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Engineering of the Highest Caliber: Kazimierz Siemienowicz and the Culmination of the Military Revolution

Abstract

The *interregnum* between the death of Galileo and the publication of Newton's *Principia* produced great advances in military science and technology. Particularly noteworthy are Kazimierz Siemienowicz's contributions to artillery and to the field of rocketry. The dominating nature of these weapon systems remain as relevant today as it did in 1650 with the publication of his opus, *The Great Art of Artillery*. Rocket technology defines power relations, whether fired indiscriminately across a national border or positioned menacingly in a silo as an intercontinental ballistic missile. Siemienowicz's designs, namely his multi-stage rockets with delta-wing stabilizers and ejection nozzles, became

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instruments of state power. The standardization of the caliber scale, the writing of the science of artillery, the optimization of gunpowder quality, and the pioneering work in rocketry, which became his legacy, qualify him as principal in the culmination of the military revolution.

Keywords: *Siemienowicz*, *rocketry*, *artillery*, *Polish-Lithuanian Commonwealth*, *caliber*, *Tipu Sultan*, *William Congreve*

Inżynieria najwyższego kalibru: Kazimierz Siemienowicz i kulminacja rewolucji wojskowej

Abstrakt

Okres między śmiercią Galileusza a publikacją *Principiów* Newtona przyniósł wielki postęp w nauce i technologii wojskowej. Na szczególną uwagę zasługują dokonania Kazimierza Siemienowicza na polu techniki artyleryjskiej i rakietowej. Dominujące znaczenie tych systemów uzbrojenia pozostaje tak samo aktualne, jak w 1650 roku, kiedy ukazało się dzieło Siemienowicza pt. *Wielka sztuka artylerii*. Technika rakietowa definiuje stosunki władzy, niezależnie od tego czy rakieta wystrzeliwana jest na oślep przez granicę państwową, czy jest groźnie umieszczona w silosie jako międzykontynentalny pocisk balistyczny. Projekty Siemienowicza, czyli wielostopniowe rakiety ze stabilizatorami delta-skrzydła i dyszami wyrzutowymi, stały się instrumentami władzy państwowej. Spuścizna Siemienowicza: prace nad nauką o artylerii, ujednolicenie skali kalibru, optymalizacja jakości prochu oraz pionierska praca na temat rakiet, kwalifikuje go jako główną postać w kulminacji rewolucji wojskowej w XVII w.

Słowa kluczowe: *Siemienowicz*, *rakieta*, *artyleria*, *Rzeczpospolita Obojga Narodów*, *kaliber*, *Tipu Sultan*, *William Congreve*

1. Introduction

What constitutes the culmination of the Military Revolution? Is it plausible that an engineer – and not a head of state – was its architect? The history of science and technology is punctuated by a myriad of revolutions; some are singularities on the historical timeline, while others form a series in an evolutionary pattern. One common denominator is a generally clear delineation of their timelines as well as acknowledgment of the principals involved, notwithstanding the occasional disagreement as to whom the final credit should be attributed. This is not the case, however, for the Military Revolution, and the debate finally reached a climax at the 1991 Meeting of the American Military Institute. Clifford Rogers, a panel member of that august gathering, summarized the findings that economic and military developments are closely related, and that the "control over means of violence, as sociologists from Aristotle to Weber and Andreski have argued, can have as much impact on social and political systems as does control over the means of production."[11] Thus, historiography of military matters became a relevant topic.

Michael Roberts's seminal paper, "The Military Revolution, 1560–1660", which he first presented as a lecture at the Queen's University of Belfast in 1955, drew upon his scholarship of Gustav II Adolph of Sweden and the Thirty Years' War (1618–1648). Viewing that protracted conflict as a watershed, Roberts believed it validated his choice of timeline. He wrote,

> The military revolution which fills the century between 1560 and 1660 was in essence the result of just one more attempt to solve the perennial problem of tactics – the problem of how to combine missile weapons with close action; how to unite hitting power, mobility, and defensive strength.[12]

Geoffrey Parker in his work, "The 'Military Revolution, 1560–1660' – a Myth?" largely agreed with Roberts that the four strands of this epoch were: (1) revolution in tactics, viz. Maurice of Nassau of the Dutch Republic, (2) revolution in strategy, (3) an extraordinary increase in the scale of warfare, and (4) a greater impact of military affairs on society.[13] Finally, Parker's emphasis on the innovation of defensive fortification, known as the *trace italienne*, was, according to Rogers, "a key

[11] Rogers 1995, p. 1.
[12] *Ibid.*, p. 13.
[13] Parker 1995, pp. 37–38.

new ingredient to the Military Revolution debate: military technology as a causative factor."[14]

By focusing their research on the countries of Sweden, the Dutch Republic, the Italian States, Spain, England, and France, Western scholars have largely ignored the significant contributions to the Military Revolution from the Polish-Lithuanian Commonwealth (Rzeczpospolita Obojga Narodów). The shibboleth of viewing cavalry as an archaic and outdated branch of the military, and the *trace italienne* as the *sine qua non* innovation of the Military Revolution, may largely be responsible for this oversight. Yet that long-held position is being re-evaluated, notably first in Robert Frost's "Poland-Lithuania and the Military Revolution."[15] More recently, Vitalij Penskoj offers a fresh perspective to this geographical region's importance in his 2010 book *Velikaja Ognestrel'naja Revoljucija* (The Great Firearms Revolution). He asks those involved in the Military Revolution debate:

> Indeed, if in fact we believe that Gustav II Adolf, having borrowed new tactics from the Dutch, was able to fully reveal his strengths during the Thirty Years War, then for those who are familiar with the history of Eastern Europe, it is no secret that military reforms, carried out by the Swedish king, were the result of not very successful clashes between the Swedes and the Russians, and especially with the Poles at the turn of the 16th – 17th centuries.[16]

The Polish-Lithuanian Commonwealth, forged by the Union of Lublin in 1569, was a catalyst for developing a highly effective army, largely in part to counter the multifaceted threats of invading Tatars, wars with Sweden, Cossack uprisings and the proximity of the Ottoman Empire.[17] Adam Zamoyski attributes the success of Polish-Lithuanian forces to the military science developed by Hetman Jan Tarnowski, who published his *Consilium Rationis Bellicae* in 1558.[18]

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14 Rogers 1995, p. 4.
15 Frost 1994, pp. 19–47.
16 Penskoj 2010, p. 124.
17 Wisner 1972, pp. 605–613.
18 Zamoyski 2000, p. 154.

