FEATURE ARTICLE

Thomas Edison as a Manager of R&D: The Case of the Alkaline Storage Battery, 1898–1915

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Abstract — **From 1898 to 1915, Thomas Edison devoted the resources of his laboratory at West Orange, New Jersey to developing an alkaline storage battery. Initially, Edison intended that this battery would be used in electric automobiles, but technical problems prevented him from introducing his battery before this market disappeared. This article argues that in the course of this invention Edison modified his style and approach. In particular, Edison became less of a tinkerer and more of a research director supervising a team of college-trained chemists and engineers. As a research director, Edison motivated his experimenters by using informal management techniques and he insisted on keeping research closely connected to manufacturing. But most of all, his approach shifted from being "divergent" in which he tried many solutions to being "convergent" in which he directed experiments toward a highly specified goal.**

For many Americans, Thomas Edison will always be the "Wizard of Menlo Park." When we think of Edison, we conjure up the image of a scruffy fellow working into the night in quest of a better mousetrap. Although a talented experimenter himself, Edison in our memories is assisted by a faithful crew of ruffians and mechanics. This crew pursued numerous simultaneous experiments, yet somehow by informal banter, practical jokes, and an occasional bet for a cigar, Edison guided their efforts and invented revolutionary technology. Often Edison and his team produced new inventions on a limited budget and in only a few weeks; hence it is not surprising that contemporary newspaper reporters invoked magic and wizardry to explain Edison's work at Menlo Park.

Underlying this image of Edison as the "Wizard of Menlo Park" is a romantic view of invention. [1] Invention is uncontrollable, unpredictable, and ultimately, unmanageable. It is based on genius and luck, both of which Edison claimed to have in abundance. When the muses of invention spoke, they spoke; when they were silent, they were silent, and no amount of management, bureaucracy, or procedure could force them to reveal their secrets.

Although this romantic view of invention may well describe Edison at Menlo Park in the 1870s, it does not represent the mature Edison at West Orange in the 1900s. At Menlo Park, Edison may have permitted too much chaos and disorder, but it was perhaps necessary in order to create revolutionary technology. In contrast, at West Orange Edison modified his style of invention to suit the challenges of twentieth century business. Edison's approach shifted from being informal and craft-based to being routinized, formal, and science-based. Rather than turning out inventions in days and weeks on a shoestring, Edison chose large, capital-intensive projects that took years and decades. Instead of trying many divergent solutions to solve a technical problem, he now had his staff converge on a single design. And Edison himself became less of a tinkerer and more of a research director who supervised a large staff. Although this transformation in Edison's style of invention began when he moved to West Orange in 1887, these changes fully manifested themselves in his efforts to develop an alkaline storage battery from 1898 to 1915. Through the story of the storage battery, one can see that Edison was not just a heroic inventor but also an effective manager of R&D. [2]

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TAKING UP THE ALKALINE STORAGE BATTERY

Like other inventions developed at his West Orange laboratory, the storage battery was an idea that Edison had when he established the lab in 1887. At that time, Edison was struggling to find a power source for the electric motor he was then using in his phonograph. Edison and his associates experimented extensively with non-rechargeable or

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primary batteries using copper oxide and zinc plates immersed in a liquid electrolyte of caustic soda or sodium hydroxide. Edison began manufacturing these cells in 1889 at his Silver Lake chemical works in Bloomfield, New Jersey. Edison and his staff also investigated rechargeable or storage batteries for the Edison Electric Light Company that was interested in using cells to store power for consumption during peak demand. These battery investigations continued throughout the 1890s, forming a body of knowledge that Edison could exploit when the opportunity arose. [3]

That opportunity came in the late 1890s, in the wake of Edison's last unsuccessful efforts with iron ore separation. [4] As it became clear that iron ore prices would never be high enough to permit profitable operation of the ore separation plant, Edison revived his old ideas about a better storage battery. Edison wanted to invent a storage battery that was genuinely rechargeable and that efficiently converted chemical energy into electrical power. "A storage battery," he declared, "...should be a perfectly reversible instrument, receiving and giving out power like a dynamo motor, without any deterioration of the mechanism of conversion." [5]

From the outset, Edison's interest in an efficient rechargeable cell was closely related to the development of an electric vehicle. From 1895 onward, America entered into an automobile craze, with the popular press celebrating every invention related to the automobile. Many prominent inventors, including Elmer Sperry and Elihu Thomson, were attracted to the excitement surrounding the automobile and developed their own vehicles. The potential of a self-propelled vehicle captivated Edison, too, and as early as 1896 he had the lab build a motorized tricycle. A little later, the Edison household acquired an electric carriage and in October 1899 Mrs. Edison requested that the lab build a garage for recharging this vehicle. [6] Experience with these vehicles apparently convinced Edison that the future belonged to the electric car and he began developing a battery for it. He was confident that a large and growing demand for his battery would offset the high R&D costs he might incur.

