientists that had been organized for the defense effort was what later became the National Research Council (a committee of the National Academy of Science). NRC was the brainchild of George Hale, who for years had been trying to move American research away from its tendency toward simple fact gathering and technical details to what he called "large relationships," which he hoped could be achieved on a national scale through large-project approaches and through a vigorous cultivation of pure science. Hale argued that scientists should "stress to manufacturers how Faraday's work had laid the foundations for electrical engineering."

Unlike Edison's group, which solicited ideas from practical men and an untrained public, NRC adopted a strategy of building cooperation among scientists and engineers based in many institutions dedicated to research around the country, including leading people from universities, government laboratories, industry, and the military. The purer research approaches of NRC, especially in its successful work on antisubmarine detection devices, won the day. By the war's end, it was clear that Edison's less scientific methods had been surpassed.

As science historian Daniel Kevles notes, "For thoughtful military observers the meaning of it all—of Edison's failure and . . . [of the scientists'] success—was clear: the advance of defense technology required the organized efforts of scientists and engineers whose first steps often had to be . . . in a sense, backwards into the unexplored regions where fundamental truths and engineering data were concealed."

Thus, there was one more incremental turn away from the Edison era. The models for modern R&D had been established. The end of World War I began the seed time in which many R&D laboratories began to be set up throughout the American industrial structure.



Edison on submarine inspection tour: Although he had come to symbolize American ingenuity, Edison and the work of the Naval Consulting Board during World War I were to be surpassed by those possessing more advanced scientific knowledge.

was the lure of new science and new investigative opportunities within industry. Mysterious X rays, which Röntgen discovered in 1895, had opened up a radical view on the structure of matter and the fundamental character of electromagnetic phenomena and had awakened the general realization that research frontiers had expanded beyond perceptible limits. In 1897 the British physicist Joseph John Thomson confirmed that cathode rays in a partially evacuated tube could be deflected by both electric and magnetic fields. He deduced the existence of charged particles, which are basic building blocks of matter and basic elements of electricity. (These charged particles were later called electrons.)

Science historian Daniel Kevles writes: "At the opening of the twentieth century, physics was suddenly alive with new and revolutionary questions. What was the nature of X rays? How account for radioactivity? How reconcile the apparent endlessness of its emanations—radioactive processes yielded far more energy than any known chemical reaction—with the conservation of energy? How incorporate the electron into a general theory of electricity and magnetism? And how was the electronic atom constructed? Amid the turmoil and excitement, an American observer assessed the outlook for young men in physics. The recent advances had vastly multiplied the opportunities for new discoveries'."

These discoveries brought about a revolutionary shift of viewpoint, boring inward into the substructure of matter where different and then unknown sets of laws governed the behavior of the basic atomic building blocks. At the end of the nineteenth century, a microscopic peephole had been opened into this substructure. But to open that peephole wide and to stretch it into a large clear window would take a new order of tools and resources that were, in most cases, beyond the reach of universities. Thus, young scientists, their minds filled with tantalizing new questions and frustrated by the lack of necessary but expensive

Industrial R&D laboratories—a middle way

The model created for industrial research at General Electric should not be seen in overly simple terms: as a successful bidding away of scientists from academic posts by offering them fabulous salaries; or as a haven for second-rate scientists who could apply knowledge, but not add to it; or as an institutionalization of a social role, in which scientists were broken to industrial work as a horse is broken to pull a plow.

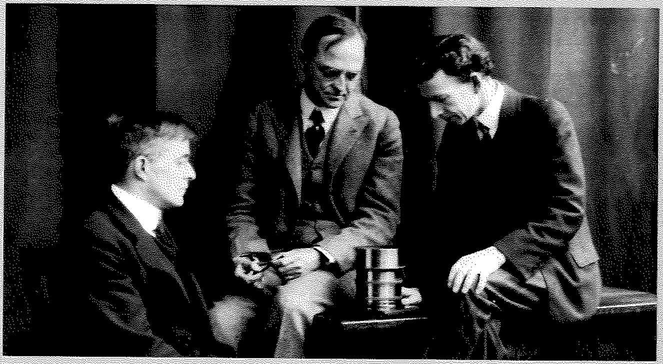
Industrial research as practiced at General Electric—and, soon afterward, at Kodak, at AT&T, at Du Pont, and at numerous other American corporations—represented a new alternative. Individuals who found elements of both the academic and entrepreneurial paths appealing could combine them. For Willis R. Whitney, it meant the possibility of prestige and achievement, without the need for intensive specialization or prolific publication. For William D. Coolidge, it meant the opportunity to conceive and develop inventions of major social impact—ductile tungsten and the Coolidge X-ray tube—without the financial and publicity pressures placed on the independent inventor-entrepreneur. For Irving Langmuir, it meant the freedom to carry out broad-ranging scientific research without the pressures of undergraduate teaching.

By 1915 the new concept of industrial research was making a deep impression on promising young American physical scientists.

The new model of industrial research was not without its weaknesses. At General Electric, for example, an excessively inward-looking orientation (Whitney's 'we against the world') caused the laboratory staff to overlook some potential applications of their discoveries—such as the application of Langmuir's electronics work to radio broadcasting. The empirical bent of individuals like Whitney and Coolidge caused the laboratory to undervalue theory. Managerial informality sometimes bordered on anarchy. These weaknesses were to provide lessons to other great American research directors—such as Jewett of AT&T, Mees of Kodak, Sullivan of Corning, and Kettering of General Motors—just as the strengths did.

In both its strengths and its weaknesses, however, the main historical significance of the General Electric Research Laboratory was in opening up and making known a new career path for American professional physical scientists. They no longer had to choose between the academic community of scholars and the risky independence of the entrepreneur. Those attracted by both the content of physical science and the need to make practical contributions could choose a middle course.

George Wise
R&D Historian
General Electric Research and
Development Center



Langmuir Whitney Coolidge

tools, might be lured to look at nontraditional arenas—industrial situations in which to channel their research aspirations.

But there was a hurdle of prestige to overcome. The pride of physicists was in the purity of their research and their scorn of mere application. The hauteur of a Michaelson, who for years was appalled by Edison (whom he regarded as a yahoo), by his tinkering and his publicity stunts and who blocked Edison's election to the National Academy of Sciences, was representative of the split between physicists and practically oriented people. Thus, the scientists hesitated on the doorstep of this possible new direction and crossed it only by slow degrees.

A model for the future

In the case of the General Electric Research Laboratory as described by historian George Wise, the experiment of bringing science into industry did work, perhaps beyond all expectations. The laboratory's first scientist, Willis Whitney, was brought into the new research laboratory, and headed up its work as it expanded. He had been working as an instructor in chemistry at MIT, where he had studied as an undergraduate before going off to Germany to obtain his PhD (as did most graduate students of his day). He came with some trepidation in the late fall of 1900, worked part-time, journeying back and forth between Schenectady and Cambridge, where he continued teaching. But he gradually shook off his ties with MIT and the academic career as he discovered the satisfaction of directing research with prodigious resources and a growing support staff. He soon brought in other MIT people, including William Coolidge, an assistant professor of chemistry, who had received his PhD at Leipzig a few years after Whitney. He, too, came with some fears that there would be no opportunities to do fundamental research in an industrial laboratory. Still another arrival, in 1909, was Irving Langmuir, who had earned his PhD in Göttingen in 1906, studying under Walther Nernst, whose invention of the ceramic lamp had caused such anxiety in Schenectady. Langmuir was teaching physical chemistry at Stevens Institute but was apparently frustrated with the rate of his advancement, both financially and in the institute hierarchy. He was on the point of cutting his ties with Stevens, his immediate future uncertain, when Whitney offered him a post at General Electric, doing research in chemical reactions of gases at low pressures.

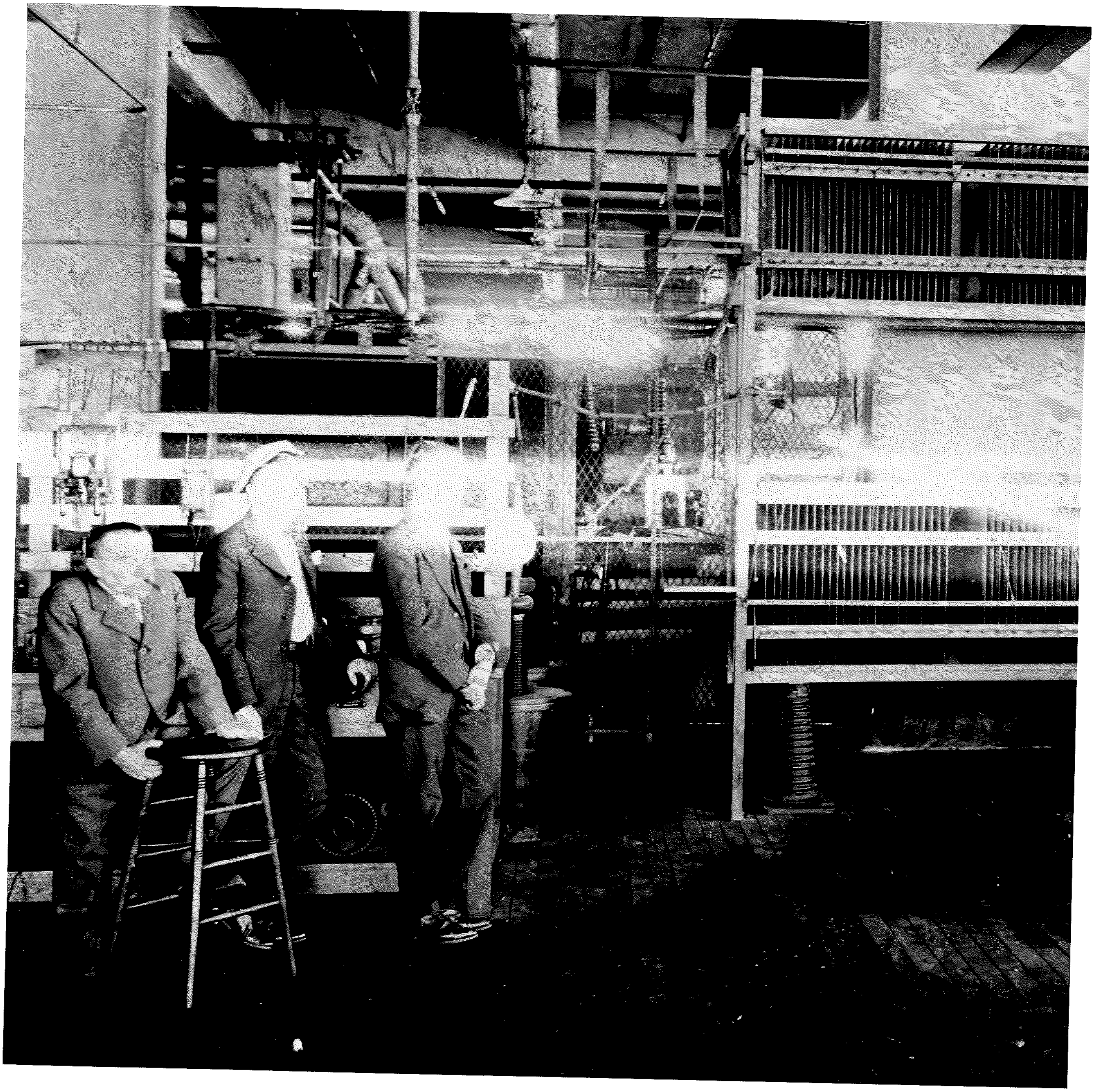
These scientists, and others, made outstanding contributions in applied science. Langmuir went on to win the Nobel Prize for his work in surface chemistry, work that he started at General Electric while doing research on the incandescent lamp. This achievement alone went a long way in making industrial research respectable.

Whitney's first contribution was an improvement in the existing carbon filament, in which he used a newly developed electric furnace to change the composition of the surface of the carbon filament to improve its characteristics. This development was an example of a research tool—the electric furnace—that had been made possible by electrification and was used to advance the understanding of the behavior of materials. The lamp produced by Whitney's process, called the GEM (General Electric metallized), was 25% more efficient than the older, Edison-type carbon filaments. It was put on the market in 1905 and was sold until 1918. But it was Coolidge, after an incredibly persistent campaign of research reminiscent of Edison's original methodical pursuit, who succeeded in finding a method of making tungsten ductile. It could then be used in filaments that were strong, flexible, and more efficient by far than any other lamp type at that time, and it gave General Electric the basis for its modern lamp business. The new—second generation—lamp had arrived from persistent applied research. Says Wise of the achievement, "The Coolidge process for making tungsten wire, in combination with purchased European patents on the use of tungsten in lamps, proved the most valuable additions to General Electric's patent portfolio since the work of Edison."

All in all, these scientists and their colleagues had succeeded on a number of levels. They had solved the specific problems they had been hired to attack; they had restored and bettered their company's competitive position by developing and applying a deeper scientific understanding of the chemical and electrical behavior of materials; and they had fulfilled their sponsor's best expectations. More than that, they had redefined the then-vague role of the researcher in industry, and they had proved that although their role was somewhat narrowly conceived, scientists had a real place in the industrial structure. How these same men might have fared had they elected to stay in academic research and teaching would be purely speculative, but they had at least demonstrated to their academic brethren that there was an alternative career path.

These same men went on to widen the scientific agenda of the research laboratory and, in the years 1910 to 1915 especially, brought it to world distinction in work on lamps, radio, X rays, and fields of related theoretical interest. Even scientists from the famed Cavendish Laboratory at Cambridge University regarded the General Electric Research Laboratory as a first great industrial laboratory. Among others, J. J. Thomson, who had identified the electron, came to Schenectady to speak and honor the laboratory, and many others held it up as a model for industrial research.

Although the laboratory has had its ups and downs, its alternations between basic science and narrow application, it has survived as a viable institutional entity and a profitable one for its founding company. It has continued to serve as a useful model for other laboratories. From just a few at the turn of the century, more than 500 companies were supporting modern R&D laboratories by the time World War I ended. Today such laboratories number in the thousands.



The incredible electrical machines of the early twentieth century like those in Steinmetz's lightning laboratory were the subject of a new romance. Charles P. Steinmetz, inveighing against the literary men who failed to see the wonders coming out of engineering, wrote: "There is more poetry, more romance in the advances which we have seen in our lifetime than ever Homer described." These young scientists worked with the sense that their ideas could go out to change the world.

Electrification came first to the cities then gradually began to spread out to rural areas. As local utilities prospered and grew, they tended to merge like drops of water absorbing one another. This centralization into more efficient and economic units was facilitated by standards for equipment, which, in turn, helped to foster wider technical unification within the industry. The growth of the electric power grids posed unique challenges in different regions of the country. Some of the challenges were geographic, some historic, some personal, and some social and political. These challenges are traced here in four case studies from four different regions: the Far West, the Northeast, the Midwest, and the Southeast. Each is unique in its character, but all share and illuminate generic issues.

Throughout the nation, as the utilities grew, there was a fairly discernible and consistent pattern of development as the common technology evolved and as use of electricity became more general. In one sense, the story of any one utility is the story of all. Yet, each of the enterprises in making and selling electricity was unique, especially in the earlier periods, owing to local and regional differences. Thus, to look at the history of a utility is to look at the history of the region it serves and at the history of the nation as reflected in that region.

In the Far West, for instance, the explosive growth of California in the mid-nineteenth century, combined with the great distances over which many vital resources—wood, water, coal, ice, and eventually electricity—had to be transported, led that state to pioneer many aspects of electrical development. It was first to have a central generating station (it only served 21 arc lights initially), first to install truly long-distance lines, first in extensive hydropower exploitation, and because of unusual agricultural irrigation needs, really the first in rural electrification, which was well advanced by the 1920s.

In contrast to the hugeness and relative violence of the western landscape—high mountains, enormous valleys, alternations of flood and drought, icy peaks and searing deserts, mud slides,

ELECTRIFYING A NATION

Growth of the Utilities

sand storms, and earthquakes—the small clusterings of older settlements of the Northeast helped to nurture the infant electrical industry with manufacturing facilities, with highly skilled artisans and craftsmen (many of whom had come from Europe and settled in the eastern cities), and with financial and intellectual resources. Eastern utilities pioneered in urban generation and distribution systems, including the use of underground cables, storage batteries, and tidewater plants. Later, in the 1920s this part of the country also led the way in the extensive development of home appliances.

Growth in the Midwest, especially in the farmlands of Illinois and the financial circles of Chicago, was dominated for a long period by the personality of Edison's former secretary and business organizer, Samuel Insull. For example, he was the first in this country to use the modern turbine generator designed by Charles Curtis for General Electric, and he might have become known as the father of rural electrification had not the Depression and holding-company scandals toppled his empire. Before others, he was pushing out transmission lines into the flat Midwest farmlands, long before it was economic to do so in such a thinly populated region.

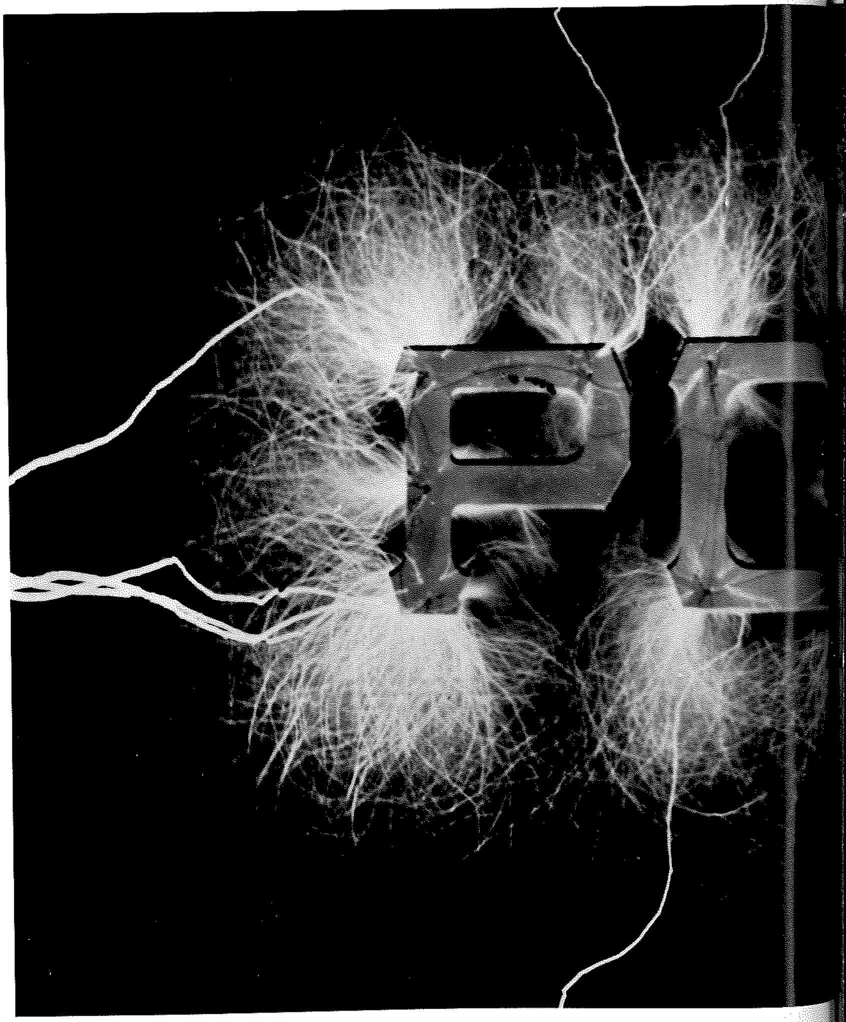
The Southeast was marked by another kind of growth, in which power for running the machinery of the textile industry led the way for lighting rather than the other way around. Consequently, the southeastern states developed interconnected grids sooner than the rest of the nation. Historically and geographically the region was ripe in the 1920s and 1930s for the birth of the experiment in public power called the Tennessee Valley Authority.

Details of utility development vary from region to region and from period to period, depending on the character of native industries, on the supply of natural resources, and on the relative growth of population centers, transportation systems, and new industries. Refrigeration, mining, textile making, railroads, lighting, shipping, aircraft, communications, and thousands of other industries were touched and transformed by electricity, and thousands more, born of electricity, could not have come into existence.

Far West

Some of the great color of the early industry is found in California, where in 1840 the aliens—trappers, sailors, adventurers—numbered only a few hundred. But a year later, the wagon trains began rumbling in, and the following decade of influx from land and sea boosted the population to 93,000 in 1850, the year California joined the Union. That year was also the advent of street lighting in the form of oil lamps in San Francisco. At last, people could cross the muddy streets with less fear of getting mired or being robbed.