Fig. 1. The Grand Ensign of the Crown Leading the Husaria.
Source: *Wikimedia Commons*. Public Dmain. URL: https://upload.wikimedia.org/wikipedia/commons/5/58/Great_Chor%C4%85%C5%BCy_of_the_Polish_Crown.jpg

> The high degree of mobility and the need to live off the land were both reasons for Polish armies operating in divisions, while most European armies marched in a great mass until the end of the eighteenth century.[19]

Subsequent military reforms under King Stefan Batory (1576–1586) yielded tangible results, which saw

[19] *Ibid.*, p. 154.

> the Polish new formation regiments introduced during the 1632–1634 Smolensk War, Muscovy's unsuccessful attempt to wrest Smolensk and the upper Dnieper Valley from Polish control.[20]

Dividends of the Batory reforms were manifested on a number of fronts, as described by Penskoj:

> The secret of the success of the Polish-Lithuanian troops was now in the effective tactics – developed by its military leaders – of close interaction among infantry, artillery, and heavy and light cavalry. Skillfully combining the best elements of European and Eastern traditions, the hetmans of the Commonwealth formulated a kind of recipe for invincibility. Infantry and artillery with their fire "softened" the enemy's battle formations, thus preparing a crushing attack of the brilliant hussar. Neither the Tatar and Moscow horsemen, nor the Swedish or imperial racers could resist the ram strike of hussar gonfaloniers.[21]

In the Commonwealth, the first project for a school of engineering – focused on artillery – was set up by Andrea dell'Aqua in Warsaw during the years 1622–1623. Later, in 1635, he would found a similar institution in Lwów.[22] While Gustav II Adolphus is credited to have formed the first purely artillery regiment[23] in 1629, the Polish-Lithuanian Commonwealth followed immediately thereafter – within several years – during the reforms initiated by King Władysław IV Wasa.

The Commonwealth's artillery was made uniform to facilitate supply of ammunition and maintenance. Moreover, the artillery had its own budget, and its commanders received a new rank-the elder over the cannon.[24] In this pioneering environment, during the first half of the 17th century, and at the height and greatest extent of the Polish-Lithuanian Commonwealth, emerged the engineer Kazimierz Siemienowicz, a "Lithuanian Knight and Lieutenant-General of the Ordnance to

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20 Brown 1982, pp. 55–69.
21 Penskoj 2010, p. 168.
22 Nowak 1997, p. 9.
23 Roberts 1995, p. 24.
24 Świętochowski 2010, p. 38.

Fig. 2. Portrait of (Hetman) Jan Amor Tarnowski by Marcello Bacciarelli (1781). Source: *Wikipedia*. Public Domain; URL: https://en.wikipedia.org/wiki/Jan_Tarnowski#/media/File:Jan_Amor_Tarnowski.PNG.

the King of Poland."[25] What makes Siemienowicz such an illustrious figure in the history of technology is that he standardized the caliber scale, optimized the production of gunpowder, and designed multi-stage rockets with stabilizers on which basic principles operate the most sophisticated weapons systems of the 21st century. His monumental work, *Artis magnae artilleriae*, also known as *The Great Art of Artillery*, served as an indispensable reference for both military commanders and engineers for several centuries after his death. The rapid growth of artillery in Poland – from the first manuscript on the subject in 1547 to Siemienowicz's publication in 1650 – not only reflects the vast scope of practical applications but also the development of the sciences in the Commonwealth during the Renaissance.[26] Siemienowicz's contributions to science, technology, and the culmination of the Military Revolution is the focus of this essay.

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[25] Siemienowicz, Kazimierz. 1650. *Artis Magnae Artilleriae Pars Prima*. Amsterdam: Jan Jansson.

[26] Nowak 1970, p. 72.

2. A Technology-Driven Military Revolution

Much of the Military Revolution's historiography is a dialectic on the various tactics and strategies employed by the great powers during the 16th and 17th centuries. Unfortunately, the decisive role of technology had not been emphasized, with the noted exception of the *trace italienne*. Scorecards were kept on battles won or lost, but even by that metric, it was difficult to discern what variables were most instrumental in victory. As a result, a certain dissonance permeated this field.

According to Robert Frost, the "standard of technical knowledge was high" in the Polish-Lithuanian Commonwealth, as evidenced by "a further period of energetic activity under Władysław IV (1632–1648) [that] left Poland well-supplied with modern artillery."[27] This premise would appear to have supported Rogers's assessment of an epic 17th battle, when he wrote,

> After all, it was only in the century after the failure of the siege of Vienna in 1683 that Western European arms showed a reasonably consistent ability to overcome their most advanced opponents – Ottomans, Mughals, and other civilizations with developed gunpowder technology.[28]

Yet, in his same work, Frost appears to retreat from the technology position by suggesting,

> The victories of Sobieski over the Turks in the 1670s and 1680s merely disguised Polish weaknesses by triumphing over an enemy who had also failed to respond to new patterns of warfare.[29]

Parker too was cognizant of the criticism directed at him for not establishing a direct link between technical innovation and military growth.[30] His defense centered on the unquestionable role of the artillery fortress, i.e. *trace italienne*, which he emphasized, as well as a caveat that "we must not fall into the trap of technological determinism."[31]

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[27] Frost 1994, p. 25.
[28] Rogers 1995, p. 6.
[29] Frost 1994, p. 24.
[30] Parker 1995, p. 339.
[31] *Ibid.*, p. 345.

In an attempt to explain such examples of analytical incoherence, Carl Mitcham posits,

> the word 'technology' has, in current discourse, narrow and broad meanings, which roughly correspond to the ways it is used by two major professional groups – engineers and social scientists.[32]

Hence, the rise of engineering philosophy of technology (EPT) is an objection to the

> humanities philosophy of technology (HPT) [that] often does fail to pay sufficient attention to engineering experience and technological reality – presuming that it is possible to think on the cheap.[33]

Billy Vaughn Koen, a noted engineer-philosopher, has highlighted the importance of studying the heuristics in the engineering method[34], which he directly attributes to many groundbreaking discoveries.

