

# FLUORINE AND DIAMONDS: A RETROSPECTIVE VIEW OF HENRI MOISSAN (1852-1907) ON THE 100th ANNIVERSARY OF HIS DEATH

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On December 10, 1906 Sweden's King Oscar II awarded the 1906 Nobel Prize in Chemistry [1, 2] to Henri Moissan (1852-1907) [3-23] of the Université de Paris (Fig.1-3) “in recognition of the great services rendered by him in his investigation and isolation of the element fluorine, and for the adoption in the service of science of the electric furnace called after him” (Fig.4) [24]. The award for that year amounted to SEK 136,796 [25]. Moissan did not present a Nobel lecture.

Peter Klason, President of Svenska Kungliga Vetenskapsakademien (the Royal Swedish Academy of Sciences), concluded his presentation speech: “The whole world has admired the great experimental skill with which you have isolated and studied fluorine – that savage beast among the elements. With the aid of your electric furnace you have solved the riddle of how diamonds are formed in nature. You have unleashed a mighty wave into the world of technology, a wave which has not yet attained its full height” [26].



Figure 1. Henri Moissan (1852-1907). (Courtesy, the Nobel Foundation)



Figure 3. Moissan's portrait in the Faculté de Pharmacie's Salle des Actes, a grand hall with 91 other portraits of famed scientists associated with the Faculté de Pharmacie. Photograph by James L.Marshall. (Courtesy, J.L.Marshall)

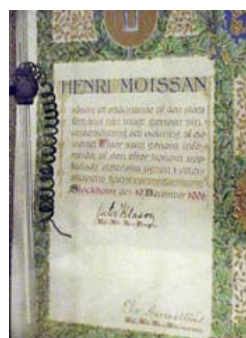


Figure 4. Moissan's Nobel Diploma in the Musée Henri Moissan, Paris. Photograph by James L.Marshall. (Courtesy, J.L.Marshall)



Figure 2. Postage Stamps Honoring Henri Moissan. From Left to Right: 1. Sweden. 1906 Nobelists Henri Moissan (Chemistry), Camillo Golgi and Santiago Ramón y Cajal (Physiology or Medicine). Issued December 12, 1966. Scott Catalog No.711 (40 ö). 2. France. Issued February 22, 1986. Scott Catalog No.B576 (1.8+0.4 fr). The equation is in error:  $H_2 + F_2 \rightarrow 2HF$  is the reverse of the equation for preparing fluorine. 3. Togo. Issued July 20, 1995. Scott Catalog No.1658c (200 fr). 4. France. Centennial of Moissan's Nobel Prize. Issued October 14, 2006. Scott Catalog Number Not Yet Available (0.54 €). (All Stamps, Courtesy, Foil A.Miller)

Ferdinand-Frédéric-Henri Moissan was born on September 28, 1852 in Paris, the son of François Ferdinand Moissan, a railway company employee, and Joséphine Théodorine Almédorine Moissan (née Mitel; also spelled Mitelle, Mittel, or Mittelle on various documents), a Jewish seamstress. In 1864, when Henri was 12, the family moved to Meaux, a small town in the Département of Seine-et-Marne about 20 miles northeast of Paris. Here he attended the municipal college. Because of the family's limited financial resources, he was able to enroll only in an abbreviated secondary education program that did not include Latin or Greek or lead to the *Baccalauréat* examination required for entrance to a university. However, his father gave him his first chemistry lessons at the age of 14-15 years.

After leaving school in July, 1870, possibly for financial reasons, at the age of 18 years, young Moissan was apprenticed to a watchmaker and might well have become a watchmaker himself had it not been for the Franco-Prussian War, which broke out on July 19, 1870. When Meaux was threatened with invasion, the family returned to Paris, where Moissan was conscripted and served in the battle of the Plateau d'Avron in December. After the armistice he decided to study pharmacy and acquire the diploma of *Pharmacien de Deuxième Classe*, the only degree possible for those who had not passed the *Baccalauréat* examination. From February, 1871 to June, 1874 he served as an apprentice at the

Baudry pharmacy in Paris, where his knowledge of chemistry enabled him to save the life of a man who had swallowed arsenic in a suicide attempt.

