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RICHMANN'S AND LOMONOSOV'S RESEARCH IN THE FIELD OF THERMOELECTRICITY (1745 – 1753)

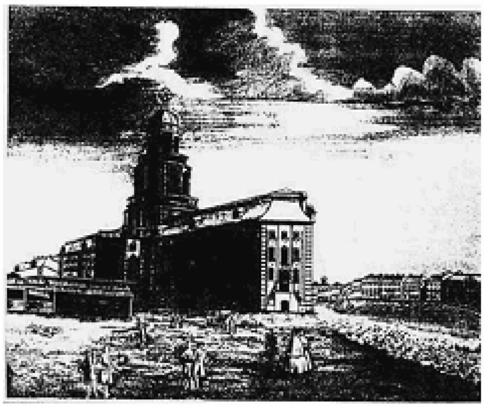
The works of G.-W. Richmann and M.V. Lomonosov, academicians of Saint-Petersburg Academy of Sciences (1745 – 1753) on studying "heat ↔ electricity" cross effects in the gaseous, liquid and solid dielectrics are considered. These effects are compared to thermoelectric (TE) effects observed in other thermoelectrically-active media. It is shown that TE effects in dielectrics feature large operating voltages (U up to 10^3 – 10^5 V or more) and small discharge currents (I ~ 1 – 10 μA) due to high intrinsic resistivity ρ of the samples. The paper is dedicated to the thousandth anniversary of cultural interaction between Russia and Germany commemorated in 2012.

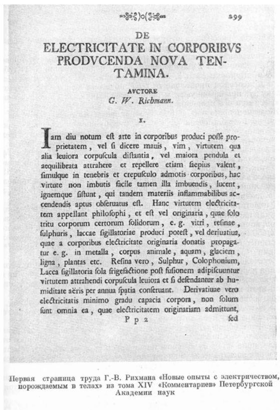
Key words: thermoelectrets, atmospheric electricity, thermoelectricity.

Introduction

The sequence of discovery of the basic TE effects in various thermoelectrically-active media has been studied previously [1-3]. According to [3], the first TE effects were found in dielectrics where they are of the highest value (the measured voltage U is up to 10^2 – 10^3 V or more).[1] It was not until later, with increasing instrument sensitivity, that TE effects were also found in metals (1821) where their value is essentially limited by the strong Fermi degeneration of samples ($U \sim 10^{-3}$ V) (T.I. Seebeck (1770 – 1831)). The present paper contributes to further research [3]. The paper discusses the experiments of academicians G.-W. Richmann (1711 – 1753) (Fig. 1)[2] and M.V. Lomonosov (1711 – 1765) (Fig. 2) in thermoelectricity carried out in St. Petersburg Academy of Sciences in 1745 – 1753 [4-5]. The Academy (founded in 1724) was specialized in natural science research, both academicians working at the junction of the theories of electricity and heat. As a result, Richmann was the first to discover and study a series of TE effects in dielectrics (charge transfer by flame, TE effects in sulfur and resins, etc.) [4]. Together with Lomonosov he was the first to discover and study complex atmospheric TE effects responsible for the electrization of clouds [4, 5]. It is shown that one of these atmospheric TE effects could have caused the tragic death of Richmann (1753).

[1] Some of these effects have been known since ancient times [3].
[2] Richmann and Seebeck were born in the Russian Empire, in the families of Baltic Germans - Lutherans. Both were at various times trained in the former Swedish Gustav II Adolf's grammar school in Reval (now Tallinn, Estonia) of what the local regional specialists E. Velmre and E. Keerov have kindly informed us.





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DE
ELECTRICITATE IN CORPORIBVS PRODVCENDA NOVA TENTAMINA.

AVCTORE
G. W. Richmann.

I.

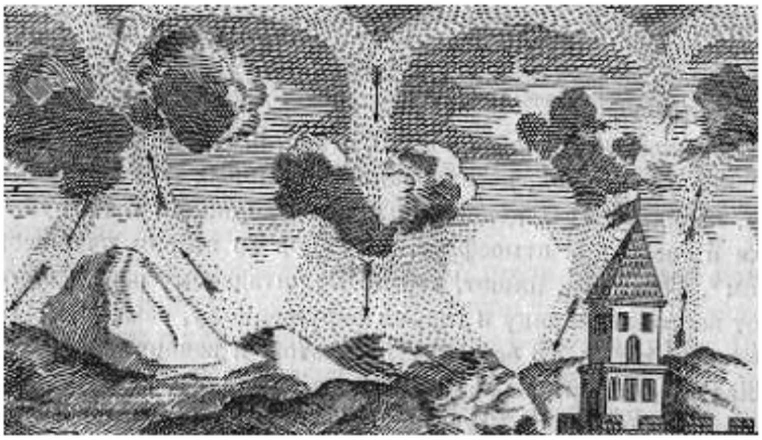
Iam diu notum eſt arte in corporibus produci poſſe proprietatem, vel ſi dicere mauis, vim, virtutem qua alia leuiora corpuſcula diſtantia, vel maiora pendula et aequilibrata attrahere et repellere etiam ſaepius valent, ſimulque in tenebris et crepuſculo admotis corporibus, hac virtute non imbutis facile tamen illa imbuendis, lucent, ignemque ſiſtunt, qui tandem materiis inflammabilibus accendendis aptus obſeruatus eſt. Hanc virtutem electricitatem appellant philoſophi, et eſt vel originaria, quae ſolo tritu corporum certorum ſolidorum, e. g. vitri, reſinae, ſulphuris, laccae ſigillatoriae produci poteſt, vel deriuatiua, quae a corporibus electricitate originaria donatis propagatur e. g. in metalla, corpus animale, aquam, glaciem, ligna, plantas etc. Reſina vero, Sulphur, Colophonium, Lacca ſigillatoria ſola frigefactione poſt fuſionem adipiſcuuntur virtutem attrahendi corpuſcula leuiora et ſi defendantur ab humiditate aëris per annua ſpatia conſeruant. Derivatiuae vero electricitatis minimo gradu capacia corpora, non ſolum ſunt omnia ea, quae electricitatem originariam admittunt,

P p 2 ſed

Первая страница труда Г.-В. Рихмана «Новые опыты с электричеством, порождаемым в телах» из тома XIV «Комментариев» Петербургской Академии наук

a) *b)* *c)*

Fig. 1. A monument to Richmann in his homeland in Pärnu (Estonia) (sculptor E. Kuulbush, 2011) (a), the Kunstkamera Museum in SPb, (engraving 1730 – 1740) (b), and the priority paper on the thermoelectrets discovered by Richmann ("Comments of the Petersburg Academy of Sciences", V. 4, 1751) (c) [4].



