Tracking Down the Origin of Arc Plasma Science.

II. Early Continuous Discharges

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ABSTRACT

Continuous discharges could only be obtained after enduring energy sources became available, namely in the form of a battery of electrochemical cells, invented by Volta in late 1799. Humphry Davy is generally credited with the discovery of the arc discharge and the invention of the carbon arc lamp. Indeed, as early as 1800, he obtained short pulsed arcs with his Voltaic pile. Independently, and earlier than Davy in the sense of continuous discharges, the Russian Vasilii Petrov of St. Petersburg made carbon arcs in 1802. Petrov used a pile of 4200 electrochemical cells to drive what was the most powerful discharge at that time. Petrov's publication of 1803 appeared only in Russian, and his work was ignored and forgotten for over century. Davy pursued highly successful electrochemical experiments and was unaware of Petrov's work. He increased the size of his battery in several steps, which led to increasingly powerful discharges, most likely an undesired side effect. After 1808, using the new 2000-element battery of the Royal Institution, Davy demonstrated continuous arc discharges in the institution's theatre before large audiences, thereby establishing arc physics as a lasting science.

"In all sciences there are many truths for the reception of which it is absolutely necessary that men's minds, even those of the higher order, be suitably prepared…If these truths are discovered before this time, they will be contended, smothered at birth and forgotten. They appear as flashes of light, piercing the gloom of a cavern, illuminating it for one brief moment, only to abandon it once more to the darkness of night."

Pierre Sue, *Histoire du Galvanisme*, 1802

I. INTRODUCTION

The year of the discovery of arc discharges appears to be clouded in mystery, most likely because of the fuzzy understanding what constitutes an arc discharge, aggravated by the way reports have been written and distributed and also by the fact that the discovery occurred in several steps before being recognized.

A standard entry from a well-known physics encyclopedia reads: "The electrical arc is a form of discharge first observed by Davy (1810), who used a battery of galvanic elements between horizontally aligned carbon electrodes. After interruption of the contact, an arched-shaped, very bright discharge remained, which gave the phenomenon its name." [1] Most texts on the history of electricity and lighting concur in principle but give different dates: Thompson [2] and Knight ([3] p.41) date it back to 1800, while most literature refers to Davy's demonstrations at the Royal Institutions in 1809 or 1810 (e.g. [1, 4-6]), Alglave and Boulard believe it was in 1813 ([7] p. 21), and Hoppe [8] places it as late as 1821. Bowers does not mention a year when discussing "early demonstration of arc lighting" ([9] p.66) but refers to the great battery of the Royal Institution arranged by public subscription in 1808 ([9] p.64). It appears that all of these authors were unaware that parallel research was done by Vasilii Petrov in St. Petersburg, who, at least in the sense of a continuous discharge, was ahead of Davy of by several years. Only the Russian Encyclopedia of Physics ([10] p.185) states that Petrov observed the arc in 1802 and Davy independently discovered the arc discharge in 1808. The second centennial anniversary of these events is a welcome opportunity to discuss both Davy's and Petrov's work. As in the first part of this publication, the development of new, more powerful energy storage systems appears as the key for the discovery of new electrical discharge phenomena, and therefore a large portion of the present work is devoted to the history of the power source: the electrochemical battery.

II. GALVANI AND VOLTA: THE ELECTRICAL BATTERY AS A PRECONDITION FOR CONTINUOUS ARC DISCHARGES

The history of electrochemical phenomena goes back at least to the middle of the 18th century. The Swiss Johann Georg Sulzer (1720-1779) described in 1754 that if two different metal wires are connected at one end and the other ends touched the tongue of the observer, he or she can feel an acidic or alkaline taste, depending on the type of metal used. Similar experiments were repeated by numerous physicists and medical doctors, including by Georg Christoph Lichtenberg (1742-1799), professor in Göttingen, Germany, and by Alessandro Volta (1745-1827), professor of Natural Philosophy at the university of Pavia, Italy.

In Bologna, Italy, the professor of anatomy Luigi Galvani (1737-1798) performed numerous experiments on "animal electricity." As published in 1791, he reported about the motion of frog legs when the frog is placed on an iron plate and its spinal cord is touched with a copper hook [11]. The story of this discovery is a very interesting on its own and shall not be further mentioned because it has been extensively discussed in the literature of history of science [5]. Galvani's experiments were repeated throughout Europe, and especially Volta, by that time already a well-respected scientist, tried to identify the nature of Galvani's animal experiments.

In Berlin, Alexander von Humboldt (1769-1859) received a letter from Dr. Ash, Oxford, dated April 10th, 1795, in which Ash reports

"If you put two homogeneous zinc plates, wetted with water, on top of each other such that the disks touch on as many places as possible, next to nothing can be observed. If, however, you bring zinc and silver together, you will quickly see a strong effect; the zinc seems to oxidize, and the silver will be covered on its surface with a fine white powder. The same can be observed with lead and mercury, and also with iron and copper" [12].