Finding that his interest in pharmacy had waned and inspired by Jules Plicque, a friend and fellow classmate from Meaux, Moissan joined Plicque at Edmond Frémy's (1814-1894) *École de Chimie Expérimentale* at the Musée d'Histoire Naturelle in Paris, where he became a student for the 1872-1873 academic year and then joined the laboratory of Pierre Paul Dehérain (1830-1902), who encouraged him to enroll in the course in the classics that would enable him to attend a university. He made rapid progress in chemistry, but he also became interested in literature and art [27] and even submitted a comedy play in verse, "Un Mariage imprévu" (An Unexpected Marriage), that he had written for performance at the Odéon theater in Paris. It was rejected by the selection committee. Of this disappointment in playwriting he later joked, "Je crois que j'ai mieux fait d'étudier la chimie" (I believe that I did better to study chemistry) [4]. In 1874 Moissan received the *Baccalauréat* and published his first article – on the respiratory activity of plants in the dark. Beginning in November, 1875, he served his year of military service as a hospital attendant in Lille in northern France near the Belgian border (Fig.5). In 1877 he received the *Licence ès Sciences* (roughly equivalent to an American B.S. degree), and in 1878 and 1879 he published two more articles on plant physiology. In the latter year he submitted the thesis [28] that earned him the diploma of *Pharmacien de Première Classe*.

The lectures on inorganic chemistry of Professor Alfred Riche at the *École de Pharmacie* led Moissan to become interested in the field and further estranged him from plant chemistry and physiology. In a letter of September 20, 1876 to Jules Plicque [29] he wrote that he had begun to study iron(II) oxide. He investigated pyrophoric iron and the oxides of the iron family, and in 1880 he presented a thesis for the degree of *Docteur ès Sciences* [30]. He discovered a new form of magnetic iron oxide and similar polymorphism in manganese and nickel oxides. In his subsequent study of chromium oxides and their salts he devised the first process for preparing pure chromium by distilling its amalgam in a stream of hydrogen.



Figure 5. Henri Moissan (second from left) in Lille, 1875-1876. Musée Henri Moissan, Paris. Photograph by James L.Marshall. (Courtesy, J.L.Marshall)

After his first academic appointment as *Répétiteur de Physique* at the Institut Agronomique (1879), in 1880 Moissan was appointed *Maître de Conférences* and *Chef de Travaux Pratiques* at the *École Supérieure de Pharmacie de Paris*. In 1882 he presented a thesis on the cyanogen series [31] and was appointed *Professeur Agrégé* there. He retained this position until 1900 when he was nominated to succeed Louis Joseph Troost (1825-1911) at the *Faculté des Sciences* at the *Université de Paris* (Sorbonne), where he found better working conditions than at the ill-equipped *École Supérieure de Pharmacie*. In 1887 and 1889 he was appointed *Professeur de Toxicologie* and *Professeur de Chimie Minérale*, respectively, at the *École Supérieure de Pharmacie de Paris*,

On May 30, 1882 in Meaux Moissan married Marie Léonie Lugan, a Meaux pharmacist's daughter. His father-in-law provided him with financial and moral support so that he could pursue his scientific research with minimal disturbance [32]. The couple had only one child, a son, Louis Ferdinand Henri Moissan, born on January 3, 1885, who became a chemical engineer in 1908 at the Institut de Chimie de Paris (since 1948, *École Nationale Supérieure de Chimie de Paris*) and then *Pharmacien de Première Classe* in 1913 and *Assistant de Toxicologie* at the *École Supérieure de Pharmacie de Paris*. The family regularly vacationed in Italy, Spain, Greece, the Alps, or the Pyrenees, and in 1904 Moissan attended the World's Fair in St. Louis, Missouri [4]. A *Sous-lieutenant* in the infantry, Louis was killed in the Meuse in one of the first battles of World War I on August 10, 1914 and was buried in the Champ d'Honneur [33]. Before the war Louis had left 200,000 francs to the *École Supérieure de Pharmacie* to endow two prizes – the *prix Moissan* for chemistry and the *prix Lugan* for pharmacy, in memory of his father and mother, respectively [8, 9].

As early as 1529 Georgius Agricola in his "Bermannus" described the use of fluorspar or fluorite ( $\text{CaF}_2$ ) as a flux [34], and in 1670 Heinrich Schwanhard of Nuremberg, a member of a family of glass cutters, found that when treating it with strong acids, the lenses of his glasses were etched from the

hydrogen fluoride that was evolved [35]. Through the years numerous other scientists including Johann Sigismund Elsholz, Andreas Sigismund Marggraf, Carl Wilhelm Scheele, Martin Heinrich Klaproth, and Jöns Jacob Berzelius investigated fluorspar and hydrofluoric acid. In his famous *Traité élémentaire de chimie* of 1789, which marked the beginning of modern chemistry, Antoine Laurent Lavoisier (1743-1789) included the *radical fluorique* among his Table of Simple Substances (elements) with the pure element (fluorine) designated as *inconnu* [36].

