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SCIENTIFIC PRACTICE FOR TECHNOLOGY: HERMANN ARON'S DEVELOPMENT OF THE STORAGE BATTERY

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In 1880 Hermann Aron, a lecturer in physics at Berlin University, invented a high capacity lead storage battery, i.e. an electrochemical cell that could store and release considerably higher amounts of electric energy than earlier accumulators. At the time, the storage rechargeable battery promised to play an important role within the rapidly developing system of electric power, which attracted more attention than any other contemporary technology. Consequently, research on the storage battery flourished. Indeed, Aron was not the only inventor of a high-capacity lead battery; at least three other individuals developed similar ideas independently.

Simultaneous inventions, like this one, are familiar in the history of technology. The telephone, the electric incandescent light, and the roll film camera are just a few contemporary examples that come to mind.[1] Cases of simultaneous inventions are perhaps even more common than those of simultaneous discoveries. Of course, only rarely do two individuals separately invent or discover exactly the same thing. Yet often the ideas and the artefacts are close enough to be regarded equivalent by contemporaries and/or by later commentators. Historians of science found such cases of independent (or partly independent) discoveries particularly illuminating. In his classical analysis of the simultaneous discovery of energy conservation, Thomas S. Kuhn employed the phenomenon to reveal the dependence of apparently independent geniuses and their ideas on their scientific, intellectual and social contexts. Following Kuhn, historians have exploited cases of simultaneous discovery to illuminate and compare the works and concepts of "simultaneous discoverers" and to study the origins of their ideas and practices, and the central factors that led to and shaped the discovery and its establishment in the scientific community.[2] Although historians of technology recognized many cases of simultaneous discoveries, they have paid less attention to the concept and its implications for historical understanding.[3]

In a rare discussion of the concept Charles Susskind observed that "[s]imultaneous invention occurs when technology has reached a certain level at which the prerequisites have been achieved and the next step occurs to several minds at once".[4] Like historians of science, Susskind saw in the analysis of co-inventions a means to identify the tools, intellectual and material alike, necessary for the innovation. While the recognition of these resources is highly important for technological innovations, such an emphasis misses the equally important question of motives:[5] What led different researchers to search for a particular technology, in the case at hand, the improved storage battery? What were the problems that they attempted to solve, why did they try solving them at that time, and what were the techno-social conditions that made

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the question important for the protagonists? A comparison among different inventors can illuminate the "motives" question, no less than the question of available resources. The simultaneous interest in the storage battery circa 1880 suggests that the emergence of electric lighting stimulated the development of the battery. While the question of motives is important for the history of science, it is crucial for the history of technology, since one develops technology only in expectation for its possible use. In other words, while simultaneous discoveries originate from common sources, knowledge, beliefs and open questions, the immediate stimulations for simultaneous inventions often originate from a common aim. Technological developments can point at such an aim, like that of preventing an anticipated waste of resources, and thus money, in the uneven demand (technically "load") for electric power for the storage battery. Current knowledge of technology and science can make such an aim feasible. Still, societal conditions determine if it is an aim at all.

In his history of the storage battery, Richard Schallenberg identified the design of its high-capacity kind as a case of simultaneous innovation. Unaware of Aron's work, however, he recognized three co-inventors of the high-capacity battery: the French engineer Camille Faure, the American Charles Brush "one of the giants of early electric power and lighting technology" and his compatriot Nathaniel Keith, who worked as an electro-metallurgic engineer. The former two received scientific education in engineering schools, while the latter acquired it informally. Yet, the three men gathered most of their relevant knowledge and virtually all of their experience working with electrochemical technology. Schallenberg, thus, concluded that "it was [this] background ... so similar in many crucial ways, that led them both to conceive of the new role for the storage battery and to redesign it accordingly".[6] Aron's development of a similar battery, however, indicates that a background in electrochemical technology was not essential for developing a high-capacity battery. Unlike the other three inventors, Aron acquired experience in the research and teaching of science rather than in technology. His expertise ranged from theoretical physics and mathematical technics to experiments. It included a laboratory experience in physical chemistry, but not with related technologies.

Schallenberg's emphasis on the inventors' practical experience with related technologies is common in histories of electric innovations of the 1870s and 80s.[7] Such experience, however, had not excluded the need for scientific knowledge and even scientific investigations. Historians, like Paul Israel, have shown that science played a more significant role in the practice of inventors than many of them, prominently Thomas Edison, had suggested.[8] Novel problems that followed the use of alternating current system, Sungook Hong has shown, required a new kind of research based on scientific knowledge and methods, deployed in some cases by a novel kind of scientist-engineer.[9] That physics became useful for electric technology is suggested also by the way the discipline of electrical engineering emerged either from departments of physics (e.g. Britain, US), or by recruiting physicists to teach in academic schools of engineering (e.g. Germany).[10] During the same period other branches of physics, like optics, also began affecting products and production methods.[11] The later development of radio, at the turn of the century, has provided historians with a few examples to study interactions between scientists and technologists and between scientific-based methods and those of the art of telegraphy.[12] Yet, the role of scientific knowledge and practice in leading to innovations in "electric power technology" has received less attention.

Notwithstanding important studies on the influence of physics, much recent historiography, including that on engineering education and training, stresses the gap between science and practical design and the debt of physics to electric technology. According to a common view "engineering science" — systematic and explicit theoretical knowledge related to technology, gained higher autonomy during the second half of the nineteenth century.[13] This historiography puts less effort into examining the effect of science on practical innovations. In this vain, historians tracked the effect of novel practical electrical systems on the growth of physics, and have claimed also to find its influences on the content of science.[14] This emphasis on the independent standing of electrical technology from physics can be seen as part of a larger current tendency by historians of technology to downplay the contribution of science and scientific knowledge in the development of practical instruments and methods.[15] Electrochemistry, the science that describes the process in batteries, indeed, well exemplifies the claim that articulated theory is an inadequate guide to viable technology, a claim often made in pointing at the limited contribution of science. That theory of electrochemical interactions was insufficient for reaching a useful device does not mean, however, that science could not have provided major resources for developing related technologies. The recent historiographical emphasis on scientific practice reminds us (if one needed such a reminder) that science is much more than a formal structure;[16] it includes a variety of expertises and kinds of knowledge that formal theory does not cover. These expertises, including experimental "know how" and rules, allowed Aron to develop a rechargeable battery. Thus, scientific practice provided means for technological design even when theory and articulated knowledge fell short from showing the way to a practical method.

This paper examines the above mentioned issues through a discussion of Aron's research on the storage battery. It begins with the factors that led to a novel interest in the device. Moving closer to Aron, the paper discusses the attraction of the storage batteries to scientists in general and to Aron in particular. While elsewhere, I discuss his unique path from the academy to industry,[17] here I analyse his efforts to develop an improved battery and his research about the physical-chemical processes in the cells and their efficiency. This leads to a discussion of the resources on which Aron could draw in recognizing the demand for a storage battery and the means to improve it, comparing with the resources of the other simultaneous inventors. As discussed in an epilogue, Aron's storage battery, like those of the other co-inventors, however, was not a successful enterprise, and Aron left for other technological endeavours.