Eventually, a new perspective, encompassing the close interrelationship between technology and tactics, would develop. Jeremy Black, who initially placed the Military Revolution post 1660 vis-à-vis Parker, declared,

> Indeed, until opposing armies were similarly equipped, the technically inferior army tended to lose, and quite spectacularly so, in no small measure due to an inability to appreciate not only the effects of gunpowder weapons but their tactical and operational use.[35]

The crescendo of anomalies and ambiguities casts doubt on the traditional view of the Military Revolution as being limited to fundamental changes in strategy and tactics, which then serve as a fountainhead for changes in government structure. Perhaps the time has come for a paradigm shift in definition. Anthony Krepinevich has provided

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32 Mitcham 1994, p. 143.
33 *Ibid.*, p. 141.
34 Koen 2003.
35 Black 1995, pp. 85–86.

a lucid *explanans* for the Military Revolution by integrating many of the disparate variables considered by historians. He wrote:

> It is what occurs when the application of new technologies into a significant number of military systems combines with innovative operational concepts and organizational adaptation in a way that fundamentally alters the character and conduct of conflict. It does so by producing a dramatic increase – often an order of magnitude or greater – in the combat potential and military effectiveness of armed forces.
>
> Military revolutions comprise four elements: technological change, systems development, operational innovation, and organizational adaptation. Each of these elements is in itself a necessary, but not a sufficient, condition for realizing the large gains in military effectiveness that characterize military revolutions. In particular, while advances in technology typically underwrite a military revolution, they alone do not constitute the revolution. The phenomenon is much broader in scope and consequence than technological innovation, however dramatic.[36]

3. Siemienowicz's Contributions and the Great Art of Artillery

If the aforementioned definition of a Military Revolution is accepted, than Kazimierz Siemienowicz may be regarded as its principal. His contributions not only systemized artillery, but the twenty-first century's most advanced weapons systems clearly display a blueprint of his prototype designs. Paradoxically, Siemienowicz's successful efforts in systemizing smooth-bore artillery helped diminish the relative importance of rocketry – the field for which he is particularly recognized – for several centuries. Consider the comparative economic factors in warfare during the mid-17th century. As a starting point, the simplest solid rocket propellant engine was easier to manufacture than a gun barrel. Siemienowicz's rocket launchers were wooden frames with rail guides. Notwithstanding their relatively short range and low flight

[36] Krepinevich 1994, p. 30.

accuracy that reduced combat effectiveness, guns of that time fired only a few hundred paces and with a significant spread. Furthermore, the low firing frequency of guns was determined by the necessity to clean the barrel after each shot. In contrast, the rocket's warhead was more expensive than the cannon's charge comprised of gunpowder and ball. Taking into account the low level of metallurgy of the time, the cost of artillery fire was primarily determined by the price of bronze for casting guns.[37] Siemienowicz's fundamental contributions to the standardization of the caliber scale and the quality of gunpowder secured the primacy of barreled artillery. What naturally followed were innovations in breech-shot cap loading, rifled barrels, and optical sights. Moreover, subsequent advances in metallurgy transformed the cannon from a priceless commodity to a mass-produced weapon of warfare. The combat value of a 17th century long-range missile was doubtful as "no one was aiming for the horizon."[38] The seeds of technological change, however, resulting in an order of magnitude increase in combat effectiveness (an essential element of the Military Revolution) had already been planted by Siemienowicz.

At the apex of a nation's arsenal is the intercontinental ballistic missile (ICBM), which relies on a multistage design. Shown below (see Fig. 3) is a schematic of a Trident ICBM juxtaposed with Siemienowicz's design published in 1650.

Cruise missiles are another formidable weapon (see Fig. 4). Designed for low-level flight, they avoid detection from anti-missile systems. More versatile than the ICBM, the cruise missile is often depicted with a distinct delta-wing configuration for flight control and stability. That too is a Siemienowicz innovation, as illustrated below in a comparative and scaled view with the modern Brahmos missile.

Lastly, in the bottom of the Fig. 4, is another novel technical concept. It is an example of Siemienowicz's battery or multi-nozzle rockets that burn simultaneously. Such a methodology, which greatly increases both the thrust and efficiency of the first stage, was utilized successfully in the Saturn V rocket in the Apollo space program. After extensive research, Mieczysław Subotowicz – himself a physicist and a member of the International Academy of Astronautics – wrote that Siemienowicz was

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[37] Matvienko 2016, pp. 75–76.

[38] *Ibid.*, p. 77.

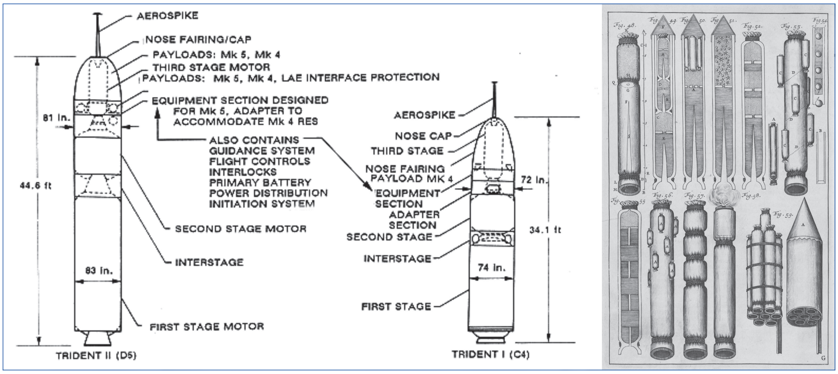

Fig. 3. Comparative Schematic of ICBM (left) with Siemienowicz Prototype (right). Sources: Trident II D-5 Fleet Ballistic Missile FBM / SLBM - United States Nuclear Forces – Federation of American Scientists; URL: https://nuke.fas.org/guide/usa/slbm/d-5.htm; Kazimierz Siemienowicz, Plate G: Rockets Mounted to Sticks. In *Artis Magnae Artilleriae*. Amsterdam, Netherlands: Jan Jansson, 1650. URL: https://digital.sciencehistory.org/works/dv13zt29d.

the "first serious attempt in the world" to create the science of artillery, which heretofore had been the domain of "artisan prescriptions."[39] The distinguished Polish military historian, Tadeusz Marian Nowak, would describe Siemienowicz's main goal of creating a new field of research, and elevating artillery into the liberal arts.[40] While the concepts of delta-wing stabilization, multi-stage rockets, and nozzles had appeared earlier (notably by Conrad Haas, Johan Schmidlap, Marcin Bielski, and Andrea Dell'Aqua), it was Siemienowicz's book that first provided a detailed construction. Moreover, he delivered a full critique – with supporting mathematics – of Schmidlap's original design that rendered the multi-stage concept more precise.[41] For that important reason, Siemienowicz's work remained the indispensable guide for developing rocket technology until the early 19th century, before the publication of William Congreve's treatise in 1827.[42]