Although the other three halogens had been isolated – chlorine by Carl Wilhelm Scheele (1774), bromine by Antoine-Jérôme Balard (1826), and iodine by Bernard Courtois (1811), attempts to isolate elemental fluorine were hindered by two main problems – the toxicity of hydrogen fluoride and other fluorine compounds and the extreme reactivity of elementary fluorine and the consequent difficulty of designing apparatus from suitable materials. The English chemist Sir Humphry Davy (1778-1829) and French chemists Joseph Louis Gay-Lussac (1778-1850) and Louis Jacques Thenard (1777-1857) suffered intensely from the effects of inhaling hydrogen fluoride in their unsuccessful attempts to isolate fluorine, while the Irish brothers George James Knox and the Reverend Thomas Knox, who nearly died, injured their health in the same way. Similarly, the Belgian Paulin Louyet (1818-1850) and Frenchman Jérôme Nicklès (1820-1869) died prematurely. In 1855 Edmond Frémy electrolyzed anhydrous calcium fluoride and obtained calcium at the cathode, while a gas that must have been fluorine escaped at the anode [37]. Although he failed to collect and identify this gas, which reacted with water to form hydrofluoric acid, Frémy claimed priority in isolating fluorine. In 1869 English electrochemist George Gore (1826-1908) liberated a small quantity of fluorine, which combined explosively with hydrogen. This was the state of affairs when Moissan began his research to isolate this elusive element.

Moissan began his work by assuming that it would be easier to isolate fluorine from its compound with a nonmetal rather than with a metal [38]. In 1884, in his first experiment, he prepared phosphorus(III) fluoride ( $\text{PF}_3$ ) and unsuccessfully tried to isolate fluorine by decomposing this gaseous compound [39]. He next prepared arsenic(III) fluoride ( $\text{AsF}_3$ ), a liquid, and decomposed it thermally and electrolytically but did not obtain fluorine [40]. The action of sparks from an induction coil on phosphorus(III) fluoride was likewise unsuccessful [41]. By passing dried bromine over dried phosphorus(III) fluoride in a freezing mixture Moissan obtained an unstable amber liquid ( $\text{PF}_3\text{Br}_2$ ), which reacted with water to yield hydrofluoric, hydrobromic, and phosphoric acids [42]. He next passed phosphorus(III) fluoride gas through a heated platinum tube containing spongy platinum and passed the resulting gas into a mixture of potassium iodide and starch, which developed a blue color [43]. Although the gas may have been fluorine, other substances are also known to produce this color reaction so the isolation was far from definitive. Although the work was affecting Moissan's health, he persisted in his efforts. He next decided to repeat Davy's electrolysis of hydrofluoric acid, but recognizing that fluorine reacts readily with water, he decided to use anhydrous hydrogen fluoride, which he electrolyzed in a platinum tube. Hydrogen gas was liberated at the cathode, and the anode, even though consisting of platinum and iridium, was corroded. The gas attacked mercury, phosphorus, and silicon.

The dilemma was the fact that while water could not be present, anhydrous hydrogen fluoride was a very poor conductor. Moissan solved the problem by increasing the conductivity of anhydrous hydrogen fluoride by adding perfectly dry potassium hydrogenfluoride ( $\text{KHF}_2$ ). On June 26, 1886, using a battery of 50 Bunsen cells, he electrolyzed anhydrous hydrogen fluoride in which potassium hydrogenfluoride had been dissolved in an apparatus consisting of two platinum-iridium electrodes sealed into a platinum U-tube closed with fluorspar screw caps covered with a layer of gum lac and cooled with methyl chloride, a gas used in refrigerators, to  $-50^\circ\text{C}$ . (Fig.6, 7). A gas appeared at the anode that was shown to be fluorine by reacting with silicon with a burst of flame.

According to Professor Jacques Rivet, an authority on Moissan's life, Moissan's apparatus was successful because it was a combination of "French ingenuity" and four factors: 1) finding a chemical system that was electrically conductive, that did not contain water, which would produce oxygen and not fluorine ( $\text{KHF}_2/\text{HF}$  solution); 2) constructing an apparatus that was inert to elemental fluorine (fluorite,  $\text{CaF}_2$ ); 3) utilizing inert electrodes at a cold temperature so the electrodes would not be attacked (Pt-Ir electrodes, in an apparatus cooled with a condensed methyl chloride bath,  $-50^\circ\text{C}$ ); 4) using a chemical test which would prove the existence of elemental fluorine (spontaneous combustion with elemental silicon) [22].