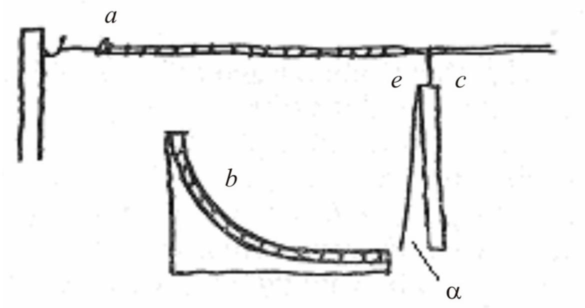
a) *b)*

Fig. 2. Complex atmospheric TE effect explaining electrization of clouds by friction of the ascending and descending air flows (1753) (a) [5]. A bust of M.V. Lomonosov (Sculptor F.I. Shubin, 1792). Lomonosov Museum, the Kunstkamera Museum, SPb (b).

1. Richmann's works on thermoelectricity

Academician Richmann went down in the history of physics as the inventor of the "electric pointer" (electrometer), the first device suitable for quantitative measurements of electric voltage U (Fig. 3 *a*) [6]. The operation of Richmann's "pointer" is based on the laws of electrostatics. When connected to a source of electricity by wire (*a*), the movable thread (*e*) and the stationary lineal (*c*) obtained electric charges of the same sign. As a result, the thread deviated from the lineal by the corner α which determines the measure of the electrical force ($U \sim \alpha$, for small angles α) (Fig. 3 *a*).

In 1745, Richmann was appointed head of the Physical Cabinet of St. Petersburg Academy of Sciences located in the Kunstkamera Museum up to the 1747 fire (Fig. 1 *b*). It was there that Richmann began the first studies of "heat-electricity" cross effects in various thermoelectrically-active media [3, 4]. At an early stage of his research, Richmann "*... carrying out his own and repeating somebody else's experiments on electricity ... came across many new phenomena that he had not found in the works of his predecessors*" ([4], p. 207).

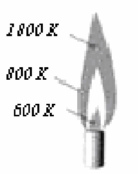


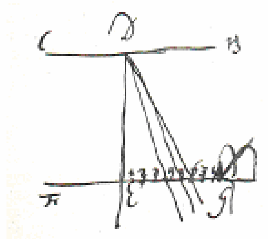
a) b)

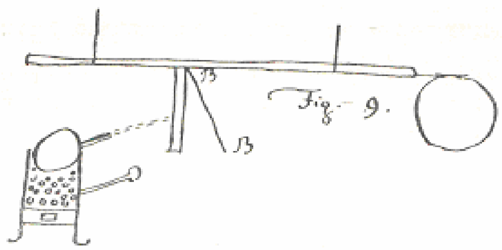
Fig. 3. Richmann's "Electric pointer" (1745) (c – "lineal" (Fe), a – lead wire (Fe), e – linen thread (weight – ½ apothecary grain (0.312 g), length – 1 ½ London ft (0.4572 m), b – wooden quadrant with a scale [4] (a) and the Cavallo electrometer (1799) with a protective case (b) [6].

The first success in Richmann's investigation of TE effects was achieved when studying the effect of electric charge transfer by flame. This effect had been described by Gilbert as applied to the case of charge transfer from dielectric to dielectric [7]. Richmann managed by the same method to transfer electrical charge from dielectrics (in his terminology – "electricitas originaria" – "primary electrical bodies" ("PEB") to metals ("electricitas derivative" – "secondary electrical bodies" ("SEB") (conductors)) [4]. Richmann wrote: "*June 30th (1746). Using a lit candle, I rejected electricity ... <from the electrophoresis> to the table, from the table to the chandelier, from the chandelier to the flame, from the flame to iron plate ...* " [4]. Richmann then investigated the effect using his "pointer": "*... I brought wax candle flame to the CB iron wire (connected to the source of the charge) ... and the pointer began to show a smaller degree* α" (Fig. 4 *a*) ([4], p. 268). Comparing the effect of the extinguished and burning candle on the pointer readings, Richmann found that it was not the candle itself that rejected electricity, but its flame ([4], p. 212). In this case, the transfer of electricity was also observed when a burning candle was sufficiently removed from the wire. Richmann found that the products of candle combustion also transferred the electrical charge: "... *an electrified body ... attracted some of the smoke from the extinguished candle, and the other part of smoke ascended as usua*l" ([4], p. 222). [3]

At the same time, a blast of water steam produced by the aeolipile (steam turbine) invented by Heron of Alexandria and directed at "electric pointer" practically did not change its readings (Fig. 4 *b*). Hence Richmann concluded that "... *for the rejection of electricity one needs a solid PEB. But water vapors are corpuscles separated by certain gaps and unable of forming a solid PEB and they can neither take nor reject any appreciable amount of electricity*. "([4], p. 312).







a) b) c)

Fig. 4. Schematics of Richmann's experiments (original figures) with candle flame (a), electric indicator (b) and the aeolipile (steam turbine) of Heron of Alexandria (c) [4].

[3] The conductive properties of flame and the charge of smoke particles are determined by ions and radicals formed in combustion process and forming a conductive halo around the flame [8].

Richmann also made a number of important discoveries in triboelectricity. As is known, charge transfer at mutual friction of different materials promotes local temperature increase in the microregions of frictional contact (ΔT_{local} to 10^3 K or more) [8]. Richmann found that the initial temperature T_0 of the samples also affects the processes of electrization by friction. He showed that dielectrics having a lower triboelectricity compared to amber (agate, jasper, porphyrites, granite, marble, etc.) can also be successfully electrified by friction. For this purpose, they "... should be hot and rubbed for long time." [4] Richmann also recommended heating "... to the point of ignition" the relevant counter-bodies (bristle, leather, parchment, paper, silk, linen, etc.). Finally, for the first time Richmann managed electrifying metal by friction using intermediary material. He inserted iron bars into thin glass jars and "... excited electricity by gently stroking, whereby these rods emitted a spark when touching them" ([4], p. 285). [5]