In the Sierra Nevada, 150 miles to the east, gold miners were setting up networks of canals and tunnels and claims to water sources—a physical and legal

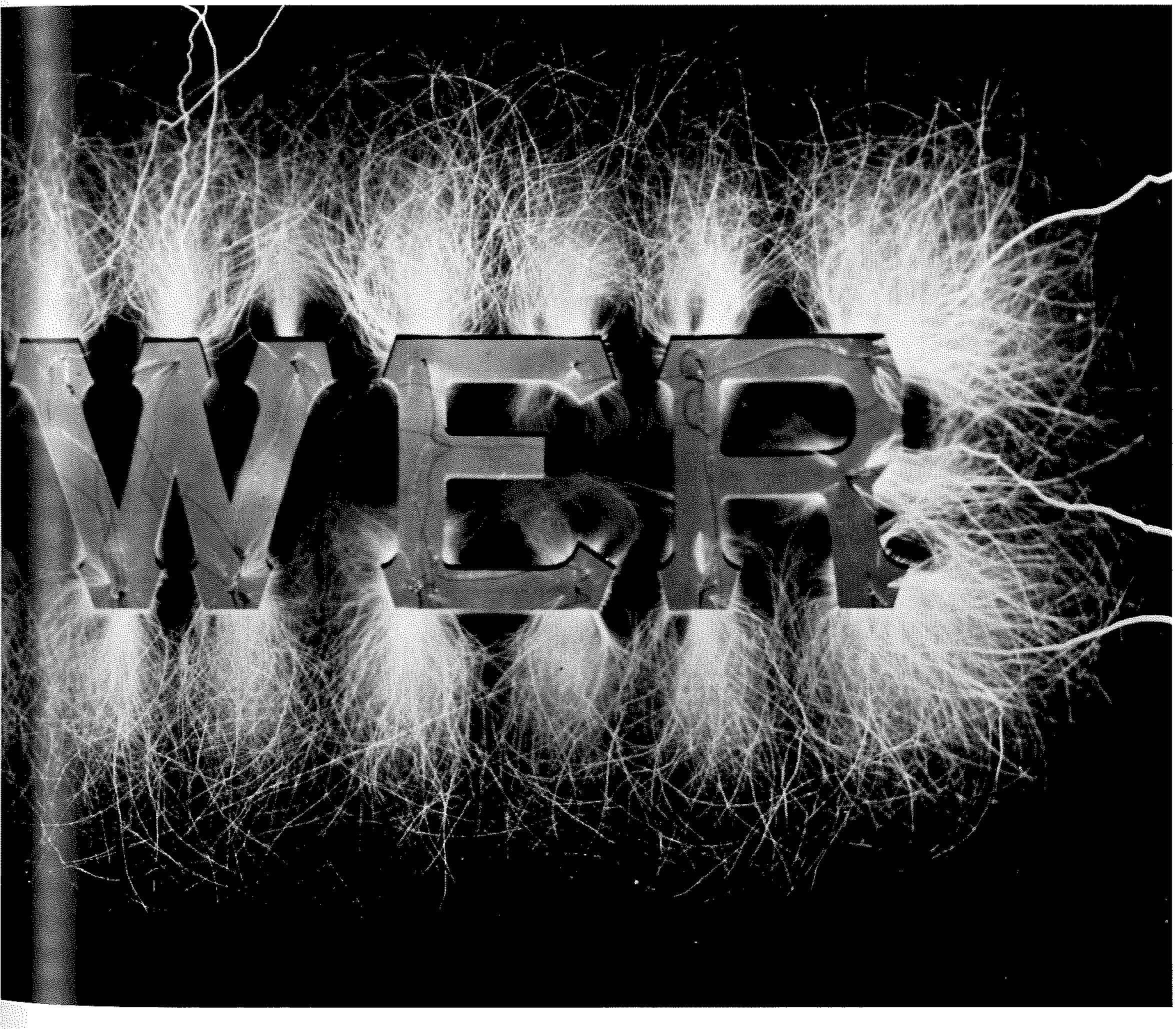


Westinghouse-Tesla high-frequency sign at the 1893 Columbian Exposition heralded the new age in which electricity began to do the work formerly done by muscle power, as well as provide light. The sign was composed of tinfoil letters on glass, energized at 400 kH.

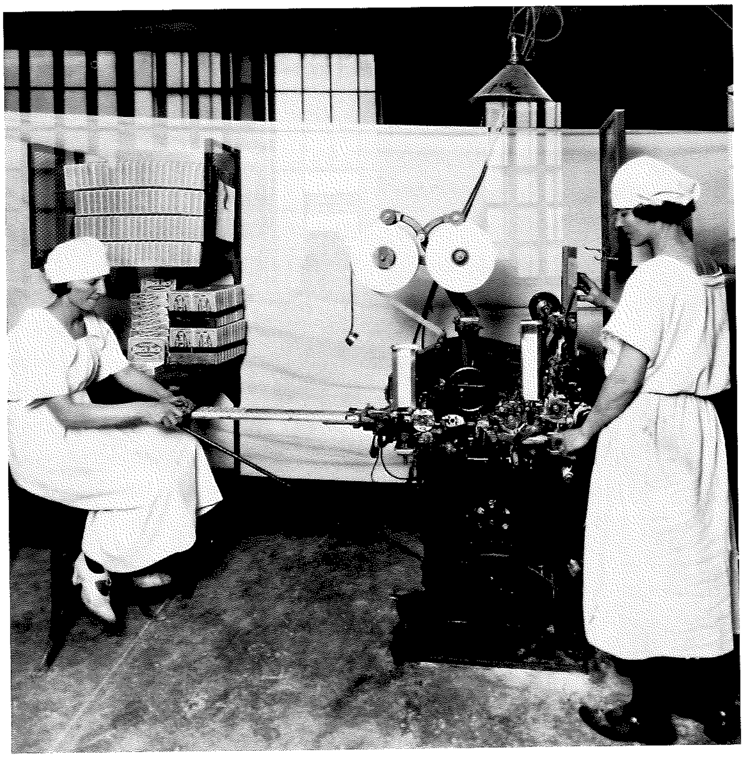
system that would support future hydroelectric developments. The northern California company that became Pacific Gas and Electric Company (PG&E) traces its roots back to 1850, when the Rock Creek Ditch Company was organized in Nevada County. Later, the small water company was consolidated with the vast canal system of the South Yuba Water Company, which itself became part of the electrical system. In 1850, too, Lester Pelton arrived in San Francisco—a millwright who invented a waterwheel in 1878 that could help operate mine machinery in the Sierra. Today, the Pelton wheel is used worldwide in hydropower generators.

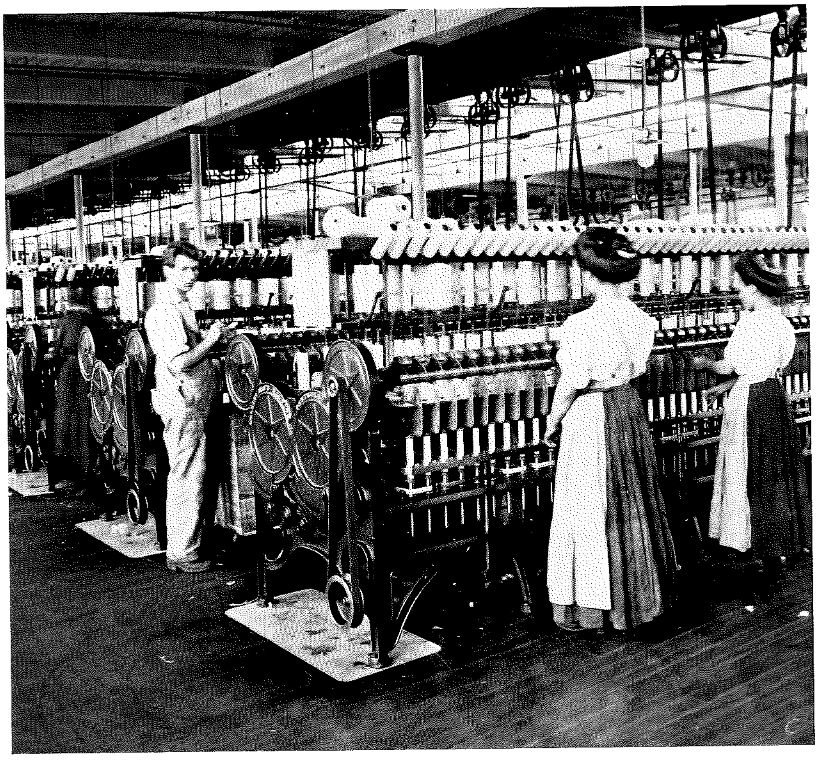
That year—1850—Peter Donahue, a young foundryman, decided the new and rapidly growing city of San Francisco needed gas. With his brother, he spent a year or two finding sources of capital, coal, piping, and know-how. He went back East, where one friend offered him a loan, and another friend, a gas engineer, decided to join the project. Coal was imported from Australia, and piping and retorts were manufactured in their Union Iron and Brass Foundry. They founded the San Francisco Gas Company in 1852 and, after building the first gas plant, began lighting the city in 1854.

People welcomed the more comfortable life that gas could provide, except for a brief period of doubt in 1879 when Oakland Gas Light Company introduced gas cooking stoves to its customers. The popular suspicion was that meals cooked on these new appliances would be some-



"The ponderous steam-powered mills of the nineteenth century," wrote Matthew Josephson, "had been darkened by their huge belts and shafts. Now the electric motor permitted the greatest flexibility in the design of the factory. Motors large and small operated at almost any speed desired and at varying distances." Introduced into factories, electric power raised industrial efficiencies by as much as 50 percent.





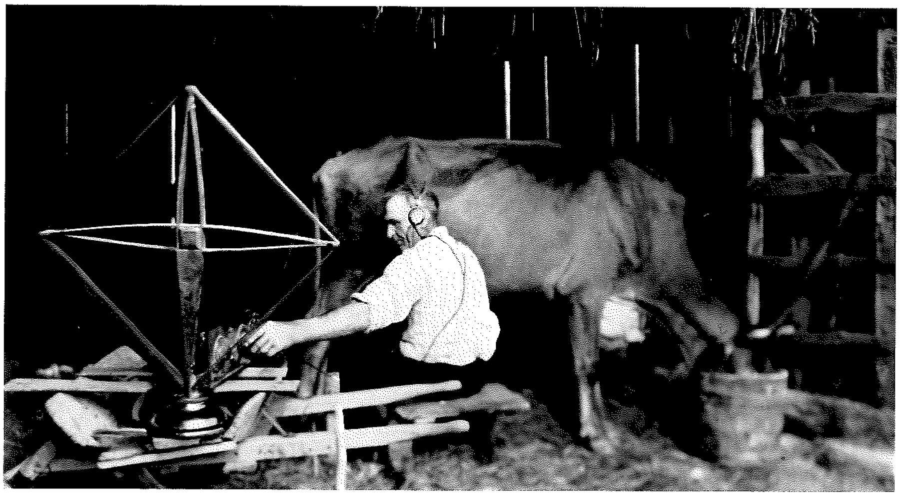
how inferior. The Oakland company had to use much promotional skill to persuade people that gas was just as efficient for cooking as it was for lighting.

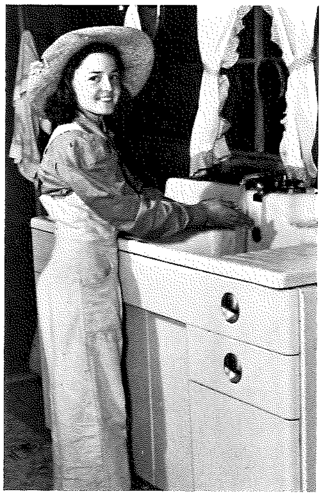
Gas lights burned in Oakland streets until 1940; in old Philadelphia they were still burning as late as the 1950s. In fact, despite the initial fears of gas companies, gas remained in demand throughout the nation even after the advent of electricity.

In September 1879, three years before the opening of Edison's Pearl Street Station (and Holborn Viaduct in London), the California Electric Light Company began a public arc lighting service, thus making San Francisco the first U.S. city to have a central electricity-generating station. The company was started by George Roe, a young Canadian who had launched his career in San Francisco a few years before with a money-brokerage partnership. During that time, a Wallace-Farmer dynamo and lamp had been left with Roe as security for a loan but had never been reclaimed. When the partnership broke up, Roe's share of the assets included the dynamo and lamp. At first a curiosity, they soon became a catalyst for bringing electricity into public service. An exhibition of arc lighting in San Francisco in 1878 by Charles Brush, the Cleveland inventor, resulted in a flood of orders for dynamos and lamps. Among those wanting arc lights were the Union Iron and Brass Foundry, the new Palace Hotel, and a Yuba County gold mine. Roe saw his opportunity; he founded the California Electric Light Company, installed Brush machinery, and began providing light to his customers from sunset to midnight at $10 per week (except Sundays and holidays).

But that first year, the plant, housed in a flimsy shack, burned down, damaging the generators. Coincidentally, the Brush factory in Cleveland also burned down, so Roe's generators had to be reconditioned in San Francisco instead of being returned to their manufacturer. Roe not only repaired the equipment but went on to build several new generating plants.

Fifty years after Edison's achievement, which the nation commemorated with a special postage stamp, electricity was beginning to alleviate labor in the home as well as in the factory. Appliances of all kinds were being rapidly accepted as the cost of electricity declined.





Roe's story is not atypical; the early years of the new industry depended upon the native ingenuity and resourcefulness of local entrepreneurs. In 1882 Edison himself was in the trenches of New York, as the first underground cables were being laid, analyzing troubles and fixing problems on the spot.

The California Electric Light Company, which got its start with arc lights, installed its first dynamo for incandescent light in 1888; but by that time the company was fighting competition from several other electricity suppliers, among them the Edison General Electric Company itself, which was considering the establishment of a utility company in San Francisco. George Roe spent a year negotiating with the Edison people; in 1891 his company became the Edison Light and Power Company. Five years later, after Roe's death, the new company merged with the San Francisco Gas Light Company to form the San Francisco Gas and Electric Company.

In the Sierra Nevada, hydropower was being tapped. Not only was the topography adaptable but the gold miners had already done much of the groundwork. From 1854 on, the South Yuba Water Company (eventually part of PG&E) built and operated water systems for miners, farmers, and townspeople. At one stage it had 450 miles of conduits in Nevada and Placer counties. In 1881 Lake Fordyce Dam was built and is still in service for PG&E. Folsom Powerhouse, built in 1895, provided hydroelectricity at 11,000 volts to Sacramento, 22 miles away—an achievement in long-distance transmission. More and more hydroelectric plants emerged along the mountain gorges. By 1903 the two leading hydro companies in northern California were California Central Gas and Electric Company and Bay Counties Power Company, which were merged into California Gas and Electric Corporation. However, it did not have access to potential customers in San Francisco or to steam generators in the event of a drought. San Francisco Gas and Electric Company, on the other hand, controlled most of the gas market but had to charge comparatively high rates for electricity because its steam plants were costly and the company had no access to lower-cost hydropower. Logic drew them together, and in 1905 they joined to form the Pacific Gas and Electric Company.

In southern California from the late 1880s to 1924—the year of a severe drought that stimulated many system interties within the region—most electricity was produced from water power. The first southern California commercial hydro station was built at High Grove in 1886. That same year the Santa Barbara Electric Light Company was formed. According to historian William Myers, these two are considered to be the earliest predecessors of the company today known as Southern California Edison Company (SCE), the other great utility serving California today, principally in the Los Angeles region. As the Los Angeles population grew rapidly in the late 1880s and 1890s, electrification was in enormous demand because so many of the new inhabitants came from eastern cities where electricity had already become part of their lives.

Among the local consulting electrical engineers was a man named Almarian William Decker, who had worked for the Brush Company in Cleveland before coming West in 1889 and who exerted a considerable influence in the development of ac systems in California. Decker was retained by the president of Pomona College to design a hydroelectric power plant for the San Antonio Light and Power Company (another of SCE's predecessors). The plant would be on the San Antonio Creek at the foot of Mount Baldy, 14 miles from Pomona. It was important, according to Myers, because it provided the first long-distance, high-voltage, electric energy transmission using transformers. For this project, ac was needed.

The same year, Decker was retained by Redland Electric Light and Power Company (another SCE predecessor) to construct an ac installation at Mill Creek in San Bernardino. It was the country's first three-phase ac generating station (and is still operating). Both projects involved unusual ac problems, which led Decker to provoke Stanley, Westinghouse, and General Electric to improve earlier Gaulard and Gibbs transformer ac designs, and thus California led the United States in the use of practical ac systems.

The Northeast

Developments were rather different in New England in that same early period. The Northeast, with its older, well-established communities, allowed the smaller local utilities to prevail into the twentieth century and tended to resist the trunks and interties that developed sooner in other regions. Instead of reaching out as in the vastness of the West, the municipally oriented utilities looked inward and worked for efficiencies in their systems in the effort to capture conservative markets.

The Hartford Electric Light Company (Helco), a company long recognized as progressive and one that set many technical and management precedents, is an example of how one of the companies grew. Owing to early close associations with the electrical manufacturers, Helco served as something of a test bed for many new technical developments. Its technical leadership may also have been related to Hartford's history of successful applications of productive principles to industry: Eli Whitney and the less famous Eli Terry were from the area, as was Sam Colt, whose line of guns were produced in Hartford with automatic machinery beginning in 1851.

Providing electricity to Hartford never involved the problems of scale faced in large metropolitan areas like New York; yet the scale of operations was potentially large enough to justify many innovative ventures. The leadership of the Hartford utility stemmed from that of a small industrial company, the Willimantic Linen Company, the first industrial

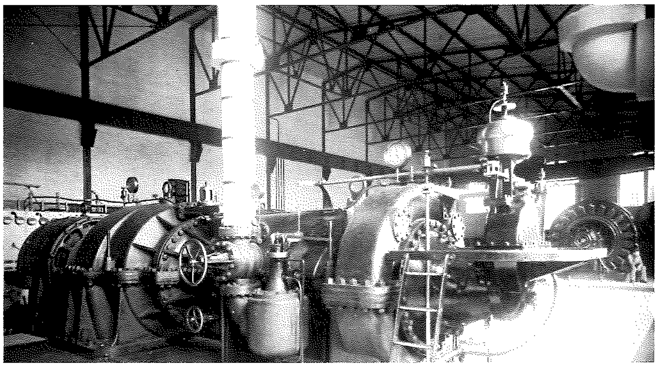
A new kind of professionalism and specialization began to be manifested in American corporations as more and more young men came out of the engineering schools and applied their design skills in a growing and intensely practical industry.

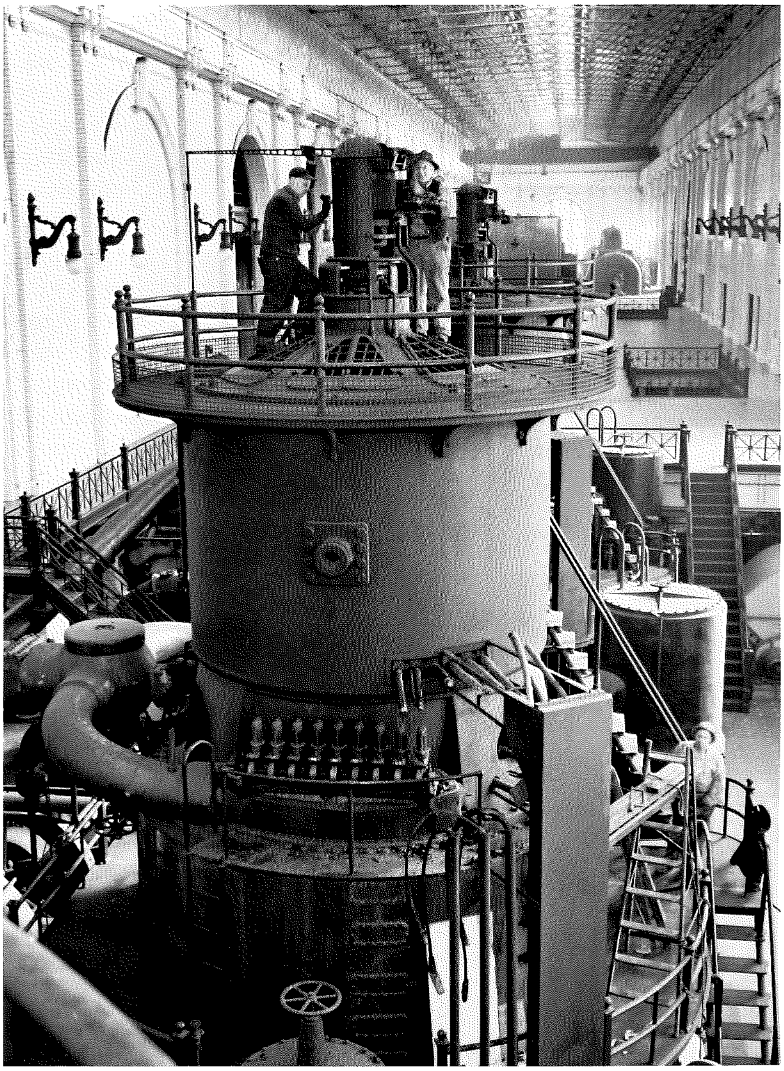
Electrical engineering education tracking utility growth

In the first decades of this century, power-oriented studies that emphasized electrical machinery dominated college programs in electrical engineering. Enrollments in these programs reflected the growth of the utilities. Between 1902 and 1927 power consumption in the United States increased 25-fold. Industrial consumption made up the bulk of the increase until 1917; following World War I, domestic consumption increased. College enrollments in electrical engineering programs numbered 3000 in 1902 and over 19,000 in 1927, a more-than-sixfold increase.

The studies themselves reflected a drift away from foundations in physics and mathematics and a movement toward emphasis on the growing scope of electrical applications. Electrical engineering educators paid close attention to the needs of prospective large employers and to the career needs of their graduates. This was in keeping with a commonly accepted pragmatic view of the pattern of development of electrical engineering education in this country—namely, that it should mirror development in the electric power and manufacturing industries.