Although Moissan had solved one of the most challenging problems in inorganic chemistry, his announcement was a most conservative one: "One can indeed make various hypotheses on the nature of the liberated gas; the simplest would be that we are in the presence of fluorine, but it would be possible, of course, that it might be a perfluoride of hydrogen or even a mixture of hydrofluoric acid

and ozone sufficiently active to explain such vigorous action as this gas exerts on crystalline silicon” [44].



Figure 6. Moissan's Electrolysis Apparatus Used to Produce Elemental Fluorine, which Stands before His Nobel Prize Certificate at the Musée Henri Moissan, Paris. Photograph by James L.Marshall. (Courtesy, James L.Marshall)

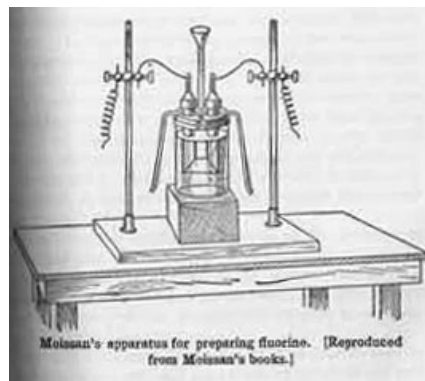


Figure 7. Drawing of Moissan's Apparatus for Producing Fluorine. Harrow, B. *Eminent Chemists of Our Time*; 2nd ed.; D. Van Nostrand Co.: New York, NY, 1927; facing p.146

Because Moissan was not yet a member of the Académie des Sciences, the announcement was read to the Académie on June 28, 1886 by Henri Jules Debray (1827-1888), in whose laboratory Moissan had made his momentous discovery [44]. The Académie's president appointed a committee of Debray, Pierre-Eugène Marcellin Berthelot (1827-1907), and Frémy to investigate the discovery [45]. After one unsuccessful attempt, Moissan was able to replicate his results, whereupon Frémy, who had earlier almost made the discovery himself, remarked, "A professor is always happy when he sees one of his students proceed farther and higher than himself" [14, p.740]. Moissan later wrote, "La recherché d'un corps simple est toujours très captivante" (The search for an element is always very captivating) [46].

From 1886 to 1891 Moissan devoted himself completely to studies of fluorine and its compounds [47-51]. In 1889 he discovered additional methods for purifying fluorine and determined its density [52], and he found that he could substitute cheaper copper for costly platinum in parts of the apparatus because a surface coating of insoluble copper(II) fluoride prevented further corrosion by the gas [53]. However, since copper(II) fluoride increased the resistance to the electric current, the electrodes still needed to be composed of platinum. Lord Rayleigh (1842-1919) and Sir William Ramsay's (1852-1916) discovery of the first noble gas, argon, in 1894 led Ramsay to ask Moissan whether this inert gas would combine with the most active of gases, fluorine. Not only would the two not react at room temperature but even under the influence of an electric spark [54].

Moissan also collaborated with Sir James Dewar (1842-1923) to determine the reactivity of carefully dried fluorine at extremely low temperatures [55-57]. At  $-183^{\circ}\text{C}$  it no longer attacked glass, and at  $-185^{\circ}\text{C}$  it condensed to a yellow liquid (Fig.8) [58], which did not displace iodine from iodides, and silicon, boron, carbon, sulfur, phosphorus, and iron did not become incandescent in a fluorine atmosphere. In 1903 Moissan and Dewar used liquid hydrogen to solidify fluorine at  $-223^{\circ}\text{C}$  [59]. Moissan found that perfectly dry fluorine does not react with perfectly clean and dry glass [60]. In 1900 he summarized his research on fluorine in a monograph [46].