Since the electric vehicle was to be the major application for his new storage battery, weight became an important consideration. Although storage batteries employing lead electrodes and an acid electrolyte had been available since the 1860s, Edison believed that they were too heavy and uneconomical for use in automobiles. Edison decided to develop a substitute and "produce a practicable battery which will permit the storage of a large[r] amount of energy per pound of material than is possible with the type of battery using lead electrodes." Edison was confident that there had to be an electrochemical combination that avoided using a metal as heavy as lead, and he intended to find the ideal combination. As he observed, "I don't think Nature would be so unkind as to withhold the secret of a good storage battery, if a real earnest hunt were made for it. I'm going to hunt." [7]

A CONVERGENT RESEARCH STRATEGY, 1899–1904

Edison started his hunt for a new battery in 1898 not with random experiments in the laboratory but with a thorough search of the technical literature. Just as he had done at key stages in developing his electric lighting system, Edison had his assistants pore over scientific and engineering journals to collect information from American, English, French, and German sources. Through this search, Edison learned that other inventors and scientists had identified alternatives to the lead-acid battery and he kept their work in mind as he undertook his own investigations. [8]

After searching the literature for about nine months, Edison was ready to begin experimenting. In the spring of 1899, he assembled a research team by selecting men already at work at his West Orange laboratory and by hiring a new group of professional chemists and engineers. With its preponderance of experimenters trained in science, the storage battery project differed from previous inventions for which Edison had relied heavily on craftsmen and mechanics. Consisting of about a dozen experimenters, this team worked primarily in the chemistry laboratory (Building 2), where each man was assigned a table. For his own experiments, Edison set up a laboratory bench in the back room of this building. [9]

Edison started the team off by having them investigate the familiar electrochemical combination of the primary battery that he was manufacturing at his Silver Lake chemical works. Edison had his researchers vary one component of the cell and conduct experiments until they obtained optimal results. Generally, Edison and his assistants tested different materials for the components of the cell by packing the selected material into porous carbon electrodes that were then placed in a test tube filled with the electrolyte, thus forming a small battery. Following this strategy, Edison and his staff investigated several different electrochemical combinations from 1899 to 1904 (see TABLE I). [10]

In adopting this time-consuming, step-by-step approach, Edison was organizing his research in a new way. In particular, he defined the overall project as a set of small tasks. Previously, Edison had used teams of experimenters to pursue simultaneously several different solutions to a technological problem. For instance, with the electric light project, Edison and his men alternated working on the lamp, the dynamo, and the distribution network; he designed a coherent system, in part, because his team worked on all fronts at once. [11] Likewise with the phonograph in 1888–1889, Edison and his experimenters did not systematically modify each component in an orderly sequence but rather experimented simultaneously with record cylinders, recorders, reproducers, and duplicating techniques. [12] In these projects, Edison allowed his experimenters to pursue "divergent" solutions to different aspects of the system, thus insuring a range of creative responses. Eventually, Edison gathered these different ideas and shaped them into a coherent and successful invention.

In contrast to this free-wheeling and divergent approach, Edison organized the storage battery project as a "convergent" set of tasks. Edison assigned a specific material or arrangement to each experimenter who then conducted a long series of standard experiments until he secured the

TABLE I
FLOW CHART OF EDISON'S RESEARCH ON THE STORAGE BATTERY, 1899–1909

Year	Anode	Electrolyte	Cathode
1899	Zinc	Sodium Hydroxide	Copper Oxide
		Potassium Hydroxide (used in all subsequent batteries)	Silver Oxide
			Copper Compounds
1900	Cadmium (too expensive)		Cobalt Oxide (too expensive)
1901	Iron (used in all subsequent batteries)		Nickel Oxide
1903		Type E Cell	
1904		(leaks & capacity drops)	
1905			Cobalt Oxide (still too expensive)
			Nickel Oxide & Nickel Flake
1909		Type A Cell	

Richard H. Schallenberg, *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage,* Philadelphia: American Philosophical Society, 1982, pp. 355–366.

best possible results. Edison reviewed the results of different chemists and chose the material for that particular component. Edison and his team then moved to the next component or problem and attacked it in the same way. In taking this approach, Edison was able to investigate thoroughly a number of electrochemical combinations and determine which one best suited his purposes. Furthermore, he was able to build on the results of one series of experiments, and thus converge on an ideal design for his battery.

Although this convergent approach produced highly reliable results, it came at the cost of requiring over 50,000 individual experiments. [13] Furthermore, Edison had thoroughly routinized the innovation process. By breaking down the research into a sequence of small, standardized experiments, Edison had altered the creative process from hands-on ingenuity and skilled observation to persistence and careful record-keeping. Gone were the last vestiges of the "heroic" myth of invention in which insight came in a blinding flash; results now came by plodding through innumerable experiments.

By so deploying his scientific troops, Edison conducted a long series of electrochemical experiments and eventually chose to employ a combination of iron and nickel oxide in his cell. Pleased with the preliminary results obtained from this combination, Edison filed patents in March 1901. To generate capital for further research and development, Edison organized the Edison Storage Battery Company in May and sold these patents to this new company for $1 million. [14]

With an electrochemical combination in hand, Edison decided that the next tasks were to improve the electrochemical qualities of nickel and iron and to determine the best form for the internal parts of the battery. By now, however, Edison and his team of chemists had been at work on the battery for over three years and had conducted thousands of experiments. To prevent boredom from setting in, Edison devised new ways to motivate his researchers. As Jonas W. Aylsworth, the chief chemist, recalled:

> To stimulate us to greater improvement, Edison hung up a card which showed the results of tests in milliamperehours given by the experimental elements as we tried them. . . . This stirred up a great deal of ambition among the boys to push the figures up. Some of our earliest tests showed around 300, but as we improved the material they gradually crept up to over 500. [15]

Clearly, Edison was not only capable of identifying the next task in the research campaign but he was also successful at introducing informal management techniques that motivated his team to complete these tasks quickly and successfully.

From improving the electrochemical properties of nickel and iron, Edison and his men moved next to designing the grids for the electrodes. Since the nickel oxide and the iron were to be finely powdered (in order to increase the area of surface contact between the electrodes and the electrolyte), it was necessary to design a special frame or grid to hold these materials. Like other steps in the storage battery project, the design of the grid pockets demanded numerous experiments and it took until 1904 to perfect this component.