Much mystery still surrounds the extraordinary life of Kazimierz Siemienowicz. Several Belarusian researchers postulate that he was born around the year 1600 in the lands encompassing the Mogilev and

39 Subotowicz 1957–1958, p. 11.
40 Nowak 1970, p. 90.
41 Nowak 1995, pp. 210–211.
42 Subotowicz 1977, p. 140.

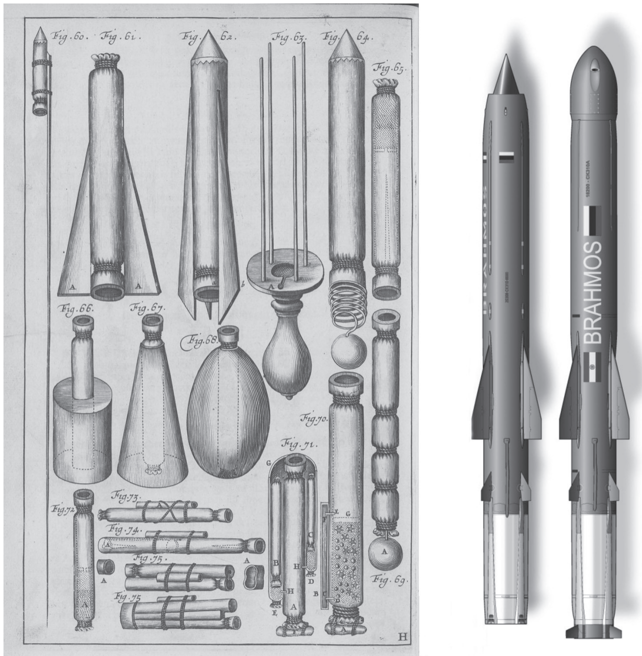

Fig. 4. Delta-Wing Stabilizer (left) and Affixed to Modern Cruise Missile (right)
Sources: Kazimierz Siemienowicz, Plate H: Rockets Mounted without Sticks; Water Rockets; Rockets Mounted to Lines. In *Artis Magnae Artilleriae*. Amsterdam, Netherlands: Jan Jansson, 1650. URL: https://digital.sciencehistory.org/works/8910jt62q. Modern Cruise Missile. Test pilots; URL: https://testpilot.ru/zp/wp-content/uploads/2017/12/pj10p.jpg.

Vitebsk regions of the Dnieper River valley.[43] One clue that supports that hypothesis is deduced from Siemienowicz's detailed description of weights and measures. There, he includes the esoteric and regional units of *pud*, *beczka, and birkowiec* that were in common use in Alba Russia, i.e. White Russia. The *birkowiec* (approximately 400 pounds), in fact, only became an official unit of measure for the Rzeczpospolita in 1764 after a decree by the Sejm.[44]

Based on archival records from Vilnius University, established in 1579 as the Jesuit Academy by King Stefan Batory, Siemienowicz was a student of Oswald Krüger[45], who eventually became a professor

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43 Bel'ski, Tkachjov 1992.

44 Siemienowicz 2011, pp. 31–82.

45 Mrozik 2018.

Fig. 5. Kazimierz Siemienowicz. *Source*: Bel'ski, Tkachjov (1992).

of mathematics in 1632, and from 1634–1648 was primarily focused on ballistics and the art of artillery.[46] In Vilnius, Siemienowicz would become familiar with Krüger's invention of the artillery sight (*Parallela horoscope ad bellicorum tormentorum directionem*) that contained a full mathematical explanation of operation.[47] Siemienowicz travelled extensively, and as some scholars suggest, to Belgium, the Rhine Provinces, Austria, Bavaria, Switzerland, and Italy as a companion to the prince-heir of the Polish throne Władysław.[48] Whether at the Jesuit Academy in Vilnius or elsewhere, Siemienowicz acquired a masterful command of Latin that he wisely chose as the language to publish his treatise in 1650. Drawing upon an encyclopedic knowledge of over two hundred ancient and contemporary authors, Siemienowicz reveals an erudition that few engineers in the seventeenth century could match.

> In order to get better acquainted with all problems of artillery Siemienowicz had to acquire (as he wrote himself) the knowledge of a "number of liberal arts and mechanics" namely: arithmetic, geometry, statics, hydraulics,

[46] Bel'ski 1998, pp. 100–110.
[47] Nowak 1965, p. 104.
[48] Subotowicz 1957–1958, p. 8.

> pneumatics, civil and military architecture, fortification, graphics, optics, and tactics. "I acquired also", writes he, "some knowledge of physics and chemistry." Wishing to command not only theoretical disciplines but also the practical ones he gets acquainted with handicrafts that are necessary for his purpose, namely carving, engraving and the art of casting.[49]

Siemienowicz's writing reveals that he participated in the Smolensk War against Muscovy.[50] At the completion of this successful campaign in 1634, and because of his close association with Paweł Grodzicki, General of the Crown Artillery, Siemienowicz was sent abroad to Holland by King Władysław IV to improve the state-of-the-art in artillery.[51] There, Siemienowicz took part in the war of Holland with Spain. Returning to the Polish-Lithuanian Commonwealth, he participated in the decisive Battle of Okhmativ against the Crimean Tatars in 1644. During the period 1646–1649, Siemienowicz served as the Commandant of the Warsaw Arsenal; he was made Engineer of the Crown Artillery in 1646 and promoted to Lieutenant General of the Artillery in 1648.[52] Other sources from that time list Siemienowicz as one of 106 men that belonged to the Royal Artillery, and that he was one of five members of the staff of the Artillery Corps under General Krzysztof Arciszewski.[53]

The artillery became the driving force of the military revolution. Both Sweden and the Polish-Lithuanian Commonwealth recognized early that this branch offered the least barriers and social impediments. To encourage recruitment among the upper classes, these two countries introduced the ranks of adelman and elder of the cannon. "And behind the artillery lay a fringe of scientific laymen and minor mathematicians – those 'mathematical practitioners' whose part in educating the seamen, gunners, and surveyors of the age has now been made clear."[54] Siemienowicz exemplified that role, albeit at a much higher and significant degree than historians have recognized.

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[49] *Ibid.*, pp. 7–8.

[50] Siemienowicz 2011, pp. 255–256.