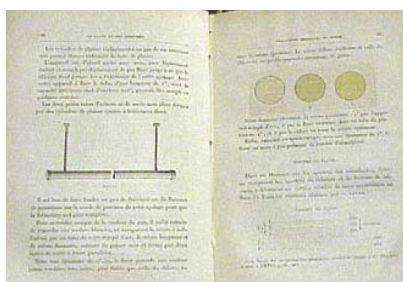


Figure 8. Book, possibly Moissan's *Le fluor et ses composés* (1900) (Ref.6), showing the yellow color of fluorine. Musée Henri Moissan, Paris. Photograph by James L.Marshall. (Courtesy, James L.Marshall)

Moissan was the first French Nobel chemistry laureate. He was nominated in every year's competition for the relatively new international award since its inception until he won the prize in 1906. He was nominated by fellow Frenchman Marcellin Berthelot in the very first Nobel chemistry competition (1901), in which the winner, Jacobus Henricus van't Hoff, received 11 nominations [61, p.196-197]. Berthelot nominated him again in the 1902 competition, in which the winner, Emil Fischer, received five nominations [61, p.198-199]. In the 1903 competition, in which the winner, Svante August Arrhenius, received 12 nominations, Moissan received three nominations – from Berthelot, Eleuthère Élie Nicolas Mascart, and Ramsay [61, p.200-201]. In the 1904 competition, in which the winner, Ramsay, received 23 nominations, Moissan received six nominations – from O.Aschan, Berthelot, Carl Graebe, Edvard Hjelt, Cornelis A. Lobry de Bruyn, and Ramsay [61, p.202-203]. In the 1905 competition, in which the winner, Adolf von Baeyer, received 10 nominations and Dmitrii Ivanovich Mendeleev received three nominations, Moissan received 20 nominations, much more than any other competitor – from von Baeyer, A.Belohoubek, Berthelot, Charles Jacques Bouchard, Waldemar Christopher Brøgger, Per Teodor Cleve, Åke G.Ekstrand, M.Fileti, Emil Fischer, Heinrich Goldschmidt, A.Guntz, T.Hjortdahl, Peter Klason, Mascart, Nikolai Aleksandrovich Menshutkin, J.Minguin, P.Muller, Ramsay, J.O.Rosenberg, and V. Rothmund [61, p.204-207]. In the 1906 competition, which he won and in which Mendeleev received four nominations, Moissan received eight nominations – from von Baeyer, V.Czerny, G.Darboux, L.Henry, Klason, Philipp Lenard, Ramsay, and Rosenberg.

However, the above numbers do not adequately reflect the entire story behind these competitions. In the early Nobel competitions many of the leading luminaries of 19th-century chemistry were still alive [62]. For example, Emil Fischer, the 1902 laureate, when he accepted his prize, expressed his disappointment that Berthelot (1827-1907) and von Baeyer (1835-1917), the elder statesmen of French and German chemistry, respectively, had not first received prizes. He also felt that Mendeleev (1834-1907) and Stanislao Cannizzaro (1826-1910), who had proposed some of the most fundamental principles of chemistry, deserved consideration. Yet, according to Alfred Bernhard Nobel's will of November 27, 1895, which established the prize, the contribution to be honored should have been made "during the preceding year" [63, p.x-xi] or for older works "only if their significance has not become apparent until recently" (§2 of the Statutes of the Nobel Foundation). Furthermore, older possible candidates such as Berthelot had been nominated for a lifetime of achievement rather than a specific discovery and could be eliminated according to the stipulations of Nobel's will.

In 1905 the Nobel chemistry committee thought that Moissan, who had received an unprecedented number of 20 nominations out of a grand total of 41 nominations, was worthy of the prize. However, they believed that as significant as his contributions were, they did not have the same far-reaching impact as those of von Baeyer or Mendeleev, and Oskar Widman of Uppsala University, a member of the Nobel chemistry committee and a former student of von Baeyer's, on the basis of the impressive number of ten nominations and the fact that von Baeyer was still active in research, was able to convince the Academy that von Baeyer deserved the prize.

In 1906 the committee again recommended Mendeleev, who was 72, for his periodic system of the elements, probably assuming that the younger Moissan could be considered in subsequent years. This time, however, Peter Klason of Stockholm's Kungliga Tekniska Högskola (KTH, Royal Institute of Technology), who had nominated Moissan, refused to support Mendeleev. Arrhenius (1859-1927), the 1903 laureate and the most internationally prominent chemist in Sweden, insisted that Mendeleev's system was 35 years old and therefore too old to be considered. The majority of the Academy overturned the committee's recommendation and supported Moissan. Many years later committee member Otto Pettersson of Stockholms Högskola learned that Mendeleev had criticized Arrhenius' electrolytic dissociation theory. Arrhenius could never forget a criticism, and his support and intervention *for* Moissan was actually one *against* Mendeleev. Regarding Mendeleev's failure to receive the prize, Arne Westgren later wrote: "It is to be regretted that the Academy felt unable on formal grounds to offer its prize to the author of one of the most important advances in chemical theory during the latter part of the nineteenth century" [63, p.303].

