REVIEW

Marie Curie: Pioneering Discoveries and Humanitarianism

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On the occasion of the 100th Anniversary of the *Nobel* Prize in Chemistry awarded to *Marie Curie.*

Marie Skłodowska-Curie, the first woman to win a *Nobel* Prize and the only person to be awarded the *Nobel* Prize twice in different scientific disciplines, is an inspiring figure. She discovered two new elements, polonium and radium, and was appointed as the first female professor at the University of Paris, when in most countries women did not yet have the right to vote. She serves as a role model for scholarly and humanitarian endeavors through what she attained in science, and through the hardships she had to overcome and the gender discrimination barriers faced by women scientists of that period, which she had to break. This article is a tribute to *Marie Skłodowska-Curie*'s achievements.

1. Childhood. – *Marie Curie* (*Fig. 1*) was born *Maria Salomea Skłodowska* on November 7, 1867, in Poland into a family that was liberal-minded and committed to learning [1–7]. Her mother was principal of a private school for girls; her father was director of a high school for boys, as well as a physics and mathematics teacher. Forced to resign from the position at the high school for political reasons when *Marie* was young, her father converted the family's home into a boarding school. Her childhood was clouded by the death of her sister in 1876. In 1878, *Marie* also witnessed her mother's slow death from tuberculosis. The survivors in the family stayed deeply committed to education, and the exceptionally gifted *Marie* graduated from high school for girls with the highest honors only to encounter a nearly insurmountable obstacle: in Poland, advanced studies were not available for women. In the 1880s, only in Geneva and Paris did universities admit women, and *Marie* wished to study at the *Sorbonne* in Paris. Even though her family encouraged scientific studies, the *Sorbonne* was beyond the family's financial capabilities, but *Marie* did not abandon her education.

Driven by her desire to learn, *Marie* began self-directed studying noting, '*I acquired the habit of independent work*' [1a], and she attended a clandestine school for women in Warsaw called '*The Flying University*' at the risk of being incarcerated or even deported to Siberia for governmental subversion [1–3]. At that time, *Marie* was also introduced to Positivism, a philosophy based on *Auguste Comte*'s '*Cours de Philosophie Positive*' ('*Introduction to Positive Philosophy*') which first emerged in France in 1830

Fig. 1. Marie Curie *in 1903* (© Museum of *Maria Skłodowska-Curie* in Warsaw)

[8]. Positivists in Poland believed in reason and logic, and that application of the scientific method would lead to improved human life. They fought for the emancipation of women, gender equality, and mass education. Ideals of Positivism would help *Curie* to overcome adversities, and to strive in scientific work, leading her to unparalleled breakthroughs.

To study at the *Sorbonne*, *Marie* and her older sister *Bronisława*, who would become a medical doctor and the first director of the Warsaw Radium Institute (*Maria Skłodowska-Curie* Institute of Oncology, founded by *Marie* herself), devised the following plan: working as a governess in Poland, *Marie* would subsidize her sister's studies, who after graduation would support *Marie*'s education. Soon after, *Marie* was appointed as governess, the future looked bleak, and her attitude significantly changed, as evidenced by her words: '*I have lost all hope of becoming anybody*' [2a]. '*I have been stupid, I am stupid, and I shall remain stupid all the days of life … I have never been, am not now and shall never be lucky … I am exceptionally unhappy in this world*', she wrote [3a]. Despite her '*black melancholy*', as *Marie* termed her depression [3b], she continued self-directed studying and correspondence mathematics classes with her father, and even organized an underground school for peasants' children, whom she taught to read and write. '*First principle: never let oneself to be beaten down by persons or events*' [3c], *Marie* wrote before coming to Paris in 1891 to study at the *Sorbonne*.

2. A Student in Paris. – At the *Sorbonne*, *Marie* realized that she lacked adequate preparation for her classes, and that she did not know the French language well enough to study advanced subjects; she devoted herself to learning it with all her determination. '*All my mind was centered on my studies*', she wrote [3d]. '*I divided my time between courses, experimental work, and study in the library. In the evening I worked in my room, sometimes very late into night*' [3d].