However, the most important result in thermoelectricity was obtained by Richmann studying thermoelectret effect in sulfur and resins (1746) [2]. [6] Richmann wrote: "*June 25, 1746. I melted the bodies which, when cooled and solidified, being protected from air moisture have long lasting (for instance, for a year) electricity (common sulfur, wax, resin or rosin) ...*" ([4], p. 244). With his "pointer" Richmann found that sulfur and resins can be electrified both by friction and by "melting-solidification" [4]. Richmann published the results of his experiments in the priority article: "Recent experiments with electricity generated in the bodies" ("Comments of the Petersburg Academy of Sciences", v. 4, 1751) (Fig. 1 *c*) [4]. [7] Table 1 shows the main types of electrets currently known and the thermoelectrets discovered by Richmann [9]. From Table 1 it is clear that Richmann is the pioneer of the monopoly (plus sign) thermoelectretic effect observed in a number of dielectrics at "melting-solidification" phase transition (Table 1).[8] Charging samples with "electricity", Richmann then investigated the possibilities of maintaining the resulting electrical charges under various conditions. He studied in detail the acceleration of charge leakage processes from the sharp parts of samples, wetted by water and depending on room humidity ([4], p. 645 and 237). According to Richmann (1748), "... *in a wooden house electricity often persisted for 50 minutes before disappearing, whereas in stone <rooms> ... it could not persist for more than 10 minutes. Possibly, moisture contained in a stone house rejects electricity*" ([4]).

According to modern concepts, the process of relaxation of the electric potential of charged bodies depending on the time t follows an exponential law

$$U(t) = U_0 \exp(-t/\tau), \tag{1}$$

where U_0 is the initial value of the potential, $\tau = \min(\tau_M, \tau_M^0)$, τ_M, $\tau_M^0 = \varepsilon_r \cdot \varepsilon_0\, \rho$ is `Maxwell relaxation time for the test material and the environment, $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m and ε_r are the dielectric constant and the relative dielectric constant (static), ρ is the resistivity of the material or medium [8, 12]. Table 2 shows a comparison of the values τ_M and τ_M^0, calculated for different materials and media according to present data [12] and according to Richmann's data (marked with *)) [4].

[4] The effects are related to decreasing the output energy of electrons from materials with a rise in temperature [8].
[5] Since the time of Gilbert, the majority of physicists had shared the opinion that metals cannot be electrified by friction [7]. The Richmann's effect is obviously related to glass electrification with subsequent charge transfer to metal.
[6] Currently one refers to electrets the dielectrics with resistivity $\rho > 10^{12} - 10^{17}$ Ω·m, which are able of accumulating and storing the nonequilibrium electric charges for 1 to 10 years or more [9].
[7] Sometimes the discovery of thermoelectrets is attributed to Epinus or Wilke (1765) [10] who found different signs of the charges received by the sulfur (-) and the casting mold (+) which in due time had been overlooked by Richmann [11].
[8] The effect is associated with the formation in sulfur band gap (E_g = 2.6 eV) of the deep donor levels [9].

From Table 2 it is clear that Richmann correctly identified the characteristic times of the charge leakage from the samples at varying humidity in the room. In particular, from Table 2 it follows that the charge on thermoelectrets (sulfur, wax, etc.) in a dry place really could persist for up to a year or more [4].

Table 1

*The main types of electrets depending on the production method**

№	Name	Method of charging	Charge	Examples	Discoverers
1	Triboelectrets	Friction on counterbody	Monopole	Amber$^-$/yarn$^+$ Glass$^+$/silk$^-$ Resin$^-$/wool$^+$ Sulfur$^-$/cloth$^+$	Thales of Miletus (625 –545 B.C.) Dufay (1733) -«- Aepinus, 1765
2	Thermoelectrets	Melting-solidification	Monopole	Sulfur$^+$/cup$^-$	Richmann, 1746 Aepinus, Wilke, 1765
3	Electro-thermo-electrets	Similarly, but in electric fields	Dipole	Wax	Eguchi, 1919
4	Ferro-electrets	Cooling below T_c (Curie temperature), electric field	Dipole	Segnett's salt, KDP (kaliumdihydro-genphosphate), TGS (triglycinesulphate)	P. and J. Curie,1880, F. Pockels, 1894

* There are also corona-, photo-, radio-, chemo-, mechano-, bio-and other electrets whose electrization is not connected directly to the thermal effects on the samples [9].

From Table 2 it also follows that candle flame reduces air resistivity ρ by 3 – 4 orders, although the value of ρ in the flame zone still retains a significant amount corresponding to "bad" dielectrics (wood). From Table 1 it is also evident that the triboelectric effect in metals under normal conditions is not observed because of the small τ_M. However, this does not preclude impact electrization of metals [8] [9].

Table 2

Maxwell relaxation times τ_M of charges for different materials and media [4, 12]

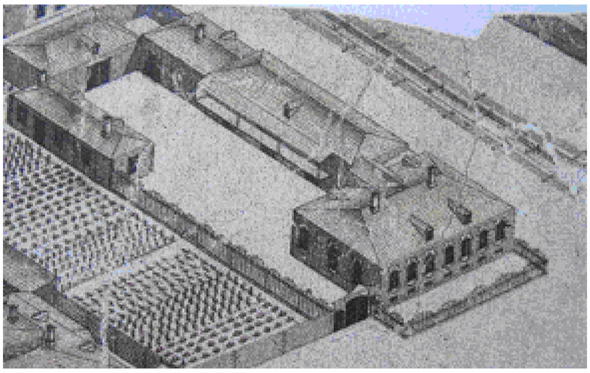
Media	ε_r	ρ, Ω·m	τ_M^0, c	Material	ε_r	ρ, Ω·m	τ_M, c
Dry air	1	$> 10^{15}$	$>10^4$ $\sim 3.10^{3\,*)}$	Sulfur	3.7	10^{17}	$\sim 10^6$ $\sim 10^{8*)}$
Natural ionization air**	1	10^{14}	10^3 $\sim 6.10^{2\,*)}$	Sealing wax	~3	10^{16}	10^5
				Oils		$10^{11} – 10^{14}$	$1 – 10^3$
Humid air (100%)	1	$< 10^{13}$	$< 10^2$	Paraffin	2.2	$10^{14} – 10^{16}$	$10^3 – 10^5$
Candle flame	~ 1	$\sim 10^{11}$	~ 1	Amber	2.9	10^{18}	10^7
Rain water	31	10^4	10^{-6}	Paper	2-4	10^{15}	$\sim 10^4$
Sea water	31	0.3	$\sim 10^{-11}$	Iron	~ 1***	10^{-7}	$\sim 10^{-18}$
Wet soil	~ 10	10^2	$\sim 10^{-8}$	Wood	3.5 – 5	$10^9 – 10^{13}$	$10^{-2} – 10^2$

$^{*)}$ – Richmann's data ** – at the Earth's surface; *** – the contribution of the crystal lattice.