Humboldt repeated the experiments and showed that oxygen is formed at zinc, while bubbles of hydrogen rise from the silver electrodes ("water decomposition by Galvanism"). Indeed, many researches performed "Galvani's experiment" in the 1790s, and it became clear that the cause of electricity observed had to do with the presence of two different metals rather than a quality inherent to muscles and nerves. One of these researchers was Johann Wilhelm Ritter (1776-1810), a professor at the university of Jena and best known for his discovery of ultraviolet light. In 1799, one year before Volta's breakthrough publication, he published a paper "on the inorganic nature and on the relation of electricity with the chemical quality of bodies" in which he shows that zinc is quickly oxidized in the presence of silver and water only if the electrical circuit is closed [13]. The time was ripe for the invention of the electrochemical battery.

As other researchers, Volta changed his initial opinion after much experimentation and concluded that the frog in Galvani's experiments was merrily a detector, and not the source of electricity. Volta showed that the frog does not move when only one type of metal is used in the experiment. It was clear to Volta that the Galvanic effect is of electrical nature but too weak in "tension" to be measured by conventional electrometers, amplification of the effect was needed. By the end of 1799, Volta accomplished a seminal improvement of the Galvanic effect by adding many pairs of dislike metals separated by "conductors of the second art" such as wet cardboard. Volta reported the invention of the "electric pile" in his famous letter, dated March 20, 1800, to Sir Joseph Banks (1743-1820), president of the Royal Society in London. His report was published in the Physical Transactions [14] and the Philosophical Magazine [15].

Volta reported in detail about piles of up to 60 pairs of zinc and silver plates (Fig. 1). One should recall that electrical instrumentation of 1800 was geared to measure charge at high potential as obtained by frictional electricity. Instruments like Abraham Bennet's gold leaf electroscope used electrostatic repulsion to quantify charging of Leyden jars, for example. Volta attempted to measure the *forza motrice* (electromotive force, a term he had introduced in 1796 [16] p.135) of the pile using his straw electrometer. He obtained a feeble deflection, which other researchers could not consistently reproduce ([17] pp.90-95). The strength of a single electrochemical cell was indeed best shown using a prepared frog leg, as extensively demonstrated by Galvani, and the strength of a pile was still best evaluated using the physiological response of the human body. Volta reports:

> *"To obtain such slight shocks from this apparatus which I have described, and which is still too small for great effects, it is necessary that the fingers, with which the two extremities are to be touched at the same time, should be dipped in water, so that the skin, which otherwise is not a*

good conductor, may be well moistened…. I can obtain a small pricking or slight shock …by touching...the fourth or even third pair of metallic pieces. By touching then the fifth, the sixth, and the rest in succession till I come to the last, which forms the head of the column, it is curious to observe how the shocks gradually increase in force" ([15] pp. 292, 293).

One should note that Volta mentioned here that his battery "is still too small for great effects," suggesting that larger, more powerful batteries should be built. Later, in 1805, Volta explicitly calls for a pile of 1800-2000 pairs to obtain 35 degrees deflection of his straw electrometer ([17] p.94). Back in 1800, Volta continues:

> *"The effects sensible to our organs produced by an apparatus formed of 40 or 50 pairs of plates…are reduced merely to shocks: the current and variety of different conductors, silver, zinc, and water, disposed alternately in the manner above described, excites not only contractions and spasms in the muscle, convulsions more or less violent in the limbs through which is passes in its course; but it irritates also the organs of taste, sight, hearing, and feeling"* ([15] p.302).

Frighteningly from today's perspective, he then elaborates on the different levels of pain felt by various senses as a function of the number of metal pairs.

The English chemist William Nicholson (1753-1815) and the surgeon Sir Anthony Carlisle (1768-1840) learned about Volta's letter to Sir Banks before it was published. In June of 1800 they constructed a Voltaic pile and succeeded in decomposing water, which they published in Nicholson's own journal [18]. Their publication triggered tremendous interest in Volta's invention and, importantly for the discovery of the arc discharge, further development of the battery itself.

Among the excited researchers was William Cruickshank (1745-1800), a chemist best known for his work with Adair Crawford (1748-1795) of Scotland. In 1790 Crawford and Cruickshank showed that a certain mineral (strontium carbonate), named strontianite in 1791, differed from similar minerals of the element barium. They concluded that the mineral contained a new earth: strontium. However it was only in 1809 that Davy isolated strontium in its metallic form by using the electric current of a very large Voltaic pile (to be discussed below!). In 1800, just months before his death, Cruickshank designed a horizontal Voltaic pile (Fig. 2) consisting of rectangular zinc and copper plates in a resign-insulated wooden trough

[19]. Using his version of the pile, Cruickshank decomposed magnesium, sodium and ammonium chlorides, and precipitated silver and copper from solutions, an observation leading to electroplating. He also found that the liquid around the anode became acid, and that around the cathode alkaline. Cruickshank's style of the electrochemical battery became a widely used standard until in the introduction of Daniell cells in 1836.

Following the publication of Volta's sensational results, many researches built their own copy of Volta's pile (increasingly using Cruickshank's version) and started experiments, mainly focusing on the physiological and chemical effects of electricity. For example, Ritter examined the decomposition the water and the electrical effects on various senses. He moved on, asking: "Can we increase the action of a battery to infinity?"[20]. He struggled, like others, with electrical quantities other than the number of metal pairs. He showed that increasing the area of the electrode plates does not increase the voltage but it increases "the strength of a spark." A similar effect can be obtained by choosing an electrolyte of better conductivity (e.g. ammoniac versus salt water and pure water). We have to recall that it was only in 1825 when Georg Friedrich Ohm (1787-1854) formulated the fundamental law that couples voltage, current, and resistance [21]). The concept of internal resistance was not clear in the early 1800s, although it was empirically recognized that batteries of large electrode area and well-conducting electrolytes are more powerful.