A NEW ROLE FOR THE STORAGE BATTERY

Shortly after Volta's announcement of the regular, non-rechargeable battery in 1800, a few scientists experimented with rechargeable cells. The 1820s discoveries of the relationships between electricity and magnetism stimulated renewed and more comprehensive study of these reciprocal cells. From the middle of the century, a few of these hitherto laboratory devices found some use as improved storage batteries in the new technology of telegraphy. In that field they promised (although rarely delivered) relatively low internal resistance and high electric tension (voltage) in comparison to non chargeable (primary) batteries, the common source of electric current in early telegraphy. This combination offered a source of a steady and strong electric current, needed for sending short clear signals over long distances of telegraph wires. By 1880, however, high expectations for a new system of electric power and light suggested other needs and therefore novel uses of the storage battery.

Electric circuits of high current and voltage became feasible with the development, at the beginning of 1866, of the powerful dynamo, which replaced the order of magnitude weaker "magnetos" and the even feebler (primary) batteries, the major sources of electric energy until then. The dynamo opened new possibilities for electric motors for machine and traction and for electric light. In particular, the incandescent light bulb promoted high expectations and attracted the attention of quite a few individuals and groups including Joseph Swan and Thomas Edison, who by l878 and 1879 had working filament lamps. Indeed, incandescent lighting became the most important factor in the electrification of Western cities in the nineteenth century. In 1881, the first international electrical exhibition in Paris "stimulated intense commercial and technological interest and competition". Yet, already by 1878–79 experts in related fields, like telegraphy, electro-metallurgy and electromagnetism, had displayed intense interest in electric power technology. Its commercial potential was not missed. For example, electricity was the central technology presented at Berlin's general industrial exhibition of 1879. Its main attraction was Siemens & Halske's small electric train running within the fair, and electric arc lamps which lit up city streets.[18]

The introduction of the dynamo, which supplies high amounts of electric energy, suggested a novel need for a method to store this energy. Although, in retrospect the storage battery clearly did not fulfill the high expectations, in the early 1880s it "attract[ed] almost as much attention and investment as the incandescent lamp itself". Since lighting was virtually the sole demand of electricity from the early power stations, the demand, or the "load" on the system, varied dramatically during the day. This uneven load raised the construction and operating costs of electric stations. Storage of electricity, which could be practically done only by batteries, suggested a way to even the load during the day and thus to reduce expenses considerably. The dynamo could have charged batteries during off-pick hours, then the batteries could be discharged at high demand, saving thereby the construction and operation of additional dynamos, and/or replacing the generators in off-peek hours (and the need to attend them). Since dynamos, or more exactly steam engines that generated their rotary motion, were much more efficient when they approached full power, it saved money to operate them close to a full load. As batteries are sensitive to the particular polarization of electricity, this technique could be used only with a system of direct current. That was not regarded as a limitation during the early days of power plants, since all systems were of this kind. It would hinder the development of batteries a decade later with the advance of alternating current.

Circa 1880 batteries had additional potential customers that due to either economic or legal constraints could not be connected to electric wires. Prominent among them were electric trams, where batteries allowed dispensing with either the need to have overhead wires, which were objected to by many municipalities, or the hazards of ground wires. Although never an economic rival to the overhead wire streetcar, from the late 1880s until World War I battery cars ran on a few commercial lines in Europe and USA.[19]

ARON'S INTEREST IN THE STORAGE BATTERY

Among those attracted to the promises of electric accumulators was Hermann Aron, a Berliner lecturer in physics at the Combined Royal Artillery and Engineering School since 1873 and at the university since 1877. Born in 1845 to a Jewish family of modest economic means in a small provincial town, Aron went at the late age of sixteen to Berlin to study at a Gymnasium. He remained at the city for medical studies, but after one year he switched to the faculty of philosophy, taking courses in physics, mathematics and chemistry. Like other students at the time, Aron divided his studies between Berlin and Heidelberg, where he became a student of the physicist Gustav Kirchhoff. In April 1872, before receiving his doctorate, Aron was an assistant to Adolph Paalzow, the professor of physics at the *Gewerbeakademie* (academy of trade), which would merge with the *Bauakademie* (academy of architecture) to form Berlin's *Technische Hochschule* in 1879. In his publications Aron applied mathematical methods to particular problems in elasticity, electromagnetism and acoustics.[20] Their subjects followed the works, techniques and interests of Kirchhoff, who supervised Aron's 1873 doctoral dissertation and supported his 1876 habilitation. Their phenomonological approach, which suspended hypotheses about the mechanism that yields the observations, also followed Kirchhoff's. At the university Aron taught courses about his expertise — theoretical physics.

Yet, towards 1880 Aron made a shift towards research that aimed either directly at designing useful devices, or at providing guidance for their design. For example, in his first publication in the field, he examined the danger of using telegraphic cables near powder magazines, providing general guidelines for their constructions. His second publication was on the storage battery, where he proposed a device of his own design.[21] This kind of research that aimed at particular useful ends is often defined as "engineering science". Since its practice is not confined to engineers, the term technological research may be more useful.[22] It differed from Aron's earlier research, which followed questions that originated in current knowledge rather than in a particular aim. In this sense his earlier studies were open ended "scientific" researches. His new kind of research resembles that of scientist-engineers like Ayrton, Perry and Fleming in Britain, who employed their scientific education for practical ends.[23]

Many scientists shared Aron's interest in electric technology and in particular in the storage battery. Electromagnetism was a central field of physics in the nineteenth century; aspects of it also interested chemists. Discoveries in the physics laboratory enabled the technological utilization of current electricity from Volta's battery to the dynamo. Additionally, scientists understood the working principles of practical devices from the laws of physics. They therefore regarded their training as helpful in understanding and judging the new technologies, in consulting companies that developed them, and (less common) in developing the technology themselves. Scientists also studied practical instruments to examine the validity of theories about nature. In addition, they showed sheer curiosity about the mechanisms of these technologies, which they were in a better position to understand than laymen. Storage of electric energy had a special appeal to physicists, who used to think in terms of energy conservation, and saw in electric power a means to convert energy from one kind to another (e.g. heat to mechanical) and to transfer it from one place to another. Due to these features William Thomson, for example, became enthusiastic for electric power in 1878 and for Faure's storage battery, after he examined it in 1881.[24] Energy, rather than voltage, which dominated earlier discussions of the battery, was a key concept also in Aron's thought of the battery. He put the question of storage of electricity in a larger context: "[t]he challenge to store up energy, available for any purpose as it is desirable, and handy as possible in any time and place, is among the most important challenges of technology."[25] Chemists also showed much interest in the storage battery, as chemical reactions were used to explain its mechanism.[26]