[9]The method was proposed by Lomonosov (1753) ([5], p. 278), and then successfully implemented for metals by acad. V.V. Petrov (1761 – 1834) in his work "The new electrical experiments" (1804) [5, 6, 8].

2. Atmospheric thermoelectric effects

In 1752, the "St. Petersburg News" published the first message on the B. Franklin's experiments proving the electrical nature of lightning [13]. Richmann immediately embarked on a study of atmospheric electricity, having adapted for measurement his "electrical pointer" (Fig. 3 *a*). A little bit later academicians M.V. Lomonosov (theoretical issues) and K.G. Kratzenstein (1723 – 1795) (creation of lightning arresters) also joined in the research on atmospheric electricity [4, 14] [10]. By that time Lomonosov had already considerable scientific developments on the matter under investigation [5, 15, 16]. In 1744 – 1748 he held systematic observations of thunderstorms at his home in St. Petersburg and established their TE nature (Fig. 2 *a*) [5, 16]. Lomonosov found that "... the storm clouds mostly in the afternoon occur ... when the actions of the sun to heat the air all the more sensitive" ([5], p. 236). p. 226).[11] The mechanism of cloud electrization was attributed by Lomonosov to mutual friction of ascending and descending air flows at convection resulting from the non-uniform heating of the Earth's surface by solar rays (Fig. 2 *a*). The widely known characteristic of atmospheric electricity by Lomonosov is "... *Electric force produced by natural heat* ..." ([5], p. 226). As the other thermal sources of atmospheric electrization, Lomonosov also considered the Earth's interior heat, fires and even smoking [5]. Richmann and Lomonosov started their experimental study of atmospheric electricity with construction of "thunder machines" – installations for the production of electricity from storm clouds by Franklin's method (Figs. 5 and 6) [13]. Since the late 1752 Richmann had in his town house (Fig. 5 *a*) two "thunder machines" with "sharp" and "blunt" rod ends (Fig. 5 *b*) which were used for comparative measurements ([4], p. 653). In 1753 Lomonosov placed one of the installations in his town mansion (Fig. 6 and 6 *b*), the other – in "the village" (Estate Ust-Ruditsa) (Fig. 6 *c*), where he built his factory of art mosaics ([5], p. 260).



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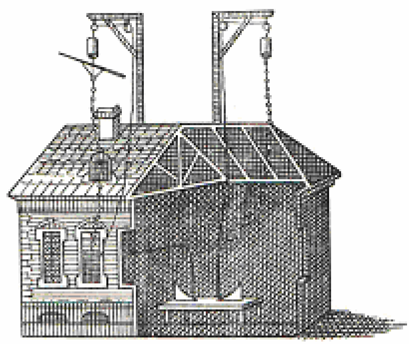


b)

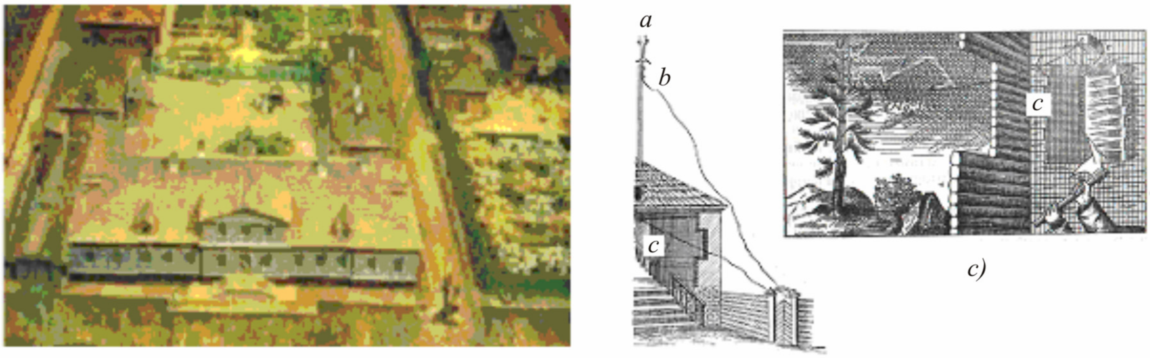
Fig. 5. Richmann's mansion with a one-story brick house "on the basement" on the corner of Great Prospects and Line 5 in SPb (right side) (a) [18] and his "thunder machine" (end of 1752) (b) ([4], p. 653) [28].

All installations were similar and consisted of isolated vertical or inclined iron rods placed on the roofs of the houses (Fig. 5 *b* and 6 *b*) or on the trees (Fig. 6 *c*). The rods acted as aerials that were connected with iron wires (or chains with Richmann) to "electrical pointers" (Fig. 3 *a*). Electrical wire insulation was carried out with a silk cloth. Richmann placed his pointers inside the house (Fig. 5), Lomonosov

[10] Acad. K.G. Kratzenstein (1723 – 1795), physician, physicist and engineer. After Richmann's death (1753) he was dismissed from the Academy at the end of the contract period (1748 – 1753). He went to Copenhagen to study the theory of gases and the application of electricity in medicine [4, 6].

[11] According to present data, the electrical activity of the Earth's atmosphere is also significantly affected by cosmic rays [12, 17].

conducted observations outdoors (points *c*, Fig. 6 *b* and 6 *c*) (Fig. 1).[12] To improve inleak of charges from the atmosphere, Lomonosov's installations had "many metal needles" at the ends of the rods (Fig. 6 *b* and 6 *c*)[5], p. 265.



a) b)

Fig. 6. "Bonn house" mansion in the second line of Vasilevsky Island in SPb where Lomonosov resided (1741 – 1757) (third building on the left in the background is Lomonosov's chemical laboratory), (a) [15] and his "thunder machines" (May 1753) (b), and (June 1753) (c) (a – aerial; b – lead wire, c – the place of observation) [5, 16].

The experimental works of Richmann and Lomonosov with the "thunder machines" proved to be extremely fruitful. Richmann identified the range of variation of pointer readings α and found that in the area of St. Petersburg "the highest degree α to which the thread is raised by the action of natural electricity was the 30th" ([4], p. 358). He found that for the clouds offset from the observer by the distance of $L > 3$ km, the value of α (that is the normal component of electric field E) at observation point decreases with increasing time interval between lightning and thunder $L \sim \Delta t$ ([4], p. 358) (curve 1, Fig. 7). [13] In turn, Lomonosov found that the primary cause of atmospheric electricity are not thunder and lightning proper, but the electrical charges of the clouds [4] (p. 269). He also found small deviations in α readings of "electric pointer" and for a cloudless sky. [14] On this occasion Richmann wrote: "*The renowned man Lomonosov observed that even in the absence of thunder and lightning, significant electricity is transferred to iron properly insulated. As for me, I observed that electricity after lightning and thunder was immediately reduced* "([4], p. 358).[15]

Using as a prototype the earlier work of I.G. Winkler (1746), Richmann concluded that the physical mechanism of cloud electrization consists in the friction of PEB (solid particles[16] or water vapors) with SEB (water droplets) ([4], p. 640). Lomonosov did not find in the air any sufficient number of solid particles, and as a PEB he considered hypothetical ether oils evaporated by animals and plants. Then, making sure there are none, as a possible mechanism of cloud electrization Lomonosov proposed "*fight (impact) of electric vapors and their friction at counter motion in the atmosphere"* [5]. The latter mechanism with variations has been used to this date to account for cloud electrization [17].