Graduating first in her class, *Marie* was the first woman in Europe to obtain a degree that is equivalent to a Master's degree in physics [6]. Her achievement in obtaining the degree brought recognition: she had become an inspiration to women, and she received the prestigious *Alexandrovitch* Scholarship to continue her studies [3e]. Later, *Curie* would teach her daughter *Ève*: '*We must seek for spiritual strength in an idealism which, without making us prideful, would oblige us to place our aspirations and our dreams very high*' [1b]. When *Marie* obtained a second degree, in mathematics, and was commissioned by the *Society of the Encouragement of National Industry* to start research on the magnetic properties of steels, it was not just the fulfillment of her cherished dream of education, it was the beginning of her extraordinary career. In these settings, she met her future husband, *Pierre Curie* [9].

3. *Pierre Curie.* – The *Nobel* prize-winning physicist *Frederick Soddy* would say: 'Pierre Curie's *greatest discovery was* Marie Skłodowska. *Her greatest discovery was that radioactivity was atomic*' [10]. Before meeting *Marie Skłodowska*, *Pierre Curie* made a legendary entry in his diary: '*Women of genius are rare*' [2b]. He believed that a conventional relationship would interfere with his commitment to science. At the time when he met *Marie*, his groundbreaking studies on crystals and magnetism were well-known, as well as his research in piezoelectricity (electric charge derived from crystals under pressure), a phenomenon, which he discovered with his brother *Jacques* in 1888 and used to construct the quartz electric balance. He also worked on improvement of an electrometer, a device designed by *Lord Kelvin* to measure conductivity; he built several versions of electrometers [11].

Pierre Curie and *Marie Skłodowska* both considered research pursuits to be '*the main source of life happiness*' [2c]. *Pierre Curie* wrote to her '*It would be a beautiful thing, a thing I dare not hope, if we could spend our life near each other hypnotized by our dreams: your patriotic dream, our humanitarian dream, and our scientific dream*' [3f]. *Pierre* and *Marie* married in 1895. '*One must make life into a dream and make a dream into reality*', *Pierre Curie* said [2e].

4. Pioneering Science: Two *Nobel* Prizes. – *Marie*, now Madame *Curie*, was fascinated by *Röntgen*'s discovery of X-rays in 1895 and *Becquerel*'s discovery of the 'uranic rays' in 1896 [9]. X-Rays and 'uranium rays' fogged a photographic plate, ionized air making it electrically conductive, but their origin and nature were unknown at the time, and no one was able to determine them quantitatively [13]. In her doctoral studies, which she began in 1897, Madame *Curie* chose to investigate 'uranic rays'. She desired to reproduce measurements of very low electrical currents generated in the air by 'uranic rays', carried on by *Lord Kelvin*, *Beatte*, and *Smoluchowski*. For her measurements, she used a system consisting of the quadrant-electrometer (E) coupled with the quartz electric balance (Q) and plate condenser (A B) (*Fig. 2*), designed by *Pierre* and *Jacques*, and located at the *École Municipale de Physique et Chimie Industrielles*, where *Pierre* worked [11][14][15].

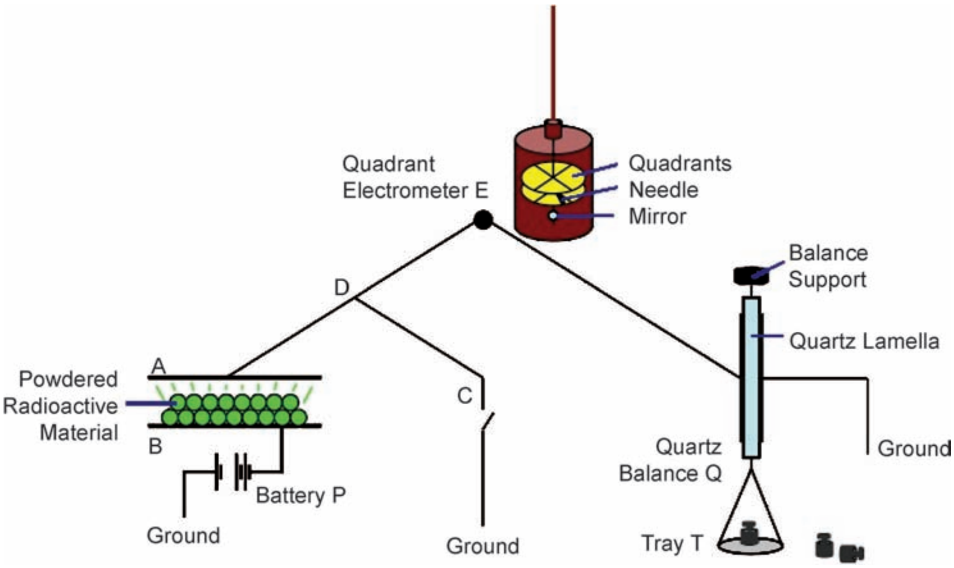

Fig. 2. *Electrometer set-up for the measurement of the intensity of radiation* (based on Figure 1 in Madame *Curie*'s thesis [14], and [3i] [11])