The turbine-generator age in America began with the introduction of the Parsons turbine by Westinghouse and the vertical-shaft Curtis turbine by General Electric. Below is a 55-ton, 1.5-MW Westinghouse-Parsons machine installed at Hartford Electric Company's Rainbow plant in 1901. Bottom is the General Electric turbine (12 MW), installed in the Commonwealth Fisk Street Station in 1909, finally being dismantled in 1956. The original 5-MW units were first installed in the Fisk Station in 1903.





user of electric lighting. Willimantic installed a small arc light system in 1878 and two years later built a large mill in which all overhead lighting was provided by arc light. In 1880 one of the company's directors, A. C. Dunham, became involved with the American Electric Company, headquartered in nearby New Britain. His involvement followed the display of that company's product, an electrical system patented by Elihu Thomson and Edwin J. Houston. Impressed, Dunham and other Hartford citizens invested in the firm, and Dunham joined Thomson and Houston on its board. It was not long before American Electric went to Lynn, Massachusetts, to become the Thomson-Houston Electric Company, but by that time (1883), Dunham had organized the Hartford Electric Light Company. Like many other utilities, Helco competed through the 1880s with the local gas lighting company for street and commercial contracts, while fending off competition from other newly formed electric companies. By 1890 Helco secured its position; Hartford became the first New England city to have all its street lighting provided by electricity.

Like other entrepreneurs of his period, Dunham sensed early the possible use of electricity for street, public, and commercial lighting, for home lighting and appliances, and as a source of industrial power; but early attempts to sell to local industries failed. Isolated systems using on-site generators were more attractive. Generally, if gas light was to yield to electric light, centrally generated electricity would have to be cheaper than gas. With this in mind, Dunham successfully encouraged a friend who had developed a water turbine to construct a hydroelectric plant 11 miles from Hartford, with Helco as primary customer. A 500-volt ac line was in operation by the end of 1890, and the hydro plant—dubbed Rainbow—led to a 300-fold reduction in the cost of electricity. Continued improvements at Rainbow were, in part, supported by Thomson-Houston, which treated Rainbow as an experimental station for its equipment. Soon, 7-kV ac was being transmitted to Hartford.

W. L. Robb, a professor of physics at Hartford's Trinity College, who had studied Swiss advances in three-phase long-distance transmission, made Helco the first eastern utility to use ac for three-phase transmission. With designs by Robb, Helco tied General Electric's first polyphase motor into its system in 1893, just a year after Decker had succeeded in his initial ac effort in California.

Other Helco innovations included the first use of a large storage battery for protection against temporary breakdowns and for peak-hour use of what would otherwise be wasted power. By 1895 power from Rainbow was being sent over an 11-kV line, the highest transmission voltage yet used east of the Rockies. Before the close of the century, Helco scored other firsts by using aluminum conductors, enclosed-arc street lamps, and conduits for underground cable. In addition, the company became a champion of the use of home appliances. It set up a small laboratory devoted to the development of cooking and heating equipment, designed a successful ice-making machine, and secured patents for a space heater, a water heater, and a cooking device. Manufacturing rights on these patented items were turned over to General Electric.

In 1900 Helco won a significant industrial contract, furnishing power at the client factory's previous generating cost. As the prospects of markets grew more and more tangible, it became clear that demand would soon surpass available output. Recognizing this and familiar with the use of a water turbine at Rainbow, Dunham ordered a Parsons turbogenerator from Westinghouse, who had bought American rights to the British turbine in 1896. Installed in 1901, Helco's steam turbine, which delivered 2000 kW, was the first ever used by an American utility.

The Midwest

Another important and a unique phase of the growth of American utilities occurred in the Midwest. In 1892 Edison's former lieutenant, Samuel Insull, became president of the Chicago Edison Company, which was to become the heart of the future Commonwealth Edison Company. By the time of the onset of the Depression, he had built an empire of 65 utilities operating in 23 states. The expansion of his systems depended, in part, on his formation of holding companies and on his initiative in developing advanced central power stations. For example, barely a year after Helco had installed its Parsons generator, Insull pushed the first of General Electric's line of modern turbine generators into service in his Chicago Fisk Street Station.

It was almost an accident, but not quite, that Insull immigrated to the Midwest, according to Insull's biographer Forrest McDonald. In fact, in earlier visits, his English formal temperament could hardly abide the disorder, dirt, rats, and low civilization of industrial Chicago, and he had to promise himself to stay at least three years in order not to back out from sheer revulsion. What drove him there—and thus led to the grand physical embodiment in the Midwest of many of Edison's early visions—was Insull's dissatisfaction with his assigned role in the new General Electric company after the merger of the Edison and Thomson-Houston companies.

After running the finances of many of Edison's holdings, Insull had been made only a second vice president in charge of sales in the new company. Piqued at J. P. Morgan (a key figure in the General Electric merger) for letting the Thomson-Houston men assume most of the responsible posts in the new company, Insull looked for openings in the utility business. Acquaintances in the Chicago Edison Company asked Insull to recommend a man for president of their company. Finding no more tactful way to express his interest, Insull nominated himself.

The shift from manufacturing machinery to manufacturing electricity challenged Insull to apply the ideas and daring he had accumulated during his years with Edison. Despite the controversy swirling around him later, Insull was unique in his efforts, based on enlightened self-interest of giving Chicago, the heart of the Midwest, the world's finest electricity generating facility. By 1907 his company was providing all of Chicago's electricity and in the next decade had transmission lines covering all of Illinois and parts of neighboring states. His rural network was so extensive that in the Depression years, Illinois was the only section of the country that did not require assistance from the Federal Rural Electrification Agency.

Moreover, Insull's technical innovations and rate-charging format revolutionized the electric utility industry. He originated the demand charge theory of pricing electricity. Unlike most industries, electric utilities had fixed costs, usually far above their operating costs. At the outset, such a capital-intensive industry had to string transmission lines, arrange distribution stations, and install generating equipment before it received any income from customers. The demand charge meant that customers had to pay a substantial bill to initiate service in an area, but as they increased their use of electricity, the price per kilowatt decreased, since the fixed costs had been covered.

Insull departed from the prevailing belief that electricity was doomed to remain a luxury because gas was less expensive and electrical equipment capital expenditures too great. Instead, he adopted a business strategy based on expansion. He ascertained that he had to obtain a monopoly in the areas he would service and was impatient with the paranoia over monopolies in America, pointing out that the waste in coal consumption engendered by competition was a far greater hazard. What he sought, he said, was a natural monopoly, a concept that was subsequently adopted throughout the country. This concept simply recognized that the character of utilities is such that they cannot compete as other businesses do. In return for its license to operate exclusively in a given region and to earn a certain fixed profit, the utility takes on the legal obligation to provide service for all who need it and to anticipate future needs as well.

In keeping with his centralization plans, Insull sought the largest generators he could find. While Alex Dow, the leader of Detroit Edison, settled for proven 3-MW generators to equip his new Delray central station, Insull insisted on going higher. He asked General Electric to manufacture a 5-MW steam turbine for installation in his Fisk Street Station. When General Electric balked, Insull threatened to offer the order to the British manufacturer Charles Parsons, whose machines had won Insull's admiration during his adolescence in England. Not to be outdone, General Electric agreed to fund a joint risk venture with Chicago Edison. Seven months later, in April 1902, when the new turbine generator was to be run for the first time, Insull ignored his chief engineer's warning that the machine might blow up and stood beside it as it warmed up, shouting, "If it blows up, I blow up with it anyway. I'll stay." In this respect, Insull was taking another leaf from the book of his mentor, Edison, who in the Menlo Park days 20 years earlier had stood boldly beside his first big steam engine dynamo that also threatened to blow up. Although it remained a critical asset to Chicago's reputation for innovative power generation, the 5-MW machine was dwarfed 18 months later by a 10-MW machine, 10 years later by 35-MW generators, and after another 10 years, by a 175-MW machine.

In 1907, after 15 years as the chief steward of Chicago Edison, Insull consolidated Chicago's electric companies into the Commonwealth Edison Company and also gained control of local gas utilities.

As a result of his use of the economies of scale, Insull's companies were able to lower the cost of electricity by as much as two-thirds or more (from 19.5 cents per kilowatthour in 1898 to 5.28 cents in 1924). Thus, Insull achieved Edison's

Superpower

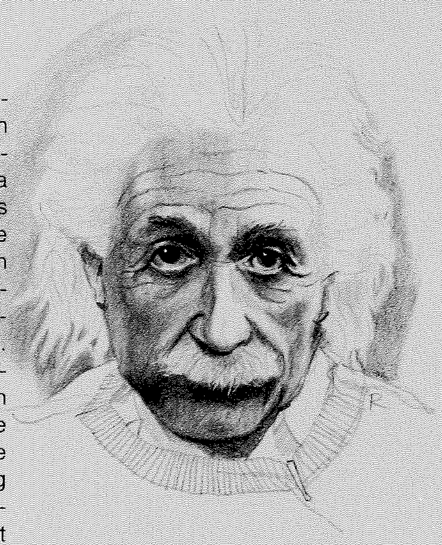
At the end of World War I, local utilities began to centralize into more efficient and economic units, aided by equipment standards, which, in turn, helped to foster wider technical standardization within the industry. As local lines grew, they began to connect economically, geographically, and socially related territories. These larger areas spread out and began to touch one another, usually at state boundaries.

But from the beginning, financing and technical advances were inseparable in what is the most capital-intensive industry on the American scene. Thus, the industry has always moved toward more economic and efficient disposition of its various generating and distribution facilities. Also, in order to support this growth, it was necessary to stimulate ever-greater use of electricity to pay for the next round. What was evident in system interconnection, which was evolving "naturally," was that the potential diversity of electric energy sources—whether from hydro or steam generation—would provide greater system economies and reliability. Surplus electric power, which could not be stored, could be sold to neighbors in need, and there would be backup in case of emergencies, such as those stemming from droughts in hydropower areas, as had occurred in California in 1924.

Generally, the movement toward interconnection in the 1920s became known as superpower, a term coined and made popular by engineer William S. Murray. It served to bring into greater public consciousness the movement that had already been underway in the industry for some time. For example, Murray had prepared a report suggesting that Connecticut power companies pool their resources. This finding agreed with a Connecticut Public Utilities Commission report in 1918 that indicated how easily Connecticut utilities could be tied together in one system and with the postwar talk of tying the Northeast into a network stretching from Boston to Washington.

For instance, the Hartford Electric Company (Helco) was among those who campaigned for power exchange and large-scale power interconnections and in 1920 called for systems that would connect Pennsylvania coalfield plants with Canadian hydroelectric plants. In 1921 interchange contracts were signed between Connecticut companies, and in 1922 Helco reached interconnection agreements with Massachusetts companies, leading to the formation of the Connecticut Valley Power Exchange. This exchange pioneered interconnection techniques and devices and became the bellwether for the industry. Load and reserve diversity permitted considerable savings in the first year of exchange operations. By 1926 Helco was making springtime use of power from New York's Adirondacks and New Hampshire's White Mountains while cutting back on its own turbine generation. During that same period Commonwealth Edison was pushing interconnections in the Midwest, and California built interconnections up and down the entire state to ensure adequate power supplies in case of further severe droughts. These were modeled, in part, on the Great Southern Grid developed in the Southeast a decade earlier.

From Edison to Einstein



Between the world wars, the utility industry expanded and consolidated, and then as the country faced the great Depression, the industry faced its own trauma of the debacle of the holding companies and the outcry for public control. At the same time, the field of physics, which would come to touch the industry so profoundly some decades later, was undergoing the revolution of nuclear physics. In opening the window on the inner structure of matter, American scientists began to play a stronger role. More and more scientists were being trained in the United States and were steadily enlarging the country's scientific community. Although there was a deep retrenchment in science in the heart of the Depression (nearly half the scientists in the then-famous laboratories were laid off), the New Deal brought back a gradual revitalization, and the number of scientists and industrial laboratories grew considerably. In 1933 there were 1575 such laboratories; by 1938 there were 1769. During that same period, about one in four physicists with graduate degrees joined the staffs of industrial laboratories. Many European scientists, who were being driven out by Hitler, were added to the pool of scientific talent. Among these illustrious scientists was, of course, Albert Einstein, who, with his renowned relativity theory, had become a folk hero in place of Edison, the great inventor. It was a symbol of the shift, of science stepping onto center stage of our society.

dream of making electricity affordable to many people, making it so inexpensive that "only the rich would be able to afford candles," as Edison had predicted.

Between 1908 and 1933 northern Illinois residential customers increased their use of electricity by 300%. A by-product of the centralization of power plants was the reduction of Chicago air pollution, which had come from many small and inefficient coal-burning stations.

Insull's initiative in rural electrification developed after he had moved to an estate north of Chicago, where he discovered he did not have access to around-the-clock reliable power. Commonwealth Edison consequently bought up the isolated stations supplying nighttime-only electric service to each of a dozen villages in the county. A later assessment by McDonald noted, "By centralizing the operation and taking advantage of the diverse uses to which customers in the area could put electricity, the company was able to improve and extend service, reduce fixed and operating costs, lower rates, and earn a reasonable return on its investment. This was the first real demonstration that electric service for small rural communities and farming areas, without the base of irrigation, was feasible."

In 1912, on the basis of that experience, Insull formed Middle West Utilities, which grew to be the holding company of the Insull empire. The Illinois rural grid, which grew from these endeavors, became one of a number of influential forebears of TVA and the rural electrification program of the 1930s.

The Southeast

The earliest large-scale interconnected grid, developed in the Southeast, became known as the Great Southern Grid. According to historian James Brittain, work on this grid started in earnest in 1905 and by 1914 had already reached significant proportions. As stated in an editorial in *Electrical World* at that time, "The independent networks have naturally touched elbows and then joined hands." It pointed out the "startling news . . . that there has quietly grown up in the South what is today by far the most extensive interconnected transmission system in the world."

The grid, which began as a power supply to the textile industry and was pioneered by the Southern Power Company, linked together seven major independent networks in North and South Carolina, Georgia, and Tennessee. "If the feat were desirable," said the editorial, "one could operate a motor in Nashville, Tennessee, by energy generated at Rockingham, North Carolina, over a circuit roughly 1000 miles long." With an extension of the line between Nashville and Memphis, it was then projected that "the western terminus of the line carrying energy derived from the Cape Fear River, which runs into the Atlantic, would lie on the banks of the Mississippi."

Although the networks had "joined hands," they had not yet begun to exchange power on any full scale; the development, which was to be repeated around the nation, showed clearly the way of the future. It pointed to the potential decentralization of the nation's work force, since the work inherent in electricity could be delivered almost anywhere with the lengthening trunklines. Factories and mills could be sited at great distances from traditional sources of power, and electricity could be brought to isolated farms and improve the quality of farmers' lives.

Origins of TVA

TVA was not simply a project for the development of hydroelectric power, although the clashes and controversies over public/private enterprise and subsequent developments within TVA have brought the power issue to the fore. In its broadest terms, TVA was created as an agency for regional development. Initially, flood control and river navigation were the primary concerns and had been for more than a century. As early as 1824, recommendations were made to President Monroe to improve the navigation of the Tennessee River as part of a national program to connect parts of the United States with roads, rivers, and canals.

The first canal was built at Muscle Shoals between 1830 and 1837; the second was built between 1875 and 1890; and the third (at Colbert Shoals) was built between 1891 and 1911 by George W. Goethals, who later became the engineer of the Panama Canal.

River traffic along the 650 miles of the Tennessee was undependable, being frequently broken by dangerous shoals. Floods had devastated the region again and again. But the valley, the watershed of more rainfall per year than any other in the United States except the Pacific Northwest, suffered from more than floods. Soil was poor, having been farmed for generations with poor agricultural methods, a condition that alternating winter floods and summer drought had aggravated. The forest cover had been stripped; there was a dearth of industry in the region; and in all ways it had become economically depressed.

At the end of the nineteenth century, those aware of the uses of electric power began to link the idea of river improvements, of dams for flood control, for better river navigation, for water storage, and for hydroelectric power. The early California hydroelectric projects, the internationally publicized great Niagara project, and success in what was then long-distance transmission of power caused the nation to begin to study its rivers with a view of harnessing their power. At the same time, a conservation-of-water-resources movement was growing and found its voice in President Theodore Roosevelt. The resultant crusade and struggle among multiple interests for an effective federal water policy lasted until 1920, when the Federal Water Power Act was finally enacted. It provided controls on the use of navigable streams and regulation of water power developments, including rate and distribution policies.

Early in this century, a number of dams were built in Tennessee and Alabama, but there was no large-scale planning for the water resources of the Tennessee River basin. Only one privately developed dam had been built on the Tennessee River (Hales Bar Dam) by the Chattanooga and Tennessee River Power Company between 1905 and 1913. In neighboring Alabama, beginning in 1916, the federal government began a second dam during President Woodrow Wilson's administration (Wilson Dam). It was to supply power to two plants being built at Muscle Shoals, Alabama, which produced nitrates for explosives in the war effort and later produced fertilizer for agriculture.

After World War I, a controversy erupted over the completion and disposition of the Muscle Shoals development. Automobile industrialist Henry Ford tried to purchase it. Ford visited the site and offered to take what many regarded as a white elephant off the government's hands. In his much-publicized visits he brought his friend, Thomas Edison, who at the age of 74 was considered a resident genius of the United States. He sanctioned Ford's plans, which seemed to include cheap fertilizer for the poor farmers, a unified development of the river, and suggestions for a giant city in the valley that would rival Detroit in size and industrial capacity. But Ford could get no support for such schemes in the congressional debates that ensued. Progressive Senator George W. Norris, who became known as the father of TVA, emerged from these debates as defender of public interests.

The Depression itself was the final factor that crystallized the issue after Norris's long fight and Franklin Delano Roosevelt's election to the presidency in 1932. Roosevelt's message to Congress on April 10, 1933, in which he proposed the creation of TVA, included the following:

"It is clear that the Muscle Shoals development is but a small part of the potential usefulness of the entire Tennessee River. Such use, if envisioned in its entirety, transcends mere power development; it enters the wide fields of flood control, soil erosion, afforestation, elimination from agricultural use of marginal lands, and distribution and diversification of industry. In short, this power development of war days leads logically to national planning for a complete river watershed involving many states and the future lives and welfare of millions. It touches and gives life to all forms of human concerns."

When TVA was established in 1933, its priorities included flood control, river navigation, hydropower, and agricultural and industrial development. But TVA also improved the lives of the people in the Tennessee Valley, and electric power came to be seen as the symbol of such improvement.

In 1914 the vision was for a continuing interconnectivity that would unite the watersheds of the Mississippi Valley and the Atlantic. "As a final engineering step," the editorial concluded, "with the energy of five states behind the work, it ought to be possible to block up one of the gorges in the mountains and construct an artificial lake large enough to tide over the dry season and utilize the prodigious rainfall of the southern Appalachians. The country is without natural lakes but there are few districts where natural facilities for impounding the flow could be more easily or cheaply obtained. The work already done brings to view a project of tremendous possibilities."

Twenty years later that vision began to be realized along the entire Tennessee River basin with the inauguration of TVA. Early utility developments in the southeastern states, including the pioneering attempts in interconnection, were soon overshadowed by the extensive TVA experiment. TVA represented a new level of R&D on a number of interlocking issues. Its priorities included flood control, navigation, electricity, agricultural and industrial development, reforestation, the economic and social well-being of the Tennessee Valley, as well as national defense. As much as anything being done in the world, it was the ecological undertaking of its time. Unlike Niagara, TVA in its early phases did not specifically push the technological art of electric generation further, although in scope and power, it was to surpass all others.

There have been many excellent accounts of the background and development of TVA and of the controversies that have enveloped it at every stage of its existence, from the conservation ideas (of men like Theodore Roosevelt and Gifford Pinchot) that prompted its germination to its important role in wartime. Particularly noteworthy are the fluent accounts of Thomas K. McCraw. He identifies three distinct phases in TVA's evolution since its inception in 1933.

In its first phase, from 1933 to 1941, TVA was a multiple-purpose program which included the construction of dams for flood control and the production of hydroelectric power; the construction of locks for shipping along 650 miles of waterway; and the building of dikes, roads, bridges, and small towns. It was involved in the operation of fertilizer plants, electric transmission and distribution facilities, and even recreational facilities, such as boat marinas and lakes for swimming and fishing. Between 1933 and 1940 TVA completed six major hydroelectric projects. It maintained this pace far beyond World War II. In 1953, for instance, TVA completed its twentieth dam in 20 years. In its second phase, from 1941 to 1961, it experienced great growth as an electric power project. In its third phase, from 1961 to the present, TVA expanded its electricity production largely with coal and nuclear power rather than with hydropower.

A number of factors made this feat possible. An important stipulation built into TVA's structure was the power to hire and build with its own personnel, rather than contracting its projects out, as did other government agencies. The Depression, which really provided the environment for TVA's birth after years of stalemate between public and private factions, assisted TVA's growth in another material way. Many talented people, whose professional opportunities in those years were rare, were attracted to this great and promising project. Thus, TVA was able to build up a dedicated, talented, and eager team. It included engineers, architects, hydraulic engineers (such as TVA's first chairman, Arthur E. Morgan), agriculturists (such as one of TVA's directors, Harcourt A. Morgan), and lawyers (notably David E. Lilienthal, the TVA director who was largely responsible for the agency's electric power program and who went on years later to head AEC).