After much experimentation, Edison settled on grids made of nickel-plated sheet steel formed into thin, flat pockets. In the pockets of the negative electrode went the iron powder while the pockets of the positive electrode were filled with nickel oxide. To improve conductivity in both electrodes, Edison mixed in graphite flakes. Edison dubbed this design the Type E cell. [16]

As the battery took shape, Edison turned to testing it. Determined to penetrate the electric vehicle market, Edison knew that his battery had to be rugged and reliable. To insure this meant extensive testing. To test durability, he had his assistants drop cells out the second and third floor windows of the lab. [17] For performance, Edison ordered his men to load cells into several different electric cars and trucks and then drive them over rough country roads in New Jersey for 5000 miles. So rigorous were these tests that if the car did not break down after several days of continuous running, Edison accused the driver of picking easy roads. [18]

MANUFACTURING AND MARKETING THE TYPE E BATTERY, 1903–1904

Even as research and testing continued, Edison began making plans for the manufacture of his alkaline battery. From the outset, Edison was anxious to reduce the price of his product, but to do so, he knew he would have to cut the cost of his raw materials. Consequently, from 1901 to 1903, he undertook an extensive search for sources of nickel, the most expensive material in his cell. Edison contemplated organizing his own company for mining and processing nickel ore, but he eventually decided that it was too risky to develop his own mines since he found it impossible to find reliable information about nickel deposits. Subsequently, Edison found it easier and cheaper to purchase this metal from producers. [19]

In May 1901, Edison established a battery assembly plant in an old brass rolling mill in Glen Ridge, New Jersey. Just as he had done previously with his ore separation and Portland cement plants, Edison took great interest in planning the production processes and he sketched the plant layout in his notebook. In setting up this factory, Edison drew upon his established enterprises: from the laboratory came machine tools and patterns, from the Phonograph Works came hardware and steel, and the Edison Manufacturing Company supplied miscellaneous materials. Full scale production at Glen Ridge began in January 1903 and soon the plant was making 200 cells per week. These first cells cost less than $10 to make and were sold for $15.00. [20]

In preparation for marketing his new battery, Edison carefully studied his chief American competitor, the Electric Storage Battery Company. Through business contacts, Edison secured information about the design of this company's lead-acid cells and about their stock prices, number of workers, and sales volume. Edison also had his staff study their batteries. Drawing on this data, Edison was able to determine what points to raise in his marketing campaign. [21]

Throughout 1904, Edison mounted a media blitz promoting his new alkaline battery and attacking the lead-acid battery. He encouraged newsmen to describe his new product as clean, and free of the foul odors and dangerous acids of the lead battery. According to one report, Edison's new battery:

> looked like a handsome little document-case, of shiny steel, neatly capped over with polished porcelain. There was no grime, no smudge, no suggestion of chemicals and currents; a battery of these cells would adorn a lady's boudoir.

In addition, Edison emphasized that his battery was practically maintenance free. "The only attention it needs is to be kept full of water. . . . Any coachman can care for it." [22] In making such claims, Edison wanted people to see his cell as modern and convenient. Thanks to this publicity campaign, the Edison Storage Battery Company enjoyed modest sales in 1903 and 1904, selling 14,000 cells for use in electric cars and trucks. [23]

GROWING PAINS, 1903–1908

Unfortunately, problems soon appeared. The battery leaked because the caustic electrolyte ate through the solder along the seams of the battery's outer steel can. More seriously, the electrical capacity of the cells dropped substantially after a number of charges and discharges. [24]

As customers reported these difficulties, Edison realized that he had not fully tested his new battery. It was simply not enough to drive a few cars around at high speeds or drop cells out of windows. From the outset of the project, Edison had been anxious to rush his battery into production, partly to offset his high R&D costs but also to counter the rival lead-acid battery manufacturers' head start in the electric vehicle market. Now it was clear that he had been too hasty in introducing this new and complex product. In November 1904, Edison shut down production at Glen Ridge and ordered all defective cells be bought back from the customers. Production was eventually resumed, but only to manufacture replacement cells for established customers. Even though new customers were willing to buy the Type E cells, Edison refused to sell them an imperfect battery. [25]

At the lab, Edison immediately redeployed his staff and resources. At once, he had two rooms fitted up for battery experiments and he set up a special research team. "I have 12 young men & 6 workmen running curves on small cells," he wrote, "& everyday we expect to strike the bug." [26] Working night and day, Edison and this team conquered the leaky can problem in a few weeks. Instead of soldering the seams of the cans, Edison had his staffers design a machine for welding the cans. [27]

In producing this welding machine, Edison managed his staff by using competition and rivalry. Originally, Edison assigned the task to John Ott, head of the second floor machine shop. Ott was uncertain as to how to design the welder, however, and he hesitated. Even though Ott was a long-time associate, Edison took the assignment away from him and gave it to the foreman of the first floor machine shop. Anxious to please the "old man," the foreman turned out an excellent welder, "a finer machine than John [Ott] ever built." Sensing that Ott and the foreman were in competition with each other, Edison used this to his advantage to secure a good machine. As he remarked about the lab, "There is great rivalry which seems to be a good thing all around." [28]

The battery's declining electrical capacity proved much harder to diagnose and solve. Edison and his men tested hundreds of cells and broke up dozens more, trying to understand what was going wrong inside. Unlike previous challenges that Edison overcame by careful observation and experiment, the capacity problem remained an abstract one. As Edison observed, "In phonographic work we can use our ears and our eyes aided by powerful microscopes; but in the battery our difficulties cannot be seen or heard, but must be observed by our mind's eye." [29]