To measure the intensity of current generated by 'uranic rays', Madame *Curie* had to distribute powdered material on plate B of the condenser, which was powered by connecting it with the battery P. The 'uranic rays' of the material would make the air between plates B and A electrically conductive. Plate A was grounded by the connection of D to C. Plate A was also connected to the quadrant electrometer (E). The quadrant electrometer measured the charge of the plate A when the connection at C was broken. The charge on plate A caused the needle to move in the electrometer from the zero position.

To avoid limitations caused by the sensitivity of the electrometer, Madame *Curie* compensated the charge on plate A by the charge generated by the quartz electric balance (Q), based on the piezoelectric effect. The quartz electric balance was connected to the plate A and was also grounded. The charge compensation was possible, because the quartz electric balance had a plate (T) hanging from the bottom end of the thin plate of quartz (called piezoelectric quartz lamella). Placing calibrated weights on the tray T caused tension in the quartz lamella, which generated known amounts of electricity q, proportional to the applied weight p, as indicated by *Eqn. 1* [11]. The charge compensation experiment was completed when the electrometer needle indicated zero on the electrometer scale.

$$q = \frac{Klp}{e} \quad (1)$$

where q is charge, K is coefficient specific for quartz, l is length of quartz lamella, e is thickness of quartz lamella, and p is weight.

Using the set-up in *Fig. 2* and metallic uranium as a standard allowed Madame *Curie* to demonstrate that the intensity of the current generated by 'uranic rays' emitted by samples of uranium, thorium, and their compounds obtained from the Natural History Museum in Paris was similar (*ca.* 10^{-11} amperes, for the condenser in which the plates had diameter of 8 cm, and the distance between plates was 3 cm). She coined the term *radioactivity* to describe this property of uranium and thorium [16]. Based on the observation that the 'uranic rays' measured by the quadrant-electrometer were not affected by the chemical composition, heat, moisture, and physical state of compounds of uranium and thorium, she postulated that radiation originates from *inside* the atom. Experiments conducted by physicists including *Becquerel*, *Meyer*, *von Schweidler*, *Giesel*, *Rutherford*, *Villard*, and the *Curies* revealed the heterogeneous nature of the radiation [14]. The three components of the radiation identified were based on their penetrating powers and behavior in external magnetic fields (*Fig. 3*). The types of radiation were described as *alpha* (α), *beta* (β), and *gamma* (γ) rays, with α-rays being the least penetrating and γ-rays the most penetrating (*Fig. 3,a*), and β-rays being the most deflected in the external magnetic field (*Fig. 3,b*).

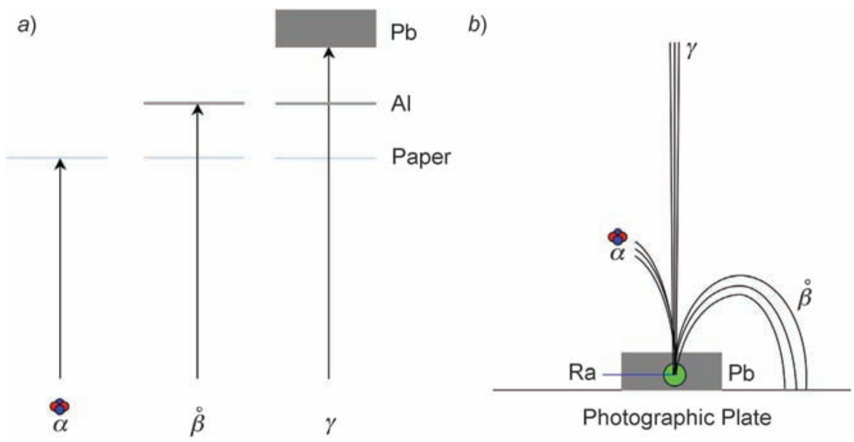

Fig. 3. a) *Penetrating power of radiation*; b) *behavior of alpha- (α), beta- (β), and gamma- (γ) rays in the external magnetic field* (based on Figure 4 in Madame *Curie*'s thesis [14])