When Aron began considering the storage battery in 1880, the common device in use was the 1859 invention of the French industrial chemist Gaston Planté. Planté chose lead for both electrodes of the battery and sulphuric acid (H_2SO_4) electrolyte as a charge carrier between them (a principle still in use in current car batteries). However, considering the needs of the 1880s, Aron identified two shortcomings of Planté's battery. First, the electric process of its "formation", i.e. its preparation for first use, was tedious and time consuming. Second, the electrochemical activity, i.e. the charge capacity of the accumulator was very low and was diminishing with time. In other terms, Aron identified the formation and capacity of the rechargeable battery as the central obstacles for storing energy in the anticipated electric power systems.[27] These, however, were not serious drawbacks for Planté's original aims. For him capacity was only of secondary importance as he designed the battery as a voltage convertor for the needs of telegraphy, emphasising its high voltage (about 2 volts) and low resistance (compared with the primary batteries). The amount of energy required for this end was relatively low.[28] The designs and descriptions of the high-capacity battery by its simultaneous inventors show, however, that circa 1880 voltage conversion became of lesser importance in the eyes of experts. They consider the secondary battery primarily as a device for accumulating high amounts of electric energy.[29]

ARON'S WORK ON THE STORAGE BATTERY

Design

Aron, therefore, sought a simpler and quicker formation method that would result in a lead-acid battery of higher capacity. To these end, in summer 1880 he began experimenting with the production of porous lead plates. A few months later Faure presented his own method. The French engineer fabricated similar porous (and thus high capacity) lead electrodes by the pasting of a lead oxide called minium (Pb_3O_4, red lead) on the two electrodes separated at this stage of formation. Immersed in sulphuric acid they were charged and ready for use in a few hours instead of a few weeks.[30] According to his later report, independently of Faure, Aron also tried the application of minium. His results, however, were disappointing, finding that the electrolyte acid solved the minium, which, thus, did not produce the required porous surface. Apparently, at this point Aron was struck by what seemed to him as contradicting requirements from the pasting material. On the one hand it should be a good conductor, on the other hand it should not be immersed in the electrolyte, which by its nature dissolves conducting materials. Thus by itself, Aron's understanding of the chemical process showed him the requirements for the production of high capacity plate but failed to suggest a way to reach that end. Only after he had learnt about Faure's success with the minium, did he try an idea that he had merely entertained before, namely devising a material whose conductivity suffices to make the electrodes porous, but at the same time is not immersed in the sulphuric acid. For this end he used a paste of collodion (nitrated cellulose). Since collodion is an insulator, he mixed it with metal oxide, in this case oxides of lead, including minium. He hoped that the metallic collodion would also prevent the creation of lead oxide (PbO) on the positive pol, which impaired the efficiency of the cell.[31] This secondary role of the collodion followed Aron's research on the electrochemical process in the battery in which he had observed the accumulation of a grey material and had identified it as lead oxide. In June 1882 Aron filed a patent on the use of metallic collodion in "forming" storage batteries and in refreshing the cathodes in primary elements (non -rechargeable batteries in which he mixed the collodion with other metals according to the chemical composition of the electrodes).[32]

Unlike Brush and Keith, who later claimed that they had not known Faure's work, Aron learnt about Faure's while still developing his own battery and before making it public. His work and patent were not, therefore, independent from Faure; still, he began carrying out research on "a reservoir-type" cell independently of the others. Although, Aron's design differed from Faure's in some details, it agreed in the central principle: pasting the electrode with lead oxide for formatting porous electrodes. The high-capacity batteries designed by its two other co-inventors, Brush and Keith, also differed in some details from that of Faure. Brush employed peroxide of lead (lead dioxide, PbO_2) in the formation process, although he mentioned also the possible use of the cheaper minium for the same effect. "Keith's idea ... differed from ... Faure-Bush. The active materials were to be deposited in the lead plates from a plating solution of lead acetate" [compound of lead and acetic acid (CH_3O_2H)] instead of pasting with an oxide of lead. "The crucial point about this technique, however", Schallenberg writes, "is that, like the method of Faure and Brush, it was designed to produce a reservoir-type storage cell".[33] This is clearly true also for Aron's method.

In developing the metallic-collodion technique, Aron analysed possible formations of the battery and processes that accompanied charging and discharging, employing chemical knowledge to interpret his observations (for example, his identification of the grey material on the positive electrode as lead oxide). Similar considerations led him to examine an alternative technique.[34] Yet, in his crucial trials he examined unknown interactions, beyond current scientific knowledge, hoping that they would yield the desired results. These trials were not blind as they were instructed by an understanding of the general processes that take place in the cell and the concrete technical aims, even if the detail of the mechanism was obscure. This approach is evident in Aron's description of his crucial decision to reexamine the use of the insulator collodion, after first rejecting it: "However, when Faure came out with his work, I thought, if so much goes, why should not this go [*wenn so Vieles geht, warum sollte auch das nicht gehen*], and I tried again with collodion."[35] Thus, not only did Faure's prior patent not discourage Aron, but it even encouraged him to pursue similar ideas of his own. As common in technological development, the basic invention (of forming porous plates) served as a starting point for seeking improvements.[36]

Research

The attempt to produce an improved battery was part of Aron's three-year long research on storage batteries. This, however, was not his first electrochemical research. In the early 1870s, he had already studied related processes as an assistant to Paalzow. The latter studied the electromotive force between water and acid solutions, among them sulphuric acid (used as the electrolyte in the lead storage battery) and zinc sulphuric acid (used in the popular Daniell cell). In the experiment, Paalzow and his doctoral assistant examined currents between the acids and between them and the water, while these electrolytes were put between electrodes. Paalzow ascribed an early short-lived current to the electromotive force. Yet by identifying chemical products, he concluded that a more steady current was due to chemical processes between these solutions.[37] This research had provided Aron with a thorough knowledge of metallic and acid solutions and their behaviour in different conditions and settings, which he would later apply in his independent studies.

In the early 1880s Aron worked alone in "a small laboratory in a rear building", probably connected to the physical institute of Berlin University, where he taught as a *Privatdozent* and his former teacher Kirchhoff was the professor of theoretical physics. The facilities and means at the laboratory were modest. Batteries, however, formed only one of his research interests. His friend and colleague, Eugen Goldstein, recalled that "when I asked him in intervals of 8 or 14 days how far his particular research is advancing, then he gave me the regular answer, 'This does not interest me at all anymore [*Das interessiert mich gar nicht mehr*], now I pursue a totally different idea.' But this new beautiful idea again had only a very short lifespan, and its fruits did not reach publication." Apparently these "beautiful ideas" were only accidentally connected to the topics examined by others at the physical institute.[38]

Aron's independent research on batteries can be divided into three kinds a) designing batteries, b) a study of the mechanism of the batteries and the causes of their deterioration, c) development of general criteria to compare the efficiency of batteries regardless of their mechanism. These researches could have been conducted independently of each other, as a few other researchers did. For example, the three other simultaneous inventors did not publish studies of the batteries. Yet, the link between the researches is clear, and Aron employed his understanding of the mechanism in inventing and improving a new battery, even if he first relied on the findings of others. In his talks and publications he presented elements from the two first kinds of research with basic elements of the third together.