From 1904 to 1908, the capacity problem absorbed much of the lab's resources and personnel. To help with this problem, Edison advertised for chemists familiar with electrolytic analysis in the electrical journals and local newspapers. By July 1907, the Storage Battery Company employed 51 workers at the lab and 34 people in a separate Testing Department. Since the Storage Battery Company had no income, by 1910 Edison had personally spent \$1.9 million on these experiments. [30]

During this period, Edison was typically to be found working in the chemical laboratory, standing at a long lab bench covered with test tubes holding various electrochemical solutions; patiently and methodically, he tried hundreds of different combinations of electrodes and electrolytes, day in and day out. [31] To maintain his own morale, Edison kept in mind the great commercial potential of the battery and his desire for a high-quality product; as he wrote to Sigmund Bergmann, who was manufacturing the battery in Europe:

> the moment we find the trouble we will let you know. It will be plain sailing then & once we get it ok...the business will be unlimited and very profitable BUT WE MUST HAVE IT RIGHT. [32]

As for Edison's assistants, they maintained their own morale by organizing "The Muckers of the Edison Laboratory." A social club, this group sought to "add a bit of the spice of life to the muck we make" by taking frequent trips into New York City to enjoy vaudeville theater, eating, and drinking. At their dinners, the Muckers frequently made jokes and puns about the chemicals used in the storage battery experiments and they always sent a note signed by all the members to the "old man" wishing him good health. [33]

Edison never let his men lose faith in their ability to overcome the capacity problem. When one chemist suggested that the situation was hopeless, Edison was quick to reply:

> I've been in the inventor business for thirty-three years, and my experience is that for every problem the Lord has made He has also made a solution. If you and I can't find the solution, then let's honestly admit that you and I are damn fools, but why blame it on the Lord and say He created something "impossible?" [34]

Eventually, Edison and his "muckers" traced the capacity problem to the nickel oxide electrodes. During charging the electrodes swelled and during discharging they shrank. This continual mechanical movement reduced electrical contact between the nickel oxide granules and the grid pockets, thus increasing the internal resistance of the cell and lowering its output. In response, Edison made two modifications to the nickel oxide electrode. He replaced the flat pockets with round ones and he increased electrical conductivity with the new pockets by sandwiching thin layers of nickel flake with nickel oxide. To minimize expansion or shrinkage during charging or discharging, Edison designed machinery that tamped down these layers with a mechanical force of 200 psi. [35]

MANUFACTURING AND MARKETING THE TYPE A CELLS, 1908–1915

Edison christened his new battery with the nickel flake and round pockets the Type A cell. Through 1908 and 1909, Edison had this new cell thoroughly tested and found that he had raised the capacity of his battery from 10.2 to 14 watt-hours per pound of battery, and that the new battery's charge could outlast that of the best lead-acid batteries. [36] Delighted with these results, Edison resumed full-scale manufacture and marketing.

As the laboratory research wound down, Edison again redeployed his staff and resources to manufacturing and marketing the new battery. Still anticipating a huge demand, Edison supplemented the Glen Ridge factory with a new battery plant. Located across the street from the laboratory, this new factory contained nine acres of floor space. Although production began in 1909 with only 100 cells a day, Edison hoped that production might reach a million cells per day. [37]

With the new plant in place, the Storage Battery Company sold over \$1 million worth of batteries in 1910. However,

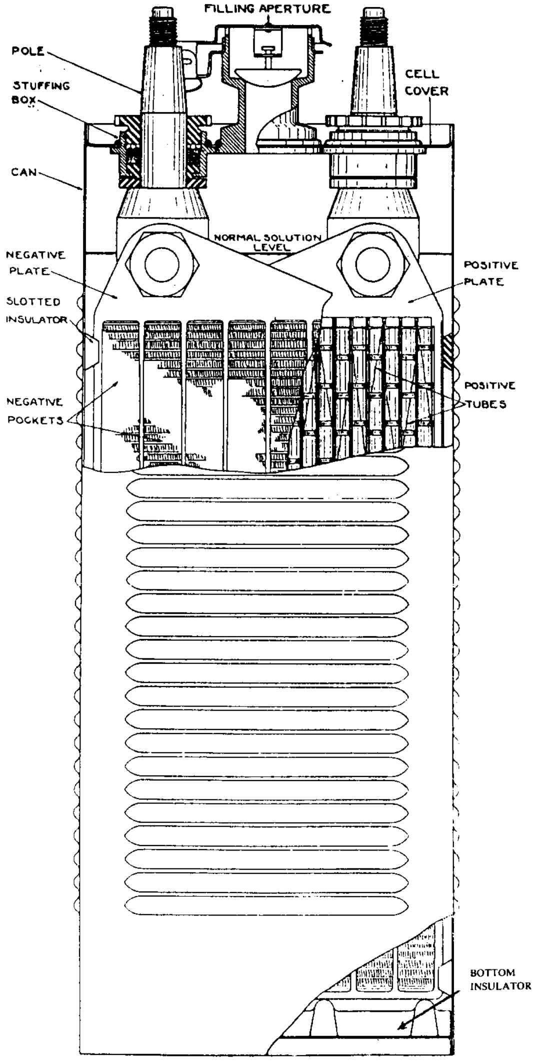

Fig. 1. Plan of Edison Type A Cell, circa 1908–1915. Note that a typical cell would have several sets of negative and positive plates arranged alternately. A version of this cell is still manufactured today. From Negative 775, Edison National Historic Site, West Orange, New Jersey. My thanks to Eric Olsen for locating this plan.

because of the enormous debts incurred in developing the battery and building the new factory, the Storage Battery Company continued for the next few years to be a drain on the resources of the Edison business organization. To help offset these heavy debts, Edison strove to reduce his production costs and market his new battery aggressively. [38]