Improvements to the voltaic pile were not only made but Cruickshank but also William Hyde Wollaston (1766-1828), best know for his contributions to optics, the French Antoine-Francois Fourcroy (1755-1809), and Robert Hare (1781-1858) of Philadelphia. Large voltaic piles were also constructed by Andrew Crosse (1784-1855), who is often portrayed as the archetypal "mad scientist" on whom "Frankenstein" by Mary Shelley (1797-1851) was modeled.

The search for the "first" continuous arc discharge is intimately related to the development of more powerful batteries because once a battery was capable of delivering enough current for a self-sustained arc, it would be hard to avoid finding arcing when performing experiments. However, to make the discovery, the experimenter also needs the skill for careful observation, interpretation, and exploration. Davy was one of such experimenters.

III. HUMPHRY DAVY: A CHEMIST USING THE VOLTAIC PILE, DISCOVERING NEW ELEMENTS AND THE ELECTRIC ARC

Humphry Davy (1778-1829) was a brilliant, outstanding scientist indeed. Still in Bristol, i.e. before his move to London in 1801, he quickly acquainted himself with Volta's pile, realizing that new chemical discoveries could be made [3]. Published in 1800, Davy reports:

> *"The earlier experimenters (*) on animal electricity noticed the power of well-burned charcoal to conduct the common galvanic influence. I have found that this substance posses the same properties as metallic bodies in producing the shock and spark (**), when made a medium of communication between the ends of the galvanic pile of Signore Volta…*
>
> *(*) The inventor of the galvanic pile discovered the conducting power of charcoal. His experiments were confirmed by Creve and Schmuck. See Paff on Animal Electricity, p. 48.*
>
> *(**) The spark is most vivid when the charcoal is hot."* [22]

In one detail, Davy was respectfully corrected in the only letter that is known to be sent to Davy by Joseph Priestley (*cf.* Part I):

> *"Sir – I have read with admiration your excellent publications,…I thank you for the favourable mention you so frequently make of my experiments, and have only to remark, that in Dr. Nicholson's Journal you say that the conducting power of charcoal was first observed by those who made experiments on the pile of Volta, whereas it was one of the earliest I made and gave account of in my history of electricity and in the Philosophical Transactions…"* [23]

He was referring to his work done in 1766 [24]. Davy's reference to charcoal is interesting because the development of the first truly continuous arc discharges made use of the graphite electrodes. From his early publications, we can infer that Davy had produced, observed, and reported on "spark" discharges with carbon electrodes, which in modern interpretation were, most likely, low-current arcs of short duration. The early Voltaic piles could not sustain continuous arcs due to their high internal resistance.

In the following year, 1801, Davy began his extraordinarily successful electrochemical research. Using increasingly powerful voltaic piles of Cruickshank's construction, he noticed discharges producing plasma:

"The apparatus employed in these experiments was composed of 150 series of plates of copper and zinc of 4 inches square, and 50 of silver and zinc of the same size. The metals were carefully cemented into four boxes of wood in regular order, after the manner adopted by Mr. Cruickshank, and the fluid made use of was water combined with about 1/100 part of its weight on nitric acid.

The shock taken from the batteries in combination by the moistened hands, was not so powerful but that it could be received without any permanently disagreeable effects…When the circuit in the batteries was completed by means of small knobs of brass, the spark perceived was of a dazzling brightness, and in apparent diameter at least 1/8 of an inch. It was perceived only at the moment of the contact of the metals, and it was accompanied by a noise or snap.

When instead of the metals, pieces of well-burned charcoal were employed, the spark was still larger and of a vivid whiteness, an evident combustion was produced, the charcoal remained red hot for some time after the contact and threw off bright corruscations.

Four inches of steel wire 1/170 inch of an inch in diameter, on being placed in the circuit became intensely white hot at the points of connection, and burnt with great vividness being at the same time red throughout the whole of their extent.

Tin, lead, and zinc, in thin shavings were fused and burnt at their points of contact in the circuit, with a vivid light and with a loud hissing noise. Zinc gave a blue flame, tin a purplish, and lead a yellow flame violet at the circumference.

When copper leaf was employed it instantly inflamed at the edges with a green light and vivid sparks,…silver leaf gave a vivid light, white in the centre and green towards the outline, with red sparks of corruscations. Platina in thin slips, when made to complete the circuit, became white hot, and entered into fusion….

A few only of these experiments have any claim to originality. On the phenomena of the combustion of bodies by galvanism we have been already furnished with many striking experiments, by our own countrymen, and by the German and French philosophers…." [25]

One may speculate that Davy, when reporting that charcoal "threw off bright corruscations," was referring to the cathodic arc mode of an arc, and the corruscations were "macroparticles" in modern terminology. At this time, however, he did not yet observe a *continuous* arc discharge.

