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Imaging the Experiments on Respiration and Transpiration of Lavoisier and Séguin: Two Unknown Drawings by Madame Lavoisier

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Abstract
This paper presents two hitherto unknown drawings by Marie-Anne-Pierrette Lavoisier dating to the early 1790s that illustrate the experiments on respiration and transpiration of her husband Antoine-Laurent Lavoisier and his assistant Armand Séguin. These works may be associated with the well-known sepia drawings that were published for the first time by Edouard Grimaux in 1888. Details contained in these newly discovered drawings by M.me Lavoisier provide fresh evidence as to the nature and aims of Lavoisier's innovative experiments. As we will show, these drawings were intended to illustrate the collection of papers on respiration being prepared by Lavoisier for his *Mémoires de physique et de chimie* (1792-1805).

Keywords
Antoine-Laurent Lavoisier, Marie-Anne-Pierrette Lavoisier, Armand Séguin, experiments on respiration

The Textual Background to Lavoisier and Séguin's Experiments on Respiration

As transpires from his laboratory notes, Lavoisier took an interest in the physiology of respiration at a very early stage.[1] He realized that the

[1] Frederic Lawrence Holmes, *Lavoisier and the Chemistry of Life. An Exploration of Scientific Creativity* (Madison: The University of Wisconsin Press, 1985), pp. 6-17. On Lavoisier's theory of respiration, see also Everett I. Mendelsohn, *Heat and Life: The Development of the Theory of Animal Heat* (Harvard: Harvard University Press, 1964)

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discovery of 'fixed air' (carbon dioxide) had important consequences for the chemistry of life and on February 20, 1773 observed:

> The operations by which one may arrive at fixing air are: vegetation, the respiration of animals, combustion, under certain circumstances calcination, finally some chemical reactions. It was with these experiments that I believed I had to begin.[2]

On March 29, 1773, while conducting experiments on the heat treatment of lead using a newly devised burning mirror, he wrote:

> At this point I began to suspect that contact with circulating air is necessary to the formation of metallic calx; that perhaps the air we breath does not enter in its entirety into the metals that one calcinates, but only a portion, which is not present in abundant quantities in a given mass of air.[3]

Thus, the portion of atmospheric air that made the calcination and combustion of metals possible was the same as the part which made human respiration possible. Yet in the spring of 1773 Lavoisier was still a long way from understanding the true nature of this gas and only in 1774, following the experiments conducted by Joseph Priestley and Carl Wilhelm Scheele, was he able to individuate the invisible substance which he described as *air vital* and eventually denominated 'oxygen'. However, for the time being the analogy between combustion and respiration remained a hypothesis.

The difficulty of preparing an efficacious apparatus for experiments on respiration in animals and humans delayed further tests. Lavoisier managed to perform his first systematic series of experiments on birds in October 1776 in the private laboratory set up by his friend and patron Jean Philibert Trudaine de Montigny at the Chateau de Montigny. Lavoisier

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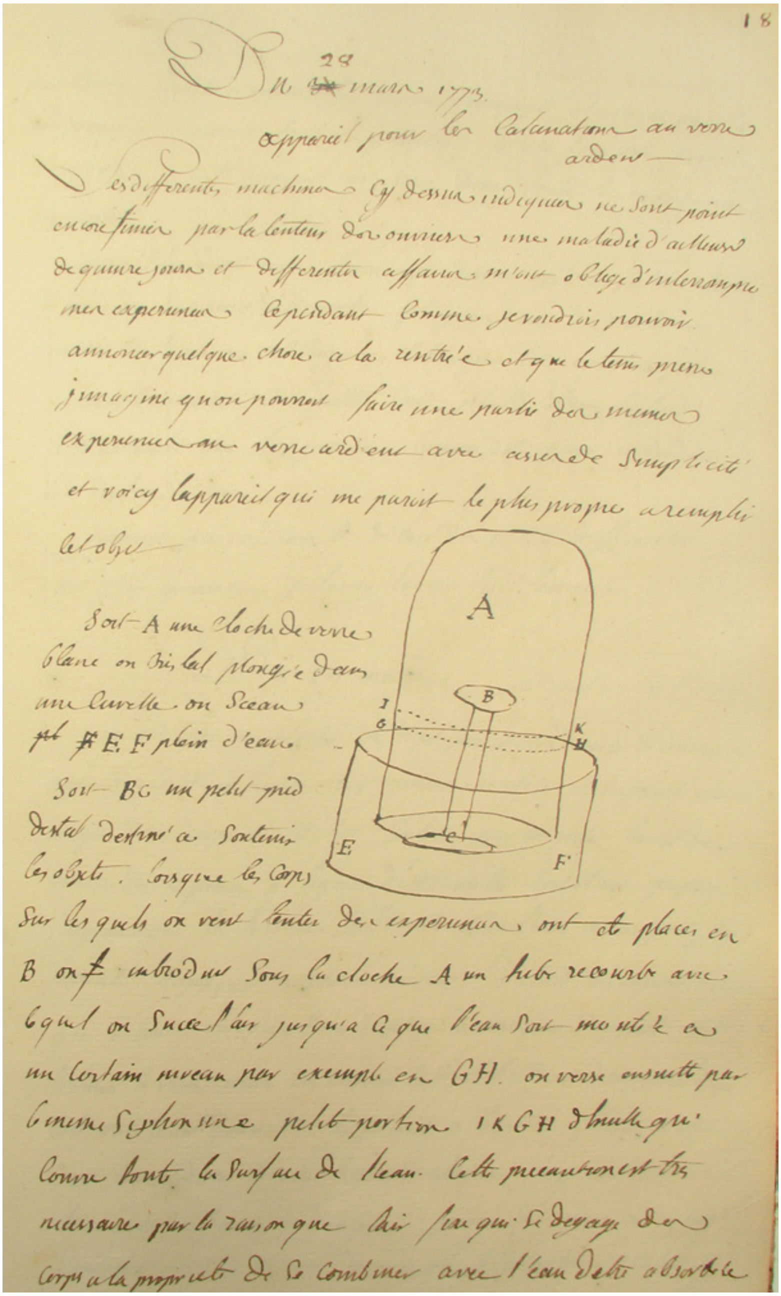
and Charles A. Culotta, "Respiration and the Lavoisier Tradition: Theory and Modification, 1777-1850," *Transactions of the American Philosophical Society*, 1972, *62/3*:3-41. For an accurate and original contextualisation of Lavoisier's theory of respiration in Europe between 1780 and 1815, see the excellent PhD thesis by Angela Bandinelli, *Dal soffio vitale all'ossigeno. Contributi della chimica antiflogistica all'indagine sul vivente tra Sette e Ottocento francese* (Florence: Università degli Studi di Firenze, 2000).

[2] "Les opérations par lesquelles on peut parvenir à fixer de l'air sont: la végétation, la respiration des animaux, la combustion, dans quelques circonstances la calcination, enfin quelques combinaisons chimiques. C'est par ces expériences que j'ai cru devoir commencer." Cited in Marcellin Berthelot, *La Révolution chimique. Lavoisier* (Paris: Alcan, 1890), p. 49.

[3] "J'ai commence de lors a soupçonner que le contact d'un air circulant est nécessaire à la formation de la chaux métallique; que peut-être même la totalité de l'air que nous respirons n'entrait pas dans les métaux que l'on calcine, mais seulement une portion, qui ne se trouve pas bien abondamment dans une masse d'air donnée." Archives de l'Académie des Sciences – Paris. Dossier Lavoisier. Registres de laboratoire, Vol. 1, fol. 20 recto.