Next, Madame *Curie* studied natural ores, which contained traces of uranium and thorium. Testing samples with the device depicted in *Fig. 2*, she found that the residues of the ore called pitchblende mined in Johanngeorgenstadt, Joachimsthal, and Pzibran containing uranium oxides (later known as UO_2 and UO_3); chalcolite, containing phosphates of copper and uranium (it was discovered later that its chemical formula was $Cu(UO_2)_2(PO_4)_2 \cdot 12\ H_2O$); and autunite, composed of phosphates of calcium and uranium (chemical formula found later as $Ca(UO_2)_2(PO_4)_2 \cdot 10-12\ H_2O$) produced currents of greater intensity than refined uranium and thorium, thus they were more radioactive (*Table*) [14].

Table. *Intensity of Current of Minerals*

Material	Intensity of current in Amperes
Uranium	2.3×10^{-11}
Pitchblende from Johanngeorgenstadt	8.3×10^{-11}
Pitchblende from Joachimsthal	7.0×10^{-11}
Pitchblende from Pzibran	6.5×10^{-11}
Chalcolite	5.2×10^{-11}
Autunite	2.7×10^{-11}

She hypothesized that samples of pitchblende, chalcolite, and autunite contained a new, strongly radioactive element. Her hypothesis was verified *via* analysis of natural and synthetic materials. She synthesized chalcolite in her laboratory from uranium nitrate and a solution of copper phosphate in phosphoric acid at 50–60° (*Eqn. 2*). The synthetic chalcolite showed radioactivity 2.5 times lower than metallic uranium [14]. The next step for Madame *Curie* was to isolate this new potential element. *Pierre* decided to assist her in this task (*Fig. 4*).

$$6\,U(NO_3)_4 + Cu_3(PO_4)_2 + 4\,H_3PO_4 + 48\,H_2O \rightarrow 3\,Cu(UO_2)_2(PO_4)_2 \cdot 12\,H_2O + 24\,HNO_3 \qquad (2)$$

The *Curies* decided to isolate the new radioactive material from uranium-free residue of pitchblende mined in Joachimsthal (Bohemia) supplied by the Austrian government at the cost of transportation. Uranium was used to obtain a yellowish green color in glass and pottery. Uranium was removed from pitchblende by first roasting the ore with sodium carbonate, Na_2CO_3, followed by washing with warm water and then diluted H_2SO_4. The process produced a residue 4.5 times more radioactive than metallic uranium [14]. In their research, the *Curies* used fractionation methods, including boiling the residue with concentrated solution Na_2CO_3, washing with water and HCl, precipitating by H_2S, NH_3, and H_2SO_4, and oxidizing with Cl_2, outlined in *Fig. 5*, and used radioactivity measurements to guide them though the purification [14].

In June 1898, the *Curies* discovered the first radioactive element [17]. They wrote, '*We thus believe that the substance that we have extracted from pitchblende contains a metal never known before, akin to bismuth in its analytic properties. If the existence of this new metal is confirmed, we suggest that it should be called* Polonium *(Po) after the name of the country of origin of one of us*' [2e]. Soon after, in December of 1898, they notified *l'Académie des Sciences* that they had strong evidence for another radioactive element, chemically similar to barium, which they named *Radium* (Ra) [18]. In 1899, *André Debierne* isolated from pitchblende the third radioactive element and named it *Actinium* (Ac) [19]. However, it was isolation and characterization of new elements polonium and radium that became the ultimate goal and challenge for the *Curies.*

The *Curies*' laborious task of isolating polonium and radium from pitchblende took place in a shed, the only place available to them. '*The days of work became months and*

Fig. 4. Pierre *and* Marie Curie *in their laboratory in Paris, 1898* (© Museum of *Maria Skłodowska-Curie* in Warsaw)

years: Pierre and Marie were not discouraged. The material which resisted them, which defended its secrets, fascinated them', the couple's younger daughter, *Ève Curie Labouisse*, wrote in 'Madame *Curie*' [1c]. The *Curies* failed to obtain polonium in pure form due to its short half-life of 138 days, but they noted the significant decrease of its radioactivity during purification [14]. Carrying out multiple crystallization steps, Madame *Curie* was able to separate 0.1 g of radium chloride to a point that allowed her collaborator, *Eugène Demarçay*, to obtain the spark spectrum; a spark passed through the powdered sample of radium chloride caused excitation of the atoms within which emitted light that was dispersed by a prism and photographed to determine spectral lines. Madame *Curie* also determined the atomic weight of 225 (current accepted value is 226.0254) for radium [14].