[51] Nowak 1965, p. 258.

[52] Bel'ski 1998.

[53] Subotowicz 1957–1958, p. 9.

[54] Roberts 1995, p. 24.

Fig. 6. Kazimierz Siemienowicz, Lieutenant General of the Artillery on a 1995 Belarussian stamp. *Source*: Belposhta. URL: https://military-history.fandom.com/wiki/Kazimierz_Siemienowicz?file=Kazimier_Siemianovi%25C4%258D_stamp.jpg.

Jeremy Black wrote, "standardization, and thus measurement and calculation, were key themes" in the Military Revolution through the introduction of "linear measure to show ball diameters, as well as caliber scale, and special curves and compasses for ballistic calculation."[55] They were much more than that. As the railway industry would have stalled without standardization of track gauges, the ascendency of artillery in the Military Revolution would have been delayed significantly without uniformity in gun barrels and ammunition. Accuracy and repeatability was a perennial problem for the gunner at the turn of the 17th century.[56] Here, scholars need to acknowledge the prodigious input of Siemienowicz to the caliber scale, whose development and refinement directly addresses one of the essential criteria of the Military Revolution, i.e. operational innovation. In fact, Siemienowicz's first book is dedicated exclusively to all aspects of the caliber scale, in which he surveys and assesses – with punctilious technical detail – both the

[55] Black 2013, p. 98.

[56] Rogers 2016, pp. 1–15.

mathematical analysis and the mechanical construction associated with this stereo metric or cubical line. Drawing upon works of ancient mathematicians, such as the conchoid curves of Nicomedes, and continuing through those of contemporary studies of peers like the Italian philosopher Mario Bettinus, Siemienowicz provides an engineering solution to the Delian problem, or doubling the cube.[57] What follows is a masterful account, replete with detailed mathematical calculations, that is part patent application and part textbook for the military engineer. Believing that it was impossible to solve the Delian problem with compass and ruler only – a fact proven only in 1837 by the French mathematician Pierre Wantzel[58] – Siemienowicz applied heuristics to generate an optimal design within those constraints, as shown below in Figure 7. He wrote:

> I shall only say, that it is acknowledged and declared by the greatest Geometricians, that it is impossible to increase the Cube by Planes; and this I affirm from the very Confession of those who have so closely fought after it. But this is not sufficient for us to condemn their Inventions, reject their laborious Efforts, or look upon them as repugnant to right Reason and Truth: No; on the contrary we ought to continue the use of them, until a more happy Age shall produce such as are preferable and more perfect. In such a variety of Practice as has been used to this End; I have pitched upon one Method only, which I here present for your Use in increasing the Cube, and to find out two mean Proportionals in a continued Order, and which, I believe, will be sufficient, in the right and proper treating of Pyrotechnical Matters.[59]

Siemienowicz had great familiarity with all weighing instruments that had been constructed and described by Ubaldus, Galileo, Stevin, et al. He incorporated the values of specific gravities obtained by Marinus Mersennus, a French Minim, in order to develop a method by which

[57] Siemienowicz 2011, pp. 25–31.
[58] Lützen 2009, pp. 374–394.
[59] Siemienowicz 2011, p. 10.

diameters of bullets could be made from different metals and minerals with the caliber scale.[60] Reference to the Mersennus tables would be given again nearly a century later in a Royal Society publication.[61]

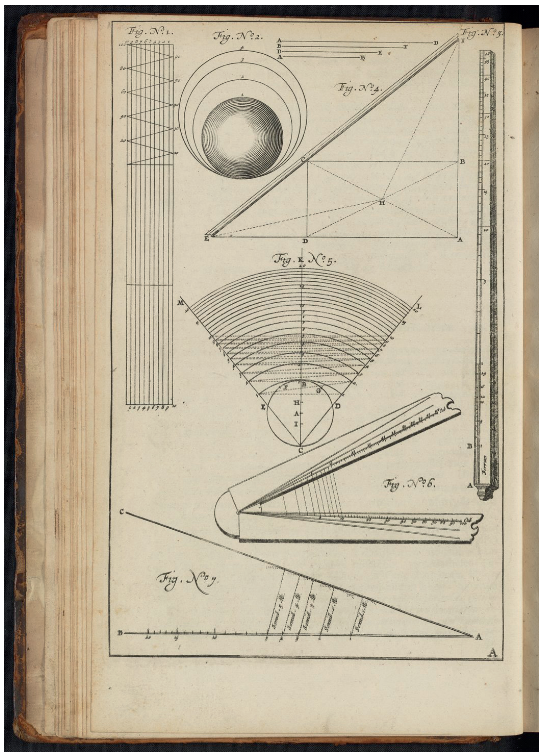

Fig. 7. Siemienowicz's Caliber Scale.
Source: Kazimierz Siemienowicz, Plate A: Diagrams and Instruments to Calculate the Caliber of Bullets and Balls. In *Artis Magnae Artilleriae*. Amsterdam, Netherlands: Jan Jansson, 1650. URL: https://digital.sciencehistory.org/works/6682x399n.

Standardization also extended into the manufacture of gunpowder. The second book of Siemienowicz's *Great Art of Artillery* is entitled "Concerning the Things which are commonly used in Pyrotechnics, or Artificial Fireworks".[62] Here, after first expressing some disbelief in

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[60] *Ibid.*, pp. 25–31.
[61] Davies 1747.
[62] Siemienowicz 2011, pp. 83–129.

the inability of Greek, Roman, or Egyptian engineers to have found military applications for saltpeter (potassium nitrate), he then expounds on its quality control and composition with Sulphur and charcoal. Siemienowicz, conducting his experiments well before Lavoisier's Chemical Revolution of 1787, formulated recipes for cannon-powder, musket-powder, and pistol powder. They are shown below in Table 1. in comparison with the standard for canon-powder adopted during the French Revolution.