In his first public discussion of the secondary battery, Aron reviewed and criticized current knowledge in the field. From his synthesis of earlier results, he (mistakenly) inferred that batteries would be too heavy to operate an electric tram. He found them, however, useful for electric lighting both in connection to a system of dynamos and as an independent source, for example, for light in train wagons.[39] Aron employed this knowledge to define the current shortcomings of the storage batteries and to look for ways of improving them. He began his original systematic study of storage batteries and the processes they undergo only when he was already in the midst of exploring methods of constructing a more useful battery. In these studies Aron sought better knowledge of the batteries and improved understanding of their mechanism. This knowledge was conceived as a means to the end of improving storage batteries, in other words it was a kind of "technological" science. His original analysis of the lead-acid battery followed the study of its chemistry by John Gladstone and Alfred Tribe, which had just appeared in print. The two British chemists divided the basic chemical reaction of the accumulator to sub- and by-processes, and explained Faure's formation process. While they examined the battery by a chemical method (identifying a few byproducts), Aron suggested a "physical examination", in which he inferred the consumption of a chemical ingredient from a decrease in the solution's specific weight, which he had weighted for this end.[40] He further supported his conclusion by measurements of the heat that evolves in the positive plate, drawing conclusions from Julius Thomsen's thermochemical theory and data.[41] In carrying out both measurements he followed techniques used in Paalzow's laboratory.[42] Yet in addition to these "physical methods" he also applied chemical techniques similar to those of Gladstone and Tribe. By such a method he inferred that the plate absorbs oxygen at the beginning of discharge, leading to a short-lived high initial discharge voltage. This observation had immediate implications for the design, as it showed that the positive plate should not be covered in any way, as inventors like Faure and Aron himself had done. So, at least partly the study of the lead-acid process was viewed as a means for providing information for improving the battery's design. Gladstone and Tribe also applied conclusions from their research to "make one or two suggestions in regard to the economic aspects of [the forming of an efficient secondary battery.]"[43]

Another part of Aron's investigation was a measurement of the efficiency of the lead-acid accumulators and its decrease with recharging. One objective of this research was to find whether the cathode or anode first loses its activity (by mixing new and used electrodes). A connected objective was to identify reasons for the sharp decrease in a battery's performance over a few recharging cycles. Estimating the efficiency of the accumulators for various possible uses was another aim. Wilhelm Hallwachs, however, claimed that Aron's definition of efficiency was inadequate, since it does not reflect the amount of energy stored in the device. The efficiency of a battery could be defined only in relation to its use, i.e. its function in contemporary technology (and thus indirectly in society), as its shifting of meaning from Planté to Faure nicely demonstrates. Aron defined efficiency as the ratio between the charge provided by the battery in discharging and that supplied to it in charging. In his own research, forming his 1883 doctoral dissertation at the Strasbourg physics institute, Hallwachs carried out a more complex experiment to measure the physical work (i.e. the multiplication of the charge squared by the resistance) needed for charging the battery and the work (i.e. energy) that it produced. Still his examination was on the external physical operation of the battery, taken as "a black box", without any effort to probe into its inner process. Apparently, Hallwachs's sound criticism stimulated further work by Aron on the subject. Aron adopted his opponent's principal claim and elaborated the concept of efficiency by dividing it into four levels (where the charge and electrical energy are the first two) useful for comparing different storage batteries and settings. Unlike his earlier research, in this examination Aron did not enter the inner mechanism of the battery.[44]

DEMANDS AND RESOURCES

That Aron identified the formation and capacity of the storage battery as a problem for the raising central power stations suggests that he was well informed about the contemporary state of technology. The other simultaneous inventors had a background in industry, and experience with electrochemical technologies, which, Schallenberg suggested, led them "to conceive of the new role for the storage battery". In 1859, at the age of nineteen, after technical studies at the prestigious *Ecole d'Arts et Métiers*, Camille Faure began working for iron works, and then (1872) designed, built and superintended a gun-cotton (a highly explosive nitrate of cellulose) plant. As a superintending engineer he had a laboratory and time to investigate improvements in batteries, a field in which he had been engaged since 1859. Then, he designed a modified form of the Grove-Bunsen (primary) battery. "Faure had been interested in electricity since his youth, but [probably] his immediate stimulus ... to actively participate in the new field of electrical power engineering and lighting came from his visit to the 1878 Paris [Universal] exhibition."[45]

Charles Brush studied mining engineering, which included metallurgy and a laboratory course in chemistry. After completing his studies in 1869, he offered his services as an analytical and consulting chemist. Four years later he moved to the iron trade, but by 1875 he returned to engineering. Among the inventors of the high-capacity accumulator, Brush had the strongest involvement with the developing electric power technology, and he was the only one who needed a good accumulator for his own system. In 1875 he entered an agreement with telegraphic supply to develop equipment in that field, which allowed him also to experiment on his own venture. In the same year he began developing a system of arc lighting: improving the dynamo (1877), the arc lamps and automatic regulator for their better operation (1878–80). By 1879 he operated an electric system for street lighting and a year later founded "the Brush Electric Company" for installing his system.[46]

Nathaniel Keith began his technical education at the chemical laboratory of his father in New York. He turned his attention to the mining industry in the early 1860s. During the following decade, while inventing and working as a mining engineer without a formal education, he became an expert in metallurgy. In this field he experimented with the use of electrical methods, which led him to "engage actively in electrical investigations". "Publishing treatises on electro-metallurgy" he earned an expert status in the field during the 1870s. Unlike the paths of the other three inventors, Keith's road to the lead battery was not guided by the need to improve electric storage devices. Rather, a side effect of his electrochemical research led him to a new venture of improving the storage battery. Examining electrochemical techniques for the recovery of trace silver from crude lead in 1877, he observed a surprisingly strong reverse current after turning off the dynamo. The strong current suggested to him a way to improve on Planté's design, on which he experimented in the coming year. Keith, however, left that research without filing a patent, probably because in 1878 he did not see a market for the improved battery. Only in 1882, he resumed the development of the battery, and patented his technique for its formation. Apparently, although Keith followed the trade and technical literatures, he did not share the early interest of the other inventors in the storage of electricity.[47]

Unlike the other inventors, Aron, had an experience in science rather than in electric technology. His invention shows that technological background was not necessary for conceiving the need for developing a high-capacity storage battery. This does not mean that scientific knowledge by itself suggested to him the need to design a high-capacity accumulator. Yet his scientific knowledge and his social roles provided him with a vantage point to identify such a need. "[P]rofessors, well read in the technical and scientific periodicals and in touch with the technical community, knew the critical problems in developing technological systems."[48] As an active member of the Berlin scientific-technological community this was clearly the case with Aron. He was a founding member of the *Elektrotechnische Verein* (association for electrical technology), "whose task is the cultivation of the whole field of electric technology (*Elektrotechnik*) in its scientific research as well as in its practical application". The association both promoted and presented a vibrant network of teachers of physics and engineering, inventors, practising engineers, and industrialists. Among others, it provided Aron with informal knowledge about expected needs of industry, in addition to technical literature and trade journals to which he had access. Moreover, it seems that at the early 1880s he considered a move from scientific research to development of electric technology, and was therefore looking for technological problems.[49]