In István Hargittai's view, "Today, Mendeleev's lack of a Nobel Prize is irrelevant because his name is eternally linked to the periodic table, displayed in every textbook and chemistry classroom" [64].

In February, 1907 both Mendeleev and Moissan died so 1906 was the last opportunity for either of them to receive the prize, which cannot be awarded posthumously. Without Arrhenius' intervention on his behalf Moissan would never have become a Nobel laureate.

Moissan thought that the extraordinary reactivity of fluorine might cause it to combine with carbon and that the resulting compound might lead to the separation of the carbon in the form of diamond. He found that fluorine readily attacked carbon even at room temperature to yield gaseous

carbon(IV) fluoride [50], but that reducing this compound produced sodium fluoride and only ordinary carbon. Because a study of meteorites containing microscopic diamonds had led to the view that diamonds could be formed from amorphous carbon by cooling from high temperatures at tremendous pressures, Moissan constructed an electric furnace (Fig.9, 10) [4, 65], which, although simple in design, was extremely useful for a variety of applications in high temperature chemistry. In December, 1892 he demonstrated his first model, which he later improved, to the Académie des Sciences [66]. It consisted of two blocks of lime (CaO), one on top of the other, with a hollow space for a crucible in the center, and a longitudinal groove for two carbon electrodes that produced a high-temperature electric arc.



Figure 9. Moissan's Electric Arc Furnace. Musée Henri Moissan, Paris. Photograph by James L. Marshall. (Courtesy, James L. Marshall)

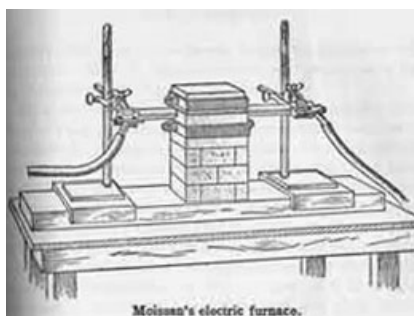


Figure 10. Drawing of Moissan's Electric Arc Furnace. Harrow, B. *Eminent Chemists of Our Time*; 2nd ed.; D. Van Nostrand Co.: New York, NY, 1927; facing p.146

On February 6, 1893 Moissan carried out his first experiment to produce diamonds [67] by heating carbonized sugar dissolved in iron to 3,000°C and then plunging it into cold water. He obtained microscopic carbon particles that seemed to have some of the properties of the diamond. However, carbides with densities differing little from that of the diamond are known that scratch rubies, but unlike carbides, diamond will yield carbon dioxide alone. Moissan's diamonds yielded CO<sub>2</sub> when burned in oxygen, but many of his later experiments failed to reproduce this [68]. Moissan continued to improve his furnace [69, 70] and to make further attempts to synthesize diamonds [71-75]. Most of his "diamonds" were black like carbonado, a massive black variety of diamond, but the largest of these, 0.7 mm in length, which his colleagues called "The Regent" after the 137-carat specimen in the Louvre, was colorless [4].

Other workers repeated Moissan's experiments with varying degrees of success [76]. Later studies of the iron-carbon phase diagram have demonstrated that transformation of graphite to diamond requires about 50,000 atmospheres pressure, whereas Moissan had not attained pressures above 10,000 atmospheres. Artificial diamond was not prepared until February 16, 1954 by the Swedish group ASEA. However, because it wanted to keep its process secret, ASEA did not publish or patent its results until General Electric announced its own successful synthesis on December 16, 1954 [68]. GE confirmed its results in 1959 by studying the diamond's properties [77]. Since then, many patents have been issued for the preparation of artificial diamonds.



Figure 11. Sample of Moissanite from the Collection of James L. Marshall. Photograph by James L. Marshall. (Courtesy, James L. Marshall)

In related research Moissan discovered a mineral, since named moissanite in his honor [78-83], as small green hexagonal plates in fragments of a meteorite containing iron found in Diabolo Canyon (now better known as Meteor Crater) in Arizona (Fig.11). His discovery was initially disputed on the basis that his sample might have been contaminated by the silicon carbide saw blades that were then on the market [82]. The synthetic material is also known by the trade name of carborundum [81]. Despite the fact that it is a compound, silicon carbide (SiC), it is sometimes classified as an element because the bonds between the carbon and silicon are very similar to the carbon-carbon bonds of

elemental minerals such as the diamond [81]. In 1998 the firm of Charles and Colvard introduced it onto the market as a lower cost alternative to the diamond [82]. Advertised as second in hardness to diamond, it is extremely resistant to scratching, abrasion, breaking, and chipping, and at first it often fooled jewelers into thinking that it was a natural diamond [83].