[12] The two houses of Lomonosov were wooden and had increased fire hazard ([5], p. 260).
[13] Recalculation of $\Delta t \leftrightarrow L$ and $\alpha \leftrightarrow E$ was made by us for relationships – $\alpha \sim E^{0.5}$ and $\alpha = 30^0 \sim /E/ = 25$ kV/m.
[14] According to our estimates (Fig. 7), the sensitivity of Lomonosov's installation was sufficient ($\Delta\alpha \sim 0.5^0$) to observe Earth's natural field $E_0 \sim 0.14$ kV / m (↓)) in good weather [12].
[15] The effect is due to the annihilation of positive and negative charges in the cloud discharges [17].
[16] As it was established later, Richmann's mechanism explains electrization of atmosphere in the zone of industrial emissions containing solid particles [17].

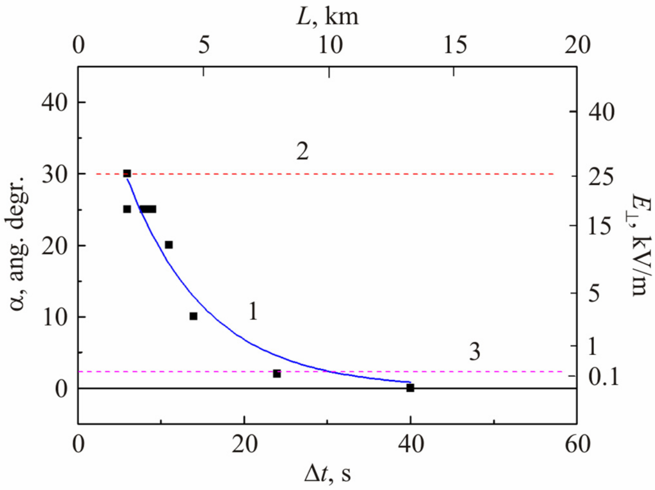
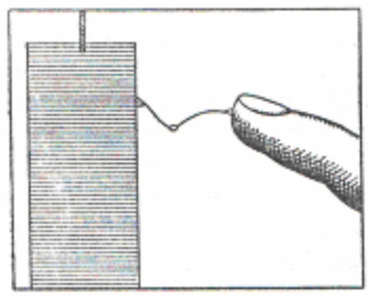


Fig. 7. The α readings of Richmann's "pointer" and the corresponding changes in the electric field E (↓ or ↑) versus the delay of "lightning-thunder" signals Δt and the distance L to the storm front (recalculation is ours). 2 – α_{max} ([4], p. 358), 3 – $E_\perp^0$ ~ 0.14 kV/m (↓) is Earth's natural field in the cloudless sky.

On July 26, 1753, Lomonosov and Richmann for the last time attended together the meeting of Saint-Petersburg Academy addressing an issue of their reports on atmospheric electricity that were appointed on September 5, 1753. About 12:00 p.m. noon, when a big storm cloud appeared over Petersburg, they left the meeting and both went to their homes for making observations. Richmann took with him the academic engraver I.A. Sokolov to create drawings for "Petersburg News" newspaper. On entering the house and getting closer to his installation at a distance of about a foot (about 30 cm), while the sky was still cloudless, Richmann was struck by a discharge of atmospheric electricity (Fig. 8 *b*). A white and blue ball the size of a fist that separated from the electrometer lineal touched the scientist's head and then exploded. Sokolov, who was standing a little aside, got a few sparks from the falling wire, flung out of the room and called the fire brigade. Richmann's wife, Anna Elizabeth Hinze, tried to give her husband mouth to mouth. Reanimation attempts were continued by Kratzenstein who urgently came to the place of accident, but he failed to reanimate the academician. Lomonosov who also arrived at Richmann's house, wrote to Count Shuvalov, favorite of Empress Elizabeth: "... *the thunder killed Professor Richmann in exactly the same circumstances I was at that time ....*".



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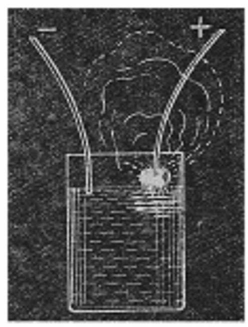
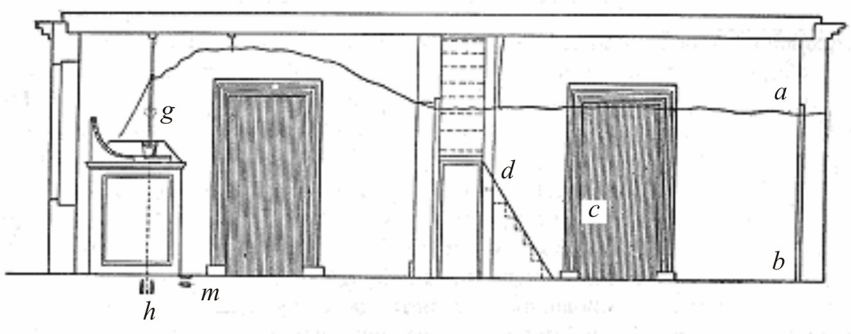


c)

Fig. 8. Different types of electrical discharges: a – an individual spark observed by Lomonosov [5], b, c – positive plasma streamers (glowing ball discharges). b – Richmann's death as described by Sokolov [4], c – Plante experience with liquid electrolyte (1883) [8].