Still, it is one thing to identify a problem, it is another to be able to suggest ways to solve it and to pursue such a solution. Based on the examples of the three other simultaneous inventors, Schallenberg suggested that "the two commercial electrical technologies of the pre-1880 period — telegraphy and electroplating" provided the required resources for solving the technological problem. Faure had experimented with lead components (but not in the electrodes) in primary "telegraphic batteries and had studied the use of rechargeable lead cells in telegraphy". He also had a long interest with electrochemistry, although no direct connection between this research and his work on the high-capacity storage battery has been shown. Telegraphy provided the context for Brush's research on primary batteries. In 1876, he modified the zinc-copper "gravity Daniell cell" commonly used in telegraphy. He replaced the cathode of copper with lead and the electrolyte surrounding it from $CuSO_4$ solution to a paste of lead oxychloride – PbCl $Pb(OH)_2$. As in previous designs, gravity ensured a separation between the paste and the zinc sulphate solution, which Brush continued to use. He even examined the reversibility of the new cell. Where the needs of telegraphy provided Brush with valuable experience in the behaviour of lead solutions, his development of a regulator for the arc-lamp extended his acquaintance with contemporary secondary cells. Arc lamps, the central component of his electric-lighting system, required adjustment of voltage during their operation. The standard solution was an electromagnetic regulator. In 1879, however, Brush patented a circuit using a secondary battery, reflecting his knowledge of electrochemistry. For this purpose, Brush preferred a gas battery of the kind known from the early 1850s, but he mentioned also the application of the lead battery.[50] Keith, as mentioned, applied the knowledge that he had acquired in working on electro-metallurgy (although unlike Faure and Brush he did not have a background in telegraphy) in developing his storage battery.

Aron, however, found sufficient resources not in industry but in the scientific study of electrochemistry. His research as Paazlow's assistant provided him with knowledge and experience useful for understanding, studying and also manipulating and improving the batteries. Above articulated theoretical rules of electrochemical phenomena, Aron gained in Paalzow's laboratory know-how of handling electrolytes used in batteries and experimental methods used in studying their phenomena. As mentioned, he later employed a few of these methods in his technological research, e.g. his "physical" measurement of specific weights. That other researchers on the secondary battery did not employ the technique suggests that Aron adopted the method from his earlier research in Paalzow's laboratory.[51]

Paalzow, applied his results to explain the behaviour of the Daniell cell, the popular contemporary primary battery for laboratory use. Yet, clarification of a technological device's mechanism was not Paalzow's chief aim. Primarily, he aimed at elucidating the relationship between the suggested chemical and contact sources of electric current and voltage differences in batteries. The source of the cell's electricity formed the major subject for theoretical and experimental controversy in electrochemistry throughout the nineteenth century. Prominent physicists like Faraday, Maxwell, William Thomson and Helmholtz participated in the controversy. Paalzow's results supported the suggestion of Helmholtz, who distinguished between the current, to which he ascribed a chemical origin, and the voltage differences, which he attributed to contact electricity. Paalzow showed that chemical reactions (rather than metallic contacts) are responsible for the electric currents in the fluids. A second scientific issue was the relation between electric and thermal currents, an issue connected to Paalzow's previous research on conductivity.[52]

Following his work with Paalzow Aron knew well the electrochemical relations among solutions and between them and metals. He surely kept some interest in the issue during the 1870s. Whether that led him also to consider the potential usefulness of the storage battery (which is an electrochemical device) or whether his interest in the device originated in another source, Aron's experience with electrochemistry seems essential to his decision to carry out a research for its improvement and in providing him the resources for carrying it through. He hoped that his knowledge of and experience with electrochemistry would help him solve the central shortcomings of the storage battery, namely its low capacity and long formation. In that he showed a belief in the usefulness of scientific knowledge and methods for technological developments. Most of his colleagues and many other contemporaries shared this view, as expressed, for example, by the *Elektrotechnische Verein* and the foundation of the *Physikalisch-Technische Reichsanstalt* (in 1887).[53] Regardless of the truth value of such a view, the belief that scientific knowledge can instruct technological development was a major force beyond Aron's attempt to amend the shortcomings of the battery and consequently in his move to technological research.

EPILOGUE — THE RESULTS OF ARON'S BATTERY ENDEAVOUR

Aron's hopes for his secondary batteries were not fulfilled. After about three years of work he left active research on the device for other technological efforts. From autumn 1883 he dedicated his time to the development of pendulum electricity meters. Unlike the storage battery, Aron's electricity meter was a remarkable technological and commercial success, on which he built prosperous companies, which by 1909 employed more than 1,000 workers in four European countries. The two inventions shared origins in Aron's earlier scientific practice. His experience as a student and a teacher of physics led him to design an electricity meter more accurate than others. In this case, experience in technology did not direct inventors to a similar instrument. As an unintended byproduct, his use of extant inadequate meters in his research on the storage batteries stimulated Aron's successful invention of a new electricity meter. Still, the battery project failed in its main aim. Aron produced only a few working batteries. Although, Eugen Goldstein used them as a reliable electric source in his experiments on cathode rays, they did not reach commercial production.[54]

With the storage battery Aron did not enjoy priority. A Belgian financier had established a company to produce and further develop Faure's invention already in

October 1880. Yet, by the time Aron filed a patent, it became apparent that in practice the high-capacity lead batteries (at least in Faure's design) showed rapid deterioration in their performance and even disintegrated after a few months of use. Since the main difference between Faure's and Aron's batteries was in their formation, which did not seem to be the problem with the long-term performance of the device, Aron's invention did not seem to suggest a solution to these problems. Neither of the original inventions of the high-capacity storage battery escaped these problems. Regardless their background in technology or in science, the four inventors produced batteries that performed satisfactorily in the first cycles, but with time and recurrent use became inefficient. A commercially successful battery evaded early efforts for a few years, as examinations in developers' laboratories did not reveal the problem that appeared in its long actual use. "It was not until the late 1880s that a few companies, after considerable research and expenditure of capital, were able to market a commercially successful battery."[55]

Since the decrease in effectivity originated in quite a few sources, some of them with customers' modes of using the batteries, it required long engineering research. This was beyond the means of an independent inventor like Aron, even if he analysed a few sources for the decrease in batteries' performance in his research (e.g. the absorption of oxygen at the beginning of discharge). Moreover, the development of a commercially viable storage battery required cooperation with either central electric stations (based on DC), or traction companies that would implement the batteries within their systems, as in the 1880s these were its only significant potential uses.[56] Only such cooperation could have secured the investment need for a viable battery, in a period when "storage battery companies tended to succeed in direct proportion to the amount of financial support they were given by larger corporations".[57]

Even as he left his main venture on storage of electricity, at the early years of his electricity meter company, Aron occasionally studied ways of improving batteries. These efforts resulted in his 1886 invention of a "dry" mercury alkaline cell. Alkalies enable a dry cell which, unlike other nineteenth-century batteries, could in principle be closed in a box and did not require maintenance — a considerable advantage as a consumer device. Aron suggested the replacement of copper in the common copper-zinc alkaline battery by mercury oxide. He pointed out two central advantages of this cell: its higher voltage (1.3v versus 0.7v) and its relative immunity to spontaneous discharges (so it is more reliable and allows for a much longer shelf life). On the other hand, the battery was much more expensive, and did not seem to answer any urgent demand. These features suggest that Aron was sometimes more interested in the device, its properties and functionality than in economy. Improvements on mercury batteries had been suggested after Aron's, but it did not reach production line before the Second World War, with the emergence of a new military market for a long shelf-life cell.[58]