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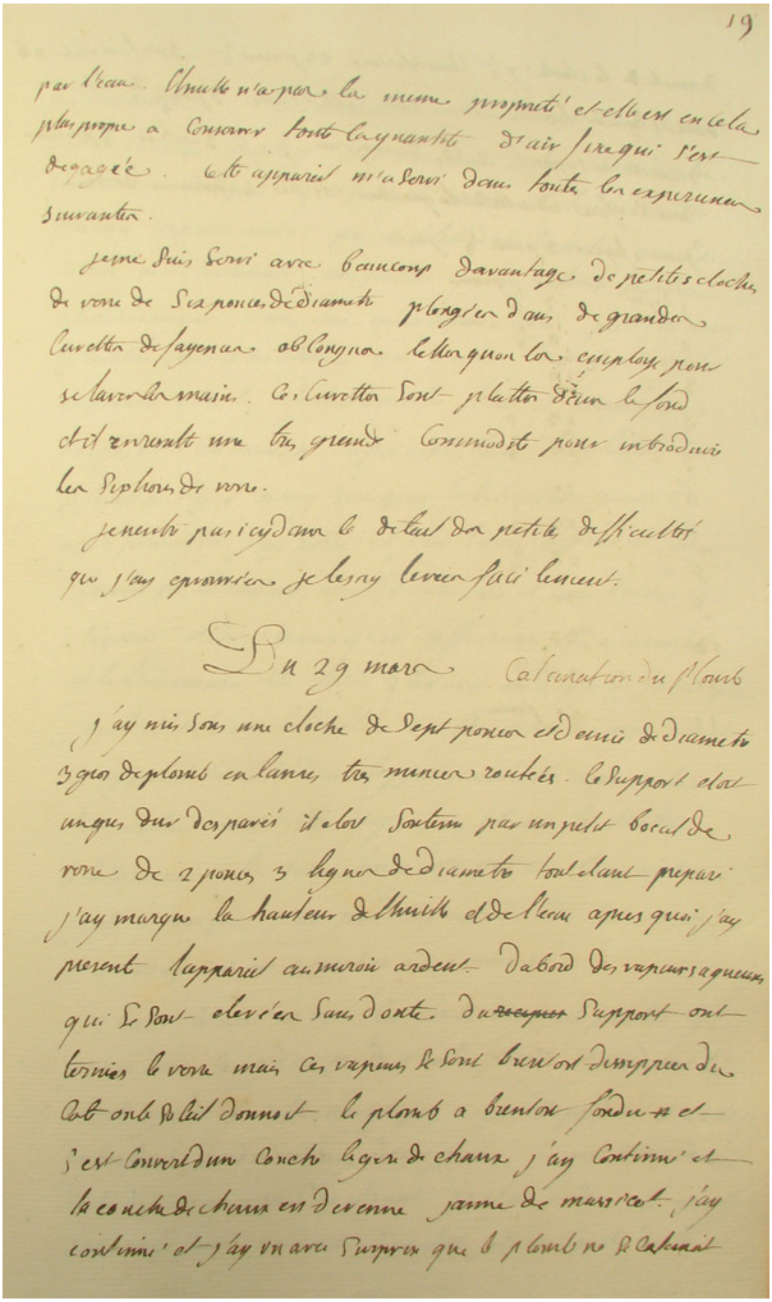
Du 28 mars 1773.

appareil pour les Calcinations au verre ardent

Les differentes machines cy dessus indiquees ne sont point encore finies par la lenteur des ouvriers une maladie d'ailleurs de quinze jours et differentes affaires m'ont obligé d'interrompre mes experiences. Cependant comme je voudrois pouvoir annoncer quelque chose a la rentrée et que le tems presse j'imagine qu'on pourroit faire une partie des memes experiences au verre ardent avec assez de simplicité et voicy l'appareil qui me paroit le plus propre a remplir cet objet

Soit A une cloche de verre blanc ou cristal plongée dans une cuvette ou sceau EF plein d'eau. Soit BC un petit piedestal destiné a soutenir les objets. lorsque les corps sur les quels on veut tenter des experiences ont eté placés en B on introduit sous la cloche A un tube recourbé avec lequel on suce l'air jusqu'a ce que l'eau soit montée a un certain niveau par exemple en GH. on verse ensuite par le meme syphon une petite portion IKGH d'huile qui couvre toute la surface de l'eau. Cette precaution est tres necessaire par la raison que l'air fixe qui se degage des corps a la propriete de se combiner avec l'eau d'etre absorbée

Figure 1. Lavoisier's burning mirror. Archives de l'Académie des Sciences – Paris. Dossier Lavoisier. Registres de laboratoire, Vol. 1, fol. 19 recto.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par l'eau. l'huile n'a pas la meme propriété et elle est en cela
plus propre a conserver toute la quantité d'air fixe qui s'est
degagée. Cet appareil m'a servi dans toutes les experiences
suivantes.

je me suis servi avec beaucoup davantage de petites cloches
de verre de six pouces de diametre plongées dans de grandes
cuvettes de fayence oblongues telles qu'on les employe pour
se laver les mains. Ces cuvettes sont plattes dans le fond
et il en resulte une tres grande commodité pour introduire
les siphons de verre.

je n'entre pas icy dans le detail des petites difficultés
que j'ay eprouvées je les ay levées facilement.

Du 29 mars   Calcination du plomb

j'ay mis sous une cloche de sept pouces et demie de diametre
3 gros de plomb en lames tres minces roulées. le support etoit
unique, sur des parois il etoit soutenu par un petit bocal de
verre de 2 pouces 3 lignes de diametre tout etant preparé
j'ay marqué la hauteur de l'huile et de l'eau apres quoi j'ay
presenté l'appareil au miroir ardent. D'abord des vapeurs aqueuses
qui se sont elevées sans doute du ~~recipient~~ support ont
terni le verre mais ces vapeurs se sont bientot dissipées du
coté ou le soleil donnoit. le plomb a bientot fondu et
s'est couvert d'une couche legere de chaux, j'ay continué et
la couche de chaux est devenue jaune de massicot. j'ay
continué et j'ay vu avec surprise que le plomb ne se calcinoit

Figure 2. Archives de l'Académie des Sciences – Paris. Dossier Lavoisier. Registres de laboratoire, Vol. 1, fol. 20 recto.

presented his results to the Académie Royale des Sciences on April 9, 1777[4] in a memoir in which he concluded that during respiration only the *air éminemment respirable* (oxygen) was inhaled, while the remaining components of the atmosphere played a purely passive role. Furthermore, he showed that in the lungs oxygen was converted into 'fixed air' (carbon dioxide). In the same period in another paper Lavoisier pointed out that this reaction was similar to the combustion of carbon and therefore that the physiology of respiration could be easily explained by the mechanism of the most commonplace chemical reaction. Nevertheless, in expanding on this analogy there was an important difference of which Lavoisier was fully aware: combustion was an operation in which each step could be easily controlled, whereas in respiration the transformation of the atmospheric 'fluids' that takes place in the lungs was concealed to our eyes.

On February 15, 1785 Lavoisier presented before the Société Royale de Médecine a memoir on alterations in the atmosphere in closed chambers. This paper described Lavoisier's eudiometric experiments, including the instruments he had perfected and the methods that he had developed in order to inquire into the nature of gases. By this time Lavoisier was able to establish that one cubic foot of atmosphere was composed of 432 *pouces* of *air vital* (oxygen) and 1296 *pouces* of *azote* (nitrogen) and that the latter played no active role in respiration. In an experiment he introduced a guinea pig into a crystal bell containing 1 cubic foot of atmospheric fluid and kept it there for 95 minutes, after which he observed a diminution in the volume of *air vital* by 55 *pouces* and the formation of 229 *pouces* of *acide carbonique* (carbon dioxide):

> It is therefore evident that independently of the portion of *air vital* that was converted into carbon dioxide, a portion of that which had entered into the lung did not come out again in the same form; and it turns out that one of two things happen in the act of respiration, either a portion of the air vital unites itself with the blood, or it could be that it combines with a portion of hydrogen to form water.[5]

[4] Antoine Laurent Lavoisier, "Mémoire sur les changements que le sang éprouve dans les poumons et sur le mécanisme de la respiration." The memoir remained unpublished until 1780 when it appeared in revised form in the *Mémoires de l'Académie Royale de Sciences* (1777) under the title "Expériences sur la respiration des animaux et sur les changements qui arrivent à l'air par leur poumon," in Lavoisier, *Œuvres,* 6 vols., Vol. 2 (Paris: Imprimerie Impériale, 1862) , pp. 174-183.