Unlike other inventors who left the problems of production to engineers and managers, Edison took an active interest in the production of his inventions. In fact, he assumed that an invention was not finished until it was being manufactured at a reasonable cost. As a manufacturer, Edison was guided by two straightforward considerations. First, he insisted on developing a high-quality product. Throughout the storage battery campaign, Edison was determined to surpass the lead-acid cell with a superior product. Notably, this insistence on quality became one of the hallmarks of many of Edison's inventions in the twentieth century such as the disk phonograph and well-designed consumer appliances. [39]

Second, Edison always sought to reduce his costs of production. No invention was successful unless it was profitable, but to do so Edison refused to cut corners on product quality. Instead, he made his products competitive by trimming manufacturing costs. In the case of the storage battery, he began with a high-quality and expensive design that he strove to make competitive by looking for cheap sources of raw materials, by developing new processing techniques, and by designing special purpose machinery for assembly. Furthermore, Edison controlled his costs by vertically integrating his operation; rather than depend on outside firms for any aspect of the battery enterprise, Edison set up facilities for every step, from processing nickel and iron powder at his Silver Lake chemical works to marketing and servicing cells. In pursuing a policy of vertical integration, Edison's business strategy paralleled the practice of other business firms in the late nineteenth and early twentieth centuries. [40]

Not only did Edison integrate backwards by undertaking all aspects of battery production, but he looked forward toward the markets and applications of his battery. With characteristic exuberance, he predicted that "inside of 15 years the entire vehicle traction in large cities in the United States will be done electrically & I am now manufacturing the battery that will permit this to be brought about commercially." [41] To secure sales contacts and marketing data, Edison sent men to state licensing bureaus to collect the names of electric vehicle owners. Unfortunately, these investigators found that by 1910 electric vehicles had begun to lose out to gasoline-powered cars. In New Jersey for example, while 800 electrics had been licensed between 1899 and 1906, 98 percent had been abandoned by 1910. [42] "The record is bad," admitted Edison, but it was

> not the fault of the vehicle but the lead battery.... A great deal of work will have to be done by all of us to remove the bad impression. A satisfied & delighted customer is the only method that will build up a permanent business. [43]

Try as he might, Edison was never able to remove the negative impressions associated with the electric car. The American public favored the gasoline car with its cheaper fuel, higher speeds, and wider cruising range. As a result, Edison was forced to look for new markets for his battery.

The bustling city seemed especially promising. The first new market Edison identified was the electric delivery trucks used by department stores. Edison felt electric trucks were ideal for intra-urban service since they could make their rounds by day and return to the garage at night for charging. Unlike gasoline trucks that had to be cranked to start, the electrics could be easily started and stopped for quick deliveries. Through the 1910s several New York stores (including Tiffany's and Altman's) used electric trucks with Edison batteries. With the introduction of the electric starter for the gasoline engine in 1912, however, electric trucks lost much of their advantage. [44]

Edison also pushed for a battery-powered streetcar. Such cars were desirable for rush hours on mass transit systems since they did not use additional power from the main generating station and hence did not require expansion of the transit system's power plant in order to meet an increased peak load. (Indeed, they could be charged late at night when the load on the system was the smallest). To develop this application, Edison built a short railway line near the laboratory during the winter of 1909–1910. To manufacture a special car, Edison gave a former General Electric engineer, Ralph H. Beach, the exclusive right to build streetcars using his battery. Beach established a factory adjacent to the Silver Lake chemical works. Unfortunately, after three years, the project died because Beach was unable to build a sales organization to promote the car and he failed to pay his debts to his suppliers. [45]

Despite Edison's best efforts to promote the electric car, truck, and streetcar, their use was limited by the technical characteristics of the alkaline cell. While the alkaline battery's active materials (nickel, iron, and nickel oxide) were lighter than lead, the weight saved was offset by the complex scheme of pockets and electrodes inside and the alkaline cell consequently outweighed its lead-acid rival. [46]

Beyond this unfavorable weight comparison, Edison was unable to bring the alkaline battery's cost below the lead battery's. By his own estimate, his alkaline cells cost twice as much as the competing lead batteries. Here the problem was not so much the cost of the materials but the expense of assembling a battery with several dozen small tubes filled with thousands of layers. Edison maintained that his battery was cheaper to operate and service, giving it a lower cost per kilowatt-year. Nevertheless, Edison knew that the price of his battery was a serious problem and he continually sought to reduce production costs. [47]

Finally, Edison's battery did not work well under all conditions. At low temperatures, the electrolyte became weak and slushy and electrical capacity fell. Furthermore, unlike the lead battery that can be designed to give a short, high current discharge, the alkaline cell was best suited for long, low current discharges. For this reason, the alkaline cell did not lend itself to many applications, including the electric starter for gasoline cars. However, the alkaline cell could hold its charge for long periods of time and it was much more rugged than the lead-acid battery. [48] Hence, while not suited for certain jobs, there were other applications for which the alkaline battery was highly appropriate, and Edison threw himself into the task of identifying these new uses.