CONCLUSIONS

Regarding the high expectations from electric power technology brought about by the dynamo and the incandescence lamp, and the consequent economic advantage in storing electric energy well-informed individuals sought a means of accumulating electricity. At least four of them independently devised methods for improving the capacity and reducing the formation time of the storage battery. Among the simultaneous inventors, Keith alone was inspired by a novel finding, even if he also pursued developing the device only after learning about its new potential use. The anticipated demand for the device motivated the work of the other three inventors, and other experts in the area, who failed to conceive of a similar solution. Their novel interest in the battery followed new developments neither in electrochemical science nor in battery technology. In that it was unlike inventions such as the radio, which followed the scientific discovery of electromagnetic waves, or the triode valve ("audion") inspired by the recent invention of the thermionic valve. It was still similar to many other inventions, including that of the incandescent light bulb, inspired from advancements in dynamos, and then inspiring the improvement of the battery. Notwithstanding the motivations of its co-inventors, scientific and technological knowledge played a crucial role in the development of the new battery by its four inventors. Moreover, following the introduction of the improved battery, chemists, physicists and scientific-engineers carried out further research on the device and its working mechanism, hoping to help in its further amelioration.

Beyond indicating a common motivation for the storage battery in the foreseen novel demand, the simultaneous invention suggests that the co-inventors had at their command similar resources for its development. Such resources were found in technological research on electrochemistry, concerning batteries for telegraphy and in electroplating. Yet, Aron's development of the high-capacity storage battery shows that this was not the only possible resource. Scientific practice and experimental work provided similar but distinct resources for solving technological problems, in the case of electrochemistry, where theory supplied only limited guidance. In other words, once the task of reaching a high-capacity battery with a short formation time was taken up, experimental knowledge and practical know-how were as sufficient to lead to a working device as was a background in technology.

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Edison's electric light: Biography of an invention (New Brunswick,1988), 90–91, 115–17 and on the historical memory of their contributions William J. Broad, "Rival centennial casts new light on Edison", *Science* (4 June 1979), cciv, no. 4388:, 32–33, 35–36.

2. Thomas S. Kuhn, "Energy conservation as an example of simultaneous discovery", in *The essential tension: Selected studies in scientific tradition and change* (Chicago, 1977), 66–104. Another classical discussion is Robert Merton, "Singletons and multiplies in science", in *The sociology of science: Theoretical and empirical investigation* (Chicago, 1973), 343–70. The concept of simultaneous discovery has also been harshly criticized, e.g. in Simon Schaffer, "Making up discovery", in Margaret A. Boden (ed.), *Dimensions of creativity* (Cambridge MA, 1994). Nevertheless, for recent uses of the notion of simultaneous discovery see for example John C. Burnham, "Accident proneness (Unfallneigung): A classic case of simultaneous discovery/construction in psychology", *Science in context*, xxi (2008), 99–118. Buhm Soon Park, "The contexts of simultaneous discovery: Slater, Pauling, and the origins of hybridisation", *Studies in history and philosophy of modern physics*, xxxi (2000), 451–74.
3. Recent historiography examines the role of the concept of simultaneous invention in past thought. Christine MacLeod, for example, discusses the mid-nineteenth-century British use of simultaneous invention in the controversy over patent law, in *Heroes of invention: Technology, liberalism and british identity, 1750–1914* (Cambridge, 2007), 267–74.
4. Charles Susskind, "Radar as a case study in simultaneous invention", in Oskar Blumtritt, Hartmut Petzold and William Aspray (eds), *Tracking the history of radar* (Piscataway, N.J., 1994), 243.
5. Arthur P. Harrison, "Single–control tuning: An analysis of an innovation", *Technology and culture*, xx (1979), 296–321, sees in "parallel" (i.e. simultaneous) invention indication for a concrete demand. He does not, however, employ the notion to study the motives or the sources of particular inventors.
6. Richard H. Schallenberg, *Bottled energy: Electrical engineering and the evolution of chemical energy storage* (Philadelphia, 1982), 48–57, quotations on pp. 53, 56.
7. Thomas P. Hughes, *Networks of power: Electrification in western society, 1880–1930* (Baltimore, 1983).
8. Paul Israel, *Edison: A life of invention* (New York, 1998).
9. Sungook Hong, "Forging scientific electrical engineering: John Ambrose Fleming and the Ferranti effect", *Isis*, lxxxvi (1995), 30–51.
10. Graeme Gooday has examined the discussion about engineering training, finding the origins of British academic electrical engineering in experiential physics ("Teaching telegraphy and electrotechnics in the physics laboratory: William Ayrton and the creation of an academic space for electrical engineering 1873–84", *History of technology*, xiii (1991), 73–114); Robert Fox and Anna Guagnini, *Laboratories, workshops and sites: Concepts and practices of applied research in industrial Europe, 1800–1914* (Berkeley, 1999), 110–20; Bruce J. Hunt, *Pursuing power and light: Technology and physics from James Watt to Albert Einstein* (Baltimore, 2010), 137–41; Wolfgang König, *Technikwissenschaften: Die Entstehung der Elektrotechnik aus Industrie und Wissenschaft zwischen 1880 und 1914* (Chur, 1995).
11. Combining theoretical optics with the methodology of precise measurement acquired is his scientific training and research on the practical device, Ernst Abbe improved the microscopes produced by Carl Zeiss. Further research, directed by the chemist Otto Schott, led to the production of a glass according to (scientific) optical specifications, not only for special instruments but to a mass market of lenses to camera objectives, spy-glasses etc. Stuart M. Feffer, *Microscopes to munitions: Ernst Abbe, Carl Zeiss, and the transformation of technical optics, 1850–1914* (PhD thesis, University of California, Berkeley, 1994); *idem*, "Ernst Abbe, Carl Zeiss, and the transformation of microscopical optics", in Jed Buchwald (ed.), *Scientific credibility and technical standards in 19th and early 20th century Germany and Britain* (Dordrecht, 1996), 23–66; David Cahan, "The Zeiss Werke and the ultramicroscope: The creation of a scientific instrument in context", in *ibid.*, 67–117.