> Despite Lavoisier's own gravimetric studies on the saturations of saltpeter and charcoal, uncertainty persisted about the optimum proportion of the constituents in gunpowder; this was, of course, aggravated by the lack of understanding of the chemical role of Sulphur in it.[63]

Tab. 1. Comparison of Gunpowder Composition between 1650 and 1789

Composition (Weight %) for Cannon-Powder (Siemienowicz)	Composition (Weight %) for Musket-Powder (Siemienowicz)	Composition (Weight %) for Pistol-Powder (Siemienowicz)	Composition (Weight %) for Cannon-Powder (Lavoisier)
Saltpeter: 67.0	Saltpeter: 72.5	Saltpeter: 78.7	Saltpeter: 75.0
Sulphur: 16.5	Sulphur: 13.0	Sulphur: 9.5	Sulphur: 12.5
Charcoal: 16.5	Charcoal: 14.5	Charcoal: 11.8	Charcoal: 12.5

From the values above, one can see that Siemienowicz's compositions for the three types of artillery are closely distributed about the Lavoisier standard for cannon-powder, which itself is very close to modern recipes for general black powder. Siemienowicz also had a keen understanding of corning gunpowder, and he recognized that changing the composition of saltpeter directly influenced the explosive power that had implications on the limits of the artillery, established by metallurgy and the strength of materials. He wrote unpretentiously:

> It is a strange and most astonishing property of Gun-powder, that it should have a more violent Effect when

[63] Mauskopf 1990, p. 405.

> corned, than when in a fine flower or Meal; the Reason of which I shall leave to the Discussion of those, who make it their particular Business to insinuate themselves into the wonderful Secrets of Nature.[64]

Siemienowicz, in many respects, was a mathematical practitioner, as Anthony Gerbino defined those engineers who established a critical bridge between that of scientist and artisan.

> Together, these figures highlight an important seventeenth-century trend, not limited to England, in which certain mathematicians actively endeavored, if not to collapse the distinction between high and low mathematics, at least to incorporate the practical under an expanding theoretical rubric.[65]

Siemienowicz accomplished this task brilliantly. While he boldly ventured to obtain solutions when the science was not yet established, e.g. chemistry, he was also critical of those artisans who dismissed the importance of mathematics to military science:

> Hence so many Engineers without Ingenuity, disappointed Searchers after the perpetual Motion, so many unhappy Squarers of the Circle, and all the Blunders of Architects. In fine, hence the Man that begins to build, and knows not how to finish or compleat what he has begun. But I would by no means have it thought, by what I have here said, that I would in the least depreciate the Military Practice, to which alone I more particularly applied myself: I am only grieved to see this illustrious Science of *Pyrotechnicks* dishonoured even by those who profess it; (I mean Practitioners without Foundation;) who have despoiled it of its ancient Glory, and stripped it of all its most beautiful Ornaments, bestowed on it by its first Inventors; and still keep it separated, and as it were, forcibly torn from the Bosom of its lawful Mother the Mathematicks, as a Science alien to and independent of it;

[64] Siemienowicz 2011, p. 103.
[65] Gerbino 2005, pp. 500–501.

> and have crowded it amongst the most illiberal Arts, and the most Mechanical Operations.[66]

Variability in gunpowder remained a problem for a number of European powers. It is notable that England was the largest west European importer of gunpowder from the Baltic ports of the Polish-Lithuanian Commonwealth through the early 17th century. Eventually, Polish suppliers were unable to meet English demand given the ongoing wars with Muscovy and Sweden.[67] James Earle notes:

> The low standard of British gunpowder had become a matter of national concern during the Seven Years War of 1756–1763, the first conflict justifiably described as global in both its geographical extent and consequence. At the start of this titanic struggle, nearly all of Britain's gunpowder was made by a multitude of small, widely dispersed, poorly regulated mills, manned by ill-educated labourers and supervised, often in the loosest fashion, by untrained foremen. Standardization scarcely existed, and substantial quantities, often adulterated with flour or other unwarlike substances, failed to reach even the relatively low standards of proof at the royal magazines in Greenwich.[68]

Years later in 1803, Sir William Congreve would devote considerable energies towards standardization of British gunpowder. He also formulated a recipe for his larger rockets consisting of 58% saltpeter, 18% Sulphur, and 22% charcoal, which became a state secret.[69] Interestingly, Siemienowicz had provided detailed compositions for all rocket sizes in his third book, entitled *Of Rockets*. Congreve, in his *A Treatise on the General Principles, Powers, and Facility of Application of the Congreve Rocket System, as Compared with Artillery*, used twelve pounds of gunpowder in his large 32-pounder rocket.[70] By way of comparison, Siemienowicz employed a similar composition of 57% saltpeter, 14% Sulphur, and 29% charcoal for rockets in the range of 12–15 pounds. Evidence reveals

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66 Siemienowicz 2011, p. 13.
67 Fedorowicz 1980, p. 130.
68 Earle 2011, p. 49.
69 *Ibid.*, p. 78.
70 Congreve 1827, p. 70.

that these recipes were also used in lands outside the Polish-Lithuanian Commonwealth. Favorable reviews of Siemienowicz's gunpowder can be found in the 1697 publication of *Breviculus Pyrotechnicus* by Valentin von Frankenstein of Transylvania, as well as a late 17th century Italian manuscript *Trattato de Fuochi Artificiati* by Evangelista Noni.[71]

Standardization of the artillery, as manifested in the caliber scale and quality of gunpowder, is undeniably a major factor in the Military Revolution – an operational innovation. Jeremy Black points out that Peter the Great of Russia was an early adopter of standardization, as evidenced by the appointment of James Daniel Bruce as the director of the Artillery Chancellery in 1704.[72] Yet to suggest that Peter the Great "a determined borrower of advanced western methods" hired Bruce because of his Scottish heritage and study in London obscures the fact that much of Russian artillery expertise was technology derived from the Polish-Lithuanian Commonwealth. The Tsar himself had a 1676 German translation of Siemienowicz's work in his personal library.[73] According to Brian Davies, no military engineer had more of an impact on Russian artillery throughout the entire 18th century as did Siemienowicz.[74]

Many novelties in rocket design were first delineated and systematized by Siemienowicz. These include nozzles, delta wing stabilization, multi-stages, as well as classification according to weight, as well as length to diameter ratios. Siemienowicz's nozzle, in particular (as shown in Figure 3), was a revolutionary design feature that unfortunately was poorly understood by historians of technology. A. Bowdoin Van Riper, despite acknowledging Siemienowicz's role in the design of multi-state rockets and stabilizers, still referred to him as "more a technician than a visionary."[75] Yet Siemienowicz's formulation of the optimal rocket length to diameter ratio – which was supported by both mathematics as well as meticulous experimentation – reveals his understanding of flight stability, notably that this condition is guaranteed when the center of pressure is aft of the center of gravity. For this purpose, he

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71 Todericiu 1970, pp. 545–553.
72 Black 2013, p. 98.
73 Bel'ski 1998.
74 Davies 2013, p. 205.
75 Van Riper 2004, p. 11.