While at the *École Supérieure de Pharmacie* Moissan carried out investigations of carbon monoxide poisoning, the toxicity of opium smoke, the anæsthetic properties of methyl and ethyl fluorides, and the detection of pathogenic bacteria in mineral waters, but his primary interest was now inorganic chemistry. By use of his electric furnace he prepared crystalline samples of previously infusible metal oxides [84], isolated pure samples of highly refractory metals such as manganese, chromium, uranium, tungsten, vanadium, molybdenum, titanium, and zirconium, by reducing their oxides with carbon [85], and synthesized numerous metal borides [86], nitrides, silicides, and carbides (Fig.12) for the first time, achievements with industrial metallurgical applications. He carried out most of this work at the Edison Works on Avenue Trudaine in Paris [8, 87]. In a practical result of Moissan's research [88] his wife was one of the world's first women to cook with aluminum cooking utensils [4]. His preparation of calcium carbide ( $\text{CaC}_2$ ) [89, 90] and metal acetylides [91-93] led to many industrial electrochemical applications and the large-scale production of acetylene and the development of its chemistry.



Figure 12. Rare Earth Carbides.  
Musée Henri Moissan, Paris.  
Photograph by James  
L.Marshall.  
(Courtesy, James L.Marshall)

In his studies of metal hydrides Moissan prepared calcium hydride and alkali metal hydrides, which reacted with carbon dioxide to yield alkali formates. By the high temperature reduction of calcium iodide with sodium, he developed a process for preparing pure calcium metal. His final research involved his unsuccessful attempts to isolate the ammonium radical [94]. He studied solutions of metals in liquid ammonia and the electrolysis of solutions of ammonium salts and mercury(II) iodide in liquid ammonia. However, by decomposing sodium amalgam with a solution of ammonium iodide in liquid ammonia at  $-80^\circ\text{C}$ , he was able to prepare pure ammonium amalgam.

A prolific researcher, Moissan published more than 300 articles as well as two important monographs, *Le fluor et ses composés* (1900) [46] and *Le four électrique* (1897) [65]. He also was Editor-in-Chief of the 5-volume *Traité de chimie minérale* (1904-1906) [95], to which he contributed numerous articles.

As a scientist Moissan was a practical man who loved to work in the laboratory rather than to speculate or hypothesize about his research in his office. His fame attracted many foreign students, especially following his invention of the electric furnace, which opened up new possibilities in academic and industrial research and exerted a great influence on progress in inorganic chemistry, which until his achievements had been eclipsed by the more popular organic chemistry [8]. In the laboratory Moissan insisted on extreme cleanness and neatness. According to his former student, German chemist Alfred Stock (1876-1946), Moissan once looked critically at the wooden floor, which was waxed every Saturday, and asked, "Qui a fait cela?" (Who did that?). Stock noticed that a few drops of water had fallen from his wash bottle [4, 8]. Moissan was a highly cultured man with a lively sense of humor [20]. A lover of paintings, he was eclectic in his collecting. During his early twenties, like many students of his generation, he was a member of a close group of friends who shared his interest in art, literature, and science.

One of the most cultivated and elegant scientific lecturers in Paris, Moissan attracted large crowds to his lectures at the Sorbonne. According to Sir William Ramsay, himself a polished speaker with knowledge of several languages, His command of language was admirable; it was French at its best. The charm of his personality and his evident joy in exposition gave keen pleasure to his auditors. He will live long in the memories of all who were privileged to know him, as a man full of human kindness, of tact, and of true love for the subject which he adorned by his life and work [4, 7].

In addition to the Nobel Prize, Moissan received numerous honors, awards, and honorary memberships, both French and foreign, including a foreign associateship in the U.S. National Academy of Sciences (Fig.13). He was elected to the Académie de Médecine (1888), Académie des Sciences (1891), Conseil d'Hygiène de la Seine (1895), and Consultant des Arts et Manufactures

(1898). He was Commandeur de la Légion d'Honneur and received the Royal Society's Davy Medal (1896) and the Deutsche Chemische Gesellschaft's Hofmann Medal (1903) (Fig.14).