[5] "Il est donc évident qu'indépendamment de la portion d'air vital qui a été convertie en acide carbonique, une portion de celui qui est entré dans le poumon n'en est pas ressortie dans le même état; et il en résulte qu'il se passe de deux choses l'une dans l'acte de la

Assisted by Armand Séguin, Lavoisier decided to further investigate the modification of atmospheric air during human respiration. He observed that in the crowded dormitory of a general hospital in Paris there was a marked diminution in oxygen accompanied by an increase in carbon dioxide by an equal amount. This disruptive corruption of the atmospheric air in crowded halls could not only have harmful effects, but also explained why it was difficult in similar environments, such as a lecture hall, to maintain the attention of the audience for more than half an hour. Lavoisier was aware of the social and medical consequences of his observations and concluded with the outline for a future project:

> It is frightening to think that in a numerous gathering, the air that each individual breathes has passed and re-passed a great number of times, be it in its entirety or only a part, through the lungs of all the participants, and that it must be suffused with more or less putrid exhalations; but what is the nature of these emanations? Up to what point do they differ from one subject to another, in old age or in youth, in a state of illness or health? What are the illnesses that are likely to profit from this type of communication? What precautions could one take to neutralize or destroy the dangerous influence of these emanations? There is perhaps no point here on which examination could not give rise to experimentation, and that is not of the greatest importance for the conservation of the human species.[6]

In the early 1780s Lavoisier also observed that heat played a crucial role in respiration and that animal heat depended on the specific heat of oxygen, which was released during the decomposition of air in the lungs. By the second half of the 1780s Lavoisier had accumulated enough experimental evidence to form a new theory of respiration which – not surprisingly – was perfectly consistent with his new theory of combustion.

The solution to innumerable problems – scientific, medical, chemical and social – depended on finding the correct explanation for the

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respiration, ou qu'une portion d'air vital s'unit avec le sang, ou bien qu'elle se combine avec une portion d'hydrogène pour former de l'eau." Lavoisier, "Altérations qu'éprouve l'air respiré" (1785), in Lavoisier, *Œuvres*, Vol. 2 (cit. note 4), p. 680.

6 "On est effrayé quand on pense que, dans une assemblée nombreuse, l'air que chaque individu respire a passé et repassé un grand nombre de fois, soit en tout, soit en partie, par le poumon de tous les assistants, et qu'il a dû se charger d'exhalaisons plus ou moins putrides; mais de quelle nature sont ces émanations? Jusqu'à quel point diffèrent-elles dans un sujet ou dans un autre, dans la vieillesse ou dans la jeunesse, dans l'état de maladie ou de santé? Quelles sont les maladies susceptibles de se gagner par ce genre de communication? Quelles précautions pourrait-on prendre pour neutraliser ou pour détruire l'influence dangereuse de ces émanations? Il n'est peut-être aucun de ces points dont l'examen ne puisse donner prise à l'expérience, et il n'en est pas de plus important pour la conservation de l'espèce humaine." *Ibid.*, p. 687.

mechanism of human respiration, and Lavoisier realized that it would be necessary to test and develop his new theory by direct experimentation on human beings, however dangerous this approach might be.[7] The experiments themselves had to wait until 1790, because he had begun an intense campaign to promote the new science of chemistry, publishing a number of fundamental texts including *Méthode de nomenclature chimique* in 1787, a French translation with commentary of Richard Kirwan's *Essay on Phlogiston* in 1788, and *Traité élémentaire de chimie* in March 1789. Moreover, with the outbreak of the French Revolution Lavoisier became increasingly involved in a multitude of other activities that left him little time to work in a systematic manner on what would prove to be an exceedingly complex series of experiments.

At this point a younger scientist inspired by his work, Armand Séguin (1767–1835), opened the way for further studies on respiration with a short article in which he recapitulated the history of the discoveries made by Lavoisier, 'créateur de la Chimie moderne,' together with those of his predecessors and contemporaries.[8] Around this time therefore, in the spring of 1790, it appears that Lavoisier and Séguin began to collaborate on experiments in human respiration.

The preliminary results of their research were communicated with unusual speed, in late autumn of the same year. On November 13, 1790 Lavoisier presented to the Académie des Sciences a memoir on studies of respiration conducted on guinea pigs and on a human subject. The presentation was made by Lavoisier alone to the gathering of scientists, but when the paper was published Séguin's name appeared as co-author.

Historians have puzzled over the exact nature of the collaboration between Séguin and Lavoisier ever since, and the authorship of the memoir

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[7] Lavoisier and Séguin were not the first to conduct experiments on human subjects. Sometime in 1785 Jean-François Pilâtre de Rozier invented a respirator and carried out a dangerous experiment on the effects of mephitic gases on human respiration. A report of these experiments is provided by De l'Aulnaye, "Description et usage du respirateur antiméphitique, imaginé par feu M. Pilatre de Rozier, avec un précis des expériences faites par ce physicien, sur le méphitisme des fosses d'aisance, des cuves de bière, & c.," *Observations sur la physique*, 1786, *27:*418-429. It is rather surprising that this important memoir was not taken into account by Holmes, because it almost certainly played a role in suggesting to Lavoisier and Séguin the possibility of conducting complex experiments. The ingenious system of valves that Pilâtre assembled in his respirator to separate the inhaled from the exhaled air surely gave Lavoisier and Séguin the idea for their approach, which was based upon the same principle.

[8] Armand Séguin, "Observations générales sur la respiration et sur le chaleur animale," *Observations sur la physique*, 1790-92, *37:*467-472. The memoir was read before the Société Royale de Médecine on May 22, 1790.

has proved problematic. Who was its principal author? Who designed the experiments and the chemical apparatus? Séguin, who had been assisting Lavoisier in his laboratory since 1785, was particularly interested in his research on respiration, indeed so much so that he volunteered to act as the subject in this new set of experiments. At this point it is interesting to note that the first edition of the *Premier Mémoire sur la respiration* was not the paper published in 1793 in the *Mémoires de l'Académie des Sciences*,[9] but an Italian translation by Vicenzo Dandolo of a preliminary draft sent to him by the French chemist on November 13, 1790 – the same day that it was presented to the Académie.[10] In fact, Dandolo published two crucial papers by Lavoisier – his first memoir on respiration and his first work on transpiration – in the fourth volume of the second edition of his translation of Lavoisier's *Traité élémentaire de chimie.*[11] The Italian version of the paper on respiration differs in many respects from the memoir that was published two years later. Indeed, some of the divergences are quite significant and it is surprising that they have passed unnoticed by historians. Lavoisier appears as the sole author in Dandolo's translation, but in the first note he explicitly acknowledges the contribution made by Séguin in a statement that probably echoes what he had declared before the members of the Académie on the same day:

> The memoir that I am about to read before the Académie is the summary of a very vast study that I have undertaken on respiration in animals. M. Seguin wished to collaborate with me in this endeavour; and it is beholden upon me to confess that the success of the experiment I will be describing is due principally to his zeal, and to his patience. Each of the experiments has been repeated more than once, and the precision of the results almost always exceeded our hopes. Here I will only present a general overview, reserving a more detailed account of the experiments for another memoir; the Académie

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9 Armand Séguin, Antoine-Laurent Lavoisier, "Premier mémoire sur la respiration des animaux," *Mémoires de l'Académie Royale des Sciences*, 1789 (pub. 1793), pp. 566-584.

10 Lavoisier, *Correspondance,* 6 vols., Vol. 6 (Paris: Académie des Sciences, 1997), p. 345.

11 Lavoisier, *Trattato elementare di chimica ... Edizione seconda corretta ed ampliata di due dissertazioni inedite dell'autore sulla respirazione e sulla traspirazione e di nuove annotazioni del traduttore*, 4 vols., Vol. 4 (Venice: Zatta e figli, 1792), pp. 3-28. Here I have used the translation that appeared in the third edition (Venice: Zatta, 1796), Vol. 4, pp. 219-244. On Dandolo's translation and on his relationship with Lavoisier, see Marco Beretta, "Italian Translations of the *Méthode de nomenclature chimique and the Traité élémentaire de chimie*: The Case of Vincenzo Dandolo," in *Lavoisier in the European Context*, edited by Bernadette Bensaude-Vincent, Ferdinando Abbri (Canton, Mass.: History of Science Publications/USA, 1995), pp. 225-248.

however can obtain an idea from the instruments that they now have before their eyes.[12]

In the French version of the memoir as well, Lavoisier was at pains to underline that it was Séguin who perfected the apparatus used to perform the experiments on human respiration.[13] Unfortunately, no description of the apparatus was given. As Lavoisier declared, the aim of the paper was to provide an overview of the experimental results obtained between 1777 and 1785 and to lay the foundations for a new theory that would explain in a comprehensive manner the role of respiration in the broader biological cycle:

> It can be seen that the animal machine is principally governed by three main regulators: respiration, which consumes hydrogen and carbon and furnishes heat; transpiration, which increases or diminishes, in accordance with the necessity to carry away more or less heat; and finally digestion, which restores to the blood that which it loses through respiration and transpiration.[14]

In envisaging the metabolic cycle of the human organism as a sequence of physical processes involving respiration, alimentation and the dissipation of energy during the course of different kinds of work, Séguin and Lavoisier were replacing metaphysical views with the radical notion that human life depended on the dynamic organization of its main constituents on a

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[12] "La memoria ch'io sono per leggere all'Accademia è l'estratto d'un'opera molto vasta che io ho intrapresa sulla respirazione degli animali. Il Sig. Seguin volle secondarmi in questa fatica; ed io deggio confessare che l'esito delle sperienze di cui avrò render conto, è dovuto principalmente al di lui zelo, ed alla di lui pazienza. Ciascuna di esse è stata ripetuta più volte, e la precisione dei risultati ha quasi sempre superato le nostre speranze. Io qui non presenterò se non delle viste generali, riservando la particolarità delle sperienze ad altre memoire; l'Accademia però può prendere un'idea dietro agli apparecchi che ora le stanno sotto gli occhi." Lavoisier, "Sulla respirazione," in *Trattato elementare di chimica* (cit. note 11), p. 219.