even developed stabilizers in the form of an iron ball that was placed in the head of the rocket.[76] In a 1971 Foreword to a republication of *Artis Magnae Artilleriae*, O.F.G. Hogg accused Siemienowicz of "charlatanism" when describing the boring of holes in the solid fuel mixture. Fortunately, Wayne Johnson would later write,

> One cannot but wonder if the writer of the Foreword recognized that what Siemienowicz was describing here, was a then recent important discovery and understanding of the principle of the Venturi meter.[77]

This is most significant because Siemienowicz, as a mathematical practitioner, developed the first engineering solution towards optimizing thrust approximately a century before Bernoulli published his General Energy Equation and Venturi formulated his effect of pressure reduction in fluids flowing through constricted sections. While Siemienowicz's writings reveal his adherence to the Aristotelian world-view and philosophy, his pioneering work on rocket motion, and the subsequent study of outflowing gases, helped forge a correct interpretation of forces. In his experiments, Siemienowicz observed that the pressures in the barrel were proportional to temperature, and the subsequent ability to impart a higher kinetic energy he described as the "moving force" in gunpowder.[78] Subotowicz observed,

> It seems that in connection with this special case of rocket motion Siemienowicz understood already the third principle of Newton dynamics, although his explanation lacked clarity.[79]

As Thomas Kuhn astutely remarked,

> because the crafts are one readily accessible source of facts that could not have been casually discovered, technology has often played a vital role in the emergence of new sciences.[80]

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[76] Nowak 1995, p. 209.
[77] Johnson 1994, p. 369.
[78] Nowak 1970, p. 105.
[79] Subotowicz 1957–1958, p. 13.
[80] Kuhn 1996, pp. 15–16.

Fig. 8. Construction of the Siemienowicz Rocket. Reproduced courtesy of NASA, Larry Toschik/ SCIENCE PHOTO LIBRARY.

The fourth book, entitled *Recreative Globes*, was a through treatment of fireworks for entertainment purposes. His fifth and final book of the first part, *Recreative Machines, Masses or Bodies Fix'd and Projectile, and Arms Artificial and Pyrotechnical*, is a study of structures and equipment employing shields, sabres, cutlasses, swords, firewheels, rods, canes, fire-lances, darts, and clubs. This, of course, pertains to systems development, another necessary criterion of a Military Revolution.

4. Aftermath and Technology Transfer

Siemienowicz composed *The Great Art of Artillery* in Latin in order to reach the widest audience of scientists and engineers. When King Władysław IV died suddenly in 1648, Siemienowicz had to secure another source of financial backing, and he found a patron in archduke Leopold-Wilhelm, viceroy of Belgium and Burgundy. To him Siemienowicz dedicates his opus in 1650. The following year, the first translation is completed into French by Pierre Noiset Marcerien. The French text was developed simultaneously with the print of the original, probably in agreement and under Siemienowicz's control, who had been in Amsterdam since the spring of 1649. The French edition, corresponding exactly to the original, was preceded by a multi-page dedication signed by Siemienowicz in honor of William Frederick, Count of Nassau.[81]

Shortly after the release of the French edition, Siemienowicz tragically died in his Amsterdam home under mysterious circumstances. The Polish-born, French and then Soviet aerospace engineer, Ary Sternfeld, would hypothesize that Siemienowicz was murdered by members of the fireworkers' guild.[82] He also claimed that Siemienowicz had sold the rights to his noble name in order to finance his artillery and pyrotechnic experiments.[83] Although this warrants further genealogical research, one interesting discovery from the book of heraldry of the Grand Duchy of Lithuania lists the noble family name "Siemionowicz."[84] The difference in one letter of spelling is intriguing.

> Echoing Sternfeld's sentiment, Subotowicz would add, Technological prescriptions hidden most jealously by gun-makers were openly published by Siemienowicz and improved upon by his own observations and experiments.[85]

Before his tragic death, Siemienowicz indicated that he was at work on the second part of *The Great Art of Artillery*.[86] A manuscript had existed in the library of Princess Sanguszko.[87] Subotowicz wrote that it was later part of the collection in The Polish Library, Biblioteka Rzeczypospolitej Załuskich.[88] After the third partition of Poland in 1795, Empress Catherine II of Russia ordered the transfer of approximately 400,000 volumes of printed books, about 20,000 manuscripts, and over 40,000 engravings to St. Petersburg for the establishment of the Imperatorskaia Biblioteka.[89] Much was lost in the transport, and despite

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81 Thor 1968, p. 91.
82 Prishhepa, Dronova 1987, p. 143.
83 *Ibid*., p. 143.
84 Kojalowicz 1897, p. 257.
85 Subotowicz 1957–1958, p. 11.
86 Siemienowicz 2011, p. 82.
87 Linde 1819, pp. 299–300.
88 Subotowicz 1957–1958, p. 11.
89 Gorecki 1978, p. 427.

a partial fulfillment of a promise from Emperor Alexander I to return some holdings back to Warsaw, Siemienowicz's manuscript to his second part of *The Great Art of Artillery* was not recovered. In 1909, the Polish military historian Bronisław Gembarzewski reported seeing a copy of the manuscript in the Artillery Museum of St. Petersburg, but after reporting its discovery in the publication *Przegląd Biblioteczny*, the trace vanished.[90] Subotowicz himself travelled to St. Petersburg (then Leningrad in 1957) to find it, but he was unsuccessful.[91]

The French polymath, François Blondel (1618–1686), had both Siemienowicz's original Latin as well as 1676 German translation in his library.[92] Amédée-François Frézier, in his 1706 *Traité des feux d'artifice pour le spectacle*, followed Siemienowicz in using the caliber scale to designate rockets.[93] He debated the artificer Perrinet vigorously, and in the second edition of *Traité*, published in 1747, he was still defending Siemienowicz's technique that relied on mathematical calculations.[94] The first English translation (from the French) was completed in 1729 by George Shelvocke, Jr. who summarized the importance of Siemienowicz's technology in his preface:

> This *Translation* then was undertaken and compleated purely by the Encouragement of Colonel ARMSTRONG, the present *Surveyor-General* of his MAJESTY's *Ordnance*, Who considering with Himself, That tho' our Language abounds in Learned Tracts on almost all the Subjects that are truly Useful, It is strangely defective in such as might tend to the Preservation of our Liberties, and the Honour of our *Arms*, amongst our Neighbors; the most Warlike Nations in the World. He concluded that by naturalizing the most celebrated *Author* in this Kind, a great Step would be taken towards recovering our *Pyrobolists* and *Fireworkers*, from the Lethargy they seem to have been wrapped in for many Years past, and towards exciting Them to an Emulation of their Glorious Ancestors, who always endeavored to

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[90] Kravchenka 2008, p. 124.
[91] Subotowicz 1957–1958, p. 11.
[92] Gerbino 2002, pp. 375–377.
[93] Werrett 2010, p. 172.
[94] *Ibid.*, p. 172.