12. Sungook Hong, *Wireless: From Marconi's black box to the audion* (Cambridge, MA, 2001).
13. E.g., Ben Marsden and Crosbie Smith, *Engineering empires: A cultural history of technology in nineteenth-century Britain* (New York, 2005), especially 235–45. For the alleged dependence of theory on engineering practice in Germany see Wolfgang König, "Science-based industry or industry-based science? Electrical engineering in Germany before World War I", *Technology and culture*, xxxvii (1996), 70–101. A similar approach about the creation of electrical engineering as a science at a later period is presented in Ronald R. Kline, *Steinmetz: Engineer and socialist* (Baltimore, 1992).
14. Fox and Guagnini argue "that the growth of physics laboratories in the later nineteenth century owed much to their perceived value for industry and to the utilitarian air that ... pervaded most of them", *op. cit.* (ref. 10), 2–3. Hunt agrees (Bruce Hunt, "Electrical theory and practice in the nineteenth century", in Mary Jo Nye (ed.), *Cambridge history of science*, v: *Modern physical and mathematical sciences* (Cambridge, 2003), 311–27, on p. 321). He further argues that the cause for the divergence between British field and continental action-at-a-distance theories of electromagnetism "in large part is the unique demands and opportunities presented by Britain's global system of submarine telegraph cables". Bruce Hunt, "Doing science in a global empire: Cable telegraphy and electrical physics in Victorian Britain", in Bernard Lightman (ed.), *Victorian science in context* (Chicago, 1997), 312–33, on p. 315. The tendency to concentrate on the effect of technology is evident also in Gooday's work on education and on practical electrical measurements, which "enables us to see how Cambridge graduates had at least as much to learn about electrical engineering from artisan-engineers as vice versa", "Fear, shunning, and valuelessness: Controversy over the use of 'Cambridge' mathematics in late Victorian electro-technology", in David Kaiser (ed.), *Pedagogy and the practice of science: Historical and contemporary perspectives* (Cambridge, MA, 2005), 111–49, on p. 112; see also Graeme Gooday, *The morals of measurement: Accuracy, irony, and trust in late Victorian electrical practice* (Cambridge, 2004).
15. For the tendency of historians of technology, which is manifested among others in their neglect of science, see Paul Forman, "The primacy of science in modernity, of technology in post modernity, and of ideology in the history of technology", *History and technology*, xxiii (2007), 1–152, and the (critical) "Responses" of Martin Collins, Ronald Kline, Chunglin Kwa and Philip Mirowski, *ibid.*, 153–88.
16. That practice is emphasized even in histories of theoretical physics and well exemplifies its central place in historiography, see e.g. Andrew Warwick, *Masters of theory: Cambridge and the rise of mathematical physics* (Chicago, 2003); David Kaiser, *Drawing theories apart: The dispersion of Feynman diagrams in postwar physics* (Chicago, 2005).
17. Shaul Katzir, "Hermann Aron's electricity meters: Physics and invention in late nineteenth-century Germany", *Historical studies in the natural sciences*, xxxix (2009), 444–81.
18. Fox and Guagnini, *op. cit.* (ref. 10), 69. A preexistent interest of a large group of experts was necessary for the construction of the exhibition. Fabienne Cardot, "L'exposition de 1881", in François Caron and Fabienne Cardot (eds), *Histoire générale de l'"électricité en France* (Paris, 1991), ii, 18–33; Sigfrid von Weiher, *Berlins Weg zur Elektropolis: Technik- und Industriegeschichte an der Spree*, 2nd edn (Gottingen, 1987), 82–83; Hughes, *op. cit.* (ref. 7), 31–37.
19. Schallenberg, *op. cit.* (ref. 6), especially, 48–51, 124–39, 221–43, quote on p. 59.
20. His 1876 habilitation also included an experimental part.
21. Katzir, *op. cit.* (ref. 17), 449–54. For more details about his biography, Shaul Katzir, "From academic physics to technology and industry: The course of Hermann Aron's (1845–1913) career", *Max Planck Institute for the History of Science preprint*, ccclxx (2009) (online at http://www.mpiwg-berlin.mpg.de/Preprints/P370.pdf; accessed on 21 Aug 2009).
22. Walter G. Vincenti, *What engineers know and how they know it: Analytical studies from aeronautical*

history (Baltimore, 1990); Edwin T. Layton, Jr, “Mirror-image twins: The communities of science and technology in 19th-century America”, *Technology and culture*, xii (1971), 562–80; Kline, *op. cit.* (ref. 13).

23. Hong, *op. cit.* (ref. 9).
24. Crosbie Smith and M. Norton Wise, *Energy and empire: A biographical study of Lord Kelvin,* (Cambridge, 1989), 712–15.
25. Hermann Aron, “Die sekundären Elemente und ihre Anwendung”, *Elektrotechnische Zeitschrift*, iii (1882), 222–28, on p. 222. Aron’s emphasis on energy efficiency seems to fit the thinking of a scientist more than that of a technologist, who, as ideal type, would prefer financial to energetic considerations. Edison expressed such a priority in his concise objection to the batteries: “I have never yet been able to learn of a 1000 horsepower of storage [batteries] than can be bought as *cheap* as 1000 hp of boiler and dynamos” (italics added). The quotation of Edison from Schallenberg, *op. cit.* (ref. 6), 174. Edison’s view, which was shared by other “electricians” was grounded, among other reasons, in severe technical problems in the performance of storage batteries, *ibid*., 67–69.
26. See for example the papers of the two British chemists John H. Gladstone and Alfred Tribe collected in *The chemistry of the secondary batteries of Planté and Faure* (London, 1883).
27. Thomas Hughes referred to this kind of problem resulting in a weak part in a system as “reverse salients”, Hughes, *op. cit.* (ref. 7), 79–81. Hermann Aron, “Theorie der Akkumulatoren und Erfahrungen mit denselben”, *Elektrotechnische Zeitschrift*, iv (1883), 58–60,100–107, on p. 58.
28. On Planté’s work and motivation, Schallenberg, *op. cit.* (ref. 6), 24–46.
29. Schallenberg, *op. cit.* (ref. 6), 51–59, and here below.
30. E. Reynier, “Sur la pile secondaire de M. C. Faure”, *Comptes-rendus hebdomadaires des séances de l’Académie des sciences*, xcii (1881), 951–3.
31. The aim of these methods was to enlarge the operational surface of the plates as the capacity is proportional to it. Materials that hang to the surface block the lead and its useful products on the plates from taking part in the chemical reactions of charging and discharging.
32. Aron, “Theorie der Akkumulatoren”, *op. cit.* (ref. 27), 58–60; Hermann Aron, “Herstellung eines neuen Stoffes aus Metall und Cellulose für elektrotechnische Zwecke”, Germany patent DE21957, filed 22-6-1882, issued 1883.
33. Schallenberg, *op. cit.* (ref. 6), 51–59, quote on 57. Charles F. Brush, “Secondary Battery”, US Patent US337299, filed 13.6.1881.
34. Salomon Kalischer informed Aron that etching forms a crystalline layer in materials, so Aron tried to chemically etch the lead electrode using nitric acid, and then to remove the acid by oxidizer. This attempt led to a useful technique, whose results, however, were inferior to the metal-collodion technique. Aron, “Theorie der Akkumulatoren”, *op. cit.* (ref. 27), 59–60.
35. *Ibid*., 59. Although this is a recollection, it seems to be quite reliable for three main reasons. First it was made close to the events. Second, Aron’s interest in making it was not very strong, as it neither provided Aron priority, nor showed his advantage as a man of science. Third, the audience included Aron’s colleagues who probably had known about his earlier work.
36. Aron was far from the only one encouraged by Faure’s invention. Edmund Hoppe provides a list of more than 50 patents related to the storage battery filed between 1880 and 1883, *Die Accumulatoren für Elektricität* (Berlin, 1882), 143–4. It is possible that a few additional inventors suggested a pasting method independently of the others. For the interest of inventors in the designs of others see, Thomas P. Hughes, *American genesis: A century of invention and technological enthusiasm* (New York, 1989), 53–74.
37. A. Paalzow, “Ueber die elektromotorische Kraft von Flüssigkeitsketten”, *Annalen der Physik und Chemie* (1874), Jubelbandes, 643–9.