[13] "Enfin il était impossible de soumettre à des expériences précises les effets de la respiration, avant qu'on eût acquis des moyens simples, faciles et expéditifs, de faire l'analyse de l'air; et c'est un service que M. Seguin vient de rendre à la chimie [In short it was impossible to study the effects of respiration in precise experiments, before one had acquired simple, easy and expeditious means, to conduct the analysis of the air; and this is a service that Mr. Seguin has rendered to the science of chemistry]." Armand Séguin, Antoine-Laurent Lavoisier, "Premier mémoire sur la respiration des animaux," in Lavoisier, *Œuvres*, Vol. 2 (cit. note 4), p. 689.

[14] "On voit que la machine animale est principalement gouvernée par trois régulateurs principaux: la respiration, qui consomme de l'hydrogène et du carbone et qui fournit du calorique; la transpiration, qui augmente ou qui diminue, suivant qu'il est nécessaire d'emporter plus ou moins de calorique; enfin la digestion, qui rend au sang ce qu'il perd par la respiration et la transpiration." *Ibid.*, p. 691.

chemical level, namely oxygen, carbon, hydrogen and heat. Interestingly, it was these two authors who introduced the term 'la machine animale' to refer to the complex organic processes that preside over life. The analogy they were drawing between man and machine was entirely different from the mechanistic reductionism proposed some fifty years earlier by Julien Offray de La Mettrie in *Homme Machine* (1748); their objective was to reveal the underlying structure of the living organism, which was regulated by chemical reactions. The explanation of life did not lie in a rigid mechanical philosophy, but in the more convincing notion of a system of chemical mechanisms. The translation of mechanical work (*la fatigue*) into chemical laws was a revolutionary step that subverted the existing hierarchy of scientific knowledge. Séguin and Lavoisier's theory played an important role in revealing the laws by which the human organism could maintain an equilibrium between all of its biological processes. As the degree of effort and fatigue increased, so did in due proportion the pulse and the consumption of oxygen:

> This type of observation leads us to compare the use of forces between which there would not seem to be any relationship. One could determine, for example, how many pounds of work correspond the effort of a man who is delivering a discourse, a musician who is playing an instrument. One could even evaluate the mechanical component in the work of a philosopher who is thinking, an author who is writing, a musician who is composing. These effects, thought to be purely moral, have something physical and material that permit them to be compared, in this context, with what man does in the way of physical effort. It is therefore not completely without reason that the French language has conflated, under the shared denomination of 'work', the exertions of the spirit with those of the body, the work of the thinker in his study with that of the merchants. The result of everything we have just said, [is] that the quantity of vital air which different individuals consume is highly variable, and that it is not rigorously equal in any circumstance of life, in any moment of the day.[15]

Aware of the revolutionary importance of their discovery, on November 17, 1790 Lavoisier and Séguin not only presented the apparatus that they had

[15] "Ce genre d'observation conduit à comparer des emplois de forces entre lesquelles il semblerait n'exister aucun rapport. On peut connaître, par exemple, à combien de livres en poids répondent les efforts d'un homme qui récite un discours, d'un musicien qui joue d'un instrument. On pourrait même évaluer ce qu'il y a de mécanique dans le travail du philosophe qui réfléchit, de l'homme de lettres qui écrit, du musicien qui compose. Ces effets, considérés comme purement moraux, ont quelque chose de physique et de matériel qui permet, sous ce rapport, de les comparer avec ceux que fait l'homme de peine. Ce n'est donc pas sans quelque justesse que la langue française a confondu, sous la dénomination

used for their experiments on human respiration, but also performed some experiments before the members of the Académie Royale des Sciences.[16]

On May 4, 1791 Lavoisier delivered a second paper on respiration at the Académie, which was co-authored with Séguin, and on the 11th of May he gave "a verbal description of the instrument that served for the experiments which he had conducted co-jointly with Mr. Séguin on transpiration. He also explained the results of these experiments."[17] Once again, no trace of this presentation has survived.

On June 10, 1791 Lavoisier presented the results of further studies on respiration carried out with Séguin in a paper that Maurice Daumas[18] believes was his *Premier mémoire sur la transpiration des animaux.*[19] In this paper Lavoisier reports on the lengthy experiments in which he measured the average water losses that take place during respiration and cutaneous perspiration, and we are provided with some rough details concerning the apparatus:

> In the procedure that we drew up for ourselves, we had three effects to examine: those of cutaneous transpiration, those of pulmonary transpiration, those of respiration; and the analytical method, the only one that could serve as our guide in these experiences, demanded that we find a way to separate these three effects, and to interrogate, so to speak, the three causes that produced them, one after another.
>
> A garment of taffeta coated with elastic rubber, that allowed neither air nor humidity to penetrate, served us to separate all of the phenomena of cutaneous transpiration from those of respiration. When one of us was inside this

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commune de travail, les efforts de l'esprit comme ceux du corps, le travail du cabinet et le travail du mercenaire. Il résulte de tout ce que nous venons de dire, que la quantité d'air vital que consomment les différents individus est très-variable, et qu'elle n'est rigoureusement la même dans aucune circonstance de la vie, dans aucun instant de la journée." *Ibid.*, p. 697.

16 "MM. Lavoisier et Seguin ont fait des expériences sur la respiration humaine et celle des animaux [...] M. Lavoisier a lu un Mémoire sur la respiration des animaux [Mr. Lavoisier and Mr. Séguin have conducted experiments on human respiration and that of animals (...) Mr. Lavoisier read a Memoir on respiration in animals]." Archives de l'Académie des Sciences – Paris. Procès-Verbaux, 1790, fol. 235.

17 "[...] une description verbale de l'appareil qui a servi à des expériences qui il a fait conjointement avec M. Séguin sur la transpiration. Il a aussi expliqué les résultats de ces experiences." Archives de l'Académie des Sciences – Paris. Procès-Verbaux, 1791, fol. 336. The reading of the memoir continued on June 10.

18 Maurice Daumas, *Lavoisier théoricien et expérimentateur* (Paris: PUF, 1955), p. 65.

19 Armand Séguin, Antoine-Laurent Lavoisier, "Premier mémoire sur la transpiration des animaux," in Lavoisier, *Œuvres*, Vol. 2 (cit. note 4), pp. 704-714. The memoir was first published in the second edition (1792) of Vincenzo Dandolo's Italian translation of Lavoisier's *Traité élémentaire de chimie* (see note 11). The first French edition appeared in 1797 in the *Mémoires de l'Académie des sciences* (1790), pp. 601-612.

> garment which could be closed above the head by a strong ligature, a tube adapted to his mouth and that was sealed to the skin, in such a way as not to allow the escape of any portion of air, gave him the freedom to breathe.[20] Everything that belonged to [the process of] respiration took place, by this means, outside the apparatus; everything that belonged to transpiration took place within. By weighing oneself before entering the apparatus and then after coming out of it, the difference gave the loss in weight due to the united effects of respiration and transpiration. By weighing oneself a few seconds after entering the apparatus, and a few seconds before leaving it, one had the loss of weight due exclusively to the effects of respiration. Of all the difficulties that we encountered during this work, the most considerable was the separation of the effects of respiration, transpiration, pulmonary transpiration and cutaneous transpiration.[21]

In addition to these results, Lavoisier and Séguin noted that

> [...] without seeking to consume each day the same quantity of food, without binding oneself to a certain kind of life, as long as meals were taken at more or less regular hours and excesses were avoided, the same individual, after having increased in weight from all the food that he had taken, returned every day, after the revolution of twenty-four hours, to the same weight that he had the

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[20] A description of this respirator is provided by Lavoisier's laboratory assistant Jean-Henri Hassenfratz in the article "Respirateur," in *Encyclopédie Méthodique. Physique*, 4 vols., Vol. 4 (Paris: Veuve Agasse, 1822), pp. 501-502. The illustration that appears with the article is not however particularly useful and there seems to have been some confusion in Hassenfratz's mind between Lavoisier's respirator and the one invented by Pilâtre de Rozier in 1785. This is probably due to the fact the he was writing the article thirty years after the experiments had been conducted and his memory of certain details was inaccurate.