IV. VASILII PETROV: THE FORGOTTEN RESEARCHER

The news about Volta's invention made it quickly also to St. Petersburg, capital of Russia since 1710. St. Petersburg was an new, attractive, quickly growing city within Russia. Since its foundation by Peter the Great (1672-1725) in 1703, the Russian Emperors promoted here the establishments of military, cultural, and scientific institutions that could match their counterparts in the West. Policies were put in place by Peter and later especially by Catherine II, Empress of Russia from 1762 to 1796, attracting many (West-)Europeans to the city. The Academy of Sciences and Arts was founded in St. Petersburg on Decrees of Peter the Great and the Governing Senate in 1724. Among the foreign scholars, many famous artists, scientists and engineers spent years or the rest of their life in the city. For example, the German-born Franz Ulrich Maria Theodor Aepinus (1724-1802) developed a theory of electrostatic phenomena in St. Petersburg. Christian Gottlieb Kratzenstein (1723-1795) was appointed as "mechanicus" to the Academy in 1748 ([26] p.460). Daniel Bernoulli (1700-1782), who became famous for developing hydrodynamic theory, was at the St. Petersburg Academy from 1730 to 1733 before being appointed as professor in Basle. The Swiss Leonhard Euler (1707-1783) was at the St. Petersburg Naval College from 1727 to 1730. He succeeded Bernoulli at the Academy in 1730 before moving the Berlin in 1744, but Empress Catherine II recalled him to St. Petersburg in 1766 to become the Director of the Academy of Sciences. The German-born Georg Wilhelm Richmann (1711-1753) worked closely with Mikhail Vasil'evich Lomonosov (1711-1765) on quantification and measurement of electricity. Richmann was killed while attempting to conduct electricity of lightning into his laboratory, an experiment based on earlier demonstrations by Benjamin Franklin. Priestley called this an "enviable, glorious death" for science ([24] p. 108).

Although still a new city, St. Petersburg had history and reputation in science when Vasilii Petrov became a professor in 1795 at the Military-Medical (formerly Medical-Surgical) Academy. Petrov has already investigated electrical phenomena at that time. He strongly advocated the expansion of the Physical Cabinet by acquisitions of equipment. Luckily, electrical phenomena were very fashionable and used for the entertainment of aristocrats. Wealthy donors helped to pay for modern equipment imported from Western Europe. In the late 1790s, Petrov could acquire two large influence machines with glass disks diameter of 40 inches and large copper conductors of 5 feet and 5 inches (1.65 m) length [27].

When the news of Volta's invention arrived in St. Petersburg, it came to researchers like Petrov, who were well-trained and prepared. Researchers all over Europe recognized that the availability of constant electricity from a Voltaic pile would allow them to perform new experiments and to make new discoveries. A race of making large batteries started. Indeed, comparable to the race for ever-greater accelerators in the 20th century, physics laboratories in the 19th century were judged by the size of their voltaic battery.

Petrov appeared at a meeting of the Military-Medical Academy and pleaded for the immediate acquisition of a "Galvano-Voltaic Pile" with the argument that many European physicists are about to conduct experiments with large batteries. His petition was successful. The Academy agreed to spend 300 Rubles, that is, 200 Rubles to order 200 zinc and copper plates, 25 cm diameter each, and the remaining 100 Rubles were assigned for a glass and copper container on a pedestal to accommodate stacks of metal and cardboard disks in wooden boxes. This battery was comparable in size with devices being built at European institutions at that time. Petrov, and other researchers, like Cruickshank, opted for the combination of copper and zinc because the use of silver and zinc was too expensive when considering scaling to large batteries. The design of the battery strongly resembles Cruickshank's horizontal battery of 1800, however it appears that Petrov did not know Cruickshank's description [19], and therefore the horizontal construction is likely his genuine (re-)invention. As it was costumary in Russian scientific literature at the time, references to previous work of others was simply given in the text by mentioning the name of the researcher. In this sense, Petrov referred to the work of Galvani and Volta. He explained his observations as being caused by the flow of the "Galvano-Voltaic liquid." Petrov did not refer to the work of Cruickshank.

Petrov realized that a larger battery would not only result in amplified effects but could lead to principally new effects. He successfully raised funds for an "enormous" battery, twenty times larger than the first. Count Dmitrii Petrovich Buturlin donated 28,000 rubles to the St. Petersburg and Moscow Medical-Surgical Academy ([28] p.2). The "enormous" battery consisted of 4200 copper and zinc disks.

Stacks of plates were mounted in four boxes of red wood and sealed by wax. Each box was 12 inch (about 30 cm) wide and 10 feet (about 3 m) long and consisted of two segments connected with movable copper bars. The bars could be used to connect or disconnect parts of the battery ([28] pp. 19-22). The four boxes were placed parallel to each other but alternately ended with zinc and copper so when connected represented a serial circuit of all 4200 electrochemical cells ([28] pp.22-25). Petrov defined and used the term "enormous battery" in the sense when all stacks were connect this way, however, other configurations were possible too ([28] p.25).

Especially for this very large battery, the horizontal arrangement appeared critical to solve a scaling problem of Volta's original design. Volta described vertical piles: If such pile was made too tall, the electrolyte, i.e. the salt water stored in cardboard disks, was squeezed out by the weight of the metal disks ([28] p.15). The horizontal design also allowed Petrov to fabricate the pile first and activate it later by adding the electrolyte (as it is done with Cruickshank batteries). Only when the pile was needed, fresh salt solution could be added, giving the battery the full strength. With the very large number of plates, the logistics of plate fabrication and pile activation needed to be worked out, and therefore Petrov devoted an extensive first chapter of his report [28] to this issue. He also addressed the issue of refurbishing the plates since he noticed that the power of the battery diminished when using it for as little as one hour. With the horizontal design and manufacturing and refurbishing procedures in place, Petrov was successful in making the world's largest battery at this time.