In June 25th of 1903, Madame *Curie* defended her doctoral thesis titled '*Recherches sur les Substances Radioactives*' ('*Researches on Radioactive Substances*') [14] and was awarded the title of Doctor of Physical Science *summa cum laude*. She was the first woman in France to receive a doctoral degree. Also in 1903, the *Curies* received

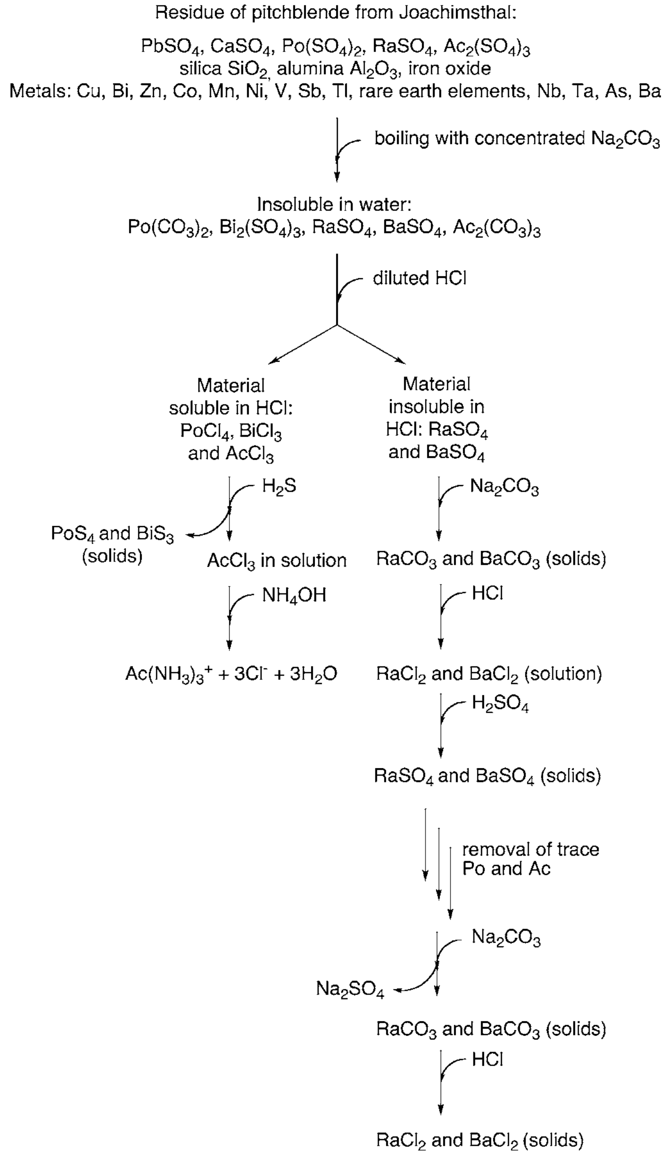

Fig. 5. *Separation of radioactive elements* (based on description provided by *M. Curie* [14])

the *Nobel* Prize in Physics, along with *Henry Becquerel*, '*in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena*' [20]. The *Curies* chose not to benefit financially from their discoveries, even though in 1904 radium was worth 750,000 of gold francs per gram (equivalent to about \$110,710) [3g].

In 1906, devastated by *Pierre*'s death in a street accident, Madame *Curie* resumed her work. In 1908, she became the *Sorbonne*'s first female professor. In 1910, she was nominated for membership of the *French Academy of Science*, and this caused intense public debate regarding the place of women in society. With a collaborator, *André Debierne*, at the *Sorbonne*, she succeeded with isolation of radium in metallic form. In 1911, she was nominated for her second *Nobel* Prize '*in recognition of her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element*' [21]. Soon after the announcement of the award, the *Nobel* Committee asked Madame *Curie* not to come to Sweden to receive her award because of French tabloid press's attacks on her personal life. Madam *Curie* had the courage to replay: '*In fact the Prize has been awarded for discovery of Radium and Polonium. I believe that there is no connection between my scientific work and facts of private life*' [3h]. She traveled to Stockholm to accept the award personally (*Fig. 6*).