In all the areas of development they undertook, these teams made outstanding marks. In their engineering they built highly efficient systems. In their architectural construction they produced outstanding modern work, functional and sharply defined, stripped of the decorative motifs that adorned other works of that era, and set a standard around the world. In their institutional promotion of electricity usage they boldly reduced rates far below national averages and thereby succeeded in reverifying that electricity use was elastic, that lower rates would encourage greater consumption (a point that Insull had proved earlier). And as a total organization, its solidity, efficiency, and success on many fronts—technological and sociological — was widely acknowledged. Even Wendell Willkie, TVA's opponent for many years, admitted, "TVA, regardless of the philosophy behind it, was an outstanding organization."

In its pure design aspects—in the integration of architecture—TVA perhaps has achieved its greatest fame. Under the design leadership of Roland Wank, who chose a teamwork approach, and created "the architecture of engineering," TVA set a consistently high standard year after year, dam after dam, project after project. "Wank," wrote architectural critic F. Gutheim, "made engineering into an architectural event. What had been designed by the Army Engineers or the Bureau of Reclamation, not to mention numerous private utilities, was here raised to the level of a great and significant human experience, not left as a mere work of technology. At Hoover Dam [which in those years was called Boulder Dam] one was impressed by the sheer size, the cost, or the acre feet of water and the kilowatts of power; but at a TVA dam one was reminded of humanistic values, of power serving man, of regional development goals, of the conservation of natural resources, of man's relation to the landscape."

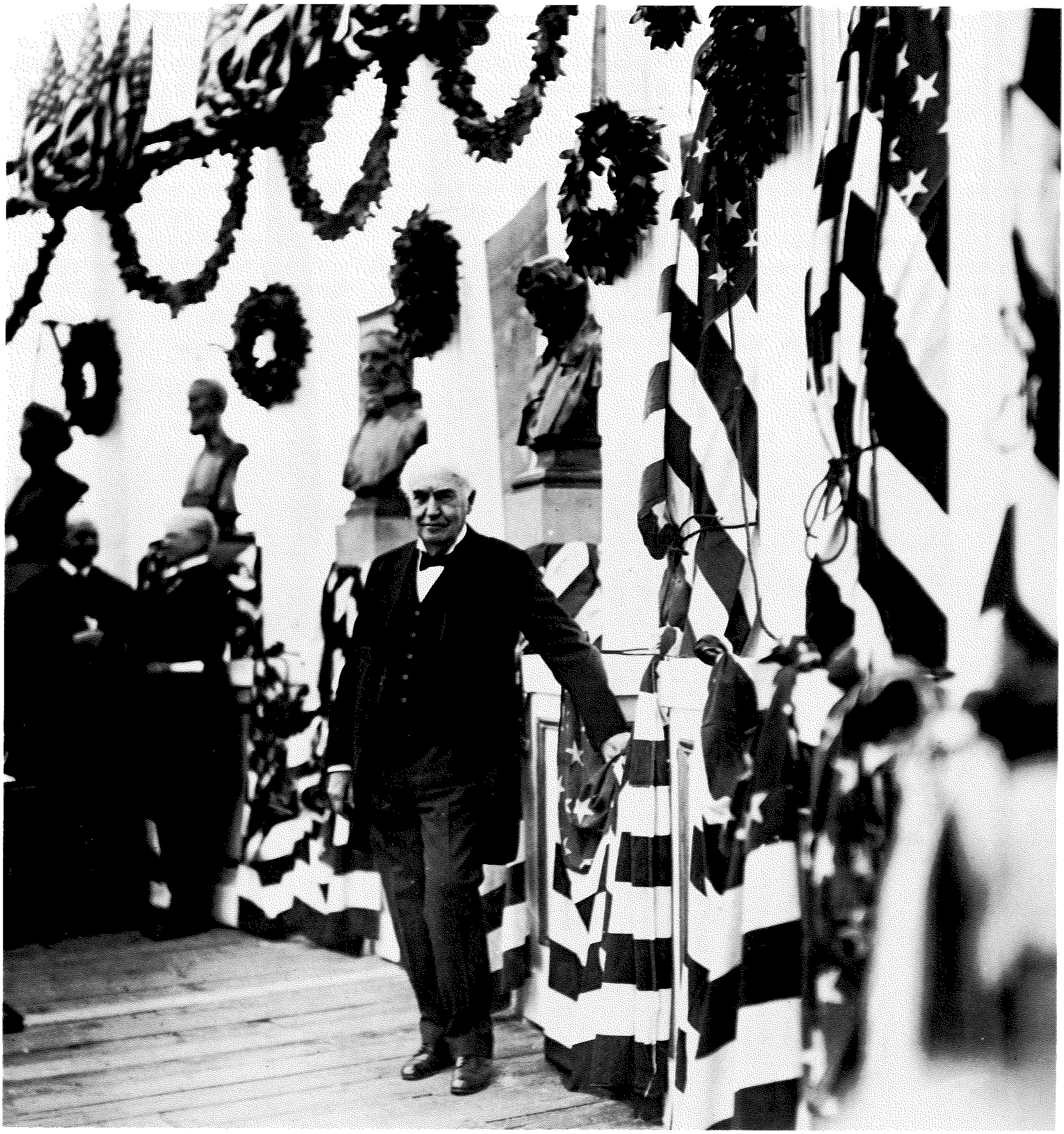
TVA was also supposed to serve as an economic yardstick, the term claimed and favored by Roosevelt. But as McCraw has pointed out, there is no direct comparison possible between TVA, which is a multiple-purpose project, and private utilities. The fact was that TVA could, and did, offer low electric rates. Writes McCraw, "The initial rates seemed ridiculously low, so low that they represented a dangerous, almost reckless gamble." He concludes, "The new rate structure was the boldest, most important decision concerning power that the TVA ever made." The gamble paid off; consumption did shoot up. TVA brought the proof that lower electric rates would encourage greater, more universal usage. As promised, electricity was brought into the homes of the rural poor and began to change their lives measurably.

Despite its success, such a regional and social program was not repeated anywhere in the country.

After 50 Years

In the 1920s and 1930s, after 50 years of growth, the electric utility industry moved from a period of preparation and into one of universal application. Although various regions of the nation experienced this application in different ways, the usefulness and indispensability of electricity had become a fact. During this first half century, the foundations for manufacturing electricity and for thousands of electric utilities had been laid. In this period, the very concept of a utility changed from one of supplying an exotic, specialized product to one of public service. From a brilliant experiment to a delightful luxury, to an indispensable tool of industry, to a commodity and service, electrification came to be regarded as everyone's birthright.

The full meaning of this newly formed dependence became apparent the day Edison died—October 18, 1931. It was proposed that President Herbert Hoover order all electric current in the United States be turned off for one minute the day of Edison's funeral, in tribute to the great inventor. But the proposal was declined when it became evident that to do so would have a paralyzing effect on the nation. Thus, 52 years after Edison's breakthrough, the country was forcefully reminded of the place of electricity in its life. There was no turning back.



From the beginning, Edison symbolized the electric age to the American people, no matter how many other ingenious inventors, scientists, and engineers made significant contributions. But the passing of Edison and the coming world crisis of World War II would finally close that great age of individual inventors.

R&D: A NEW ALLOY

World Collision

The challenge of World War II set in motion a new, high level of organization of R&D and an accentuated role for science in technology, particularly as the race for the nuclear bomb proceeded and as the new art of electronics was dramatically accelerated. This new intensity of coordination had profound consequences for the electric power industry. Following the war, engineering could no longer be functionally separated from its theoretical foundations in physics and mathematics, and in the larger context the categories of basic and applied science no longer existed. A new alloy—R&D—had been created.

Of all the wars, World War II was the most technological in history. It was fought with technology and decided by technology, and it unalterably linked science and engineering. It was the crucible that made a new alloy of R&D. During the Second World War, the physicists took the lead in the new electronic arts, and they developed the radar that was subsequently acknowledged to have had a decisive part in winning the war, as well as the atom bomb that ended it. Unlike World War I, which was called a chemists' war, World War II is viewed as a physicists' war.

On the eve of the war, it had become frighteningly evident to some physicists that there might be a practical way of releasing the great energies known to be the binding forces of atomic structure and, possibly, to release them as a bomb of supercolossal force and destructive power. Thus, the wartime race to develop the atomic bomb began.

The other crucial race—to develop various forms of high-frequency radar—was won by the collaboration of British and American scientists and this, in turn, only because the overwhelming majority of the American scientific community had sided with Britain and had been organized for war work a year and a half before the United States entered the hostilities.

The increasingly scientific nature of the technical advances made during the war led electrical engineering educators to incorporate into their curricula more modern physics and mathematics and to develop a research mentality. It transformed American engineering schools after the war.

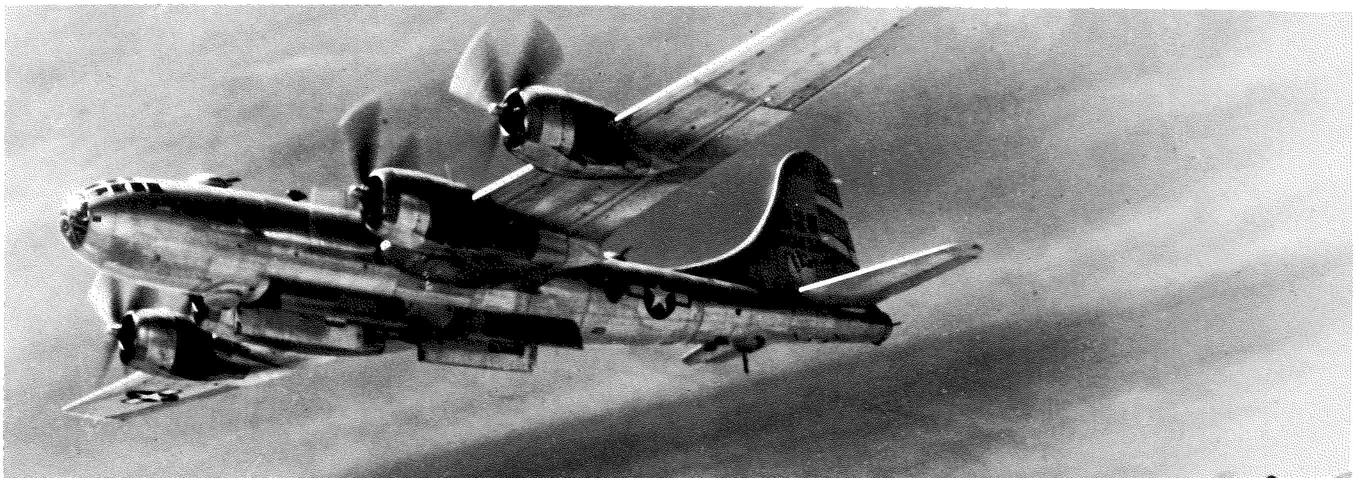
The war also brought unprecedented strain to utilities. Demands for energy pushed the capabilities of the electric utilities to their limits, and beyond. During the war, for example, TVA reached the limit of its potential hydro resources. During a frantic six years of construction (1939–1945) TVA more than doubled its output of electricity. This supported war industries, such as the secret production of nuclear fissionable material at Oak Ridge, Tennessee, but especially the production of aluminum needed to build the great air fleets that hammered at the heart of the enemy's industries.

The advent of nuclear power, which seemed a godsend to the utilities seeking to respond to rising demand, carried the seeds of future problems. The use of the atomic bomb raised moral issues, and the subsequent fear of the nuclear potential for massive destruction was transferred to the peaceful uses of atomic power.

Each of these—increasing energy demand, the organization of scientists and engineers, nuclear power, electronics, major government involvement in R&D, a greater scientific component in engineering education, high technology, moral and social issues related to energy use—is part of the varied legacy of World War II.

Mobilizing the research

On the eve of World War II there were only the frailest of connections between the technical laboratories of the military services and the community of civilian scientists. Even the several military laboratories (where some singular radar work was being done on shoestring budgets) were largely isolated from one another.



But as the tide of war ran in favor of the Nazis and the Italian Fascists, scientists in America—joined in increasing numbers by scientist-refugees from Europe—grew more profoundly worried, not only about the possibilities of an atomic weapon but also about the clearly technological tenor of the war. A number of the older scientists and engineers, who had worked on antisubmarine devices during World War I, remembered the difficulties of getting war research going and felt a deep sense of urgency to better prepare this time. Vannevar Bush, who had been dean of engineering under Karl Compton, president of MIT, and who became the chairman of the National Advisory Committee for Aeronautics in 1939, was one of these concerned men.

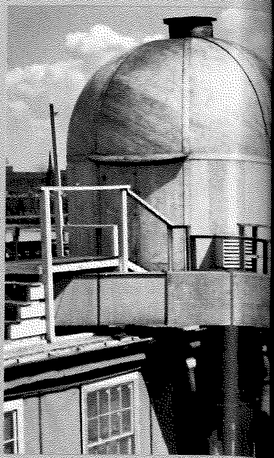
By the time he went to Washington, Bush had acquired a long list of credentials in engineering, research, and research management. After receiving his PhD in engineering from MIT–Harvard in 1916, he soon became an associate professor of electric power transmission at MIT and came to have considerable influence in the electric power field. But Bush's greatest influence in science and engineering stemmed from his major role in mobilizing the scientists and engineers for R&D before and during World War II. That mobilization—with its emphasis on large, organized projects and on support of talented scientists in the universities—fostered the infrastructure of the postwar scientific and engineering communities, accelerated R&D tremendously, and produced a flood of innovations in what became known as high technology.

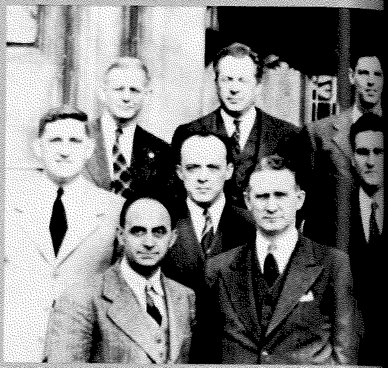
In Washington, Bush became convinced that a new federal agency was urgently needed to put the country's scientific defense efforts under the wing of the president. It was the only way, as far as he could see, of getting "anything done in that damn town." After conferring at length with MIT's Compton, Frank Jewett (head of Bell Laboratories and an influential figure in the nation's industrial R&D community), James B.

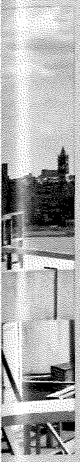
Military R&D on atomic power

The feverish race to fabricate an atomic bomb began with the urgent intervention of scientists in politics. Albert Einstein wrote a letter directly to President Roosevelt calling upon him to do something. The letter grew out of anguished talks between two Hungarian physicists, Eugene Wigner and Leo Szilard, both refugees from Hitler, but familiar with the work of German atomic physicists. They were very worried about the meaning and significance of the splitting of the uranium nucleus in Berlin by Hahn and Strassmann and the possibility of a chain reaction. And they saw more clearly than Americans, accustomed to the feeling of safety behind the barrier of the North Atlantic, the real danger of a nuclear weapon in Nazi hands.

Einstein readily agreed to lend the weight of his reputation to those of Wigner and Szilard. Their warning reached the White House on October 11, 1939. Roosevelt immediately appointed the Advisory Committee on Uranium under Lyman J. Briggs, the director of the National Bureau of Standards, to look into the matter. But the ensuing organizational efforts seemed perilously slow. In June 1940 the committee was reconstituted as a subcommittee of the National Defense Research Committee (NDRC) under Vannevar Bush, but it was not until August 13, 1942, that the Manhattan Engineering District (MED) was officially established. When MED was finally launched, Brigadier General Leslie R. Groves was borrowed from the Army Corps of Engineers and placed in command. Groves was given virtually unlimited power. Having preemptive authority, he could draft for his staff any personnel in military or government service and any material that he felt he needed, superseding other commitments, including the AAA highest priority of the War Production Board—no questions asked. This all-out approach, which spawned the expression "crash program," was the primary difference between the U.S. and the German A-bomb programs. One







During the war years, the first radomes of the MIT Radiation Laboratory appeared atop the MIT buildings overlooking Boston (top). Principal scientists of the Manhattan Project pose for a historic photo; Fermi is in the first row at left. Brigadier General Leslie Groves, U.S. Army, who commanded the Manhattan Project, is shown here with Sir James Chadwick (left) and Richard Tolman (right). Vannevar Bush (left), the head of OSRD and chief organizer of the nation's scientists and engineers during the war, confers with his close associate Karl Compton, president of MIT.

other significant difference was that the Allies were blessed with virtually limitless resources and raw materials, whereas the Germans lacked such essential strategic materials as nickel (although they had adequate uranium from Czechoslovakia).

Groves's brain trust of physicists soon realized that there were two avenues open to them. One was to find a way to separate the fissionable ^{235}U isotope from the nonfissionable ^{238}U isotope. A number of different methods to pry the isotopes apart were investigated on a huge scale by MED. Electromagnetic separation, thermal diffusion, gaseous diffusion, centrifuging, fractional distillation, chemical exchange, and electrolysis were all tried. Huge electromagnet and centrifuge plants and a half-mile-long gaseous diffusion plant were built in the backwoods of eastern Tennessee at what is now Oak Ridge. These isolated enough ^{235}U for the bomb that was dropped over Hiroshima.

The other avenue, which required an equally vast industrial complex to be built by MED, was to use plutonium instead of ^{235}U as the active material of a bomb. For this, four large reactors of simple design (producing no electricity but optimized just to convert nonfissionable ^{238}U to fissionable plutonium through irradiation) were built at Hanford, Washington. Plutonium was used for the initial test at Alamogordo, New Mexico, and for the weapon dropped at Nagasaki.

Even while the race to build a nuclear weapon was going on during the war, the Navy and leading MED scientists were thinking about harnessing nuclear energy for purposes other than weapons. The Navy was straining at the leash to mount a project to develop a nuclear-powered ship propulsion engine. Fermi and others were looking to uses of this new source of energy, such as conversion to electric power. By 1944, a year before the war ended, at least five major power reactor concepts were being considered. The Navy's drive for a ship propulsion unit that freed ships from fueling bases and tankers proved to be the strongest single incentive for harnessing the controlled chain reaction.

From 1939 on, Rear Admiral Harold G. Bowen, head of the Naval Research Laboratory (NRL), fought hard for a nuclear-propelled Navy. But by early 1946 it was clear that NRL had neither the facilities nor the personnel for the effort required, that the Navy would have to draw heavily on MED, and that the Navy's Bureau of Ships would have to take the lead. When General Groves proposed that spring that the Navy assign a few engineering officers full-time to Oak Ridge to learn the fundamentals of nuclear technology, the suggestion was quickly accepted. Thus, Hyman G. Rickover went to Oak Ridge in June 1946, the senior naval officer with a group of engineers and physicists nominated for the task. Although intentionally not named as officer in charge of the little unit, Rickover soon took charge by sheer force of personality.

Captain Rickover, a 46-year-old electrical engineering officer who had distinguished himself during the war as head of the electrical section of the Bureau of Ships, had assembled a superior technical staff in his section and had earned a reputation for a severely practical approach, tireless energy, and refusal to compromise on technical excellence in maintaining and improving the electrical equipment aboard naval vessels. By 1945, when he left the bureau to set up a ship repair base in Okinawa, his electrical section was recognized as "the most creative, productive, and technically competent section in the Bureau of Ships."

Rickover mastered the arcane new nuclear science almost by brute force. Through unflagging perseverance in overcoming all obstacles, he succeeded in designing, fabricating, and assembling a practical, working nuclear submarine propulsion plant. And it was the success of the pressurized water reactor (PWR) developed for the *Nautilus* that determined the course of utility power reactor development.

A year before *Nautilus* went to sea, the Atomic Energy Commission (AEC) considered that the PWR was "clearly of conservative design with a poor long-term prospect for producing low-cost atomic power." But despite this clouded evaluation, the PWR very shortly proved to have the best long-term prospect of any of the several dozen reactor types either proposed or worked on.

Conant (then president of Harvard and a strong advocate of scientific R&D), and others, Bush submitted a brief proposal to Harry Hopkins, then secretary of commerce for President Roosevelt. Hopkins had been given the job of mobilizing the country's scientific and engineering talent through a new kind of inventors' council, patterned after Edison's of World War I. But as historian Daniel Kevles writes, Hopkins was "aware that the trained scientist and engineer had long since won the day against the Edisonian inventor," and he agreed with many of the basic aspects of Bush's plan, which Roosevelt promptly approved.

In June 1940, fully 18 months before the U.S. entry into the war, Bush was given charge of the new agency, the National Defense Research Committee (NDRC). It set in motion many civilian-scientist research projects in five major areas, with many sections taking up specific R&D problems. Within its first six months, NDRC had initiated 126 research contracts.

By the following May, NDRC was reconstructed to allow not only the research of new military devices but also their subsequent development into prototypes and production models, an extremely important link in speeding up the process of bringing concepts into real, usable systems. The new agency, the Office of Scientific Research and Development (OSRD), gave Bush more power and resources, and it gave him valuable lead time for the war effort. In contrasting the two world war R&D efforts, Kevles writes, "In 1917, by the time Congress declared war, the jealously private National Research Council had accomplished virtually nothing for national defense; by that fateful Sunday in December 1941 NDRC, then the more potent OSRD, had provided the country with almost 18 precious months of military research and development."