> be Foremost in all *Martial Knowledge*. And since the *Genius* of our Nation is still equally inclined to *War* and to *Peace*, it is to be hoped, That our Military Artists will as readily improve upon this *Stranger*, as our Civil Artists have upon innumerable *Foreigners* in their Way.[95]

The French connection is also a critical link to analyzing the transfer of Siemienowicz's technology to Asia. Claude Martin (1735–1800), who from humble beginnings in Lyon, France, eventually became the richest European in India, as an officer in the French, and later the English East India Company's army. As a superintendent of an arsenal, he used Siemienowicz's text to produce guns, rockets, and cannons.[96] Given the evidence of this technology's presence on the Indian subcontinent, it remains a fertile area of research to investigate what role Siemienowicz's designs may have had in the evolution of the Mysorean war rocket.

During the last three decades of the eighteenth century (1767–1799), the Anglo-Mysore wars were fought between the British East India Company and the kingdom of Mysore, which was ruled by Hyder Ali and later Tipu Sultan. Both men were renowned military strategists, and the latter, nicknamed the "Tiger of Mysore" commissioned a manual *Fathul Mujahidin* or "The Triumphs of Holy Warriors".[97] In this treatise, a *Jauk*, or company of rocket men, is described as attached to each *Kashun* or regiment. The mass of the Mysorean rocket was approximately 2 kilograms, and it had a sword blade as a warhead. Moreover, five to ten rockets could be launched almost simultaneously through the ingenious application of a wheeled rocket ramp.[98] The Mysorean rocket exhibited one notable advantage over the Siemienowicz design. It was the world's first iron-cased, and hence heat-resistant missile. This technological innovation can be directly attributed to the superiority of Indian metallurgy, particularly iron works, as samples were routinely shipped to Sheffield for the manufacture of fine cutlery.[99] As a result, much higher chamber pressures could be realized, and consequently ranges

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[95] Siemienowicz 2011, p. ii.

[96] Llewellyn-Jones 2003, p. 8.

[97] Husain 1950.

[98] Jaim, Jaim 2011, p. 134.

[99] Narasimha 1985, p. 21.

of 900 meters to 1.5 kilometers were demonstrated.[100] Stabilization of the Mysorean rocket was realized with the attachment of a long bamboo pole; no evidence of the delta-wing configuration, as advanced by Siemienowicz, has been recorded.

Tipu Sultan long sought the aid of the French in his wars against the British. In 1788, he sent a delegation to Versailles to meet with King Louis XVI. By the end of the eighteenth century, Napoleon continued that alliance with Tipu Sultan as French military officers provided technical assistance in shipbuilding arsenals, canals, irrigation works, and workshops boring tiger-muzzled cannon.[101] Given the adoption of Siemienowicz's ideas in caliber scale, gunpowder, and rocketry by leading French engineers – both in France and in service with the East India Company – it seems plausible that Tipu Sultan was the beneficiary of a technology transfer from a country, i.e. Poland-Lithuania, which no longer existed on the map of Europe. This point, however, should not diminish the very important role of the Mysoreans, as it is well known that India had experience with military rockets, or *baana*, since the sixteenth century.[102] Tipu Sultan's genius was recognizing the superiority of Indian iron and enabling its use in the rocket's design. This evolutionary design feature unleashed the Mysorean rocket's devastating potential. Nonetheless, Tipu Sultan's death during the siege of Seringapatham in 1799 marked not only British victory, but it also heralded the development of England's own rocket program at the Royal Woolwich Arsenal under Sir William Congreve.

In 1814, while observing the British bombardment of Fort McHenry in Baltimore, Maryland, Francis Scott Key would pen the words "…and the rocket's red glare, the bombs bursting in air," which would later become immortalized in the national anthem of the United States. He, of course, was witnessing the power of the Congreve rockets, which many historians of technology attribute to being "re-engineered" versions of the Mysorean prototype. In what appears to be an egregious omission of prior invention, Congreve makes no mention of Siemienowicz's *The Great Art of Artillery*. Moreover, as Simon Werrett writes,

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[100] Rani 2018, p. 444.
[101] Werrett 2012, p. 601.
[102] *Ibid.*, p. 601.

> Congreve was also quick to dismiss Indian rockets, which he represented as another unchanging eastern art, negligible compared with his own rockets devised through experimental science.[103]

Notwithstanding these claims, Congreve clearly was very successful in demonstrating the efficacy of rocket warfare – not only as a land-based weapons system but also as fired from naval vessels.

5. A Culmination of the Military Revolution

The legacy of Kazimierz Siemienowicz – his standardization of the caliber scale, writing the science of artillery, optimization of the quality of gunpowder, and pioneering work in rocketry – is a towering achievement of seventeenth century engineering. As a rare amalgam of mathematical practitioner, general and visionary designer, he earns his rightful place in the pantheon among those whom historians designate as principals in the culmination of the military revolution. As this paper has illustrated, Siemienowicz's ideas exhibited major advances in technological change, systems development, operational innovation, and organizational adaptation. For these reasons, his book, *The Great Art of Artillery*, was instrumental in advancing military science and engineering in Western Europe, Russia, and India throughout the nineteenth century. As if anticipating his premature death shortly after the publication of his work in 1650, Siemienowicz wrote:

> Have [I] laid myself too open to the ungenerous Attacks of the Malevolent? Yet all this gives me no Trouble; for I hope, my real Friends will have it in their Power to suppress the Calumny, and repel the unmanly Efforts of the Ignorant and Envious; with whom it were to no Purpose to content, except I put myself upon a Level with them.[104]

To that end, may the analysis presented herein serve as that amicable contribution towards restoring the probity of the "Lithuanian Knight and Lieutenant-General of the Ordnance to the King of Poland."

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[103] Werrett 2009, p. 42.
[104] Siemienowicz 2011, p. 404.

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