Fig. 6. Nobel *Prize Certificate* [22]

In 1912, Madame *Curie* traveled to Warsaw for the ground breaking of the Polish Radium Institute. In 1913, she completed the radium standard sample, named *Curie* in her and *Pierre*'s honor, for the *International Radium Standard Committee*. Madame *Curie* used her influence to negotiate with the French government the establishment of the *French Radium Institute* (now the *Institute Curie*). Completed in 1914, it has become one of the world's leading medical, biological, and biophysical research centers and produced four *Nobel* Prize winners. The research and discoveries of Madam *Curie* and her husband revolutionized physics and chemistry, pioneered modern fields including nuclear physics [23][24], radiochemistry, and radiobiology [24][25], radio-

Fig. 7. *Mural in Warsaw to commemorate the 100th Anniversary of the* Marie Curie Nobel *Prize in Chemistry by the artist* Igor Cholda, also known as Acqaloopa, *2011* (photograph and © by *M. Brzostowska*)

therapy, and radiology in medicine [26][27], especially oncology [28], and remarkably have also inspired writers and artists [1–3] over the years (*Fig. 7*).

5. Humanitarianism of Madame *Curie*. – After the end of World War I in 1918, *Marie Curie* mentioned that she '*had the good luck to find a means of action*' [2f]. As *Susan Quinn*, a prominent biographer of *Curie*, noted: '*Luck had very little to do with it*' [2f]. Realizing that portable X-rays machines could save soldiers' life and limbs literally by allowing surgeons to locate bullets and broken bones, Madame *Curie* put her research on hold and designed a radiology unit, a car that carried X-ray equipment powered by an internal generator. She had to learn anatomy, find donated vehicles, and solicit donations to purchase the equipment. Later, these life-saving cars, called '*Petites Curies*', would be displayed in museums. Using charity money and her *Nobel* Prize earnings, she equipped over twenty radiology cars, and she founded nearly 200 permanent radiology posts in France and Belgium. She (*Fig. 8*) and her daughter *Irène* drove to the battlefields themselves. Madame *Curie* estimated that, during the winter of 1917–1918 alone, her vehicles and posts took over a million X-rays. Some of '*Petites Curies*' examined as many as 10,000 wounded soldiers. Madam *Curie* also established a school for radiology personnel, and she was personally involved in teaching. Her

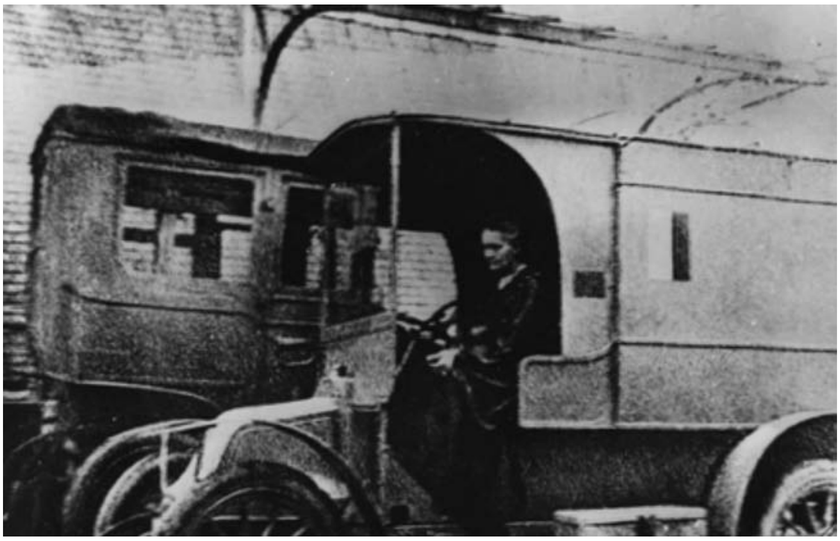

Fig. 8. Marie Curie *in a* Renault *automobile, called* 'Petite Curie'*, 1917* (© Museum of *Maria Skłodowska-Curie* in Warsaw)

involvement in war efforts and humanitarian work served to deepen her commitment to science as a way to help society grow and improve.