In some ways, the storage battery campaign had gone the same way as the ore separation venture; Edison had begun by assuming that a large market existed for his product, only to discover that the market shifted during the long years of development. But unlike ore separation, Edison persevered, and from 1910 to 1915 he cultivated new markets for his battery. With the assistance of Miller Reese Hutchison, Edison pursued military applications. Having served as an electrical engineer in the United States Lighthouse Service, Hutchison had numerous contacts in the Navy and among officials in Washington. [49] Through his contacts and skillful preparation of advertisements, Hutchison arranged for the Edison battery to be used to power submarines, torpedoes, wireless sets, and electric motors on battleships. Although these military uses brought profits into the company, the most promising application, submarines, proved disastrous. In January 1916, Edison cells were installed in the U.S. Submarine E-2 that exploded while in drydock in the Brooklyn Navy Yard. Although the explosion was probably due to the crew failing to open a hatch and vent the battery gases, the Navy subsequently demanded stringent testing of batteries that prevented further use of Edison batteries in submarines. [50]

This disaster, however, did not set Edison back; while Hutchison had pursued the military market, Edison had promoted his battery for other uses. Optimistically, he made one list in 1911 of 64 different applications, including many of the tasks to which the alkaline battery was successfully applied: lighting railway cars; providing back-up power for generating stations, lighthouses, miner's lamps, and railroad signals; and lighting isolated houses and yachts. In addition, the list reveals several new applications for electricity, and Edison had his men experiment with a battery-powered bicycle, plow, and lawn mower. Sensitive to America's growing appetite for energy, Edison even dreamed of using the storage battery to accumulate power from the sun, tides, wind, and rivers. [51]

Thanks to these diverse uses, the Edison battery eventually proved to be a commercial success. Until 1960, the McGraw-Edison Company manufactured the battery using the production techniques designed by Edison and his team in the 1910s. Since then, ownership of the Edison battery and related alkaline battery technology has changed corporate hands several times, but the basic ideas of Edison's storage battery continue to influence the design and manufacture of contemporary industrial alkaline batteries. [52]

CONCLUSION

Edison's campaign for the storage battery reveals much about how he transformed the invention process at the West Orange laboratory during the first decade of the twentieth century. Whereas he had used mechanics and craftsmen to pursue earlier inventions such as the phonograph and kinetoscope, Edison developed the storage battery by drawing on a team of trained chemists and engineers. With the mechanics, Edison had taken a divergent approach, encouraging them to investigate all aspects of an invention; only at the appropriae moment did Edison, the master mechanic, pull together the various discoveries and improvements into a successful invention. In contrast, with the battery Edison carefully assigned each "mucker" his task and exhaustively studied each component of the cell. In taking this step-by-step approach and building upon the results, Edison converged upon the design of his battery.

In shifting from a "divergent" to a "convergent" style of research management, Edison altered his role within the laboratory. Whereas previously he had been just "one of the boys," or the "head mucker," in the storage battery campaign he became a project manager. To be sure, Edison performed a large number of battery experiments on his own, but his major task was to oversee the project. Like the principal investigator of the contemporary research project, Edison monitored each experimenter's line of research, identified trends, and shifted researchers to the most promising leads. He also regularly compared the laboratory results with commercial considerations, watching for the right combination that could be put into production quickly. Most importantly, as a project manager Edison motivated his research team. In the midst of long runs of routine experiments, he spurred his chemists on by challenging them to beat the posted number. Similarly, he always encouraged his staff to believe they could master the battery. Because his techniques in motivating and directing his team were decidedly informal, they have often been overlooked; yet Edison's use of a personal, folksy style may well have been deliberate. [53]

Although his informal management techniques made it seem like the old days of Menlo Park, as Edison took up the convergent approach and assumed the role of project manager, the character of the innovation process was irrevocably altered. Invention was no longer a mysterious, seat-of-the-pants affair; it became an orderly, predictable process that got results from a long series of experiments. In many ways, the convergent approach was appropriate for the large scale of West Orange. With this approach, Edison made efficient use of his large staff and substantial facilities. He also believed that this approach would sooner or later produce a marketable battery. The orderliness and routinization indicate that Edison had made the innovation process a reliable component of business strategy. Like the manager of a German chemical works that had routinized dye research, Edison could look with pride at his West Orange lab and say "Nowhere [is there] any trace of a flash of genius." [54]

Another important aspect of the storage battery project is that it shows how Edison actively moved his inventions from the laboratory to full-scale manufacture and distribution. Edison's rule was to think about production early and often. No sooner than he secured positive results than he filed patents, organized a company, and began planning the factory. By keeping production always in mind, Edison prevented his staffers from pursuing false leads and thus sped up the research process. Furthermore, in establishing his factory, Edison sought to cut costs and integrate his operations vertically; clearly Edison was a savvy and up-to-date manager. While Edison had initially hoped that his battery would be used in electric automobiles, he quickly identified new applications for his battery when the electric vehicle market disappeared. In all of these ways, we see that Edison was not only an effective manager in directing innovation within the lab but also in seeing his inventions through to commercial success.

Finally, the story of the alkaline storage battery shows that Edison possessed a style of R&D management that is still relevant today. Significantly, the practices of contemporary Japanese high-tech firms resemble Edison's approach. Like Edison, the Japanese have been successful in consumer electronics and other fields by using highly organized and motivated teams, linking R&D with manufacturing, and insisting on quality. Indeed, one might argue that if more American firms in the 1960s had organized their research efforts like Edison and avoided creating "ivory tower" labs isolated from production, they might have done better in competing with the Japanese. [55] Thus, although it is tempting to romanticize Edison as the "Wizard of Menlo Park," we would do far better to study his career for insight into how R&D can be effectively and creatively managed.

REFERENCES

Unless otherwise noted, all documents are from the archives at the Edison National Historic Site, West Orange, New Jersey.

Abbreviations used:

LB year/month/day: letterbook with date of first entry
Ed. SB Co.: Edison Storage Battery Company
N year/month/day: laboratory notebook with date of first entry
SB: storage battery
TAE: Thomas A. Edison
WO: West Orange

[1] Wyn Wachhorst, *Thomas A. Edison: An American Myth,* Cambridge: MIT Press, 1981, pp. 19–32 and pp. 37–40.