Results of wartime R&D

The OSRD programs established many firsts just before and during the war and, more profoundly, laid some of the groundwork for the postwar world of science and technology as a central part of the economic and social fabric of the country. The ongoing R&D, conducted under the most urgent conditions, tended to melt traditional barriers—especially after the first successes with radar—between civilian scientists and the military, between science and development, between national enterprises, between industry and science, and between science and government. After the war, therefore, a federal policy on science would have to be established.

Moreover, the science and engineering communities, once having experienced the dynamics of group effort, appreciated what might be accomplished in the future if such group endeavors were to be maintained in peacetime.

Of the laboratories established by NDRC and OSRD, one that became famous was the radiation laboratory at MIT. It began its work on ultra-high-frequency radar, centered initially on the magnetron developed by British scientists. This allowed enormous and previously unattainable amplification, paving the way for greater accuracy and range in the detection of aircraft, ships, and other targets.

The magnetron and other developments were brought to the United States by a secret British mission in 1940, which marked the beginning of significant collaborations between the scientific and technical communities of the two countries. As that work progressed, the collaboration reached a point at which MIT even established a British branch of the radiation laboratory (BBRL) in 1943. The various radars researched and developed proved to be the pivotal instrument for pushing back the wolf packs of submarines that threatened to strangle vital wartime shipping. It became possible to detect those submarines when they surfaced at night.

The more spectacular wartime weapon, the atomic bomb, which in its earlier stages was developed at Oak Ridge and in Chicago, began drawing physicists to the special weapons laboratory established in Los Alamos in March 1943. But, as historian Kevles observes, "To most American physicists before 1943, and to the many who even after that time never joined the Manhattan Project, physics in World War II meant the Rad Lab—and two other essential projects. One, at the California Institute of Technology, was for solid fuel rockets; the other, at Johns Hopkins, was for the proximity fuse, a small, rugged radar set installed on and designed to explode an artillery shell at a set distance from its target." Vannevar Bush raised more subtle questions—essentially ones of policy—on the role of scientists in strategic planning. These questions led to mathematical operations research, or OR as the field became known, in all kinds of operations and decision making.

As a new world opened at the end of the war, a coalition of scientific and technical leaders had effectively been brought into being, a cadre trained by war exigencies in the new art of the management of organized R&D. This new world carried new sets of questions: How should research be conducted? How could effective bridges be built between research, development, and practical devices and systems? What would be the appropriate role of R&D in the postwar economy? How could the deepening grasp of science now foster invention on order and on schedule? How could it foster the specification of new materials to be created? How could it enhance human creativity and inventiveness? On a total scale (human, social, political, and economic) what kinds of R&D policies and strategies should be adopted by organizations and institutions—small, private ones, the federal government, and those in the international arena?

For engineers now better versed in science and for scientists now more experienced in engineering, the answers to these questions would become some of the guidelines for R&D in the next quarter century.

Many of those returning from World War II headed into the engineering and science schools. R&D, which was becoming widely recognized as a major force in social and institutional change, was giving the scientific and engineering communities an unprecedented voice in national policies. The nation was about to enter the age of high technology.

Multiple challenges confronted the electrical industries in the postwar period of the 1950s and 1960s: the need to rebuild and refurbish capital equipment, the need to respond to rapid expansion in electricity consumption, and the need to take the first steps toward domesticating nuclear power for peaceful electricity generation. In addition to these challenges was the problem of ensuring the reliability of operation of increasingly large interconnected systems. Given such pressures and the traditional separation of industrial R&D and utility operations, an R&D gap began to appear, as evidenced by the Northeast blackout of 1965. Not least of the utility industry's problems in this period was its own declining image, as many young, talented people were drawn into the more glamorous fields of electronics, computers, and communications.

NEW DIRECTIONS

Postwar Growth

In 1945, as World War II was reaching its climax, the man who had been the chief organizer of America's scientists and engineers for the war effort was already laying out a plan for the future. In a 1945 paper entitled "As We May Think," Vannevar Bush argued that since the engineering and scientific communities had been brought together in the intense teamwork needed for the war effort, they ought not to disband again. He urged a continuation of cooperative R&D programs.

When Bush considered the enormous flood of scientific and technical information that was being produced and now threatened to overwhelm scientists and engineers, he proposed that these communities mobilize for the building of systems—computer-based systems—that would assist researchers in documenting, collating, and retrieving data and information relevant for R&D. Although Bush's plan was not adopted immediately by the scientists and engineers, it was influential in setting an important path for the computer sciences that began to emerge in the following decade. The resultant computer systems would play an important role in the functioning of America's electric utilities. (That in the next three decades, informational systems would begin to emerge as information "utilities," in many respects reminiscent of electric utilities, was then hardly dreamed of.)

Bush's concern about the possible disruption of the cooperative R&D established during the war was obviated by events. R&D actually increased after the war with the formation of new research institutes and under the pressure of the cold war, during which the federal government became the major sponsor of R&D programs centered in defense in-

dustries. In the 1960s the space programs accelerated R&D activities even further.

World War II R&D had produced a spate of inventions and innovations, which like the sciences of the nineteenth century, had yet to be exploited for practical ends. Developed during the war, radar would become the father of microwave communications. Electronics, which began in early radio and experimental television, was about to come into extensive use and before long become the glamour field of the postwar era. But in 1945, few really knew that.

Growth and interconnection

A key problem was for American industry to recover from its immense war efforts and, without missing a step or breaking stride, to serve again a hungry civilian economy at home while assisting in the reconstruction of those parts of the world most devastated by war. For the electrical industry, which had had to build greater capacity at a frantic pace without fundamental innovations during the war, there were new challenges as the demand for electricity began to grow at an unrelenting pace.

This great increase in electric energy demand stemmed from many sources. Among them were needs of the consuming public for all forms of appliances; the creation of an entire range of new products, many depending on electricity for their functioning; a growing population; the need to supply cold war production of nuclear fuels, metals, and materials; and the gearing up of a product economy (in which all products represented a significant energy investment).

In many respects there was continuity in the power industry from the long period of development before the war. The interconnection of systems, which evolved at a considerable rate through the 1930s, continued and brought with it new kinds of engineering problems as transmission voltages, boiler pressures, and turbine-operating temperatures increased and as regulation and control methods in extraordinarily interconnected power systems grew even more complex.

In the postwar period the electric utility industry still relied on the scientific and engineering expertise that had been developed over the years in the laboratories and shops of the great electric companies, such as General Electric and Westinghouse. R&D remained primarily the function of the supplying industries, the vendors, as they are commonly called. Working closely with the utilities, these vendors pushed forward, attempting to solve the development needs of spreading electrification.

This expansion involved an intensive recruitment program for scientists and engineers, for whose services competition developed in the postwar years. It was a radical shift from the period just before the war. In 1940 a young student might choose to study pure physics or pure mathematics with the same élan with which he might decide to become a poet—and with the same assurance of a regular income. But by the end of the war industry began to employ young scientists as fast as the graduate schools could produce them. Their starting salaries zoomed steadily upward, so rapidly, in fact, that young scientists acquiring positions in the 1950s might find their initial salaries greater than those of other scientists who had started a few years earlier and who were being governed by an older compensation machinery that had not yet caught up with the R&D race.

Mainstream R&D

The expansion of the new technology-based industries was so rapid that they began to encourage an ever-increasing mobility among the scientists and engineers. These people, in turn, were lured on to new and better-paying opportunities, and hundreds of new companies were spun off. Such mobility and breadth of opportunity did not exist before the war.

Numerous companies were based on the new technologies and grew extraordinarily, and many new products and services that were created out of techno-

World War II impact on engineering education

Reflecting on the character of electrical engineering education in the decade prior to World War II, Gordon S. Brown, dean of MIT's School of Engineering, observed, "Engineering education was based on the assumption that what students learned in college would serve them throughout most of their professional lives. This doctrine stemmed from the philosophy that technology would not change appreciably during an engineer's lifetime." But the dramatic wartime advances in electronics, microwaves, nuclear physics, automatic control, operations research, and much more, which were developed largely by the community of physicists and mathematicians, led to the first efforts to modernize electrical engineering curricula soon after the war. Those efforts were further enhanced by the development of the transistor in 1948 by physicists at Bell Laboratories. In that same year, Claude Shannon, also at Bell, published his first influential treatise on information theory, which transformed the way electrical engineers looked at problems.

However, the transistor—simple and elegant, like the light bulb, and therefore, in a sense, universally applicable—symbolized the rejoining of advanced physics and electrical engineering, which had parted ways at the turn of the century.

Government research grants encouraged the development of scientific courses in engineering departments. The rapid growth of student enrollments also influenced engineering curricula. The GI Bill provided funds for many who were attracted by the availability of jobs in electronics, and enrollments in electrical engineering exceeded 56,000 in 1947, including 3500 graduate students.

As the electronic technologies became more sophisticated, graduate work in electrical engineering expanded markedly, with enrollments topping 6000 in 1952 and 12,000 in 1960. By the early 1960s different schools had different approaches to modern electrical engineering education. Each sought what Brown called "the innermost core of interdisciplinary technology."

Nuclear power— breaking the logjam

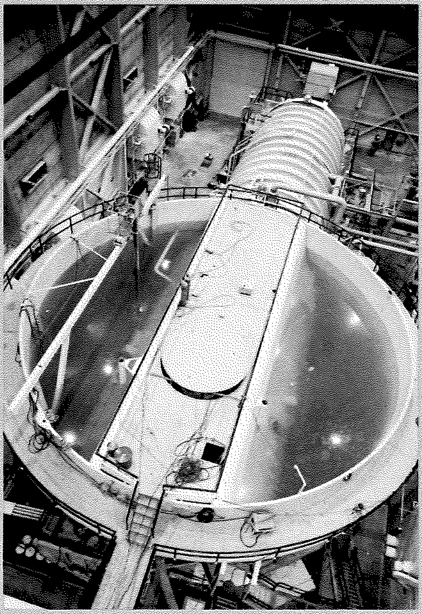
Utility participation in the use of nuclear power for electricity production falls roughly into three periods.

The first period is from 1954 to 1963, when industry was permitted to enter what had been a government monopoly under the Atomic Energy Act of 1946 (McMahon Act). During this period some utilities interested in getting in on what appeared to be the wave of the future joined study groups and built demonstration plants under one of the various joint government-industry programs sponsored by the Atomic Energy Commisson (AEC). A few daring utilities built nuclear plants that proved economically and technically successful, some of which are still operating today. Most utilities waited for economic nuclear power that would be cheaper than coal or oil.

The second period is from 1963 to about 1974. In 1963 the long-sought, long-awaited economic nuclear power suddenly arrived with publication of Jersey Central Power & Light Company's detailed calculations comparing the capital and operating cost of a nuclear plant with an equivalent coal-fired power plant. The report showed the former to be cheaper. Its effect was like the breaking of a logjam. Three nuclear plants were ordered that year, 7 in 1965, 20 in 1966, 30 in 1967; by the end of 1969, 91 units had been ordered and by the end of 1972, 160 units.

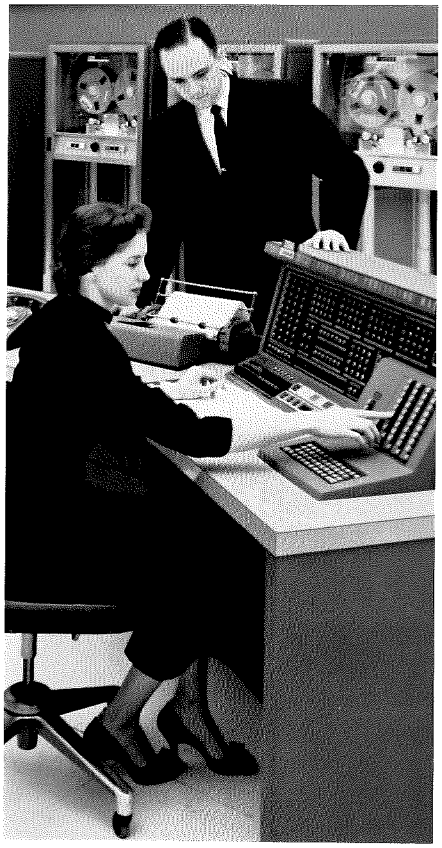
The third period began in 1974. A nationwide utility-financing crisis forced some utilities to postpone construction or actually cancel some of the nuclear units they had ordered. In addition to financial difficulties, utilities discovered that the amount of time required to build a nuclear plant, from the applications for a construction permit to the start of commercial operation, had risen from about 6 years to 10 years or longer. This was largely due to the requirement for environmental impact studies introduced by the passage of NEPA; longer, more protracted, and more bitterly fought adversary hearings on licensing; and constantly tightening regulatory requirements for licensing. The result was to drive up the capital outlay for nuclear plants, partly because of the greater interest on borrowed money over the lengthened construction period and partly because of the increased costs of legal work involved in the licensing process.

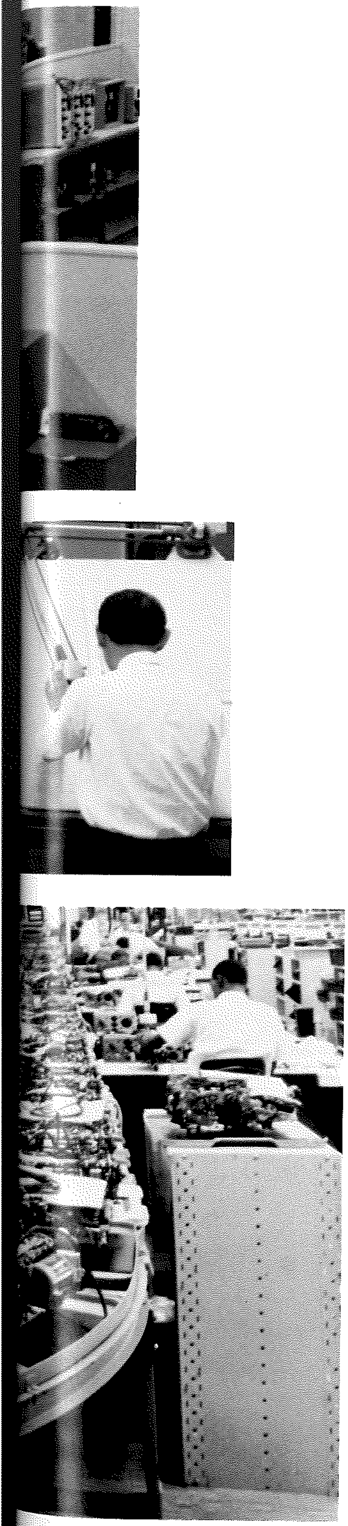
This economic hurdle and the uncertainty of having a producing nuclear plant on schedule has diminished a number of utilities' enthusiasm for nuclear power. However, virtually every utility that has built a nuclear power plant has been able to cut average residential and industrial power bills because the fuel cost is so much lower than it is for coal or oil. Despite its economy, the future of nuclear power is uncertain. There remain grave reservations about its possible dangers, and the cost/safety dilemma has yet to be resolved.



The prototype of a nuclear submarine reactor was built in a simulated submarine hull within a water tank (above). It was later redesigned for utility use and became the first commercial-scale nuclear power plant in the United States at Shippingport, Pennsylvania. At top is the first utility-designed, utility-built version, the Yankee plant at Rowe, Massachusetts.

In the two decades after the war, there was a flowering of electronics in industrial, military, and consumer fields. Large central data processing systems—forerunners of today's interconnected information utilities—were penetrating all kinds of organizations and creating new kinds of specialized jobs.





logical innovations, out of R&D, entered into the American economy. The style for the big, diversified electric companies was to have many R&D laboratories; the style for small companies was often based on single inventions or innovations. A chain of companies, for instance, was spawned around the Harvard–MIT complex of scientific and technical skills, which became a model wherever there were great academic-scientific centers. In this period, it was even proposed that the nation deliberately cultivate 100 centers of excellence, great pools of scientific and engineering enterprises around outstanding universities.

During this period R&D began to prove itself a thousand times over and became mainstream or, at least and at long last, it was recognized as the mainstream and major component of the national economy. Besides advancing people's lives and providing amenities of all kinds, R&D became the occupation of millions. These new occupations emerged primarily in the electric and chemical fields.

But, by an ironic turn, the power and light industry, which had given birth to many of these new fields, failed to attract its needed share of the young engineers and scientists. The electric power option in the best engineering schools had the fewest students; for every one studying electric power, there were 50 studying electronics and physics.

Impact of new technologies

The new fields and the new industries—electronics, computers, semiconductors, systems and control theory, microwaves, nuclear physics, the aerospace sciences, and many others—had a profound impact on the growth of electrification.

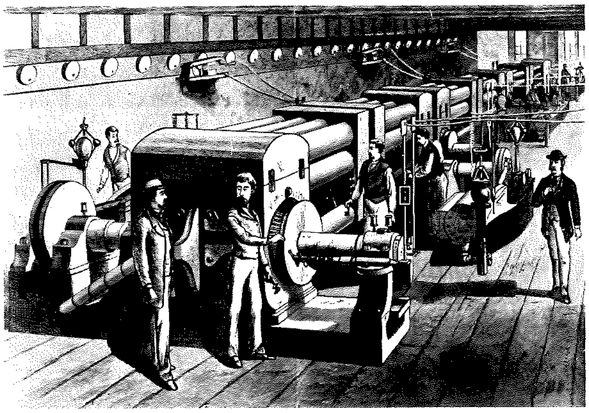
The most dramatic of these new developments was, of course, the domestication of nuclear power. Yet other developments had more pervasive impact. The semiconductor, which was invented to order at Bell Laboratories by Bardeen, Shockley, and Brattain in 1948, fostered an industry that grew hand in hand with a sister industry—computers. Both had a profound, though more subtle, effect on electric utility systems. However, solar cells, as well as new kinds of batteries, fuel cells, and the like, also had their origins in the immediate postwar period but have yet to play their role in the production of electricity.

Many laboratories sprinkled throughout all industries would deliberately or inadvertently contribute to solutions of electrical systems problems. However, very few of those R&D laboratories were directly supported by the electric utility industry itself. But that factor—the traditional split between the operators of the utilities and the vendors—gradually pushed into the foreground a new challenge: the increasing scale of problems to be addressed by an R&D approach. To understand something of the character of this challenge and how it was met, one must look more closely at the growth of electrical systems during the postwar period and into the 1960s.

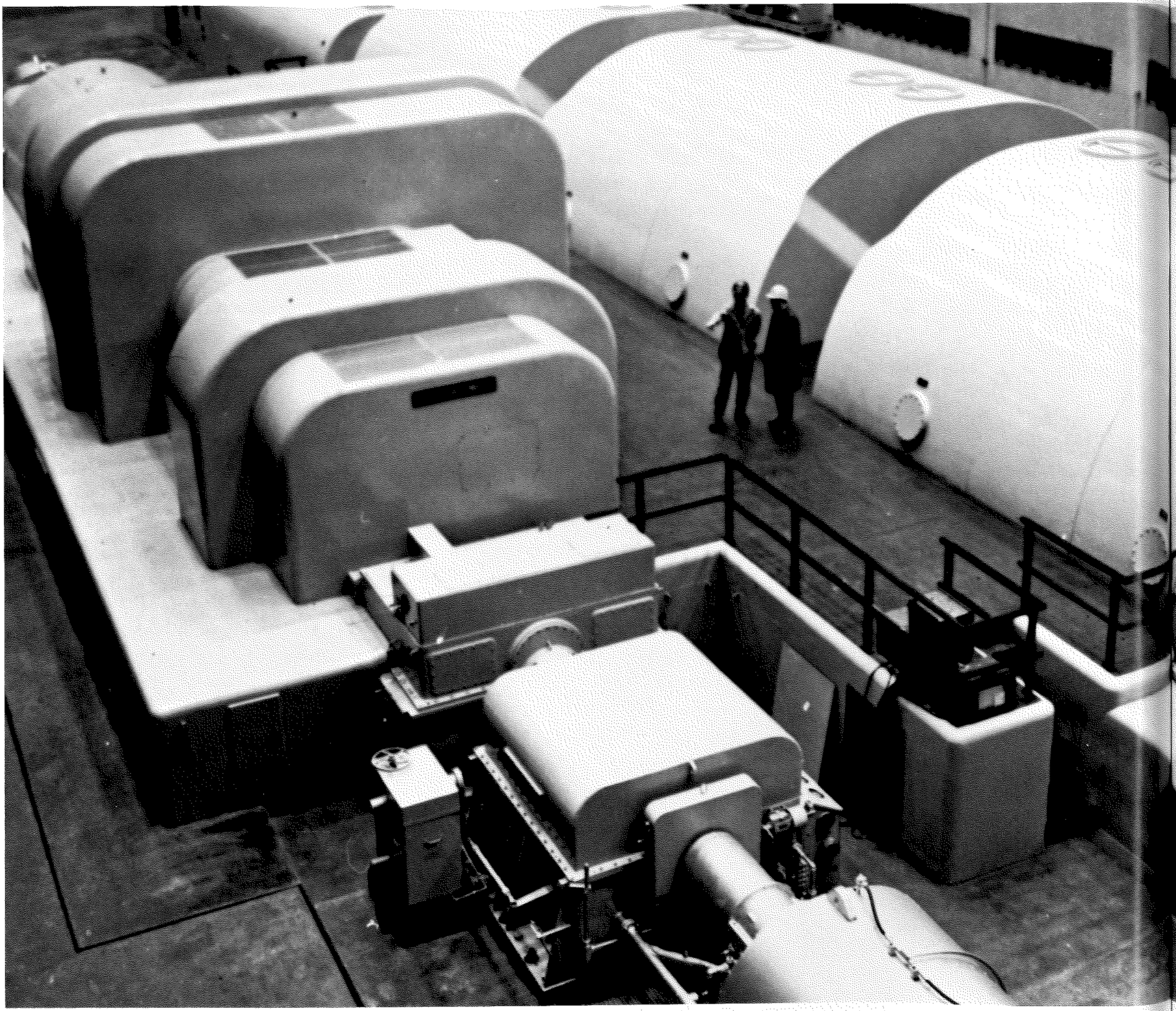
Electrical system development

During the 1950s and 1960s, the process that had begun to be established in the 1930s—the gradual evolution of relatively small, isolated electrical systems into larger and larger interconnected ones—led to extensive integrated systems and large regional pools. Several interrelated developments drove this evolutionary process. The use of higher transmission voltages, for instance, allowed the bulk delivery of large amounts of power over great distances from large generating systems close to fuel sources (such as coal mines) or great hydro sources. But it was the presence of large markets, which interconnected systems made possible, that also supported the building of bigger generating units. With interconnected systems, there was less likelihood of service interruptions, greater reliability, the introduction of more efficient generators, and the retirement of less efficient systems.