[21] "Dans le plan que nous nous étions tracé, nous avions trois effets à examiner: ceux de la transpiration cutanée, ceux de la transpiration pulmonaire, ceux de la respiration; et la méthode analytique, la seule qui puisse servir de guide dans les expériences, exigeait que nous trouvassions des moyens de séparer ces trois effets, et d'interroger, pour ainsi dire, l'une après l'autre, les trois causes qui les produisent. Un habillement de taffetas enduit de gomme élastique, qui ne laisse pénétrer ni l'air ni l'humidité, nous a servi à séparer tous les phénomènes de la transpiration cutanée de ceux de la respiration. L'un de nous étant dans ce vêtement qui se fermait par-dessus la tête au moyen d'une forte ligature, un tuyau qui s'adaptait à sa bouche et qui se mastiquait sur la peau, de manière à ne laisser échapper aucune portion d'air, lui donnait la liberté de respirer. Tout ce qui appartenait à la respiration se passait, par ce moyen, en dehors de l'appareil; tout ce qui appartenait à la transpiration se passait en dedans. En se pesant avant d'entrer dans l'appareil et après en être sorti, la différence donnait la perte de poids due aux effets réunis de la respiration et de la transpiration. En se pesant quelques instants après être entré dans l'appareil, et quelques instants avant d'en sortir, on avait la perte de poids due seulement aux effets de la respiration. De toutes les difficultés que nous avons rencontrées dans ce travail, la plus considérable a été la séparation des effets de la respiration, de la transpiration, de la transpiration pulmonaire et de la transpiration cutanée." Armand Séguin, Antoine-Laurent Lavoisier, "Premier mémoire sur la transpiration des animaux," in Lavoisier, *Œuvres*, Vol. 2 (cit. note 4), pp. 707-708.

> day before. If this effect did not take place, the animal was in a state of pain or illness.[22]

In their *Second mémoire sur la transpiration*,[23] presented before the Académie on February 22, 1792, it was apparently Séguin who spoke, providing further details on the apparatus and the procedures used to perform the experiments, and these deserve to be quoted at length:

> The scale that we used for this research was constructed with the greatest of care. Loaded on each side with a weight of 125 pounds, a *demi-gros* would make it tip markedly; from which it turned out that at each weighing the error could not exceed 18 grains, either more, or less.
>
> But since all of our experiments required two weighings for comparison, one could surmise that this error of 18 grains, if observed in opposite directions in the two measurements, would completely disappear; all the same, even supposing it to be in the same direction, the error in each experiment could not be but 36 grains.
>
> Therefore, since the greatest difference that we obtained between the two comparative weighings was approximately 4,000 grains (or what comes to the same of 6 *onces*, 7 *gros*, 40 grains) and since the smallest difference was 1280 grains (or what comes to the equivalent of 6 *onces* 1 *gros* 56 grains), it turns out, supposing all of the most unfavourable conditions, that the error in our experiments could not have been, in the first case, more than one in one hundred and eleven, and, in the second case, not more than one in thirty-five.
>
> The precision of this scale required great skill to make the best use of it. Very often an involuntary movement by the individual undergoing the experiment, would make the beam oscillate. But what was even more troublesome was the loss in weight experienced by this individual during each weighing, a loss that; on average rose to 17 or 18 grains per minute. As soon as one had the correct weight, it was necessary to look at the watch promptly; because if one waited one minute more, the scale would begin to tip toward the weight-bearing side.
>
> By taking these precautions, we could easily determine the united effects of cutaneous transpiration and pulmonary transpiration.
>
> I was weighed, and note was taken of my weight, and the hour in which this was determined.

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22 "[…] sans s'attacher à ne prendre chaque jour que la même quantité de nourriture, sans s'astreindre à un genre de vie déterminé, pourvu que les repas soient pris à des heures à peu près réglées et qu'on évite les excès, le même individu, après avoir augmenté de poids de toute la nourriture qu'il a prise, revient tous les jours, après la révolution de vingt-quatre heures, au même poids qu'il avait la veille. Si cet effet n'a pas lieu, l'animal est dans un état de souffrance ou de maladie." *Ibid.* p. 713.

23 The memoir was only published in 1814: Antoine-Laurent Lavoisier, Armand Séguin, "Second mémoire sur la transpiration," *Annales de chimie*, 1814, *90*:5-28. This paper was not included in Lavoisier's *Œuvres*.

I then remained at rest for three or four hours, taking great care above all not to blow my nose, or spit, or even to occupy myself, whether physically, or morally with things that could have accelerated my pulse.

After four hours, I placed myself once again on the scale, I was again weighed, and in the same way note was taken of my weight, and of the exact hour in which this weight was determined.

One knew as a consequence, by means of a simple subtraction, how long the experiment had lasted in minutes, and what level my weight loss had reached during this period.

By then dividing the loss in weight by the number of minutes, we had the average weight loss for each minute.

Since we then wished to determine separately the effects of cutaneous transpiration and pulmonary transpiration, we made use of a gown of taffeta, coated in elastic rubber, and so well sealed on all sides, that, for more than fifteen days, it did not allow any portion to escape of the atmospheric air that we had introduced to inflate it.

This garment open in its upper part, had at the height of the mouth, an aperture garnished with a thin band of copper.

I placed myself in this envelope; its upper part was closed by means of a tight ligature; the copper mouth was sealed to my lips with pitch, mixed with a little turpentine, and it was kept firmly in place with the aid of cords that were knotted behind my head.

Thus arranged, I placed myself on the seat of the scale; I was weighed; I remained seated quietly for three or four hours; and, at the end of this time, a new weighing was done.

The difference between these two weighings, indicated to us the weight that I had lost in a given amount of time solely through pulmonary transpiration.

I then emerged from the envelope; I was weighed again; and at the end of a certain time, the weighing began again.

The difference between these two new weight measurements then indicated to us the loss in weight occasioned, both by pulmonary transpiration, and by cutaneous transpiration.

Subtracting from this total loss in weight, the loss in weight occasioned solely by pulmonary transpiration, the remainder represented the loss in weight occasioned by cutaneous transpiration.

It was by taking all of these precautions that we finally succeeded in obtaining satisfactory results, both on transpiration in general, and on cutaneous transpiration and pulmonary transpiration.

Our work on this objective lasted nearly eleven months.

Every day I was weighed [at least] once at the same hour, but more usually three or four measurements were carried out on me, in accordance with what was necessary to isolate [the different components of] the experiments or to make comparisons between them.

At each weighing the barometer, the thermometer, and the hygrometer were read; note was taken of the degrees they indicated; and the condition I found myself in was also recorded.

As soon as the atmospheric temperature rose even slightly, I placed myself in shirtsleeves in order to make it easier for the air to dissolve my transpirable [bodily] humour; but if the temperature was less elevated, I covered myself more, taking above all, care, in the comparative weighings, to be wearing exactly the same things.

Since I needed to know with precision the quantity of food that I was taking, I put on a plate the solid food, and in a carafe the liquid foods. I then weighed the plate and the carafe, and I re-weighed them after I had dined sufficiently; the difference between the two weights indicated the quantity of solid and liquid food that I had taken.

When I wished to eat and drink determined quantities, I first weighed out these quantities, and I then consumed them in totality.

Sometimes I would also place myself on the scale and eat a quantity of food that had previously been weighed out; I determined in this way the loss in weight that one experiences directly during meals.

At other times, I would weigh all the food that I nourished myself with over a period of several days; equally, I weighed all of my solid and liquid excrements; and adding this last weight to that of my imperceptible transpiration, I examined whether the sum yielded by this addition was equal to the food that I had nourished myself with.

Often for a dozen days I would measure out the food with which I was supposed to nourish myself; I then had a portion dried out in an oven at a given temperature; likewise I had all of my solid and liquid waste matter dried under similar conditions; and I compared the difference in weight of these solid residues, to the loss of solid substances due to the united effects of pulmonary and cutaneous transpiration.