[2] In describing Edison's management style, I am following the tradition begun by Thomas Hughes of interpreting inventors as rational actors who shaped and controlled their creations and their environment. Inventors may be lucky in their discoveries, but more importantly they know what to do when luck strikes. They know how to impose order and structure on a new idea. See Thomas P. Hughes, *Elmer Sperry: Inventor and Engineer,* Baltimore: Johns Hopkins University Press, 1971 and "Edison's Method" in W.B. Pickett, ed., *Technology at the Turning Point,* San Francisco: San Francisco Press, 1977.

[3] On Edison's work on primary cells, see Frank J. Prial, *Seventy-Five Years of Packaged Power: Primary Battery Division—Thomas A. Edison Industries,* Bloomfield, N.J.: McGraw-Edison, 1964, 13; N870301, N880610, N880103, N921109; see also the following shop orders: 28 "Storage Battery," (Jan. 1888); 288 "Testing storage cell for E.L. Co.," (ca. May 1889); 300 "New battery for phonograph to run 200, 400, & 600 hours," (June 1889); and 496 "Test of 2 English Storage Cells" (Dec. 1890) in N871124.

[4] W. Bernard Carlson, "Edison in the Mountains: The Magnetic Ore Separation Venture, 1879–1900," *History of Technology* 8:37–59, 1983.

[5] TAE, "The Storage Battery and the Motor Car," *North American Review* 17:1–4, July 1902 on p. 2.

[6] Hughes, *Sperry,* pp. 80–89; Pope Mfg. Co. to TAE, Feb. 21, 1899; *New York Tribune,* June 25, 1899; Shop order 957, "Charging house for elec. carriage, Mrs. Edison," ca. Nov. 1899, N871124.

[7] The first quote is from TAE, Caveat for Storage Battery, Apr. 11, 1900 and the second from Frank L. Dyer and T. Commerford Martin, *Edison: His Life and Inventions,* 2 vols., New York: Harper & Brothers, 1910, 2:554.

[8] Richard H. Schallenberg, *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage,* Philadelphia: American Philosophical Society, 1982, p. 353.

[9] Shop order 935 "Storage Battery (Personal TAE)," June 1899 in N871124; "Minutes of the Mucker Society of Thomas A. Edison Laboratory at Orange, N.J.," Cat. 1269, pp. 215–217; N020617.

[10] For more information on the chemical research conducted by Edison and his staff, consult Schallenberg, *Bottled Energy,* pp. 355–364.

[11] Robert Friedel and Paul Israel, *Edison's Electric Light: Biography of an Invention,* New Brunswick: Rutgers University Press, 1986, pp. 63–88 and pp. 119–145.

[12] Mark E. Ham, "Edison and the Phonograph, 1877–1889," unpublished report prepared for W. B. Carlson and A. J. Millard, West Orange