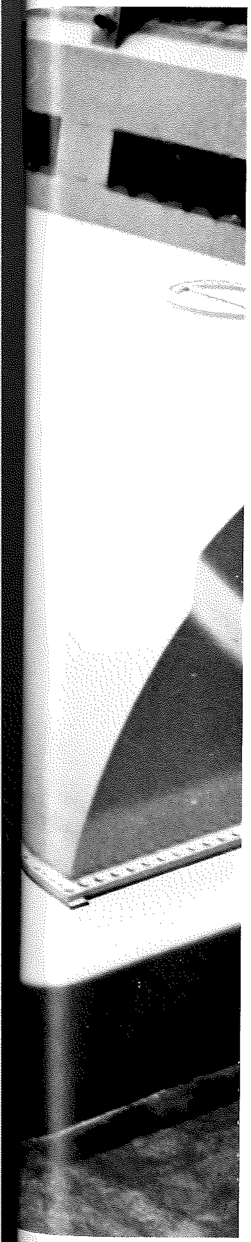
With the ability to move blocks of electric power flexibly around the system as needed, there was also a reduced need

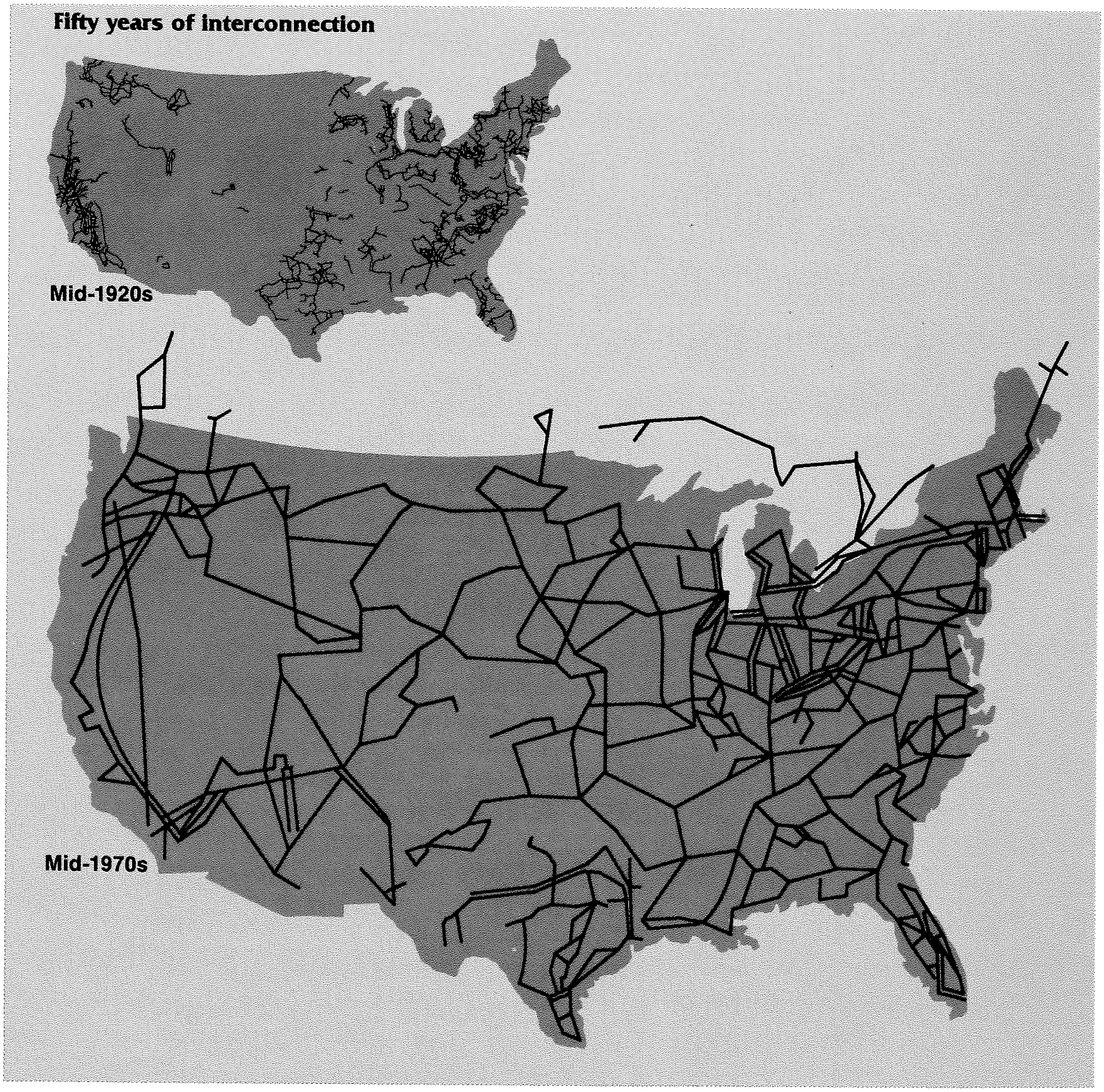


The Edison Electric Lighting Company, which started its operations at Pearl Street in 1882 with the dynamo equipment (left), was destined to become a giant utility, the Consolidated Edison Company of New York. In 1965, Con Ed's biggest turbine generator unit, Big Allis, with a 1-GW capacity, started operation at the Ravenswood generating station in Queens.



The growth of major electric interconnection on the American continent between the mid-1920s and the mid-1970s is depicted on these two maps. The gradual spread of local lines in the major populated regions during the 1920s is readily apparent. By the 1970s, major interties were spanning the entire continent.





Fifty years of interconnection

for reserve generating capacity that a smaller system would require against emergencies. Through this whole loop of interactions, greater overall efficiencies were achieved, so that even with the greater costs of the new larger systems, it was possible to continue lowering the price of electricity through this period. The falling price continued to stimulate consumption, which, in turn, allowed the development of still bigger generating units and greater transmission distances.

During the period from the mid-1930s, when the interconnection process moved forward in earnest around the entire nation, until roughly 1960, electricity generation increased by 700%, or two and a half times as fast as the real gross national product during the same period.

There were many technological advances that made these big, integrated systems possible. They involved changes in steam-electric generation; in hydroelectric generation; in transmission and distribution systems; in transformers; in switches, circuit breakers, and relays; in communications; in system control, regulation, dispatching, lightning protection; in insulators, cables, and connectors; and, in short, in virtually every component that makes up an electrical system. At each major step-up in voltage, in generator size, in steam temperatures and pressures, fundamental problems had to be solved in each of the components. By and large, these problems were solved in the R&D laboratories of the major equipment suppliers in response to utility requirements. What drove the entire process was the unceasing growth in the consumption of electricity, which in the postwar period was doubling in each decade.

In tracing some of the highlights of these developments, Philip Sporn, prominent in the utility industry for many years and president of the nation's largest privately owned electric power system, American Electric Power Company, pointed out in 1959 that the great growth "was more than a simple multiplication in kind." In particular, he noted the steam-electric plants being installed in the late 1950s and early 1960s, compared with the plants of the mid-1930s, could "hardly be classified as the same species." There was an impressive growth in unit sizes of turbine generators from 1935 to 1965, as well as a steady increase in steam pressures and temperatures. The specialized field of engineering called heat energy conversion technology had pushed the ability of these great machines to change heat energy into electric energy almost to their theoretical limits and in the process had brought in (especially in the 1950s) new methods of cooling, principally by hydrogen. Although, as with every innovation, there was caution in the acceptance of hydrogen cooling by the utility industry, the method had become standard by the 1960s. (Looking ahead, electrical machinery researchers see that the next great leap forward in generators will be superconductive generators operating at near absolute zero, but these machines may take the next decade or more to develop and perhaps a decade beyond that to begin to find their place in utility operations.)

Emergence of new systems problems

With the growth of interconnected power pools and high-voltage transmission systems, problems of a new kind on the system level, not just on the component level, have emerged. Never before have scientists and engineers in the power field had to deal with such multiple interconnected systems. (Telephone engineers have had to deal with systems comparable in complexity.) In these large systems, they began to encounter behavior and responses—strange resonances reverberating throughout the system—that could not be explained by theory then available. Thus, the postwar period saw the rise of systems theory and automatic control theory. But systems, including all the people who run them and use them (for they now embrace populations of machines and men) have literally too many variables to be taken into account except on a statistical or probabilistic basis. The fact is that the electrical systems and the human systems have become so closely intertwined and so inseparable that they cannot be easily isolated and studied separately. Thus, the new science of cybernetics, which deals specifically with man-machine systems, or as defined by Norbert Wiener in 1947, the science of "communication and control in animals and machines," began to emerge in the postwar era. It went hand in hand with the information theory first propounded by Claude Shannon at the Bell Laboratories in 1948 and developed continuously since, with developments in neurophysiology, in psychology, and, in general, with the movement of interdisciplinary research, which requires the close collaboration of experts from several fields.

Although the systems theorists and the computerists were able to make contributions to the electric utility systems in the 1950s and 1960s through the development of automatic controls and regulating devices, through better communications between generating units (by microwave links and the like), through automatic dispatching of loads, through automatic switching and automatic circuit breakers, the systems were being pushed to their limits. An emerging problem, then, was that the traditional vendors could not undertake research on problems of such vast size and scale, and the operating utilities, responsible for the running and maintenance of the systems, could not afford the R&D teams that would be needed to get ahead of the technical systems problems. The massive 1965 Northeast blackout that knocked out an entire region came to serve as a symbol of the general systems problem. Socially, the problem was the need to seek a new balance between energy use and its cost in relation to the environment and the quality of life. The energy-ecology-cost dilemma was just surfacing. Some of the consequences of unremitting technological growth were beginning to raise grave new questions about the ways in which people live and work.

The dark and light sides of man's growing dependence on all forms of energy were becoming evident. Diminishing resources, a growing interdependence of all functions within society, and an unprecedented scale of required R&D pointed to the need for new kinds of institutional innovations.

The Industry Organizes

FRAMEWORK FOR THE FUTURE

As a technology matures, the opportunities for its further development become basically a matter of scale. In the semiconductor technology, for instance, the scale goes down. Progress is measured by the implanting of an ever-greater number of circuits (or circuit functions) on an ever-smaller surface area of silicon. Today, entire systems are contained on a tiny chip that only 20 years ago was the size of a single transistor. Likewise, the price-per-circuit function has plummeted, and the scale of electrical organization approaches the scale on which neurons in the nervous system are organized.

In electric power systems, on the other hand, the scale goes up. Greater efficiencies, greater reliability, greater power output have been achieved with generating units that have grown in size and with transmission networks that have grown in capacity and length.

The physical prototypes of new systems of the future must in some cases also be large, requiring hundreds of millions, perhaps even billions, of dollars to build and test (for instance, coal gasification and liquefaction plants or fusion generators). Because R&D is always a high-risk operation, the question of who should properly carry the risk of spending enormous sums of money on systems —the effectiveness, workability, or acceptability of which are uncertain—became a significant factor.

These risks were approaching such proportions in the 1960s that no individual enterprise, whether electric utility or giant equipment supplier, could afford to shoulder the entire burden. This was part of the challenge that the electric industry began to confront in the late 1960s.

The utility industry leadership perceived that time was running out. Massive technological R&D enterprise was required, and if the industry did not do it, it was clear that the federal government should and would. A mammoth undertaking was required; another historic threshold had been reached. Diminishing fuel supplies and continued growth in electricity demand and projections of electrical consumption to the end of this century gave some indication of the scope of the problem. At the same time voices were being raised, asking whether or not there ought to be limits to growth. Pollution, resource depletion, In the late 1960s the utilities moved toward a new mode of handling their generic R&D problems and established a central research institute to serve the needs of the entire industry. The new R&D organization, the Electric Power Research Institute (EPRI), now manages more than a thousand projects in all aspects of electric energy generation, delivery, and use, with the actual R&D going on in industries, utilities, and universities throughout the country. It engages in collaborative projects with the federal government's Department of Energy, with the Environmental Protection Agency, and with many others, including both national and international organizations. Some of the great challenges being confronted by our society and by our R&D organizations—characterized by the energy-ecology-cost dilemma—are matched against some of the possible future options.

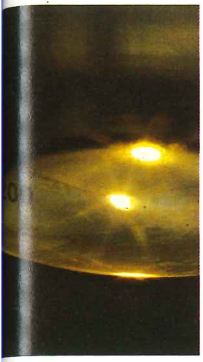
the impact of accelerating technological change on social institutions, the family, and the quality of life were also emerging concerns. Old issues of electrification dating from the Edison era—of centralization versus decentralization of systems—were being reviewed.

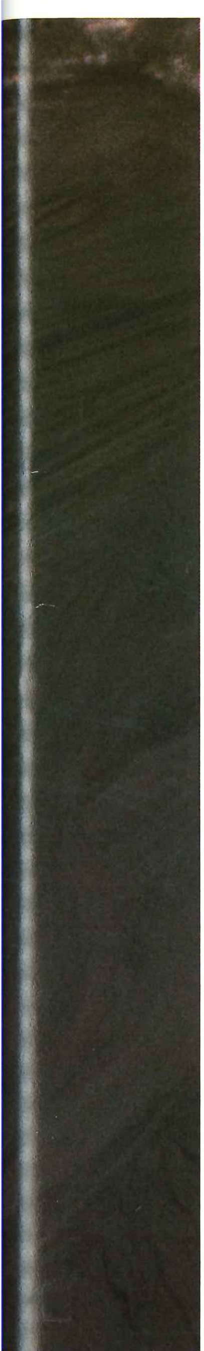
The technological problems facing the industry had been accumulating, and they were of a character that could not be expected to be handled by the traditional vendors alone. The utility industry began to perceive that it had reached a plateau in new technology for the generation of electricity. On the one hand, in the 1950s and 1960s, it was getting more kilowatthours out of the same amount of fuel but was reaching temperature and pressure limitations. Consequently, there was a flattening of expectations for fossil fuel generation. There was also the recognition that much more was to be done with nuclear energy, and exotic concepts, such as fusion, were looming as tremendously large undertakings of a long-range, high-risk nature. Of that period, one utility leader reflected, "There was within our industry a perception that greater technological efforts were needed than even the vendors could be expected to make." If the manufacturers had to make great investments and could not expect a return in less than 30 years, the responsibility really became a larger, societal one. But there was no existing mechanism that could address such technological needs.

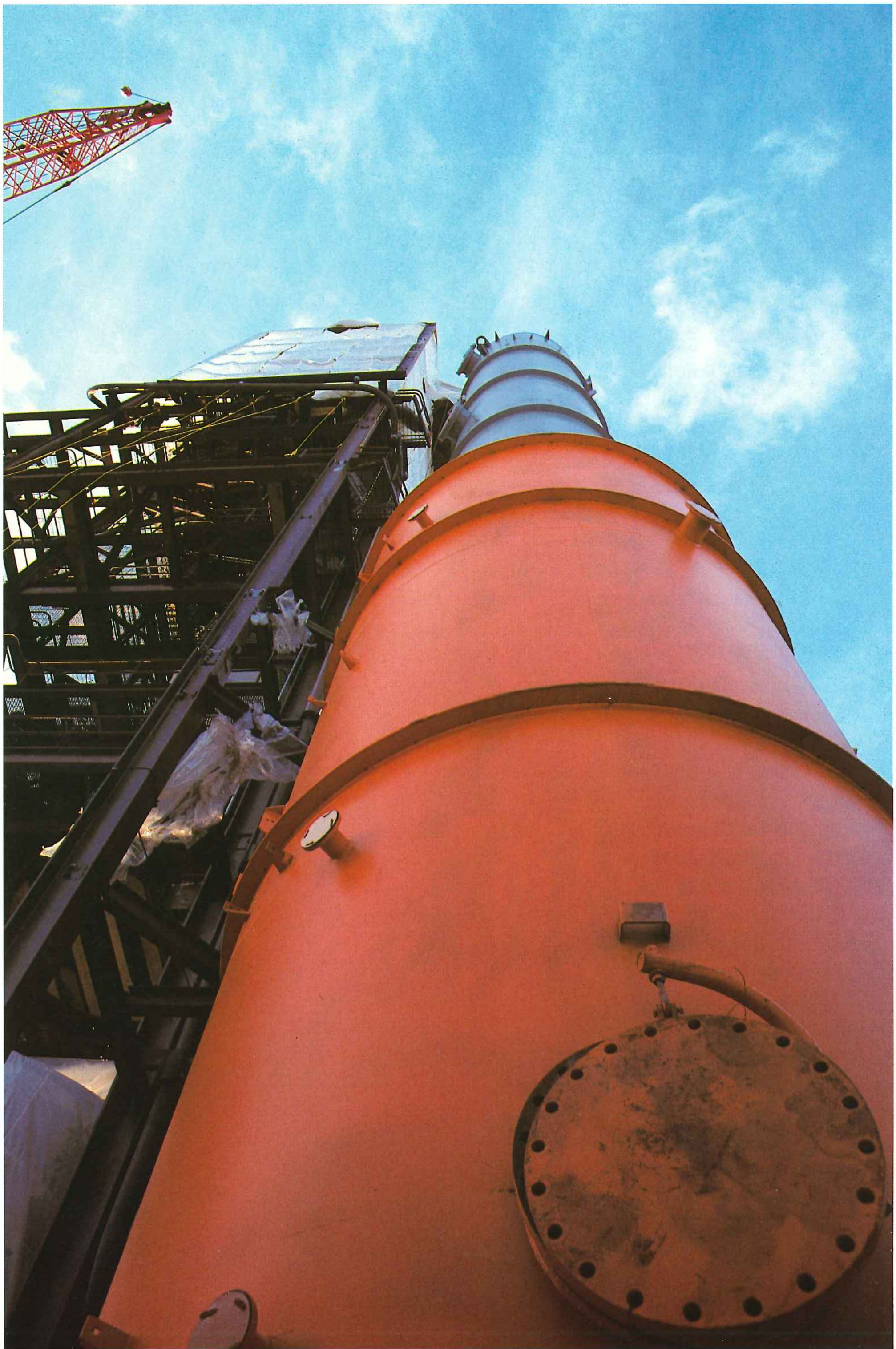
Another perception of the same basic problem was that the electric systems were simply getting larger and more important than their individual components. As the utilities grew, the vendors continued to supply the hardware and give counsel on system interconnections, but the performance of the systems—their overall reliability—became more and more the responsibility of the utility in-house engineers. Then, because of the complexity of the problems, a whole series of incidents pointed to the need for the utility industry to have its own independent technical center.

Multiple challenges in the production and use of energy face our society today. As population density increases and as energy needs grow, we are challenged to find ways of transmitting more power through a given space. Higher and higher voltage is one way.

Another great challenge is that of finding environmentally acceptable replacement fuels for diminishing oil and gas supplies. Coal, which is abundant, could be such an important fuel for the next half-century and more, if it can be made clean enough and cheap enough and in sufficient quantities to meet projected needs. The transformation of coal by liquefaction and gasification techniques looks promising.