Richmann's unusual death caused a wide resonance in Russia and abroad. The incident was investigated by the academic committee (Ch.G. Kratzenstein, M. Schreiber, M. Kleinfeld) [4], [17] Lomonosov pursued his own independent inquiry [4, 5]. Kratzenstein reported (Fig. 9) that a loop of electric shock ran from the left side of Richmann's forehead to his left heel (with separate outputs for left chest and under the ribs), which, according to contemporary statistics, is typical of head electrocutions [20]. Kratzenstein also established places of electrical breakdowns in the house (Fig. 9 *b*) and stated the main reason for the accident, namely the violation of safety rules (the installation was not grounded) (Fig. 5).[18] According to Kratzenstein, lightning did not spread from the roof of the building, but "*... a ray of lightning "entered" the door, which was carried by a gust of wind into the house, and then along the wire to Richmann, passing by Sokolov".* [19] Lomonosov did not support Kratzenstein's conclusions and wrote that *"many a man said to have seen the lightning flash outside*" ([5], p. 547).



a) *b)*

Fig. 9. Academician Ch.G. Kratzenstein (1723 – 1795) [14] (a) and places of electrical breakdown in the hall of Richmann's house (b) [4], p.653]. g, h – the breakdown of Richmann' s body, m – Sokolov burns with sparks from the fallen wire, c – breakdown in the kitchen door jamb (d – bounced piece of wood), a, b – breakdown and falling of entrance door ([5], p.653).

Foreign scholars of the day came out with their own versions of the incident. Thus, I. Winkler (1753), W. Watson (1754) and I.-F. Hartman (1764) showed that Richman was killed not by lightning, but by electricity induced in the aerial by clouds. I.K. Wilke (1759) supposed that Richmann came up to the lineal at a dangerous distance, since he did not know that *some clouds may induce positive electricity in the aerial, the others – negative, and sometimes it changes instantly* ([4], p. 700). But all the details of the incident remain unclear up to now [4].

In this paper, we have undertaken further investigation of the incident using current data on the affecting factors of atmospheric electricity [12, 17]. Comparing the data by Kratzenstein [4], Lomonosov and Sokolov [5], we have determined the position of a storm front at the time of the incident (Fig. 10), assessed the readings of Lomonosov's and Richmann's electrometers, as well as restored the sequence of the observed electrical discharges and their nature (Fig. 11). According to Fig. 10, at the time of the incident the storm front was far from Richmann's house at a distance of 1 km. Therefore, we also believed that the scientist was struck not by a direct stroke of lightning into the

[17] Special dossier «About the death of Prof. Richmann» № 433 ([4], p. 695) has remained.
[18] Richman did not ground the lineal intentionally, as in that case the installation was transform into an arrester and its sensitivity would become equal to zero [4].
[19] Kratzenstein's report gave rise to known hypothesis of Richmann's injury by a fireball that flew into the open door of the house.

"thunder machine", but by the discharge of electricity induced in the aerial by the charged cloud [4]. Based on the time coincidence of discharges (2 and 3, Fig. 11) [4, 5], we believed that the peripheral lightning near Lomonosov's house (3, Fig. 10) became a "trigger mechanism" for the discharge in Richmann's house (Fig. 8 *c*).

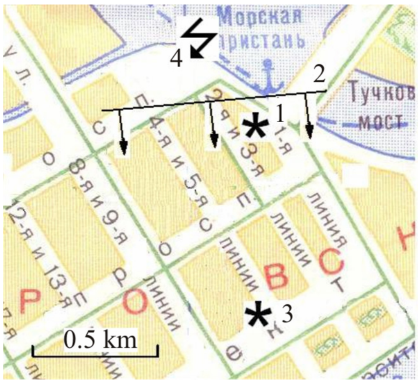


Fig. 10. Position of storm front (2) and direction of its motion at the discharge of periphery lightning (4) in the experiments of 26 July 1753. 1 – Lomonosov's house, 3 – Richmann's house.

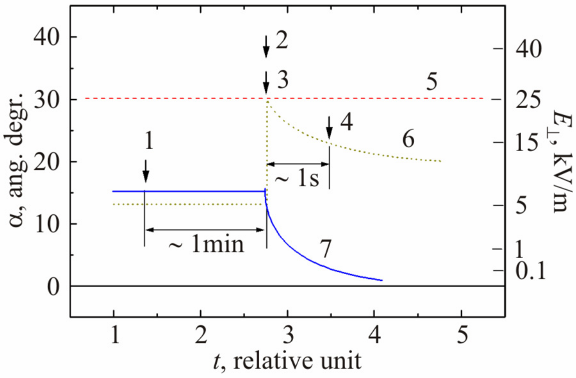


Fig. 11. The α readings of Lomonosov's (7) [5] and Richmann's (6) electrometers (our estimate) depending on time t in the experiments of July 26, 1753. Discharges: 1 – lineal-Lomonosov's hand, 2 – peripheral lightning, 3 – lineal-Richmann's forehead, 4 – wire-Sokolov. Type of discharge: 1, 4 – plural spark (brush-type), 2 – lightning, 3 – positive streamer.

In turn, the discharge was caused by the scientist's careless approach to the "pointer". According to Sokolov, Richmann approached the "pointer" because he wanted to clarify its contradictory reading, namely the cloud was near (Fig. 10), but low α showed that "*thunder is still a long way*" (see Fig. 7).[20] Our estimates of Richmann's electrometer readings (curve 6, Fig. 11) confirm this version of Sokolov.[21] The supposed electrical circuit of Richmann's injury is shown in Fig. 12. The estimates of the circuit parameters (Fig. 12) prior to and at the moment of air breakdown of "lineal – Richmann's forehead" gap (R_2) are shown in Table 3. From the characteristic shape of the discharge (the ball) and the direction of its motion from the "lineal" to Richmann's forehead, we supposed that at the breakdown of R_2 there was positive plasma streamer formation (Fig. 8 *b* and 8 *c*) [8]. This assumption is confirmed by the discharge duration (several seconds) and characteristic "collapse" and explosion of the ball [4, 5]. Hence it follows that at the discharge the lower edge of the cloud closest to Richmann's house was charged positively (+) (Fig. 13). Moreover, the concentration of positive ions in the electrode gap R_2 exceeded the critical value $N_{crit}^+ \sim 10^{12}$ cm^{-3} necessary for self-discharge of this type, and the energy of the breakdown was sufficiently large [8, p. 238]. We determined the magnitude of the voltage $U_2 \sim 25$ kV in the discharge gap R_2 (Fig. 12) from the tabulated data for the air breakdown of the "point-plane type" (edge of the lineal (+)-Richmann's forehead (–)) for the length of $L = 1$ foot (about 30 cm) (Table 3) [12]. Hence, when aerial height $h = 4$ m and cloud height $H \sim 1$ km we have $E_\perp \sim 25$ kV/m (↓) (Fig. 13), which yields $U_1 \sim 25$ MV at

