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1. INTRODUCTION

"The measure of a man's life is the well spending of it, not the length." - Plutarch (AD 46?-120)

Plutarch could easily have had Antoine Laurent Lavoisier (1743-1794) in mind when he wrote this well known quote. Few men in history have contributed as much to the scientific disciplines as Lavoisier did. He certainly would have continued to contribute if he had not been executed in his 51st year, during the Reign of Terror in the French Revolution.

Antoine Lavoisier is well known as the father of modern chemistry. His work on the chemistry of oxygen and the development of the concept of mass balance illuminated the way for future chemists to apply rigorous scientific methods in their work. However, Lavoisier also made considerable contributions to other scientific disciplines, including meteorology and atmospheric science. This paper surveys Lavoisier's life and his considerable scientific contributions. Highlighted are his work on lightning and his attempts to develop a meteorological network and make temperature and humidity measurements for weather prediction.

2. EARLY LIFE AND EDUCATION

Antoine Laurent Lavoisier was born to Jean Antoine Lavoisier and his wife, Emilie Punctus on August 26, 1743. Jean Lavoisier was a well respected attorney who had married into rich, influential family. Antoine's mother died when he was five years old, leaving him to the care of his aunt, Constance Punctis, who made sure that he could obtain the best of educations (McKenna 1910; Gurlac 1973).

Lavoisier received his formal training at the College des Quatre Nations, sometimes referred to as the College Mazarin (for Cardinal Mazarin, who founded the school). Beginning schooling there at the age of 11, he received the best training in science available in the Parisian schools (Gurlac 1973).

While at the College Mazarin, Lavoisier had the good fortune to be taught by Lacaille, a renowned astronomer and mathematician. Lacaille had led an expedition to the Cape of Good Hope and charted the stars of the Southern Hemisphere. His influence is apparent in Lavoisier's first scientific paper, a description of the aurora borealis observed on a clear night in October of 1763 at Villers-Cotterets.

Lavoisier, following the family tradition of careers as attorneys, transferred to the Faculty of Law in 1761 and received his baccalaureate degree in 1763. A year later he was licensed to practice law, but his interests had turned to science.

During the summers of 1763 and 1764, Lavoisier worked with the botanist Bernard de Jussieu in the Paris area. He had also begun to take considerable interest in meteorology and had initiated barometric measurements that continued throughout his lifetime. He became much more interested in quantitative work than the qualitative, descriptive work of the botanist, and thus he turned toward chemistry.

A family friend and geologist, Jean-Etienne Guettard, whetted Lavoisier's interest in mineralogy and geology, particularly in the use of chemistry to analyze and classify minerals. It was likely Guettard who suggested that Lavoisier enroll in a chemistry course taught by Guillaume Francois Rouelle (Gurlac 1973). We have written of Rouelle in past articles on mentors who influenced atmospheric chemists (Gaffney and Marley 2002).

Rouelle was a showman and an excellent orator who taught at the Jardin du Roi lecture hall. During 1762-1763, Lavoisier is believed to have joined a number of Rouelle's students in the technical study of the chemistry of minerals, likely taught in Rouelle's apothecary near St. Germain des Pres.

Lavoisier and Guettard took four months in 1767 to map the Vosges Mountains and portions of Alsace and Lorraine, where Lavoisier used his barometer to accurately and systematically measure the heights of the mountains and the inclination of the terrain. Lavoisier went on in 1788 to use this information and his notes on strata observed in the region to support his theory of stratification before the Academy of Sciences in Paris.

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Geology was always of interest to Lavoisier, whose first chemical study involved examination of gypsum. He copied nature by using water to examine the substance's solubility and chemical properties. He wrote (Gurlac 1973; Lavoisier 1864-1893, p. 112), "Water, this almost universal solvent . . . is the chief agent she employs; it is also the one I have adopted in my work." During these studies he showed that plaster of paris and gypsum are the same chemical, differing by the "water of crystallization."

This work was first read to the Academy of Sciences in February of 1765 and later published in *Memoires des Savants Etrangers* in 1768. This journal was for nonmembers of the Academy of Sciences who aspired to membership, on which Lavoisier clearly had set his sights.

Indeed, water had a special fascination for Lavoisier. His paper on hydrometry, given to the Academy of Sciences in 1768, led to his election to that august body with a special appointment as adjoint *chimiste surnumeraire* in his 25th year. Shortly before his election to the Academy that year, Lavoisier entered the *Ferme Generale*, a private tax collection group that worked for the government. These two agencies would play major roles in Lavoisier's life. His role for the latter in collection of tax on salt would lead to his ultimate demise during the Reign of Terror.