Often as well, I engaged in forced exercise, and I determined in this way the influence of the pulse and breathing on my transpiration.[24]

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[24] "La balance dont nous nous sommes servi dans ces recherches, était construite avec le plus grand soin. Chargée de 125 livres de chaque côté, un demi-gros la faisait trébucher très-sensiblement; d'où il résulte, qu'à chaque pesée, l'erreur ne pouvait aller qu'à 18 grains, soit en plus, soit en moins. Mais comme toutes nos expériences exigeaient deux pesées comparatives, on pouvait soupçonner que cette erreur de 18 grains, existant en sens contraire dans les deux pesées, s'évanouissait en totalité; cependant, eu la supposant dans le même sens, l'erreur de chaque expérience n'aurait pu être que de 36 grains. Or, comme la plus forte différence, que nous ayons obtenue entre les deux pesées comparatives, a été de 4,000 grains environ (ou ce qui revient au même de 6 onces, 7 gros, 40 grains), et comme la plus petite différence a été de 1280 grains (ou ce qui revient au même de 6 onces 1 gros 56 grains), il en résulte, qu'en supposant toutes les conditions les plus défavorables, l'erreur de nos expériences n'a pu être, dans le premier cas, que d'un cent onzième, et, dans le second, que d'un trente cinquième. Cette exactitude de la balance exigeait une grande habitude pour s'en bien servir. Très souvent un mouvement involontaire de l'individu soumis à l'expérience, faisait osciller le fléau. Mais ce qui gênait d'avantage, c'était la perte de poids qu'éprouvait cet individu pendant chaque pesée, perte qui, terme moyen, s'élevait à 17 ou 18 grains par minute. Lors donc qu'on avait le poids juste, il fallait promptement regarder la montre; car, si l'on attendait encore une minute, la balance commençait à trébucher du côté des poids.

The reported results of these experiments were the following: 1. insensible transpiration accounted for a loss in weight of 2 *livres* 13 *onces* (1,376.7 g) in 24 hours; 2. a man consumes 600 *pouces* (11,900 ml) of oxygen

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En ayant égard à ces précautions, nous pouvions facilement déterminer les effets réunis de la transpiration cutanée et de la transpiration pulmonaire. On me pesait, et l'on tenait note de mon poids, et de l'heure à laquelle on l'avait déterminé. Je restais ensuite en repos pendant trois ou quatre heures, ayant sur-tout grand soin de ne pas me moucher, de ne pas cracher, et même de ne pas m'occuper, soit physiquement, soit moralement d'objets qui auraient pu accélerer mes pulsations. Au bout de quatre heures, je me remettais sur la balance, on me pesait de nouveau, et l'on tenait de même note de mon poids, et de l'heure précise à laqu'elle [*sic*] poids avait été déterminé. L'on savait conséquemment, à l'aide d'une simple soustraction, combien l'expérience avait duré de minutes, et à combien s'était élevée pendant ce tems ma perte de poids. Divisant alors la perte de poids par le nombre de minutes, nous avions la perte de poids moyenne pour chaque minute. Lorsque nous voulions connaître ensuit séparement les effets de la transpiration cutanée, et de la transpiration pulmonaire, nous nous servions d'un habillement de taffetas, enduit de gomme élastique, et si bien clos de tous les côtés, que, pendant plus de quinze jours, il ne laissait sortir aucune portion de l'air atmosphérique qu'on y introduisait pour le gonfler. Cet habillement ouvert à sa partie supérieure, avait à la hauteur de la bouche, une ouverture garnie de cuivre mince. Je me plaçais dans cette enveloppe; on la fermait à sa partie supérieure, au moyen d'une forte ligature; l'on mastiquait sur mes lèvres avec de la poix, mêlée d'un peu de thérébentine, la bouche de cuivre, et on l'y maintenait fortement à l'aide de cordons qui se nouaient à la partie postérieure de ma tête. Ainsi ajusté, je me plaçais sur le siège de la balance; on me pesait; je restais tranquille pendant trois ou quatre heures; et, au bout de ce tems, l'on faisait une nouvelle pesée. La différence entre ces deux pesées, nous indiquait le poids que je perdais dans un tems donné par la seule transpiration pulmonaire. Je sortais ensuite de l'enveloppe; l'on me pesait de nouveau; et, au bout d'un certain tems, on recommençait la pesée. La différence entre ces deux nouvelles pesées nous indiquait alors la perte de poids occasionnée, et par la transpiration pulmonaire, et par la transpiration cutanée. Diminuant donc de cette perte de poids totale, la perte de poids occasionnée seulement par la transpiration pulmonaire, le restant représentait la perte de poids occasionnée par la transpiration cutanée. C'est en prenant toutes ces précautions que nous sommes enfin parvenus à obtenir des résultats satisfaisans, tant sur la transpiration eu général, que sur la transpiration cutanée et sur la transpiration pulmonaire. Notre travail sur cet objet a duré près de onze mois. Tous les jours l'on me pesait une fois à la même heure, mais le plus ordinairement l'on faisait sur moi trois ou quatre pesées, suivant qu'il était nécessaire d'isoler les expériences ou d'en faire de comparatives. A chaque pesée l'on regardait le baromètre, le thermomètre et l'hygromètre; l'on tenait note des degrés qu'ils indiquaient; et l'on notait également la situation dans laquelle je me trouvais. Pour peu que la température de l'atmosphère fut un peu élevée, je me mettais en chemise, afin de donner plus de facilité à l'air de dissoudre mon humeur transpirable; mais si la température était moins élevée, je me couvrais davantage, en ayant sur-tout, soin, dans les pesées comparatives, d'avoir exactement sur moi les mêmes choses. Lorsque j'avais besoin de connaître au juste la quantité d'alimens que je prenais, je mettais dans une assiette les alimens solides, et dans une carafe les alimens liquides. Je pesais ensuite l'assiette et la carafe, et je les repesais, lorsque j'avais assez diné; la différence des deux pesées m'indiquait la quantité d'alimens solides et liquides que j'avais pris. Lorsque je voulais manger et boire des quantités déterminées, je pesais d'abord ces per hour;[25] 3. oxygen serves for the production of 8.6 *pieds cube* of carbonic acid and 13.6 *pieds cube* of water; 4. out of five parts of oxygen, two serve for the formation of carbonic acid, and three for the formation of water; 5. the volume of carbonic acid liberated by our lungs in 24 hours consists of 'à très-peu-prés [very close to]' 14,930 *pouces cube* (296,614 ml); 6. the weight of the water formed in the lungs in 24 hours is 1 *livre*, 7 *onces,* 5 *gros*, 20 *grains* (722.5 g); 7. the quantity of water released from the lungs is 5 *onces*, 5 *gros*, 63 *grains* (ca. 160 g); 8. by putting all the data together the overall loss in weight of a man due to transpiration is 2 *livres*, 13 *onces*, 1 *grain* (ca. 1,377 g).

These results were, to say the least, quite approximate and this is perhaps the reason why Lavoisier wished to conduct more studies in the laboratory before publishing them. Nevertheless, despite all his other activities, he was as eager as his assistant to see their groundbreaking contribution to the new science of chemistry reach as many members of the intellectual community in Europe as possible. It is in this light that we should view the letter he wrote on November 19, 1790 to Joseph Black, in which he provided an excellent summary of the results of his experiments.[26] Just a few months earlier Black had embraced Lavoisier's new chemical system, and he too was working extensively with other Scottish chemists and physicians on the problem of respiration. By communicating his results to Black, who was universally recognized as one of the pioneers of pneumatic chemistry, Lavoisier could count on their being propagated in the appropriate circles. And so they were.

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quantités, et je les prenais ensuite en totalité. Quelques fois aussi je me mettais sur la balance, et j'y mangeais une quantité d'alimens préliminairement pesés; je déterminais ainsi la perte de poids qu'on éprouve directement pendant les repas. D'autre fois, je pesais pendant quelques jours tous les alimens dont je me nourrissais; je pesais également tous mes excremens solides et liquides; et, ajoutant ce dernier poids à celui de ma transpiration insensible, j'examinais si la somme qui provenait de cette addition égalait le poids des alimens dont je m'étais nourri. Souvent je dosais pendant une douzaine de jours les alimens dont je devais me nourrir; j'en faisais fortement dessécher une partie dans un four à une température donnée; je faisais également dessécher dans des circonstances semblables, toutes mes déjections solides et liquides; et je comparais la différence des pesées de ces résidus solides, à la perte des substances solides due aux effets réunis des transpirations pulmonaire et cutanée. Souvent aussi, je faisais des exercices forcés, et je déterminais par ce moyen l'influence des pulsations et des inspirations sur la transpiration." *Ibid.*, pp. 6-12.