[20] The majority of academicians of SPb AS suffered from short-sightedness, as they worked much by candlelight [4, 5].
[21] Richmann ([4], p. 212) and Lomonosov [5] often used the "over head" discharge for research and medical purposes. Richmann suffering "strongest toothache" ([4], p. 92) could treat it by "electricity". However, this cause of the incident seems to us less likely.

the moment of discharge (Table 3) [12]. According to Sokolov, "... t*he thunder was still not very close but in the hall there was already smoke, at the same moment lightning flashed, the door to the kitchen was opened, and Professor fell down on the chest*" (Fig. 4 *b*). From this we concluded that, even before the main electrical discharge, lethal for Richmann, there was a leakage of current from a supply wire to the ground[22]. The leakage took place through the damp wooden parts of the doors leading to the kitchen and to the street (*c* and *ab*, Fig. 9). The values of resistances $R_i = \rho l/s$ ($i = 1, 2…6$) (Table 3) (here ρ is ambient resistivity, *l* and *s* are characteristic lengths and the effective sections of conducting channels) were estimated by us according to Table 2, for damp wood and brick we assumed $\rho \sim 10^4\ \Omega{\cdot}\mathrm{m}$ [12]. In the calculations we used the values l (m) = 10^3; 0.3; 1; 2; 1 and s (m^2) = 10^5; 0.01; 10; 10^{-2}; 10 for i = 1, 2, 4, 5, 6 (Table 3), resistance $R_3 = 10^4\ \Omega$ was taken from [20].

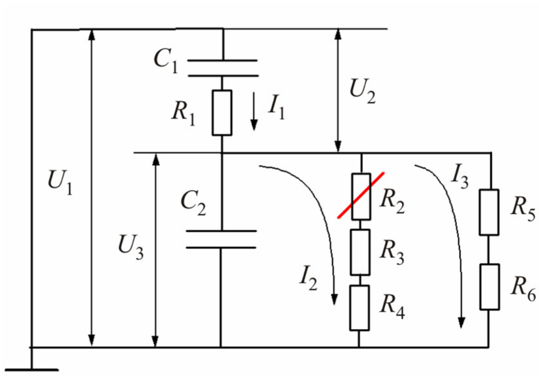


Fig. 12. Schematic of Richmann's injury with a discharge of atmospheric electricity (The notation – see Table 1).

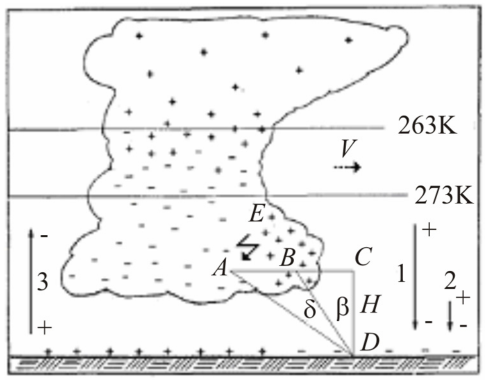


Fig. 13. Schematic of storm cloud and the mechanism of increasing the electric field E at the Earth surface (point D) with a peripheral electric discharge AE. Cloud areas: 1, 2 – "positive", 3 – "negative". E: 1 – after discharge, 2 – prior to discharge [17].

Under normal conditions, the indoor air comprises $N = 10^3\ \mathrm{cm}^{-3}$ ions of opposite sign, the outdoor air before the storm – $N = 10^5\ \mathrm{cm}^{-3}$, and electricity leak into the ground through the damp walls could have increased the concentration of ions in the air up to $N \leq 10^6\ \mathrm{cm}^{-3}$. This is in conformity with plural spark ("brush-type") injury of Sokolov [4], however it is obviously not enough to form a positive plasma streamer in the R_2 space (Fig. 11). According to [3], formation of plasma streamer in the R_2 gap (Fig. 8 *b*) could have been caused by the scientist's breath due to the effect of interfacial charge separation during evaporation of water $H_2O\ (L) \rightarrow K{\cdot}H_2O^{-1}\ (L) + H_2O\ (G) + K{\cdot}p^+$. The effect is accompanied by formation of a small amount of free protons p^+ (here $K \sim 10^{-6}$ is the coefficient of the distribution).[23] Under normal conditions, the pressure of saturated water vapor amounts to $p = 2.3{\cdot}10^3$ Pa, the concentration of water molecules in the air is $N(H_2O) \sim 6{\cdot}10^{17}\ \mathrm{cm}^{-3}$. As a result, even with a single exhalation of the scientist the concentration of free protons in R_2 gap could have reached $p^+ \sim 10^{12}\ \mathrm{cm}^{-3}$, which is sufficient for the development of a positive streamer (Fig. 8 *b*) [8, 19]. In this case, the "trigger mechanism" for R_2 breakdown (Fig. 12) was a sharp increase in the voltage U_2 caused by peripheral lightning discharge (4, Fig. 10). Such abrupt changes of $E \sim U_3 \sim \alpha$ are common with the segmented clouds close to the observer [17]. The abrupt changes of α were

[22] It was lunch time, meal was being cooked in the kitchen, oven was burnt and water vapors were deposited on the doors. Subsequently exactly these door areas were destroyed at the main breakdown.
[23] The effect was discovered by Volta (1770), it accounts for the negative charge of the Earth surface [17].

repeatedly observed by Richmann and Lomonosov for clouds of $L < 3$ km (Fig. 7), but the authors failed to find due explanation of this effect [4, 5].[24]

Table 3

Parameters of schematic of Richmann's injury by a discharge of atmospheric electricity (Fig. 12)

Parameter	Prior to discharge	At the moment of discharge
Cloud-to-ground voltage, U_1, MV	~ 6	25
Cloud-to-aerial voltage, U_2, MV	~ 6	~ 25
Aerial -to-ground voltage, U_3, kV	25	100
Electric field at the surface of the Earth, $E_\perp$, kV/m	~ 6 ↓	25 ↓
Atmosphere-land current , I_1, A	~ 0.025	~ 2.6
Aerial-to-ground current, I_2, A	~ 0	2.5
Leakage current (house walls), I_3, A	~ 0.025	~ 0.1
Atmospheric resistance, R_1, kΩ	~ 10^8 (10^{11}*)	~ 10^7 (10^7**)
Breakdown resistance, R_2, Ω	10^{17}	~ 0
Body resistance, R_3, Ω	10^4	10^4
Leakage resistance (raw wood), R_5, Ω	10^6	10^6
Ground resistance, $R_4 \sim R_6$, Ω	~ 10^3	~10^3
Released, W_{R5}, W	625	10^3
Released power, W_{R2}, W	0	$2.5 \cdot 10^5$

* – estimate for non-ionized air. ** – estimate with regard to thunderstorm air ions ($N \sim 10^5$ cm^{-3}).