In more modern terms, one may do the following estimate. The open-circuit voltage of a battery is determined by the electrochemical potential difference of one cell multiplied by the number of cells. A cell containing copper and zinc will show

oxidation $Zn \rightarrow Zn^{2+} + 2\,e^-$ with an electrochemical potential of 0.76 V,

reduction $Cu^{2+} + 2\,e^- \rightarrow Cu$ with an electrochemical potential of 0.34 V.

Therefore the total cell voltage could be as high as 1.1 Volt. Replica copper-zinc cells of Cruickshank's (year 1800) construction show 0.85 V ([29] p. 8), which is less tha than the theoretical value due to internal resistance and leakage current. Still, with this number, an open-circuit voltage of 4200 copper-zinc cells in series was about 3500 Volt! Cells must have had significant internal resistance, which is most important when the load resistance is low, as it is the case when the load is an arc. The internal resistance depends on the electrolyte, electrode area, and construction and is difficult to estimate. Based on the effects Petrov obtained, the internal resistance must have been clearly less than 1 Ω per cell.

Once the large battery was completed, experiments could begin. Petrov noticed sparks at metals pieces when he interrupted the electric circuit. Using graphite electrodes, he observes:

> *"If two or three charcoal pieces are placed on a glass plate or on a bench with glass legs, and if the charcoal is connected to both ends of an enormous battery using metallic but isolated conductors, and if the two pieces are brought in close distance of one to three lines* [2.5-7.5 mm]*, then a very bright cloud of light or flame shines, burning the charcoal more or less fast, and one may illuminate a dark room as bright as one wants to."* ([28] pp. 163-164)

Petrov had made, observed, and described the first continuous arc discharge. Moreover, he suggested that the bright light or "flame" (plasma) could be used for lighting purposes – the first possible real application of electricity apart from entertainment of aristocrats.

When Petrove replaced on of the electrodes with metal, he observed melting, burning, and erosion of the metal.

> "If an iron spiral… holding a drop of mercury as one electrode, was …brought to the charcoal, which is connected to the other pole of the battery, than also between them a more or less bright flame appears, from which the mercury burns, but the end of the wire, almost in an instant, becomes red glowing, melts, and starts burning with a flame and throughing a very large number of sparks in different directions." ([28] pp.165-166)

While the carbon arc may have quickly switched into thermionic mode, the iron wire "throwing sparks in different directions" was in the cathodic arc mode, emitting the characteristic incandescent macroparticles.

Petrov conducted a number of experiments, including physiological studies of the large pile's electricity on the human body and senses, and experiments in the new field of electro-metallurgy. He reports:

> *"Finally, with the help of the flame accompanying the flow of the galvano-voltaic liquid, using the enormous battery, I tried to convert red lead and mercury oxide, and also grayish tin oxide, into their metal state; and the result was such that the before-mentioned oxides, mixed with*

powdered charcoal, lard, and pressed butter, sometimes burnt near hot bodies, assuming true metallic state." ([28] p.171)

Obviously, Petrov conducted groundbreaking experiments and may have even preceded Davy in some electrochemical results.

Returning to the "light bearing phenomena" in chapter 8 of his report, Petrov also investigated the phenomena in "vacuum" (rarefied background gas by today's understanding).

"The light, accompanying the flow of the Galvano-Voltaic liquid in the airless space, was bright, of white color, and not rarely form the glowing ends of the needles [electrodes]*, or from the sparks coming off like little stars."* ([28] p. 176)

Here there is little doubt that Petrov refers to a cathodic arc with maroparticle emission. He found the light emission in low gas pressure enhanced to atmospheric air, and he emphasises:

"The electric light in most perfect evacuated air represents an unequaled greatest phenomenon, as I could not have wished to obtain from the Galvano-Voltaic liquid." ([28] p. 190)

The question may arise, why did his work disappear in obscurity for about a hundred years, before his publication was accidentally discovered in a library by A.L. Gershun, a student of the same academy? Kartsev [27] gives three reasons. First, Petrov published his work only in Russian, a language that was ignored in the West. Second, the scientific community of Russia was isolated. Regular communication around 1800 largely depended on time-consuming travel. For example, even the communication between Volta and his German and English colleagues was slow and difficult [30], and it was slower to distant Russia. Finally, there was a "German Sway" in St. Petersburg that was at odds with Petrov [27]. Lomonosov's collaboration with foreigner Richmann was an exception rather than the rule ([26] p.392). Unlike today, politics was not free of bias, envy, and intrigue. A group of scientists in St Petersburg, most noticeable the Academicians Kraft, Fuchs, and Georg Friedrich Parrot (1767-1852) delayed Petrov's election as member of the academy and prevented the distribution of his work [27].