25 The figure is exceedingly high as we inhale ca. 7-8 litres of oxygen per hour.

26 Antoine-Laurent Lavoisier, *Correspondance*, 6 vols., Vol. 6 (Paris: Académie des Sciences, 1997), pp. 197-199.

Lavoisier and Séguin's New Project (1792-1793)

As time passed Lavoisier became increasingly absorbed in the politics of the revolution then in course, and a new and more effective strategy for publishing his work had to be found. Lavoisier managed to write just one memoir on respiration for the transactions of the Académie des Sciences and, as we have noted, he sent the manuscript of his second *mémoire* to Vincenzo Dandolo, who published it in Italian in 1792.

However, because his results were of such extraordinary importance, in 1792 Lavoisier decided to prepare a new collection of his scientific memoirs together with Séguin.[27] He planned to include revised editions of his most important papers, as well as all of the new material that he had accumulated after the publication in March 1789 of *Traité élémentaire de chimie*.

As is well known, the publication of *Mémoires de physique et chimie* was interrupted in the summer of 1793 owing to the financial difficulties of Lavoisier's printer, his friend Pierre Samuel Du Pont de Nemours. The first page proofs for the five projected volumes arrived at the Dupont printing house on 10 March 1793, and it appears that work went ahead under the direct supervision of Lavoisier, and probably also Séguin, until July 1793. Sadly, Lavoisier lived to see only a part of the *Mémoires* completed: of the five volumes envisaged, just 416 pages of the first (almost complete) volume, the whole of the second volume (413 pages), and 64 pages of the fourth were produced.

The fourth volume was intended to contain Lavoisier's memoirs – both recent and past – on "des principaux phénomènes de l'économie animale." The 64 pages extant include updated versions of Lavoisier's memoirs on respiration from the years 1777 and 1785, two short memoirs by Séguin on animal heat and respiration, and the fragment of a revised version of the memoir on animal respiration by Lavoisier and Séguin that had been presented at the Académie in November 1790. The fact that Lavoisier was working on a comprehensive edition of his research shows that he never truly interrupted his work in this area. The *Mémoires* were not ever officially published.

[27] I have examined the genealogy of this work in detail; see Marco Beretta, "Lavoisier and His Last Printed Work: The *Mémoires de physique et de chimie* (1805)," *Annals of Science*, 2001, *58*:327-356. See also *id.*, "Introduction" to Antoine-Laurent Lavoisier, *Mémoires de physiques et de chimie*, 2 vols. (Bristol-Chicago: The Thoemmes Press-The University of Chicago Press, 2004).

Because Madame Lavoisier wrote a brief preface to the *Mémoires* and distributed a few copies of it after her husband's death, it has often been taken for granted that she had also in some way participated in the editing of the work. As I have discussed in another essay, this was almost certainly not true. In contrast, unpublished documents show that Armand Séguin was assigned an important role in the writing and editing of the *Mémoires*. Then, in 1796 Madame Lavoisier herself entrusted Séguin with the task of writing an introduction to the work. However, almost immediately a disagreement between the two arose and prevented the publication from going ahead. The origin of the controversy lay in Madame Lavoisier's refusal to recognise Séguin as the co-author of the memoirs on respiration and transpiration. This is particularly surprising because the prominent contribution made by Séguin was underlined in Lavoisier's famous paper *Détails historiques, sur la cause de l'augmentation de poids qu'acquièrent les substances métalliques, lorsqu'on les chauffe pendant leur exposition à l'air*,[28] in which the scientist gave his younger colleague full credit for having collaborated in establishing the foundations of his theory of respiration.[29]

As we have already noted, Séguin continued up until 1814 to publish memoirs and reports on the series of experiments that he had conducted in 1790 and 1791 with Lavoisier, and this indicates that he was in possession of the manuscripts, and possibly also the laboratory notebooks, pertaining to these experiments. The *registres de laboratoires* conserved in the Archives de l'Académie des Sciences in Paris contain a record of the experiments conducted between 1765 and 1788. It is therefore probable that Lavoisier gave the respiration notebooks to Séguin so he could prepare the publication of the *Mémoires de physique et chimique*, and it may be conjectured that after the friction with Madame Lavoisier in 1796, they remained in Séguin's hands. Such a scenario would be consistent with what is known to have transpired in connection with Lavoisier's famous experiments on the analysis and synthesis of water, in which he gave custody of his laboratory notebooks to Jean Baptiste Meusnier de la Place, who died before being able to publish their contents.

Thus, in 1796 Madame Lavoisier found herself with some 1,500 copies of the *Mémoires de physique et chimique*, still unbound and lacking the unpublished experimental results originally destined to be included in the collection.

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[28] *Mémoires de Physique et de Chimie*, 3 vols. (Paris: Dupont, ca. 1793-1805), Vol. 2, pp. 78-87.

[29] "[...] la théorie de la respiration, à laquelle Séguin a concouru avec moi [...] [(...) the theory of respiration, on which Séguin worked with me (...)]". *Ivi.*

Madame Lavoisier's Drawings

At the end of 1796, following the turmoil of the revolution, all of Madame Lavoisier's belongings were returned to her and, in addition to the unbound copies of the *Mémoires,* she regained possession of her collection of the drawings of her husband's chemical experiments and apparatus.

Madame Lavoisier was a talented painter and illustrator and from the mid-1780s collaborated with her husband on many of his projects, both scientific and editorial. She made the preparatory drawings and engraved the thirteen plates for the *Traité élémentaire de chimie* (1789) and I believe that she would have played an equally central role in the publication of the *Mémoires de physique et de chimie*. The text of the *Mémoires* makes more than one reference to engraved plates, which in the end were never printed with the original copies of Lavoisier's unfinished opus. The citations in the surviving text show that the publication of at least five *planches* had been envisaged. Of these, only two engravings retraced by Denis Duveen and Lucien Scheler can be attributed with any certainty to Madame Lavoisier.[30] Two other plates found by Edouard Grimaux among Lavoisier's papers and published in the last volume of his *Œuvres* had been commissioned to illustrate the experiments carried out by Lavoisier and Laplace with the optical pyrometer, but their authorship is unknown.[31] One of them (Fig. 3) is quite interesting because, unlike the illustrations in Lavoisier's earlier publications, they show not only the apparatus but a man performing the experiment.

In my belief, this is the context in which we should view Madame Lavoisier's two famous drawings of her husband's experiments on respiration (Figs. 4 and 6),[32] which have been described in detail by Johann Peter Prinz.[33] The first (Fig. 4) depicts an experiment on respiration in a subject

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[30] Denis I. Duveen and Lucien Scheler, "Des illustrations inédites pour les *Mémoires de Chimie*, ouvrage posthume de Lavoisier," *Revue d'Histoire des Sciences*, 1959, *12*: 345-353. The engravings were reproduced in the cited (see note 27) 2004 edition of Lavoisier's *Mémoires*.

[31] Lavoisier, *Œuvres*, Vol. 6 (cit. note 4), pp. 711-712. Another plate illustrating the calorimeter, drawn and etched by Fossier de Le Gouaz in the early 1780s, had been adapted for the *Mémoires*.

[32] These drawings were reproduced for the first time in 1888 by Edouard Grimaux in his biography of Lavoisier; Marco Beretta, *Imaging a Career in Science. The Iconography of Antoine Laurent Lavoisier* (Canton, Mass.: Science History Publications/USA, 2001), pp. 47-52, 84.