In 1771, when he was 28 years of age, Lavoisier married Marie Anne Pierrette Paulze, the only daughter of farmer-general Jacques Paulze, was not quite 14. The marriage was very happy, and Mme. Lavoisier was quite talented as an artist. She also acted as an able assistant and recorded the results of her husband's experiments, urging him and promoting his "new chemistry" during their years together.

3. LAVOISIER — AIR, WATER, COMBUSTION

Lavoisier and many scientists of his era were beginning a revolution in chemistry. Alchemists who had preceded them had begun trying to define the materials around them as being made of earth, air, water, or fire — the four elements.

In 1768, Lavoisier began a continuous refluxing of water from a preweighed glass flask (a pelican). Previous workers had found earth remaining after rainwater was evaporated from flasks and had concluded that water could be transmuted into "earth." Lavoisier was concerned that the "earth" was coming from the glass. He was aware, from past work on gypsum, that water was an excellent solvent.

Lavoisier's careful weighing of the flask and the solid matter found to be transferred with the water clearly showed that the two weights were equal and that

the appearance of the "earth" was caused by the hot water dissolving silica from the glass. This work led to further studies examining the relationships between fire and water.

In 1776, Lavoisier suggested that air, when combined with the matter of fire (heat), might be a fluid in a permanent state of expansion. The release of effervescence and "fixed air" from fermentation and chemical reactions of acids had been noted by Stephen Hales in his studies of plants, animals, and minerals. Lavoisier noted that effervescence produced a cooling effect and was not caused by frictional processes. He also studied melting ice and in 1771 noted that the temperature of an ice-water mixture is "fixed" until the ice is completely melted.

These observations, plus his interest in an article on expansion written by Turgot, led Lavoisier to begin his famous experiments on combustion and a revolution in chemistry. He carefully showed that oxygen is a key kind of air and that it is responsible for combustion. This accomplishment led to the isolation and chemical characterization of many substances, beginning with the oxyacids. Lavoisier's theory of the gaseous state led to explanations for heat and light produced from combustion processes and rang the death knell for the phlogiston theory.

Other workers, notably Joseph Black, had discovered "fixed air" (carbon dioxide), although Lavoisier apparently was not aware of this work or at least was not very impressed by it. Joseph Priestly had indicated to Lavoisier that the red precipitate of mercury, when heated, would give rise to a new kind of air (oxygen). Lavoisier used this chemical reaction to produce oxygen. He passed the "new air" through lime water and showed that it did not react to form a precipitate, as "fixed air" was known to do. He also verified Priestly's observation that a candle flame burned brighter in the "new air." Lavoisier concluded not only that the "new air" (oxygen) was common but that it was purer than the surrounding air. Further experiments with his friend, Trudaine de Montigny showed that "new air" was quite respirable and indeed that birds in closed systems lived longer in "new air" than in common air. They also noted that "fixed air" was the gas produced by living birds breathing either common air or the "new air" produced by the decomposition of the red mercuric oxide.

Once he had a source of oxygen, Lavoisier performed reactions with a variety of substances. In many cases he showed that oxides or calcines and acids were formed by oxidation reactions with the pure "new air." He went on to suggest (erroneously) that all acids must contain oxygen, even though he was aware of muriatic acid (hydrochloric acid). He explained that this compound likely contained oxygen but resisted

analysis (Gurlac 1973). This was Lavoisier's greatest mistake, and it reflected his overall confidence in his ability to resolve the complex chemical world with simple methodology. Nevertheless, his steady, mathematical approach led to many more successes than this one failure.

Lavoisier went on to examine the "inflammable air" formed by the reaction of weak acids on iron or copper surfaces. We now know that this product is molecular hydrogen. If his theory that all acids contain oxygen was correct, oxygen reactions should produce acids with any gas combusted. However, when he combusted "inflammable air," he observed no product, especially no acids. This led Lavoisier to produce an apparatus for generating the two gases, hydrogen and oxygen, in sufficient quantities for an experiment on a much larger scale. He stored the gases in an apparatus he called a pneumatic chest that could be transported and used to run a double-nozzle burner for demonstrations.

Benjamin Franklin, the American ambassador to France during this period, noted that this device was capable of producing the "strongest fire we yet know." The hydrogen torch system that Lavoisier had devised gained much fame because it was able to melt platinum metal, a feat that had not been accomplished up to that point (Gurlac 1973).

4. BALLOONING AND METEOROLOGY

As noted previously, Lavoisier was very much interested in meteorology and measured the barometric pressure daily. He also developed an interest in using balloons to explore the atmosphere. His studies of hydrogen directly aided this pursuit.