Although Moissan's life was certainly shortened by his lengthy exposure to fluorine, hydrogen fluoride, and carbon monoxide (a by-product of his electric furnace), it was not the actual cause of his death (Fig.15). On February 6, 1907 he suddenly suffered from an attack of appendicitis, which rapidly worsened. He died at the age of 54 on February 20, 1907, only 72 days after receiving the Nobel Prize. During his later years he said, "My life has been one of the simplest – happy in my laboratory and in my home" [8].



Figure 13. Diploma Appointing Henri Moissan a Foreign Associate of the U.S. National Academy of Sciences. Musée Henri Moissan, Paris. Photograph by James L. Marshall.  
(Courtesy, James L.Marshall)



Figure 14. Telegram from the Deutsche Chemische Gesellschaft Congratulating H.Moissan on His Isolation of Fluorine and Invention of the Electric Arc Furnace. Musée Henri Moissan, Paris. Photograph by James L.Marshall.  
(Courtesy, J.L.Marshall)



Figure 15. Henri Moissan in His Later Years, Undated Portrait. Musée Henri Moissan, Paris. Photograph by James L.Marshall.  
(Courtesy, James L.Marshall)

The Faculté de Pharmacie in Paris houses the Musée Henri Moissan, which contains exhibits and mementos, including diplomas of the Nobel Prize and other decorations, documents, photographs, and books [22]. A monument, dedicated to Moissan (Fig.16, 17), is located about 200 meters from the Lycée Henri Moissan, 20, cours de Verdun in Meaux (Fig.18) [9, 22, 96]. A commemorative session of the Académie Nationale de Pharmacie in his honor was held on June 17, 1998 [23].

Prior to World War II fluorine was still a laboratory curiosity; few chemists had ever seen or worked with it. Today it is still prepared by modifications of Moissan's original method. It was employed in the Manhattan Project to prepare uranium(VI) fluoride ( $UF_6$ ), used to separate the fissionable  $^{235}U$  isotope from the nonfissionable  $^{238}U$  isotope for the atomic bomb by the application of Graham's law of diffusion [17, 97, 98].





Figure 16. Moissan Monument near the Lycée Henri Moissan in Meaux. Photograph by James L. Marshall. (Courtesy, James L. Marshall)

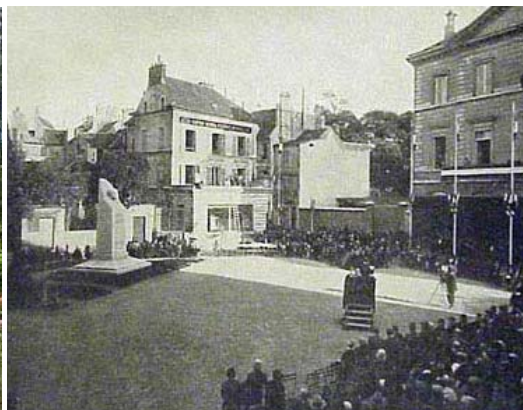


Figure 17. Dedication of the Moissan Monument in Meaux, October 4, 1931. Photograph by James L. Marshall. (Courtesy, James L. Marshall)



Figure 18. The Lycée Henri Moissan in Meaux. Photograph by James L. Marshall. (Courtesy, James L. Marshall)

Fluorine is now produced in tens of thousands of pounds per year in the United States alone. Because it releases tremendous amounts of energy on combining with other elements, it is used as an oxidizer in rocket fuels. It reacts with hydrocarbons to produce fluorocarbons, which are characterized by great stability, chemical inertness, and other valuable chemical and physical properties conducive to myriad applications. For example, Teflon is fireproof, resistant to almost all corrosive chemicals, and possesses non-sticking properties useful for kitchen utensils (Ronald Reagan was known as the Teflon president because none of the scandals with which he was involved seemed to stick to him). Chlorofluorocarbons (CFCs) have been used as coolants in refrigerators and air conditioners and as aerosol propellants. They are being phased out because of their deleterious effect on the ozone layer of the troposphere, an example of the Janus-like face of science with its possibilities for good or bad. Fluoroacetic acid is used as a rodenticide. Also, one part of fluoride per million parts of water has been found to reduce the incidence of cavities without mottling tooth enamel, and many cities now routinely fluoridate their water supplies, although some critics have questioned the utility of this treatment. As mentioned previously, the principle of Moissan's furnace is used in the industrial production of calcium carbide and calcium cyanamide and the numerous important chemicals derived from them [17, 20]. For all these reasons Moissan, who was one of the greatest scientists of his time, has exerted an extraordinary influence on inorganic and industrial chemistry.

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