6. Family Life. – '*I have frequently been questioned, especially by women, of how I could reconcile family life with a scientific career. Well, it has not been easy*', *Marie Curie* admitted [29]. She raised her daughters, the older *Irène*, born in 1897, and the younger *Ève*, born in 1904, as a single parent when most women were relegated to homemaking, and working outside the home was considered detrimental to family and children. *Pierre* died when *Irène* was eight and *Ève* was eighteen months old.

Irène, along with her husband *Frédéric Joliot-Curie*, was awarded the 1935 *Nobel* Prize for chemistry for their discovery of artificial radioactivity. *Ève* became a writer and journalist, and was driven by her mother's example of humanitarian work, which led her to work with *The United Nations Children's Fund*. Thus, Madame *Curie* set an inspiring example by proving that it is possible to have a brilliant scientific career and succeed as a parent.

7. The Road to the Panthéon. – Madame *Curie* continued to conduct research and teach, even when she became almost blind (*Fig. 9*). Her efforts, sense of purpose, and enthusiasm for science brought her worldwide admiration. In 1921, Madame *Curie* undertook a trip to the United States, during which a number of universities conferred honorary degrees on her. *Fig. 10* shows President *Harding* with Madame *Curie*. In a White House ceremony, President *Harding* presented her with a gift of a gram of radium. In 1929, Madame *Curie* made a second trip to the US, raising money for a second gram of radium for the Warsaw Radium Institute and funds for her laboratory in France.

Fig. 9. Marie Curie *in her office at the French Radium Institute in Paris, 1921* (© Museum of *Maria Skłodowska-Curie* in Warsaw)

In 1922, *Marie Curie* became the first woman elected to the *French Academy of Medicine* for her contributions to radiological medicine. From 1922, she served on the *League of Nations' International Committee on Intellectual Cooperation*. The Committee promoted goodwill in the post World War I era, striving to stimulate collaborations and improve working conditions for scientists, teachers, and artists. Loyal to her Positivist ideals, Madame *Curie* worked to assure that imaginative and creative scientists like her husband *Pierre Curie* had '*the efficient means of accomplishing their task, in a life freed from material care*' [30]. She lobbied French politicians to increase funding for science, returning favors with such undertakings as giving lectures in Rio de Janeiro to improve Franco-Brazilian relations at the request of the French Minister of Foreign Affairs.

Marie Curie died from aplastic anemia related to overexposure to radiation on July 4, 1934. In 1995, *Marie* and *Pierre Curie*'s remains were transferred to the Panthéon, the French necropolis dedicated to distinguished French citizens. Even after death, Madame *Curie* broke another boundary; she was the first woman interred in the Panthéon for her own accomplishments.

8. Conclusion. – The year 2011 is the 100th anniversary of *Marie Curie*'s *Nobel* Prize in Chemistry. Partly for this reason, the United Nations designated 2011 the *International Year of Chemistry* [7]. This year, we have another opportunity to celebrate the life and achievements of Madam *Curie* who said '*Life is not easy for any of us. But what of that? We must have perseverance and above all confidence in ourselves.*

Fig. 10. Marie Curie *and President of USA* Warren Harding, *1921* (© Museum of *Maria Skłodowska-Curie* in Warsaw)

We must believe that we are gifted for something and that this thing must be attained' [1d].

We thank Professors *Robert Butler*, *John Wahlert*, and *Keith Ramig* of Baruch College at the City University of New York (CUNY), and Professor *Sergei Tolmachev* of the United States Transuranium & Uranium Registries, for stimulating discussions. We thank *Sarah Moon* and *Olga Lavinda* for inspiring us to write this article. We thank Professor *Olga Dmytrenko* of the University of Delaware for the paining of 'The Fighter' used in the Table of Contents, *Marta Brzostowska* for the photograph of the Aqualoopa's mural, and *Paweł Ciepielewski* and *Małgorzata Sobieszczak-Marciniak* of the Museum of *Maria Skłodowska-Curie* in Warsaw for providing pictures of *Marie Curie*. We acknowledge Baruch College of the CUNY, the *PSC-CUNY Research Award Program*, and *The Eugene Lang Foundation* for support.

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Received August 29, 2011