The same "inflammable air" was applied in 1783 by the physicist J. A. C. Charles and his assistants for lighter-than-air ballooning. Using bags of sand as ballast, Charles was able to ascent to a height of over 10,000 feet and descend safely. Previously, hot air balloons had only been able to ascend to approximately one-tenth of that height. Lavoisier was very impressed with the ease with which Charles was able to control his flight.

The Academy of Science was also impressed, and Lavoisier was quickly appointed to a standing committee to find ways to improve balloons. In particular, his attention was on ways to improve the production of hydrogen.

Lavoisier accomplished the decomposition of water into its constituent gases, oxygen and hydrogen, by thermal breakdown of water passed very slowly through a red-hot gun barrel (Gurlac 1973). This study clearly showed that oxygen is at the heart of the combustion process.

Lavoisier's work also led to better sources of hydrogen and flights by other scientists who began to investigate the composition of the atmosphere. For example, Gay-Lussac took samples of the atmosphere as a function of height and showed that it did not differ from the ground to altitudes above 10,000 ft.

Although Lavoisier was best known for his chemical research, meteorology was his specialty. Daily measurements of atmospheric pressure and temperature began at his residence in 1765 and continued throughout his lifetime. In 1776 (same year as the Declaration of Independence), he reported a comparison of the lowest wintertime temperatures he had observed with the minimum temperature (-15.5°F) of the winter of 1709, which was colder by 1.5°F. He also noted that thermometers of the older Reamur 1732 design were not giving the same values as more recent methods for air temperature determination. In true Lavoisier fashion, he then spearheaded the standardization of temperature measurement. This entailed rules for fabrication and graduation of thermometers and the development of standards kept by the Academy of Sciences for future reference.

Lavoisier not only was fascinated by natural electricity and thunder, but he applied his chemistry studies to that area of research and noted that phase changes could lead to measurable electric charge. These studies led him to work with Benjamin Franklin, who was also interested in natural electricity and lightning. Indeed, Lavoisier and Franklin collaborated to install lightning rods on a number of buildings, including Saint Paul's Cathedral.

Lavoisier's studies of gases, phase changes, and heat were quite consistent with his visions about weather. He felt that with sufficient wind direction, speed, pressure, and humidity measurements at different altitudes, one could predict the weather. Comparing the difficulty of weather forecasting to that of medicine, he noted that one would continually need to monitor the parameters to accomplish the task.

To this end, Lavoisier established a number of weather stations with collaborators in France and Europe. They corresponded with Lavoisier, sharing their measurements of air pressure and temperature, wind directions, etc.

On the basis of this work, Lavoisier noted: "With all this information, it is almost always possible to predict one or two days in advance, within a rather broad range of probability, what the weather is going to be; it is even thought that it will not be impossible to publish daily forecasts which would be very useful to society" (Lavoisier 1864-1893, page 771).

5. CONCLUSIONS

Lavoisier continued to contribute and write key papers in many areas. In medicine, he studied respiration and correctly showed that oxygen was a crucial part of that process. He also played an important role in the public arena, fighting for social reforms in taxation and, in education, establishing the Lycee de Arts in his later years. In 1793 Lavoisier sent a petition to the Convention on Public Education, requesting that technical education be made available to farmers, factory workers, and craftsmen to increase French technical expertise.

After the Reign of Terror had executed the monarch, Charles XVI, and Marie Antoinette, attention turned to other members of the *Ferme Generale*. The Revolutionary Tribunal in a *trial farce* accused Lavoisier of watering down tobacco and sentenced him to execution by the guillotine. During the trial, Lavoisier, in his 51st year, asked for time to complete some scientific work in progress. Legend has it that the presiding judge answered his request with the statement, "The Republic has no need of scientists."

The noted French mathematician Joseph Louis Lagrange was present at the execution on May 8, 1794. After the guillotine had fallen, he commented: "It took them only an instant to cut off that head, but it is unlikely that a hundred years will suffice to produce a similar one" (Gurlac 1973).

Lavoisier's biographers noted that in his last letter he wrote, "I have had a fairly long life, above all a very happy one, and I think that I shall be remembered with some regrets and perhaps leave some reputation behind me" (Gurlac 1973).

Antoine Laurent Lavoisier certainly made significant contributions to atmospheric science and chemistry, and he definitely has found a place in the history of this important area of study. Indeed, his work in chemistry and meteorology would make a good case for considering him the *father of modern atmospheric science*.

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7. REFERENCES

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