Lab History Project, 1986, p. 10.
[13] Dyer and Martin, *Edison*, 2:561.
[14] See the following U.S. Patents granted to TAE for "Reversible Galvanic Batteries:" 678,722 (filed Mar. 1, 1901, granted July 16, 1901); 701,804 (filed Mar. 1, 1901, granted June 3, 1902); 704,304 (filed Mar. 1, 1901, granted July 8, 1902); 700,137 (filed Mar. 5, 1901, granted May 13,1902); 700,136 (filed Mar. 5, 1901, granted May 13, 1902); TAE to Bergmann, July 26, 1905. On the formation of Edison SB Company, see H. F. Miller to A. J. Clymer, n.d., 1910 SB, Experiments and Tests, 2 of 2 file.
[15] "Edison's Alkaline Storage Battery," Meadowcroft Box 73.
[16] Arthur E. Kennelly, "The New Edison Storage Battery," *Trans. AIEE* 18: pp. 219-230, 1901.
[17] TAE's notes in 1903 SB, TAE's Notes file.
[18] Edison Storage Battery Co. to J. T. Mann, June 10, 1902, 1903 SB, Ed. SB Co. file; *NY Sun*, June 8, 1902; Dyer and Martin, *Edison*, 2: 565.
[19] TAE notes in 1901 Nickel Search file; F.R. Hanna to TAE, n.d., 1903 Nickel Search, Mines & Minerals file.
[20] N010420; Charles Batchelor Diary, Cat. 1345, pp. 254-255; W. Mallory to Caskey, Apr. 23, 1902, 1902 SB, Ed. SB Co. file; and TAE to Dick, n.d., 1903 TAE Handwriting file.
[21] Pilling and Crane to TAE, Feb. 15, 1901.
[22] Both quotes are from "Edison's Most Important Discovery," *Harper's Weekly*, Dec. 21, 1901.
[23] TAE to Bergmann, Nov. 9, 1904.
[24] Edison may have recognized the problem of the leaky cans early for in an undated note to the manager of the Glen Ridge plant, Edison wrote "eight out of 21 Baker batteries leak at Top where soldered. You probably use too much sodium amalgam — should use only enough to clean Iron—Better look into this soldering question & improve it for it certainly is very bad." See TAE to Hays, n.d., 1902 TAE Personal Handwriting file.
[25] Memo, Edison Storage Battery Co., 1911 SB, ESB Co., General, 2 of 2 file; J. W. Allison to J. F. Randolph, March 31, 1906, 1906 SB, Ed. SB Co., Jan.-June file.
[26] TAE to Bergmann, Nov. 29, 1904; TAE to Bergmann, Dec. 9, 1904; See also TAE notebook N041102 titled "New Experiments started at Laboratory in our new test room to discover why nickel elements in some cases lose their amp capacity after being in use and also to discover a remedy that is practical and commercial."
[27] TAE to Bergmann, Feb. 21, 1905.
[28] TAE to Bergmann, Jan. 11, 1905, 1905 SB, TAE's Notes file.
[29] "Edison's Alkaline Storage Battery," Meadowcroft Box 73.
[30] Pay Rolls, July 23, 1907; clippings in 1905 Employment, Applications, Chemist file; H. F. Miller to A. J. Clymer, n.d., 1910 SB, Experiments and Tests, 2 of 2 file; F. L. Dyer to Stockholders of Ed. SB Co., April 5, 1910.
[31] TAE to L. C. Weir, July 7, 1905; "Storage Battery Work," Meadowcroft Box 66.
[32] TAE to Bergmann, Feb. 27, 1905.
[33] "Minutes of the Mucker Society of Thomas A. Edison Laboratory at Orange, N.J.," 1902-1909; "Constitution of the Muckers of Edison Laboratory," n.d., Cat. 1269; Menu in 1906 WO Lab, Employees.
[34] M. A. Rosanoff, "Edison in His Laboratory," *Harper's Monthly*, 165:402-417, Sept. 1932 on p. 416.
[35] [F. L. Dyer?] to Meffert and Sell, Nov. 28, 1905; Schallenberg, *Bottled Energy*, p. 363; "The Edison Alkaline Storage Battery," Orange, N.J.: Edison Storage Battery Co., 1924 in Warshaw Collection of Business Americana, National Museum of American History, Washington, D.C., pp. 17-19.
[36] TAE to L.C. Weir, June 11, 1909.
[37] W. G. Bee to B. F. Arthur, Jan. 3, 1907, 1907 Auto file; letter to S. Bergmann, Feb. 18, 1907, 1907 SB, General Correspondence file; TAE to H. E. Dick, Oct. 14, 1909, 1909 SB, TAE's notes file; "The Edison Alkaline Storage Battery; Fred Colvin, "The Mechanics of the Edison Battery," *American Machinist*, Aug. 10, 1911.
[38] TAE to Bergmann, Dec. 24, 1910; H. F. Miller to A. Clymer, Oct. 26, 1910, LB100829, 325.
[39] For a discussion of Edison's policy of manufacturing high quality products, see A. J. Millard, "A History of Edison's West Orange Laboratory, 1887-1931," unpublished manuscript, Edison National Historic Site, West Orange, New Jersey, chapter 14.
[40] 1909 Edison Chemical Works, Weekly Reports file.
[41] P. Manoury to TAE, May 6, 1908, 1908 SB, TAE's notes file.
[42] TAE to General Healey, June 11, 1910, 1910 Auto, TAE's notes file.
[43] TAE to Carlisle, June 22, 1910, 1910 Auto, TAE's handwriting file.
[44] TAE to Insull, June 20, 1910, LB100521, 204-205; TAE, Draft of "Talking Points" for selling electric trucks, 1910 SB, Wagons and TAE notes file.
[45] TAE to B. J. Arnold, June 3, 1910; TAE notes, n.d., 1909 Railroad, Electric, 1 of 2 file; F. J. Lisman, Memo, July 23, 1913, Dyer Correspondence.
[46] Schallenberg, *Bottled Energy*, p. 372.
[47] TAE to Bergmann, Dec. 24, 1910.
[48] Byron M. Vanderbilt, *Thomas Edison, Chemist*, Washington: American Chemical Society, 1971, p. 220.
[49] "Miller Hutchison, Inventor, 67, Dead," *New York Times*, Feb. 18, 1944.
[50] For a detailed account of the E-2 explosion and its impact on the Edison Storage Battery Company, see M. R. Hutchison to Josephus Daniels, Feb. 19, 1936, Special Correspondence, Container 84, Reel 53, Josephus Daniels Papers, Library of Congress Manuscripts Division, Washington. I am grateful to David van Keuren of the Historian's Office of the Naval Research Laboratory for bringing this document to my attention.
[51] TAE, "Uses for Edison Battery," Oct. 11, 1911; G. A. Halford to TAE, Nov. 24, 1908, 1908 SB, TAE's notes; Hutchison Diary, Nov. 7, 1911 and Jan. 22, 1912.
[52] Vanderbilt, *Thomas Edison, Chemist*, pp. 225-226 and Schallenberg, *Bottled Energy*, p. 374.
[53] For further discussion of Edison's informal management techniques, see W. Bernard Carlson and A. J. Millard, "Edison as a Manager of Innovation: Lessons for Today," *New Jersey Bell Journal* 8:24-32, Winter 1985-1986.
[54] The quote from the German manager is from Henk van den Belt and Arie Rip, "The Nelson-Winter-Dosi Model and Synthetic Dye Chemistry" in W. E. Bijker et al., *The Social Construction of Technological Systems*, Cambridge: MIT Press, 1987, pp. 135-158, on p. 155.
[55] John A. Young, "Technology and Competitiveness: A Key to the Economic Future of the United States," *Science* 241:313-316, July 15, 1988 on pp. 315-316; Makato Kikuchi, *Japanese Electronics: A Worm's Eye View of Its Evolution*, Tokyo: Simul International, 1983; and Michijuki Uenohara, "Utilization of Engineering Personnel" and Roland W. Schmitt, "Successful Corporate R&D" in D. Christiansen, ed., *Engineering Excellence*, New York: IEEE Press, 1987, pp. 69-75 and 133-140. I am grateful to George Wise for suggesting that I compare Edison's management style with that of the Japanese.