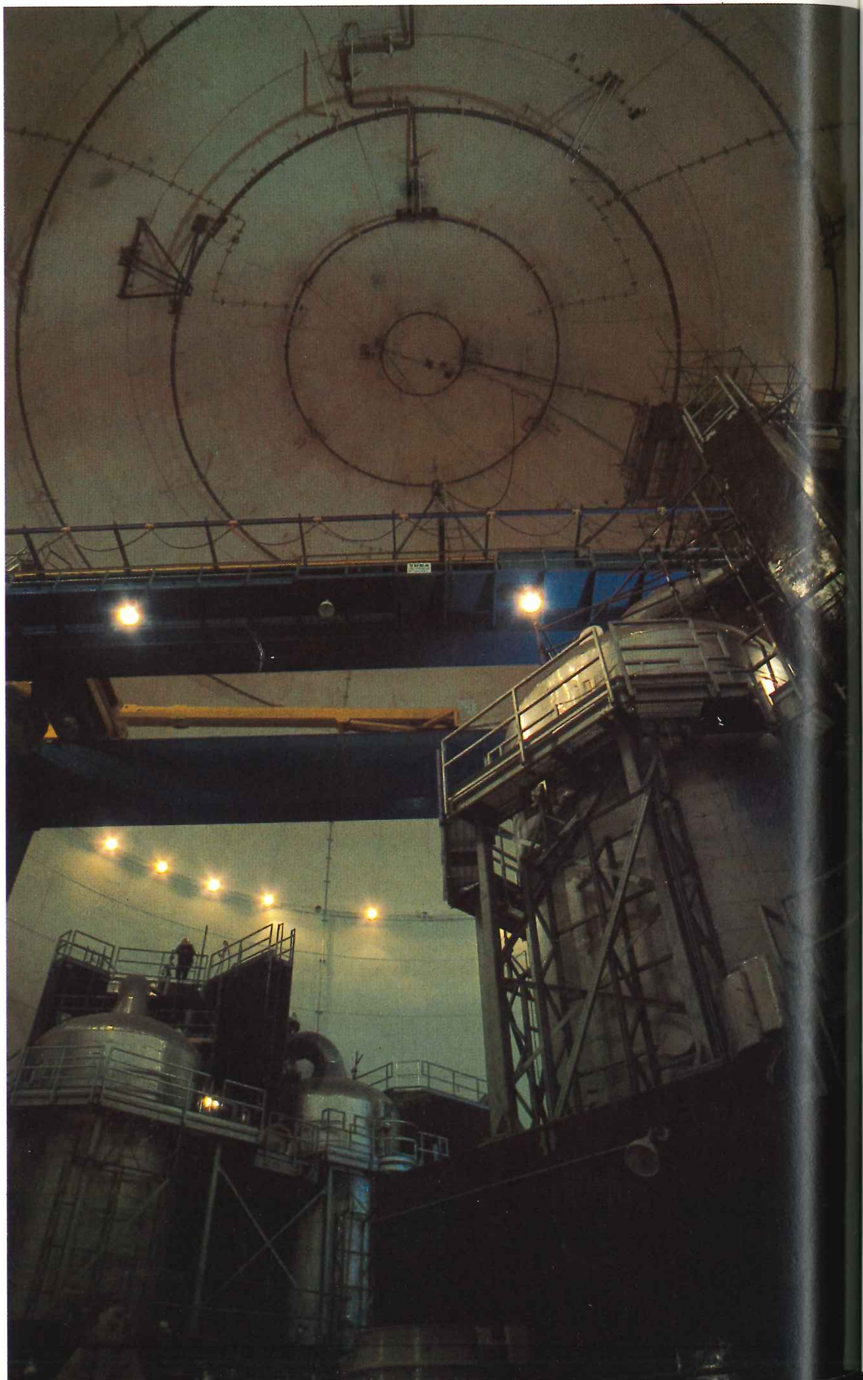
Toward a new R&D organization

The very first efforts to get the industry interested in setting up a new R&D organization go all the way back to 1954. But it was not until 1963 that Joseph Swidler, who had worked with TVA for many years and who was then chairman of the Federal Power Commission, addressed the Edison Electric Institute (EEI) on the serious need for an organized research program. Under his thoughtful prodding, a study group called the Electric Research Council (ERC) was formed by EEI and sponsored some modest research studies through the late 1960s.

Another prod to the industry came from the 1965 Northeast blackout. It triggered public and government criticism and led to proposed legislation in the early 1970s for a federal R&D agency to be set up for the industry. The work of this agency was to be supported by a tax on utilities. These forces dovetailed with the growing ecological and environmental concerns and gave rise to the need for R&D on pollution control technologies.

About the same time, ERC was completing a report for the electric utility industry on the R&D needs for the remainder of this century. That study pointed to the need for $30 billion of R&D to be sponsored over the next three decades by public and private institutions. In contrast to the $7 to $10 million being expended annually in support of ERC's studies, which already looked pretty large to the cost-conscious utilities, this $30 billion was an absolutely staggering figure, even though it included projections of possible government financing. It was also clear that the part-time counseling and task-force committees of ERC were not the kinds of institutional mechanisms that could grapple with the levels of required R&D management. The question was whether or not the utilities generally would be prepared to undertake the support of such a gigantic, long-term mission.

Also, because the utility industry was so diverse, there were all kinds of different ideas about what was best for com-



panies in the short term. Few utilities were prepared for the level of coordinated effort that would address the total technological needs over a long period of time.

Added to such problems was the considerable skepticism at the federal level that the electric utility industry would ever do what it should about R&D. Leaders in government were pushing hard for a proposed kilowatthour tax to set up a trust fund for a government agency to handle electric R&D.

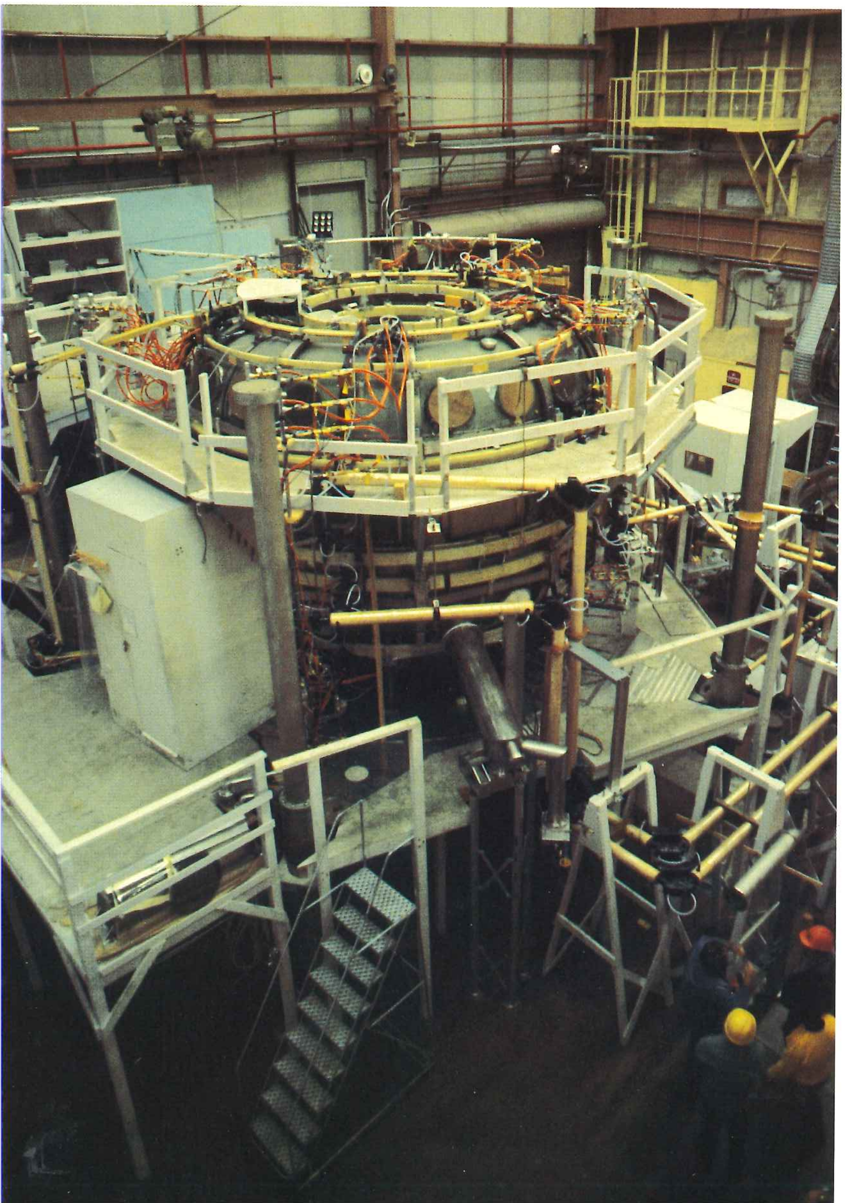
In the perspective of the nearly 90 years of growth in which the electric utility industry had come to depend upon the R&D of its pioneering inventor-entrepreneurs and then on the diverse organized R&D activities of the industries that had been founded by those same pioneers, the idea of a nationwide industry supporting a single R&D center was a novelty. The organization of such a center, one dependent upon the support and interest of more than 3000 individual utilities with different local and regional characteristics was a major challenge. Although all utilities had come to depend upon the results of R&D, very few—generally only the largest—had direct experience of, or feeling for, what it would take to set up and manage a successful R&D organization. The challenge was similar to that at the turn of the century, when industry first set up its pioneering R&D groups, but now approached a scale thousands of times more vast and with many more dimensions.

Regionalism or centralization?

Nor was it a straightforward matter as to exactly how such an R&D effort should be organized for maximum effectiveness. For instance, in 1965 Philip Sporn favored the organization of regional R&D. He maintained that questions of fuel availability and climatological, topographical, and sociological factors would favor the treatment of particular generation, transmission, distribution, and utilization problems on a regional basis. He also argued that cross-regional efforts would often make sense on an ad hoc basis, in

Harnessing the very binding forces of nature while guaranteeing their containment has been the challenge of the nuclear age. Fission research focuses on greater reliability and verified safety in today's plants (left).

Nuclear fusion (below) presents one of the great challenges of the future—releasing the fuel potential of the oceans (deuterium) for practical use. The challenge is the equivalent of creating, confining, and controlling a miniature star on earth.



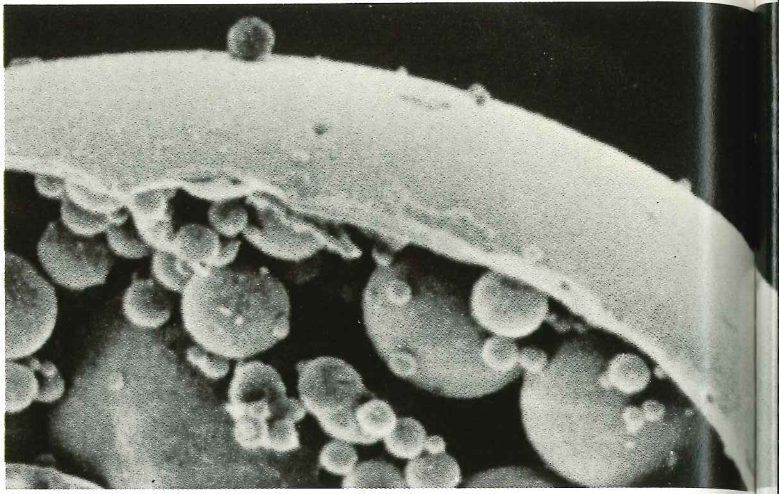
dealing, say, with distribution problems faced by large urban systems. He also believed that regional centers could be started up more readily than a national one; he pointed to early successful nuclear power R&D efforts carried on by cross-regional and regional groups. Looking for regional factors at work, Sporn observed that in areas where fossil fuel costs were high, construction and consideration of construction of nuclear plants took place early. In areas not faced with such cost pressures, research centered on more advanced reactor concepts.

But the forces favoring the formation of a national center–namely, the wide range of common or generic problems facing the entire industry–proved too strong. This center might meet another need pointed to by Sporn–an authentic voice for the utility industry, especially in its relations with those government agencies whose decisions were often of direct significance and concern to the utilities.

The utility industry was not alone in responding to such problems, when in 1972 it established the Electric Power Research Institute (EPRI). A variety of governmental private and semiprivate agencies and institutes were established, and some were reorganized in this period. For instance, the Environmental Protection Agency (EPA) was formed in 1970; the Federal Energy Research and Development Agency (ERDA) was formed in 1974; ERDA was reorganized as the Department of Energy in 1977; and just recently the gas utilities have set up their own R&D organization, the Gas Research Institute (GRI) modeled on EPRI. In addition, many existing organizations intensified their in-house R&D efforts. The giant American Electric Power Company, for instance, which did not join EPRI, was one of those.

Electric industry R&D programs

Shortly after it was formed, EPRI began letting out contracts for R&D projects that were to be carried out in laboratories throughout the country–in private companies, in academic centers, in spe-



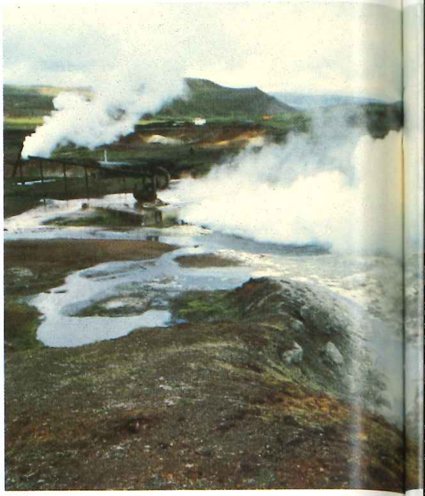
A particular challenge engendered by technology is the necessity for understanding its effects on the environment and on life. Only through such understanding can the potential harmful effects be alleviated. Typical of studies with such objectives are those that test the effects of high-voltage fields and those that trace the character and impact of particulate matter created by industrial processes.

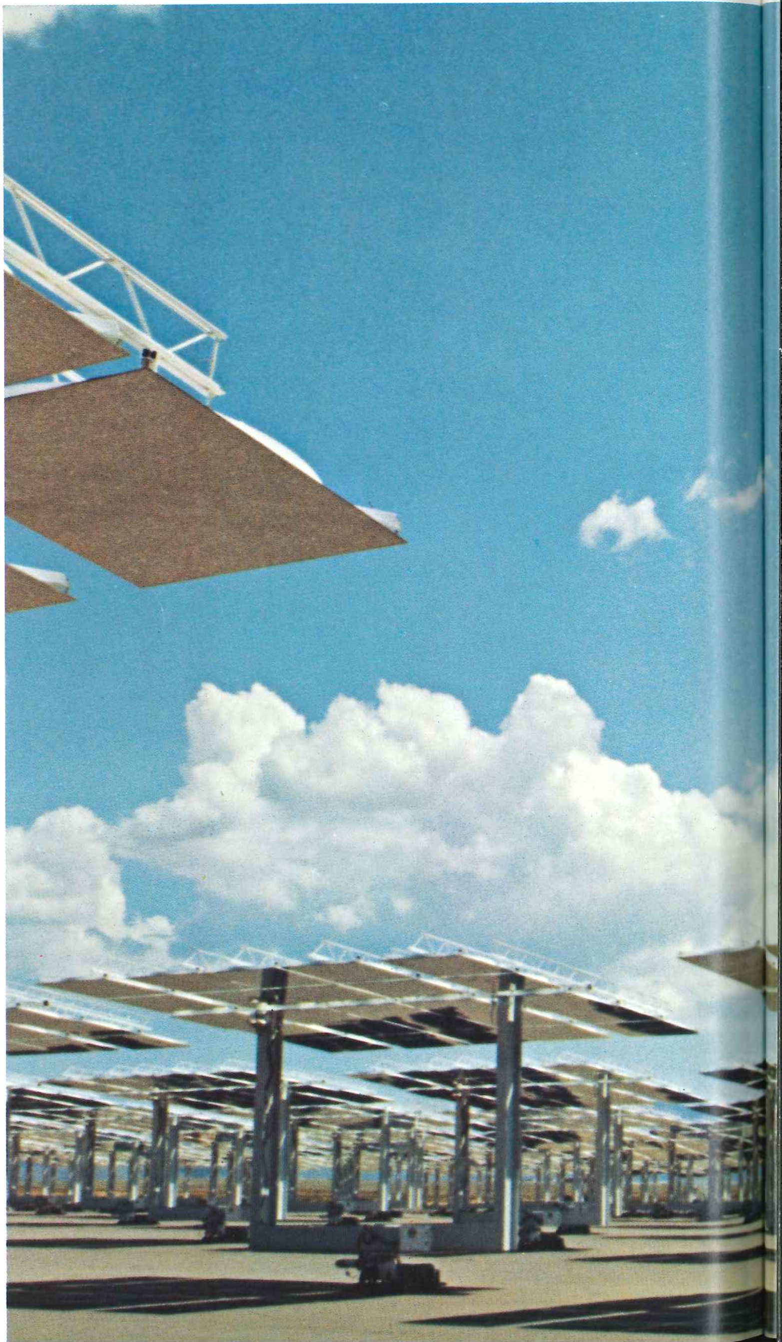
cialized research organizations, and in utilities themselves. The range of this work has steadily grown more extensive, so that today more than 1000 projects are going on—in transmission and distribution, in nuclear and fossil fuel plants, in new forms of clean fuels, in new energy sources such as fusion and solar, in energy resource supplies, in systems behavior, in environmental problems, and much else. Only the Department of Energy surpasses the extent and range of R&D in energy areas; indeed, DOE and EPRI engage in many cooperative R&D programs on crucial energy issues.

Through EPRI the utility industry encourages the traditional R&D role of the manufacturers and vendors. Thus, through a kind of tripartite responsibility—DOE (federal), traditional industry (private), and EPRI (quasi-public/private)—there is the hope that the necessary R&D in the energy field will be accomplished to provide the future options needed by our energy industries and that the involvement of the private sector will facilitate the translation of R&D results into commercial applications.

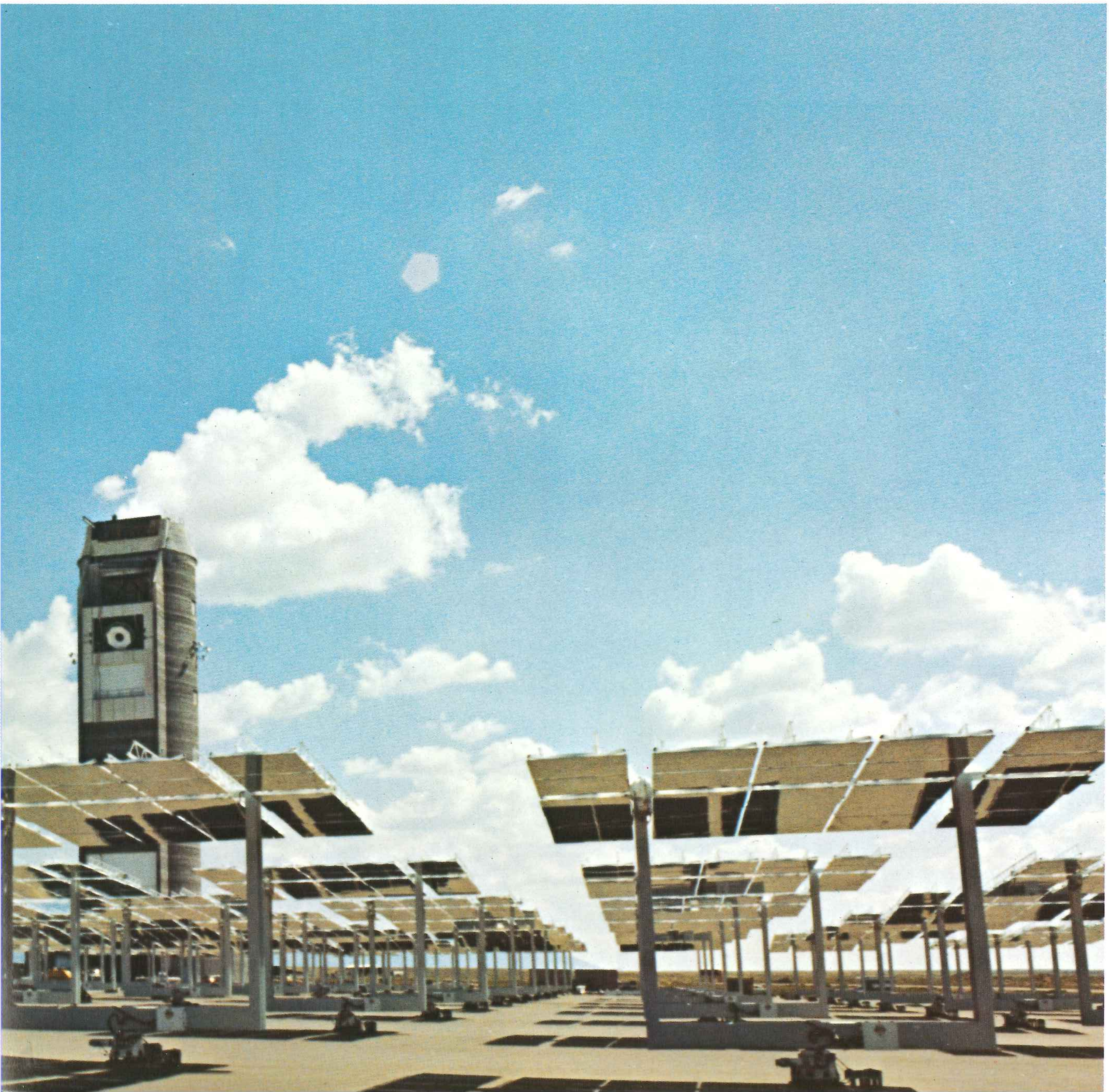
A new threshold?