V. DAVY'S ARC DEMONSTRATIONS

About three years after Petrov's publication, and unaware of it, Davy in London made breakthrough electrochemical experiments using a large voltaic battery of several hundred metal pairs. He succeeded in the electrolytic decomposition of potash and soda, obtaining the metals potassium and sodium, which he announced at his famous Bakerian Lecture of 1807 ([31], also in [32]). He continued, isolating the elements barium, strontium, calcium, and magnesium in 1808. Because he used fairly large batteries, discharge phenomena accompanied the chemical research. Davy writes:

> *"…I acted upon aqueous solutions of potash and soda, saturated at common temperatures, by the highest electrical power I could command and which was produced by a combination of Voltaic batteries belonging to the Royal Institution, containing 24 plates of copper and zinc of 12 inches square, 100 plates of 6 inches, and 150 of 4 inches square, charged with solutions of alumn and nitrous acid….*
>
> *The flame of a spirit lamp, which was thrown on a platina spoon containing potash, this alkali was kept for some minutes in a strong heat red heat, and in the state of perfect fluidity. The spoon was preserved in communication with the positive side of the battery of the power of 100 of 6 inches, highly charged; and the connection from the negative side was made by a platina wire.*
>
> *By the arrangement some brilliant phenomena were produced. The potash appeared a conductor in a high degree, and as long as the communication was preserved, a most intense light was exhibited at the negative wire, and a column of flame, which seemed to be owing to the development of combustible matter, arose from the point of contact.*
>
> *When the order was changed, so that the platina spoon was made negative, a vivid and constant light appeared at the opposite point: there was no effect of inflammation round it: a aerifom globules, which inflamed in the atmosphere, rose through the potash.*
>
> *The platina, as might have been expected, was considerably acted upon: and in the cases when it had been negative, in the highest degree." [32]* (pp.58-60)

Not surprisingly, by 1808 his large battery at the Royal Institution was exhausted (the zinc consumed by oxidation, [29] p. 9). In July of 1808 Davy laid a request before the managers of the Royal Institution for a public subscription for the purchase of a very large voltaic battery. Davy, who was later knighted (1812) and became president of the Royal Society (1820), was already a leading figure of English science at that time, and his request was taken seriously. To continue his experiments he was provided with a battery of 2000 pairs of plates, whose total active electrode area was 80 m^2 ([7] p.21). Figure 4 show a contemporary drawing of the large battery located in the basement of the Royal Institution. This battery was so powerful that it allowed him to obtain continuous arcs, which he demonstrated several times, starting in 1809, to a very impressed audience in the theatre of the Royal Institution [3].

Indeed, it must have been a very impressed spectacle. One may roughly estimate the power of the electric discharge by considering that the arc voltage was about 30 Volts (cathode fall of about 15 V plus a voltage drop in the plasma column at atmospheric pressure), and the arc current may have been in the range of 10-100 A, leading to 300-3000 W. Compared with today's typical 40-100 W incandescent lamps one realizes that, in early 1800s, the presentation must have been truly spectacular and memorable. There exist several pictorial records, showing the very large battery in the vaults of the Royal Institution and enthusiastic crowds in the packed theatre (Figs. 5(a) and (b)). Davy's presentations of the carbon arc light (Fig. 6) made this type of discharge well known; it became part of established, documented science. However, the cost of a large voltaic battery was prohibitively high, and its capabilities for delivering power over longer times was limited, and therefore Davy did not suggest that illumination by arc discharge was an imminent technical development. Indeed, only after the discoveries of Hans Christian Oersted (1777-1851) and Michael Faraday (1791-1867), generation of electricity by electromagnetic induction promoted relevant development of arc lamps [7, 9, 29]. Before commercial development occurred, research in the first decades of the 19th century focussed on the development of longer-lasting carbon rods, the effect of the relative electrode position, i.e. horizontal versus vertical, with either the positive or the negative electrode on top. To reduce carbon mass loss, the arc was also placed in an exhausted glass chamber (Fig. 7), but this development goes beyond the early discharges, which were the subject of this paper.

Summary and Conclusions

The previous discussion showed why it is difficult to the answers the questions "Who was the discoverer of continuous arc discharges, and when was the discovery made?" It appears that Petrov and Davy have made, independently, the discovery by pushing the development of very large voltaic batteries. Both have used horizontal piles, and both discovered that graphite electrodes are particularly suited for producing impressive illumination effects. According to publications, Davy made short arcs ("sparks") as early as 1800 using a voltaic pile. Petrov, in 1802, demonstrated continuous arcs powered by his "enormous" battery. Petrov envisioned the possibility of future electrical illumination. Davy, using the new 2000-pair voltaic pile made for the Royal Institution in London in 1808, demonstrated carbon arc discharges to the interested public. While Petrov could claim priority for continuous carbon arcs, it was Davy who made a lasting impact on further development.

Acknowledgements

I am indebted to my friend Gera Yushkov, Tomsk, Russia, for his effort to make a copy of Petrov's book available to me and discuss the role of Petrov. I thank Brian Bowers, former Senior Curator of Science Museum, London, for permission to reproduce Fig. 2, and Ellen Kuhfeld of The Bakken, A Library and Museum of Electricity in Life, Minneapolis, MN, for helpful discussions. This work was supported by the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

Figures

Fig. 1. One example of Volta's batteries, here consisting of two piles of 8 pairs of silver and zinc plates, each (from Plate VIII of [15]).

Fig. 2. Cruickshank's improved Voltaic pile of 1800; it consists of rectangular zinc and copper plates in a resign-insulated wooden trough; the electrolyte (e.g. salt water) could be added when the battery was needed (restored original at the Royal Institution, photo courtesy of Brian Bowers).