To explain the growth of $E_\perp$ at the peripheral discharge (4, Fig. 10), we used a model of a partitioned cloud (Fig. 13). According to Fig. 13, a discharge between points A and E causes annihilation of positive and negative charges in one of the cloud segments. As a result, the electric field $E_\perp$ at point of observation D increases in $\delta E_\perp = E_\perp^{'}/E_\perp \sim \cos^2\beta/(\cos^2\beta - \cos^2(\beta+\delta))$ by the time $t \sim 5 - 10\tau$ and more (here $\tau \sim 1 - 5$ s is the characteristic relaxation time of a cloud) [17]. The estimates were made in the approximation of point charges at the cloud height of 1 km. The angles $\delta \sim 6^0$, $\beta \sim 50^0$ (Fig. 13) were determined from Fig.10. We obtained $\delta E_\perp \sim 4$ whence under condition of $\alpha \sim 30^0 \sim E_\perp \sim 25$ kV/m at the moment of discharge we calculated circuit parameters (Fig. 12), as well the readings of Richmann's electrometer prior to discharge (Table 3 and Fig. 11). Then using the equations for a plane capacitor and coaxial line, respectively, we assessed the electric capacity of the cloud $C_1 = \varepsilon_0\varepsilon S/H \sim 10^{-8}$ F (here $\varepsilon \sim 1$ is for air, $S \sim 10^6$ m^2 is the effective area of the cloud) and "thunder machine" $C_2 = 4\pi\varepsilon_0\varepsilon l/\ln(r_1/r_2) \sim 2\cdot10^{-10}$ F (here $l \sim 10$ m, $r_1 \sim 0.5$ cm and $r_2 \sim 100$ cm is conducting wire length, its radius and average distance between the wire and house walls). Then we calculated the maximum charges of the cloud and "thunder machine" – $Q_1 = C_1U_1 \sim 0.25$ C and $Q_2 = C_2U_2 \sim 2\cdot10^{-5}$ C, and time constants of the "thunder machine" charging at the moment of breakdown $\tau_1 = R_1C_2 \sim 10^{-3}$ s and $\tau_1' = R_1C_2 \sim 20$ s for the nonionized atmosphere, respectively. From the relation $\tau_1 << \tau_1'$ it follows that the atmosphere over Richmann's house at the moment of breakdown was strongly ionized. In so doing, all the discharges in the house (Fig. 9 *b*) were

[24] Richmann and Lomonosov did not know that positive and negative charges can form simultaneously and then annihilate ([5], p. 523). The abrupt changes in α were attributed by Lomonosov to a transition of "electrical force" between clods during discharges.

determined by the energy C_2 of charged installation that was constantly "powered" by the energy of charged cloud C_1, which accounted for their total large value. [25] As a result, at the breakdown of the electrode gap ($R_2 \rightarrow 0$), Richmann could pass through himself the shock current I up to ~ 2.5 A, exceeding considerably the lethal value ($I_0 = 0.1$ A) (Table 3) [20]. The scientist's pale body and numerous burns ([4], p. 545) confirm this assumption.[26]

Thus, the cause of Richmann's death was an extremely rare combination of various unfavorable factors. [27] The key factors included the positive charge of the cloud over the house, a dangerous configuration of the discharge gap of the "point-plane" type reducing the discharge voltage by a factor of 3, damp room and clothing, as well as two TE effects that increased the affecting factors of atmospheric charges. This is increased air conductivity close to the aerial due to the burning oven in the house and high concentration of protons $p^+ \sim 10^{12}$ cm^{-3} in the gap R_2 caused by the scientist's breath. [28] It should be noted that the majority of these effects were known to Richmann, or he even was their discoverer [4]. In particular, Richmann had earlier investigated the effect of air breakdown at reduction of a discharge gap ([4], p. 233), studied "dripping of charges from the tip" and "conducting properties of flame and smoke", described the effect of "wet" room, etc.) [4]. Richmann also tried to measure the conductivity of water vapor (the experiment with the aeolipile) (Fig. 4 *c*), but did not estimate its value due to the low sensitivity of his "pointer". However, as shown above, it is exactly low proton conductivity of water vapors exhaled by the scientist that could be the main reason for his death. Accordingly, the easiest way to prevent the tragedy for Richmann would be to use an electrometer with a protective housing (Fig. 3 *b*) [20].[29] At the same time, the relative safety of Lomonosov and Sokolov under similar conditions has been associated primarily with lower ionization of air around them. As a result, electrical discharges also experienced by them during the storm of July 26, 1753, were of relatively safe spark (brush) type [8].

Conclusions

We have examined the works of Richmann and Lomonosov (1745 – 1753) related to the origin of national thermoelectricity (TE). It is shown that the authors were the first to discover or study in detail TE effects (thermoelectretic, atmospheric and so on) in various thermoelectrically-active media belonging to the class of dielectrics (sulfur, resins, air, water, etc.). All TE effects studied by them were of similar physical nature and associated with spatial separation and/or transport of non-equilibrium electric charges in samples with a change in temperature. In some cases the TE effects were further enhanced by the phase transitions and chemical reactions ("melt-crystallization", "evaporation-condensation", combustion, etc.) also related to a change in temperature. The distinctive feature of TE effects was their discreteness manifested in the processes of "charging" and

[25] Considerable decrease of R_1 could have been also caused by oven burning in the house (Fig. 5 *b*).
[26] At primary respiratory arrest the affected bodies are blue, at primary cardiac arrest – red, white color indicates a simultaneous cessation of breathing and circulation ([20], p. 236).
[27] By our estimation, the probability of a casual combination of affecting factors in the incident with Richmann was exclusively small ($P < 10^{-7}$ per single experiment). It is proved by the absence of new similar incidents with researchers for the recent 260 years.
[28] Richmann who was constantly talking to Sokolov, did not take off the robe and wet shoes, he took off only a wig, and as a result he was at the installation even with a wet head [4].
[29] In this paper, we do not consider the case of simultaneous connection of two Richmann's "thunder machines". Their series ($U_3' \sim 2U_3$), or parallel ($C_2'' \sim 2\ C_2$) connection increase essentially the likelihood of the scientist's injury by current (Fig. 5 *b*).

"discharging" of samples. Thus, even for high *U*, the TE effects remained virtually harmless for the researchers, except for the cases of electrical breakdown of dielectrics (the incident with Richmann).

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