38. Eugen Goldstein, "Aus vergangenen Tagen der Berliner Physikalischen Gesellschaft", *Naturwissenschaften*, xiii (1925), 39–45, on p. 40. Aron's laboratory was at Dortheenstraße near the physical institute. Among others he researched on artificial production of graphite for use in incandescence lamps, on a gas incandescent mantle, and allegedly on wireless communication (probably not by electromagnetic waves). His few contemporary theoretical papers were closer to Kirchhoff's interests. Katzir, "Academic physics to technology" (ref. 21), 9–10, 20.

39. Aron examined an example of a particular low velocity (10 km/h). From the deduction that a tram at that velocity would fail to carry even its own weight, he concluded that any battery-tram would be impractical. Faster trams would be able to carry even less weight and much slower cars would be of no use. As he later realized, his assumption about the weight to capacity ratio of batteries was too pessimistic even for his own time, Aron, "Theorie der Akkumulatoren" (ref. 27), and Aron, "sekundären Elemente", *op. cit.* (ref. 25), the calculation on 227–8.

40. In this way Aron supported the assumption of Gladstone and Tribe that lead-sulphate ($PbSO_4$),is formed in the process. John Gladstone and Alfred Tribe, "The chemistry of the Planté and Faure accumulators", *Nature*, xxv (1882), 221–3, 461–3, Aron, "Theorie der Akkumulatoren" (ref. 27), 101–2.

41. Aron displayed command of novel theoretical approaches. He remarked that in cases like this Hermann von Helmholtz's very recent thermodynamic theory of chemical reactions based on the concept of free energy agrees with the claims of the earlier thermochemistry. This suggests a closer connection between Helmholtz's thermodynamics and the older thermochemistry than allowed for by some advocates of the thermodynamic approach (notably Pierre Duhem). Aron, *ibid.*, 102, on the relations between the two see R. G. A. Dolby, "Thermochemistry versus thermodynamics: The nineteenth century controversy", *History of science*, xxii (1984), 374–400.

42. Paalzow, *op. cit.* (ref. 37).

43. Gladstone and Tribe, *op. cit.* (ref. 26), 463.

44. In his more detailed experiment Hallwachs examined the influence of variables like the batteries' inner resistance, the manner by which they were charged and discharged etc. Aron and Hallwachs continued to debate on insignificant points. Wilhelm Hallwachs, "Über die elektromotorische Kraft, den Widerstand und den Nutzeffekt von Ladungssäulen (Akkumulatoren)", *Elektrotechnische Zeitschrift*, iv (1883), 200–8; Wilhelm Hallwachs, "Bemerkung über die Berechnung des Nutzeffektes von Ladungssäulen", *ibid.*, 301–2; Hermann Aron, "Zur Berechnung des Nutzeffektes von Akkumulatoren", *ibid.*, 342–4.

45. Schallenberg, *op. cit.* (ref. 6), 52.

46. Harry Eisenman, *Charles F. Brush: Pioneer innovator in electrical technology* (PhD diss., Case Western Reserve University, Cleveland, 1967), 8–30, 77–92; George Wise, "Brush, Charles Francis", *American national biography* (Oxford, Online 2000, http://www.anb.org/articles/13/13-00214.html; accessed on 3 Sep 2010), and Schallenberg, *op. cit.* (ref. 6), 53–54.

47. James O'Leary, "Nathaniel Shepard Keith", in *The builders of a great city: San Francisco's representative men, the city, its history and commerce: pregnant facts regarding the growth of the leading branches of trade, industries and products of the state and coast*, i (San Francisco, 1891), 229–30. Nathaniel Keith, "Application for transfer from associate to full membership", in American Institute of Electrical Engineers, June 1893, Keith Papers, IEEE, online http://www.ieeeghn.org/wiki/images/4/42/Keith_-_application_for_admission.pdf, Schallenberg, *op. cit.* (ref. 6), 56–57. Unlike Schallenberg's claim (which follows mistaken contemporary sources), Keith did not study medicine.

48. Hughes, *op. cit.* (ref. 36), 65.

49. K. Ed. Zetzsche, "Unser Ziel", *Elektrotechnische Zeitschrift*, i (1880), 1–2, on 1. On Aron, the *Verein* and his work on technology see Katzir, "Academic physics to technology" (ref. 21), 14–17, and Katzir, *op. cit.* (ref. 17), 453–8 and passim on the move to industry. Quotation from Schallenberg

op. cit. (ref. 6), 56.

50. Schallenberg, *op. cit.* (ref. 6), 52–55, quote on 53.
51. Paalzow, *op. cit.* (ref. 37).
52. Differently than for fluids, Paalzow's findings suggested that contact electricity explains the operating voltage of batteries (but with agreement with Helmholtz, not their energy), while chemical reactions are responsible only for undesired secondary currents. This conclusion was potentially instrumental for designing batteries. This, however, was only one among a few aims of Paazlow's research, *ibid*. On Paalzow's earlier research see A. Rubens, "A. Paalzow", *Verhandlungen der deutschen physikalischen Gesellschaft*, x (1908), 451–62. On the controversy between the contact and chemical theories see Wilhelm Ostwald, *Electrochemistry: History and theory*, trans. N. P. Date (New Delhi, 1980), 909–13; Olivier Darrigol, *Electrodynamics from Ampère to Einstein* (Oxford, 2000), 271–3; Helge Kragh, "Confusion and controversy: Nineteenth-century theories of the voltaic pile", in Fabio Bevilacqua and Lucio Fregonese (eds), *Nuova Voltiana: Studies on Volta and his times*, i (Pavia, 2000), 133–157.

.53. The benefit of scientific research to technology and economy was a central theme in the foundation of these two different institutes. David Cahan, *An institute for an empire: The Physikalisch-Technische Reichsanstalt, 1871–1918* (Cambridge, 1989), 29–39; Katzir, *op. cit.* (ref. 17), 454–6.

54. Katzir, *op. cit.* (ref. 17), on the connection between the storage battery and the meter pp. 470–1; Eugen Goldstein, "Ueber electrische Leitung im Vacuum", *Annalen der Physik und Chemie,* xxiv (1885), 79–92, on p. 85.
55. Schallenberg, *op. cit.* (ref. 6), 61.
56. Expectations for electric cars emerged as a major new source of investment in storage batteries in the mid 1890s.
57. Schallenberg, *op. cit.* (ref. 6), quotation on p. 341, pp. 61, 77–81 on the important painstaking research on various variables that might have affected the battery's performance by Bernard Drake during 1883–85, and passim.
58. Of course, the battery that was eventually used was based on improved design, which required investment of time, efforts and money. Hermann Aron, "Galvanisches element", Germany patent DE38220, filed 30-6-1886, issued 1886; Eric S. Hintz, "Portable power: Inventor Samuel Ruben and the birth of Duracell", *Technology and culture*, l (2009), 24–57; Samuel Ruben, "Alkaline primary cell", USA patent US2473546, filed 23-1-1943, issued 1949; Schallenberg, *op. cit.* (ref. 6), 324–7.