Fig. 3. Front page of Petrov's book of 1803 in which he describes the making of an "enormous" voltaic battery and in which he announces the discovery of the arc discharge, among other observations [28].

Fig. 4. The large battery located in the basement of the Royal Institution. One can recognize the 200 wax-sealed wooden boxes containing metal plates and electrolyte, and also to the two wires leading up to the theatre.

Fig. 5 Two pictorial records showing the very large battery in the vaults of the Royal Institution and enthusiastic crowds in the packed theatre of the Royal Institution in London (at or after 1809). Note the sharp shadow caste by Davy's body, which emphasizes the brightness of the arc discharge.

Fig. 6 Arc discharge between carbon (graphite) electrodes in air; here the anode is above the cathode. (from [7] p.33)

Fig. 7 Early carbon arc lamps in air and in exhausted glass vessels.

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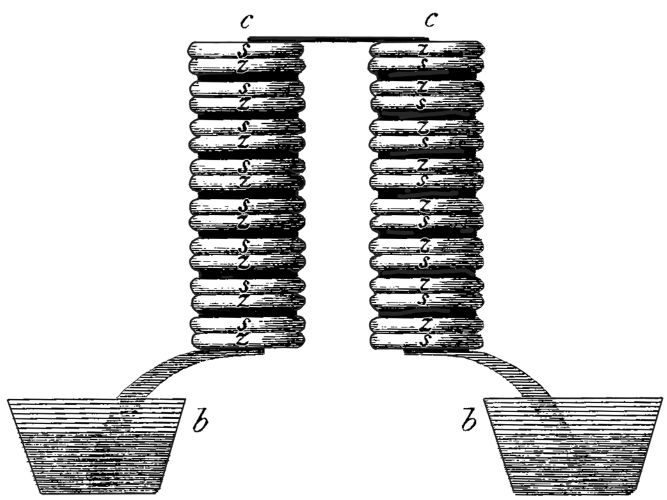

Fig. 1

Fig. 2

ИЗВѢСТІЕ

О

ГАЛЬВАНИ - ВОЛЬТОВСКИХЪ

ОПЫТАХЪ,

которые производилъ

Профессоръ Физики Василій Петровъ,

посредствомъ огромной наипаче баттереи, состоявшей *иногда* изъ 4200 мѣдныхъ и цинковыхъ кружковъ, и находящейся при Санктъ - Петербургской Медико - Хирургической Академіи.

ВЪ САНКТ-ПЕТЕРБУРГѢ,

ВЪ Типографіи Государственной Медицинской Коллегіи, 1803 года.

Fig. 3

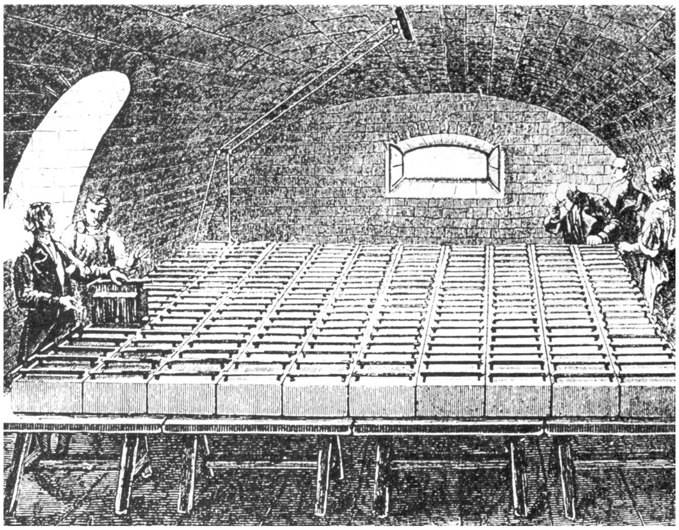

Fig. 4

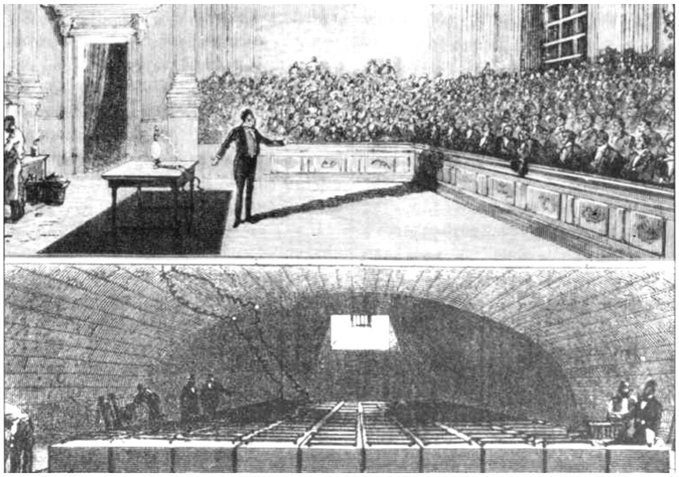

Fig. 5(a)