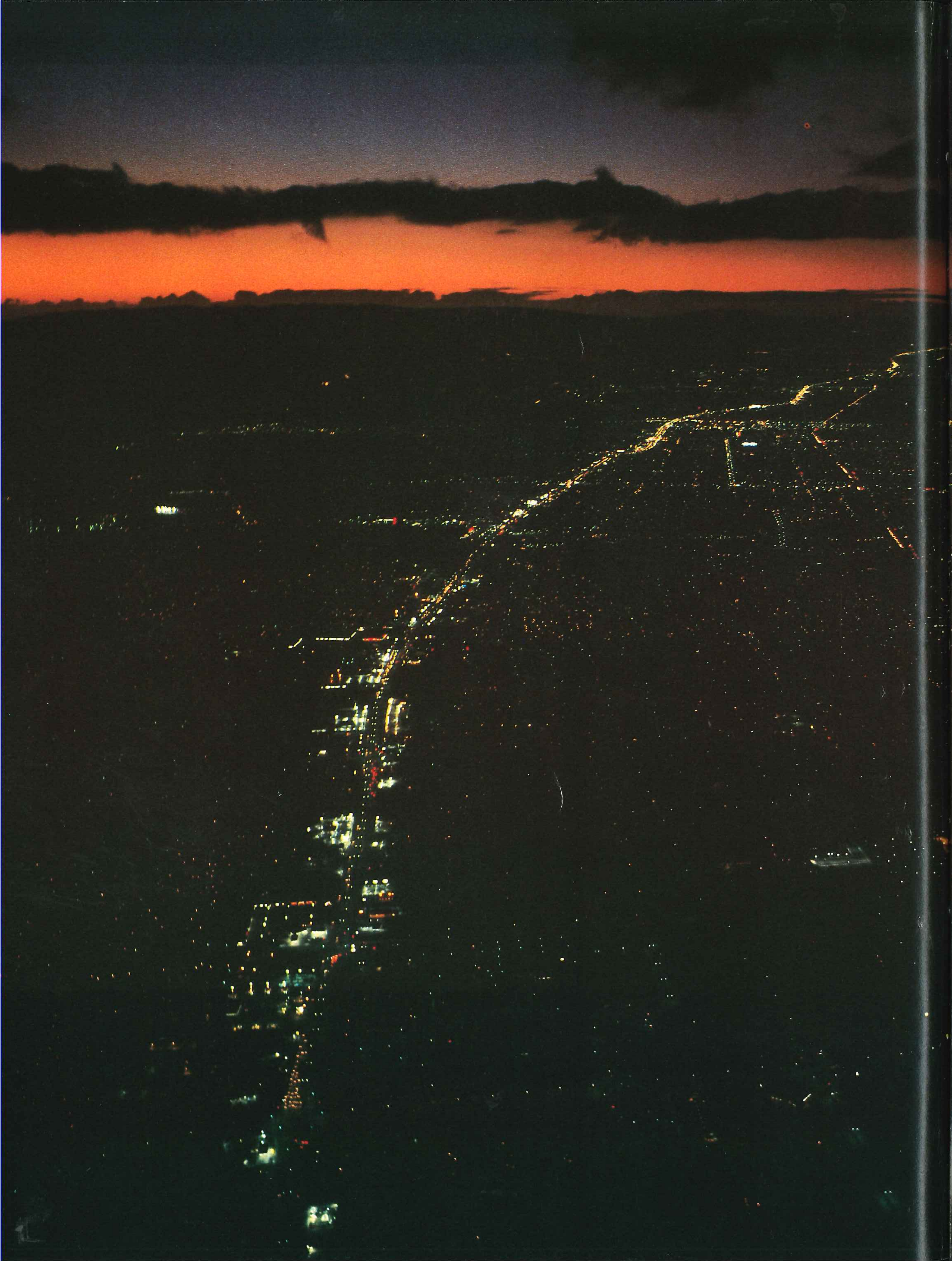
The new R&D institutions that have emerged in this period confront new challenges. These challenges include an ethic of energy conservation and environmental concern, the need to develop an entire range of technological options for serving future energy needs, and perhaps the need to evolve an entirely new science of energy and society. Cooperative R&D programs—on a scale once associated primarily with wartime emergencies—have become the hallmark of the electrical industries in the 1970s, as the whole world grapples not just with its need for electricity, but with the entire spectrum of energy needs. Today, our society seems to be once again at a threshold of change—a period of transition perhaps equivalent to the transition of a century ago when electrification was just emerging as a major technological and social force. ■





The challenge of tapping and domesticating the energy of the sun and the earth—in the form of solar and geothermal steam—has long intrigued scientists and engineers. A civilizaton that relied directly on the processes of the sun for its major energy sources might be as different from our industrial civilization as ours is from that of the preelectric one. International R&D programs are underway with this objective, although it may be well into the twenty-first century before such sources as solar, geothermal, and fusion begin to form a significant share of total energy needs.





The Edison Heritage

Almost 100 years ago the young mathematician Francis R. Upton, assistant to Edison, wrote of the electric light achievement: "Besides the enormous practical value of the electric light as domestic illuminant and motor, it furnishes a most striking and beautiful illustration of the convertibility of force. Mr. Edison's system of lighting gives a completed cycle of change. The sunlight poured upon the rank vegetation of the carboniferous forests was gathered and stored up and has been waiting through the ages to be converted again into light. The latent force accumulated during the primeval days and garnered up in the coal beds is converted, after passing in the steam engine through the phases of chemical, molecular, and mechanical force, into electricity, which only waits the touch of the inventor's genius to flash out into a million domestic suns to illuminate a myriad homes."

These, then, are elements of the Edison heritage—millions of domestic lights and, at the same time, a new concern for the totality of the cycles whereby energy is converted from one form to another.

As we reflect on this heritage, we may well ask whether we stand at the zenith of a great age or merely on a plateau before the next ascent.

BIBLIOGRAPHIES

In the preparation of this Edison centennial issue of the *EPRI Journal* far more sources were consulted than are listed in the following bibliographies. The Annotated Bibliography contains basic sources for those wishing further information on the century of electrification. The General Bibliography contains the sources relevant to each episode.

Annotated Bibliography

Belfield, Robert B. *Relics of the Electrical Age.* IEEE and Smithsonian Institution, 1977.
A directory of public and private repositories in the United States and Canada containing artifacts associated with the history of electric technology and science.

Brittain, James E., ed. *Turning Points in American Electrical History.* New York: IEEE Press, 1977.
A significant collection of original papers by many of the "greats" in the electrical field dating from colonial times to the present. Commentaries and biographical notes by historian James Brittain make this an invaluable guide to those interested in electrical history.

"Chronology of American Technology." *Industrial Research,* November 12, 1976.

Conot, Robert. *A Streak of Luck,* New York: Seaview Press, in press.
A new "warts-and-all" biography of Edison that raises many new questions about Edison's career and that challenges certain longstanding assumptions.

Hughes, Thomas P. "Thomas Edison: Professional Inventor." Chatham, England: MacKay, Ltd., 1976.
Excellent monograph that directs attention to Edison's methodical systems approach to invention.

Josephson, Matthew, *Edison, A Biography.* New York: McGraw-Hill, 1959.
The classic and highly readable account of Edison's career and times.

Kevles, Daniel J. *The Physicists: The History of a Scientific Community in Modern America.* New York: Alfred A. Knopf, 1978.
An excellent dramatic and highly readable history of the growth of the community of physicists in the United States, covering essentially the same period dealt with in this issue of the *EPRI Journal.*

National Electrical Manufacturers Association. *A Chronological History of Electrical Development from 600 B.C.* New York: NEMA, 1946.

Passer, Harold C. *The Electrical Manufacturers: 1875–1900.* Cambridge, Mass.: Harvard University Press, 1953.
The classic study of the origins and economic growth of the electrical industry.

Proceedings of the IEEE. Special issue on two centuries in retrospect. J. D. Ryder and J. E. Brittain, New York: IEEE, September 1976.
More than 20 papers by scholars on selected aspects of electrical history make it a most readable and stimulating guide.

Wachhorst, Newton Edwin, II. "A Better Mousetrap: Thomas A. Edison as an American Culture Hero," PhD dissertation, Stanford University, 1973.
A doctoral dissertation which provides an extremely interesting and informative analysis of the growth of the legends surrounding Edison, and includes an enormous bibliography of publications about Edison. (Available through University Microfilms, Ann Arbor, Mich.)

General Bibliography

The Preelectric World

Adams, Henry. *The Education of Henry Adams.* The Massachusetts Historical Society, 1918. New York: Random House, 1931.

Houghton, Walter E. *The Victorian Frame of Mind, 1830–1970.* New Haven, Conn.: Yale University Press, 1957.

Huizinga, J. *The Waning of the Middle Ages.* New York: Doubleday Anchor Books, 1954.

Post, Robert C., ed. *1876: A Centennial Exhibition.* Washington, D.C.: The National Museum of History and Technology, Smithsonian Institution, 1976.

Seizing the Moment

Agassi, Joseph. *Faraday as a Natural Philosopher.* Chicago: University of Chicago Press, 1971.

Burlingame, Roger. *Engines of Democracy.* New York: Charles Scribner's Sons, 1940.

Clark, Ronald W. *Edison: The Man Who Made the Future.* New York: G. P. Putnam's Sons, 1977.

Conot, Robert. *A Streak of Luck.* New York: Seaview Press, in press.

Crowther, J. G. *Men of Science.* New York: W. W. Norton, 1936.

Crowther, J. G. *Famous American Men of Science.* New York: W. W. Norton, 1937.

Derganc, C. S. "Thomas Edison and His Electric Lighting System." *IEEE Spectrum,* Vol. 16, No. 2, February 1979.

de Tocqueville, Alexis. *Democracy in America.* 2 vols. New York: Vintage Books, 1958.

Dyer, F. L., T. C. Martin, and W. H. Meadowcroft. *Edison, His Life and Inventions.* 2 vols. New York: Harper & Bros., 1929.

Edison, Thomas A. *The Diary and Sundry Observations of Thomas A. Edison.* Dagobert D. Runes, ed. New York: Philosophical Library, 1948.

Eisenmann, Harry James, III. "Charles F. Bush: Pioneer Innovator in Electrical Technology." PhD dissertation, Case Institute of Technology, 1967.

Elfun Society. *The Edison Era: 1876–1892.* Vol. 1. *The General Electric Story.* J. Daly, ed. Schenectady, N.Y.: General Electric Co., 1976.

Gerard, William Paul. *The American Practice of Gas Piping and Gas Lighting in Buildings.* New York: McGraw, 1908.

"The Relations Between Gas Companies and Gas Consumers," *Cassier's Magazine,* July 1894.

Habakkuk, H. J. *American and British Technology in the Nineteenth Century.* New York: Cambridge University Press, 1962.

Howell, John W., and Henry Schroeder. *History of the Incandescent Lamp.* Schenectady, N.Y.: Maqua, 1927.

Hughes, Thomas P. *Elmer Sperry.* Baltimore, Md.: Johns Hopkins University Press, 1971.

Hughes, Thomas P. "Systems—The Past Points the Way." *Consulting Engineer,* January 1968.

Hughes, Thomas P. *Thomas Edison: Professional Inventor.* Chatham, England: MacKay, Ltd., 1976.

Jehl, Francis. *Menlo Park Reminiscences.* 3 vols. Dearborn, Mich.: The Edison Institute, 1937, 1939, 1941.

Josephson, Matthew. *Edison: A Biography.* New York: McGraw-Hill, 1959.

Koolakian, Robert G. "The Menlo Park Story." Greenfield Village and Ford Museum, Dearborn, Mich., n.d.

Lewis, Floyd A. *The Incandescent Light.* New York: Shorewood, 1949. New York *Sun,* October 25, 1878.

Passer, Harold C. *The Electrical Manufacturers: 1875–1900.* Cambridge, Mass.: Harvard University Press, 1953.

Pope, Franklin Leonard. *Evolution of the Incandescent Lamp.* Elizabeth, N.J.: Henry Cook, 1889.

Prout, Henry G. *A Life of George Westinghouse.* New York: The American Society of Mechanical Engineers, 1921.

Rosanoff, Martin A. "Edison in His Laboratory." *Harper's Monthly,* September 1932.

Siemens, George. *History of the House of Siemens.* Vols. 1 and 2. New York: Arno Press, 1977.

Süsskind, Charles. *Twenty-Five Engineers and Inventors.* San Francisco: San Francisco Press, 1976.

Swan, M. E., and K. R. Swan. *Sir Joseph Wilson Swan, F. R. S.* London: Ernest Benn, Ltd., 1929.

Upton, Francis R. "Edison's Electric Light." *Scribner's Monthly,* 1880.

Ure, Andrew. *Arts, Manufacturers, and Mines.* London: Cass, Ltd., 1856.

Venable, John D. *Out of the Shadow: The Story of Charles Edison.* East Orange, N.J.: Charles Edison Fund, 1978.

Welch, Walter L. *Charles Batchelor, Edison's Chief Partner.* Croton-on-Hudson, N.Y.: North River Press, Syracuse University, 1972.

Whitehead, A. N. *Science and the Modern World.* New York: Macmillan, 1925, Chapter 6.

Whitney, Willis R. "Edison: Scientist and Educator." Paper delivered at centennial dinner honoring the birth of Thomas A. Edison, February 11, 1947. (Available from General Electric Company.)

Woodbury, David O. *A Measure for Greatness, A Short Biography of Edward Weston,* New York: McGraw-Hill, 1949.

Harnessing a Monument

Adams, Edward Dean. *Niagara Power: History of Niagara Falls Power Company, 1886–1918.* 2 vols. Niagara Falls Power Company, 1927.

Belfield, Robert. "The Niagara System: The Evolution of an Electric Power Complex at Niagara Falls, 1883–1896." In *Proceedings of the IEEE,* Vol. 64, No. 9, September 1976, pp. 1344–1350.

Brittain, James E. "B. A. Behrend and the Beginnings of Electrical Engineering, 1870–1920." PhD dissertation, Case Western Reserve University, 1970.

Elfun Society. *The Steinmetz Era, 1892–1923.* Vol 2. *The General Electric Story.* J. Daly, ed. Schenectady, N.Y.: General Electric Co., 1977.

Friedlander, Gordon D. "Tesla: Eccentric Genius." *IEEE Spectrum,* June 1972.

Leupp, Francis E. *George Westinghouse: His Life and Achievements.* Boston: Little, Brown, 1918.

Sharlin, Harold I. *The Making of the Electrical Age.* London: Abelard-Schumann, 1963.

Spurgeon, Bud. "Tesla." *The Co-Evolution Quarterly,* Winter 1977–78.

Crossing the Threshold

Birr, Kendall. *Pioneering in Industrial Research.* Washington, D.C.: Public Affairs Press, 1957.

Brittain, James E. "C. P. Steinmetz and E. F. W. Alexanderson: Creative Engineering in a Corporate Setting." In *Proceedings of the IEEE,* Vol. 64, No. 9, September 1976, pp. 1413–1417.

Dampier, Sir William Cecil. *The History of Science and Its Relations With Philosophy and Religion.* New York: Macmillan, 1942.

Fleming, J. A. *Fifty Years of Electricity.* London: Iliffe & Sons, Ltd., 1921.

Hammond, J. W. *Charles Proteus Steinmetz.* New York: Century, 1924.

Hammond, J. W. *Men and Volts, The Story of General Electric.* Philadelphia: J. B. Lippincott, 1941.

Lamme, Benjamin G. *Benjamin Garver Lamme, an Autobiography.* New York: G. P. Putnam's Sons, 1926.

Reich, Leonard S. "Radio Electronics and the Development of Industrial Research in the Bell System." PhD dissertation, Johns Hopkins University, 1977.

Reich, Leonard S. "Science, Technology, and Industrial Research: The Career of Irving Langmuir." Unpublished paper, Rensselaer Polytechnic Institute, 1978.

Ripley, Charles M. *Romance of a Great Factory.* Schenectady, N.Y.: Gazette Press, 1919.

Scott, Charles F. "Early Days in the Westinghouse Shops." *Electrical World,* Vol. 84, No. 12, September 20, 1924.

Whitney, W. R. "Research Twenty-Five Years Ago and Now." *Electrical World,* Vol. 84, No. 12, September 20, 1924.

Wise, George. "Defining Industrial Research: The Role of the General Electric Research Laboratory, 1900–1915." Report No. 77CRD273, January 1978. Schenectady, N.Y.: General Electric Corporate Research and Development.

Woodbridge, J. E. "Electrical Engineering Twenty-Five Years Ago." *Electrical World,* Vol. 84, No. 12, September 20, 1924.

Electrifying a Nation

Bigham, Truman C. "Superpower Systems: Their Development, Economics, Limitations, and Results." PhD dissertation, Stanford University, 1927.

Coleman, Charles M. *PG&E of California: The Centennial Story of Pacific Gas and Electric Company, 1852–1952.* New York: McGraw-Hill, 1958.

Cooke, Morris L., ed. "Giant Power: Large-Scale Electrical Development as a Social Factor." The American Academy of Political and Social Science, *Annals,* Vol. CXCIII, March 1925.

Dierdorff, John. *How Edison's Lamp Helped Light the West.* Portland, Ore.: Pacific Power & Light Company, 1971.

Electrical World. The 50th Anniversary Number, Vol. 84, No. 12, September 20, 1924. New York: McGraw-Hill.

Gutheim, F. "Roland Wank, 1898–1970." *Architectural Forum,* Vol. 133.

Hubbard, P. J. *Origins of the TVA: The Muscle Shoals Controversy.* Nashville, Tenn: Vanderbilt University Press, 1961.

Hughes, Thomas Parke. "Technology and Public Policy: The Failure of Giant Power." In *Proceedings of the IEEE,* Vol. 64, No. 9, September 1976, pp. 1361–1371.

Jones, Payson. *A Power History of the Consolidated Edison System, 1878–1900.* Consolidated Edison Co. of New York, 1940.

Kaempffert, Waldemar. "Power for the Abundant Life." New York *Times* Magazine, August 23, 1936.

Kyle, J. H. *The Building of TVA: An Illustrated History.* Baton Rouge: Louisiana State University Press, 1958.

Lowitt, Richard. *George W. Norris: The Persistence of a Progressive.* Urbana: Illinois University Press, 1971.

McDonald, Forrest. *Insull.* Chicago: University of Chicago Press, 1962.

McGraw, Thomas K. *Morgan vs. Lilienthal: The Feud Within the TVA.* Chicago: Loyola University Press, 1970.

McGraw, Thomas K. *TVA and the Power Fight, 1933–1939.* Philadelphia: J. B. Lippincott, 1971.

McGraw, Thomas K. "Triumph and Irony—The TVA." In *Proceedings of the IEEE,* Vol. 64, No. 9, September 1976, pp. 1372–1380.

Martin, Thomas W. *The Story of Electricity in Alabama, 1900–1952.* Birmingham, Ala.: Birmingham Publishing, 1950.

Murray, William Spencer. *Superpower: Its Genesis and Future.* New York: McGraw-Hill, 1925.

Wright, Wade H. *History of the Georgia Power Company, 1855–1956.* Atlanta: Georgia Power Co., 1957.

R&D: A New Alloy

Duffus, R. L. "A Giant Goes to War," New York *Times* Magazine, July 27, 1941.

Eames, Charles, and Ray Eames. *A Computer Perspective: A Sequence of 20th Century Ideas, Events, and Artifacts from the History of the Information Machine.* Cambridge, Mass.: Harvard University Press, 1973.

Kevles, Daniel J. *The Physicists: The History of a Scientific Community in Modern America.* New York: Alfred A. Knopf, 1978.

Miller, John Anderson. *Men and Volts at War.* New York: McGraw-Hill, 1947.

New Directions

Bancroft Library, University of California at Berkeley. Transcripts of interviews with F. E. Terman and E. L. Bowles.

Brown, G. S. "New Horizons in Engineering Education." *Daedalus,* Vol. 91, 1962.

Bush, Vannevar. "As We May Think." *Atlantic Monthly,* August 1945.

Electrical World. "The Electric Century: 1874–1974." The 100th Anniversary Issue, Vol. 181, No. 11, June 1, 1974. New York: McGraw-Hill.

Norbert, Arthur L. "The Origins of the Electronics Industry on the Pacific Coast." In *Proceedings of the IEEE,* Vol. 64, No. 9, September 1976, pp. 1314–1322.

Sporn, Philip. *Research in Electric Power.* Oxford: Pergamon Press, 1966.

Sporn, Philip. *Energy in an Age of Limited Availability and Delimited Applicability.* Oxford: Pergamon Press, 1976.

Sporn, Philip. "Growth and Development in the Electric Power Industry." *Electrical Engineering,* Vol. 78, May 1959. Reprinted in *Turning Points in American Electrical History.* Ed. James E. Brittain. New York: IEEE Press, 1977.

Suits, C. Guy. *Suits: Speaking of Research.* New York: John Wiley, 1965.

Süsskind, Charles. "American Contributions to Electronics: Coming of Age and Some More." In *Proceedings of the IEEE,* Vol. 64, No. 9, September 1976, pp. 1300–1305.

Terman, F. E. "A Brief History of Electrical Engineering Education." In *Proceedings of the IEEE,* Vol. 64, No. 9, September 1976, pp. 1399–1407.

Framework for the Future

Kaempffert, W. *Invention and Society.* Chicago: American Library Association, 1930.

Kuhn, Thomas S. "The Structure of Scientific Revolution." *International Encyclopedia of Unified Science.* Chicago: University of Chicago Press, 1962.

Lindgren, Nilo. "The First Five Years: Chauncey Starr and the Building of EPRI." *EPRI Journal,* January–February 1978.

Starr, Chauncey. "Energy and Power." *Scientific American,* Vol. 225, No. 3, September 1971.

Starr, Chauncey. "Energy, Technology and Society." Houston Club Forum and Annual Farfel Lecture, April 9, 1974. (Available from EPRI.)

Steffens, Henry J., ed. *Science, Technology and Culture.* New York: AMS Press, 1974.

Süsskind, Charles. *Understanding Technology.* Baltimore, Md.: Johns Hopkins University Press, 1978.

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Thomas A Edison