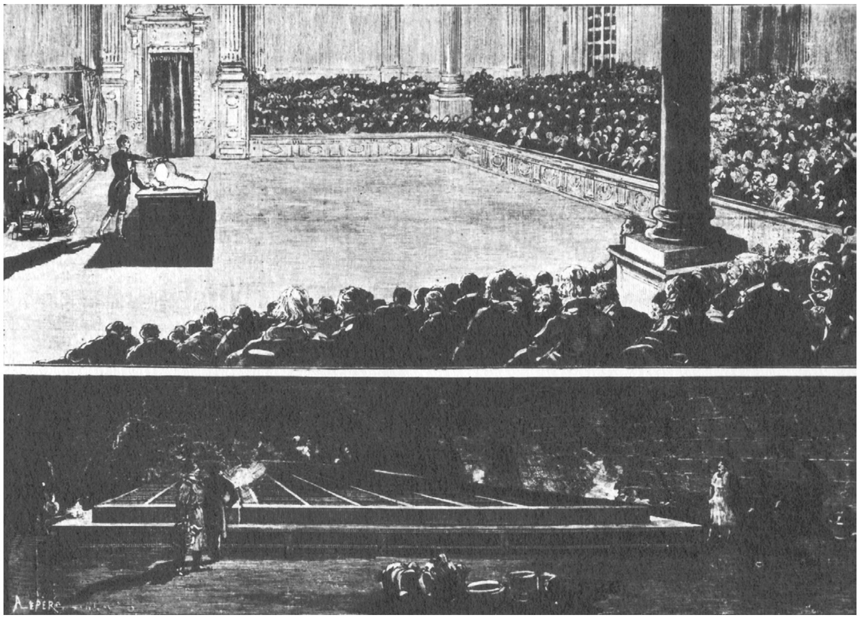

Fig. 5(b)

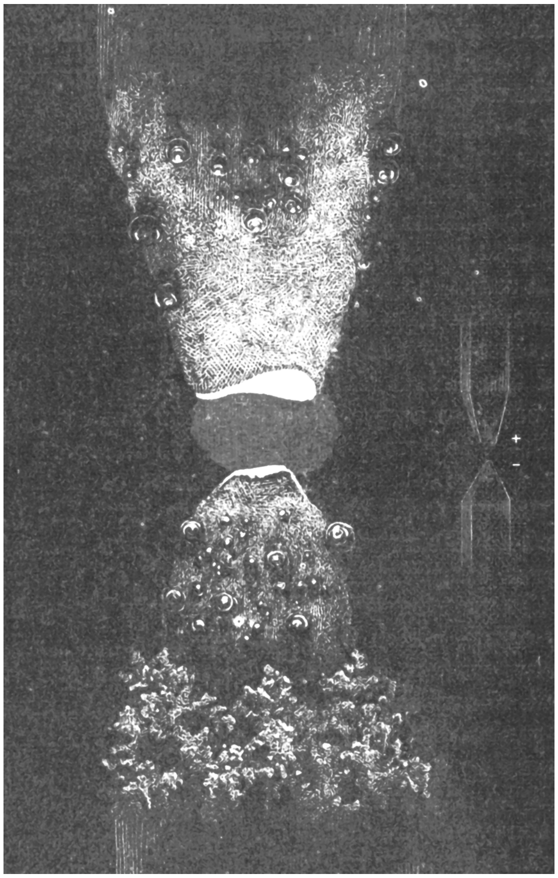

Fig. 6

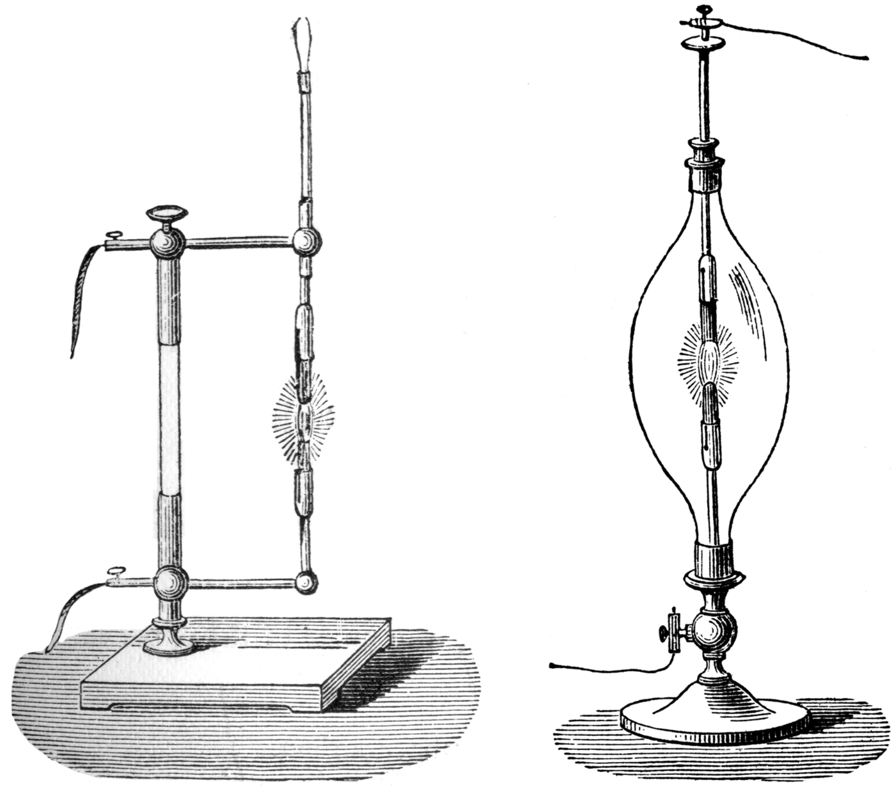

Fig. 7