[33] Johann Peter Prinz, *Die experimentelle Methode der ersten Gasstoffwechseluntersuchungen am ruhenden und quantifiziert belasteten Menschen (A.L. Lavoisier und A. Séguin 1790).*

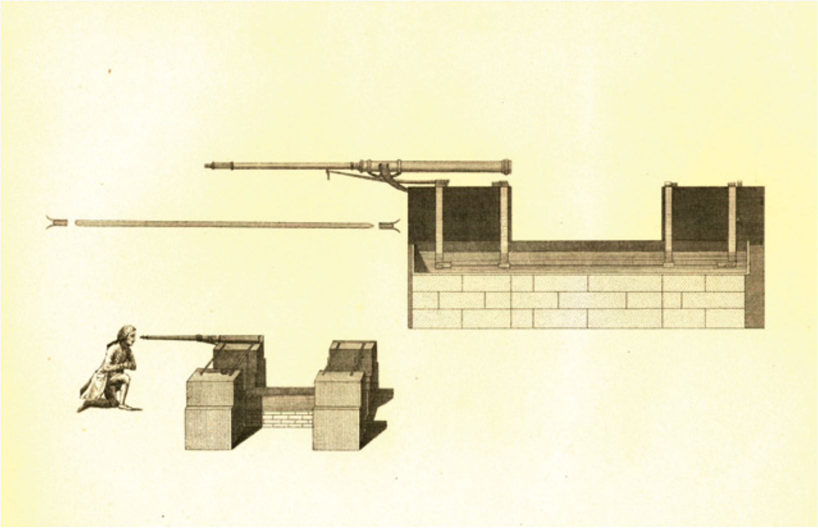

Figure 3. Engraving of the optical pyrometer devised by Laplace and Lavoisier, which can be linked to the text in the first volume of the *Mémoires de physique et chimie* (1805) at pages 246-280. The engraving is drawn from the 6[th] volume of Lavoisier's *Oeuvres* (Paris, 1893).

Figure 4. Madame Lavoisier's drawing of an experiment on respiration in a subject at rest (ca. 1790) (private collection).

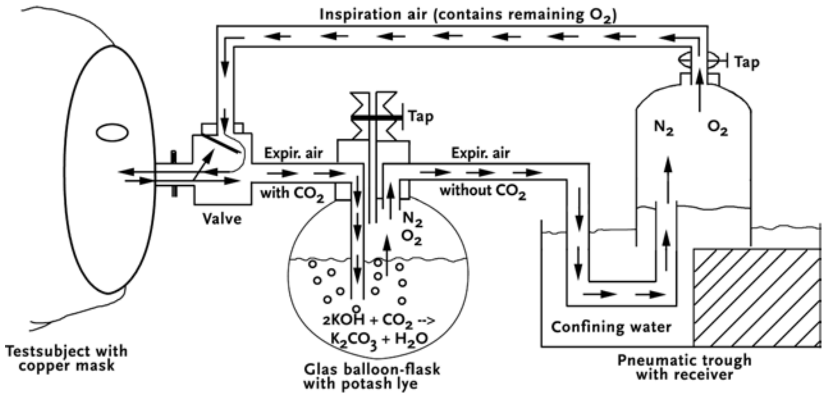

Figure 5. Johann Peter Prinz's reconstruction of Lavoisier's circulatory respiration apparatus.

at rest; on the left we see Séguin sitting and breathing through a mask that is attached to an apparatus. A physician – probably the Scotsman Hugh Gillan, who is known to have participated in the experiment – is measuring Séguin's pulse. Standing beside Gillan is a figure with his arm extended – perhaps Lavoisier – who is either directing the experiment or dictating the results to Madame Lavoisier, who is sitting at a table on the right. Opposite Séguin, at the far end of the breathing apparatus, an assistant (Hassenfratz?)[34] is collecting gas through a pneumatic trough. On the far left a *garçon de laboratoire* is carrying a bell jar. The purpose of the apparatus has been reconstructed by Johann Peter Prinz (Fig. 5), who convincingly argues that it allowed Séguin to inhale his own exhaled air "minus the consumed oxygen and the carbonic acid absorbed."[35]

The reconstruction of the apparatus in the second drawing (Fig. 6) has proved to be more problematic. On the left we see a *garçon de laboratoire* carrying a bell jar in the direction indicated by the scientist standing in front of him. Lavoisier (?) is shown in the centre, in the same pose as before,

Versuch einer kritischen Deutung (Sankt Augustin: Academia Verlag, 1992); *Id.*, "Lavoisier's Experimental Method and his Research on Human Respiration," in *Lavoisier in Perspective*, edited by Marco Beretta (Munich: Deutsches Museum, 2005), pp. 43-52. See also Yves Noël, "Commentaire sur les dessins de Madame Lavoisier," in Lavoisier, *Correspondance*, Vol. 6 (cit. note 20), pp. 437-438.

[34] Jean Henri Hassenfratz most certainly participated in some of Lavoisier and Séguin's experiments on respiration.

[35] Prinz, "Lavoisier's Experimental Method" (cit. note 33), p. 51.

Figure 6. Madame Lavoisier's drawing of an experiment on respiration at work (ca. 1790) (private collection).

with his right arm extended. Séguin is seated, wearing a mask and inhaling through an apparatus, while his right foot is attached to a pedal in order to perform some sort of physical work. Again Gillan (?) is taking his pulse, while on the right Madame Lavoisier is watching the experiment and recording the results in a *registre de laboratoire*. Ramsden's electrical machine can be seen on the right. Both experiments were certainly performed in the laboratory at the Arsenal.

Lavoisier began his experiments at the Petit Arsenal in the spring of 1776. The area consisted of the Hôtel de la Régie des Poudres et Salpêtres in Rue des Ormes, another building facing the Cour du Satpêtre, which was probably the one occupied by Lavoisier, and ateliers for the production and refining of saltpetre. In addition, there was a public garden and access to water – an essential requisite for a chemical laboratory – from the nearby Fossées de l'Arsenal, where a gunpowder warehouse was located. Lavoisier's building consisted of two floors and his laboratory was spread out over several rooms.[36] Contemporary descriptions by Arthur Young, Antoine de Fourcroy, and Madame Lavoisier provide interesting details regarding the furnishings and use of the laboratory, but no precise information as to its

[36] A comprehensive survey of Lavoisier's laboratories is under preparation by the present author.

size or architecture. Young reported seeing gasometers in one room and the apparatuses of natural philosophy in another.[37] Madame Lavoisier's drawings do not depict either of these laboratories. They show instead from two different angles another spacious room whose arching walls suggest that it was probably located not on the second but on the last floor of the building, in an attic that provided ample space and light for the performing of his experiments.

The content of Madame Lavoisier's drawings is so unusual that doubts have been raised concerning their scientific accuracy and, apart from Prinz's reconstruction, most historians have tended to dismiss the works as adding little to our knowledge of Lavoisier and Séguin's experiments on respiration.[38] I believe instead that they deserve to be taken much more seriously, based on my recent discovery of two hitherto unknown sketches in pen and ink by the same artist (Figs. 7 and 8) in the library of the Wellcome Institute in London,[39] which indicate that Lavoisier personally supervised the production of a visual record of his experiments with the intention that they should be published. If this is so, then the significance of Madame Lavoisier's four drawings requires reassessment.

The two newly discovered drawings are moderately large in size (24 x 32 cm)[40] and were purchased, probably in France, by Henry S. Wellcome for his medical collection.[41] They certainly seem to share the same provenance

[37] "That apartment, the operations of which have been rendered so interesting to the philosophical world, I had pleasure in viewing. In the apparatus for aerial experiments, nothing makes so great a figure as the machine for burning inflammable and vital air, to make, or deposit water; it is a splendid machine. [...] Another engine Mons. Lavoisier shewed us was an electrical apparatus inclosed in a balloon, for trying electrical experiments in any sort of air. His pond of quicksilver is considerable, containing 250 lb. and his water apparatus very great, but his furnaces did not seem so well calculated for the higher degrees of heat as some others I have seen. I was glad to find this gentleman splendidly lodged, and with every appearance of a man of considerable fortune." Arthur Young, *Travels During the Years 1787, 1788 and 1789* (London: W. Richardson, 1792), pp. 64-65.

[38] This is the opinion of Larry Holmes who did not have the opportunity to examine the original drawings and claimed that: "The details of the equipment portrayed for measuring the oxygen consumption are [...] fanciful and useless for elucidating the methods used." Holmes, *Lavoisier and the Chemistry of Life* (cit. note 1), pp. 443-444; see also p. 546.

[39] Wellcome Library, London, Record no. 37207i: *A man seated with his head in a glass container lit by a candle*; Wellcome Library, London, Record no. 37197i: *A man being weighed on a huge set of scales, and a man with his head in a glass container*. The titles are those provided by the Wellcome Library.

[40] The dimensions are almost identical to those of the other two drawings (22 x 36 cm).

[41] I thank William Schupbach for providing me with all the available archival references on the drawings.

Figure 7. A man seated with his head inside in a glass container (ca. 1790) (Wellcome Library).

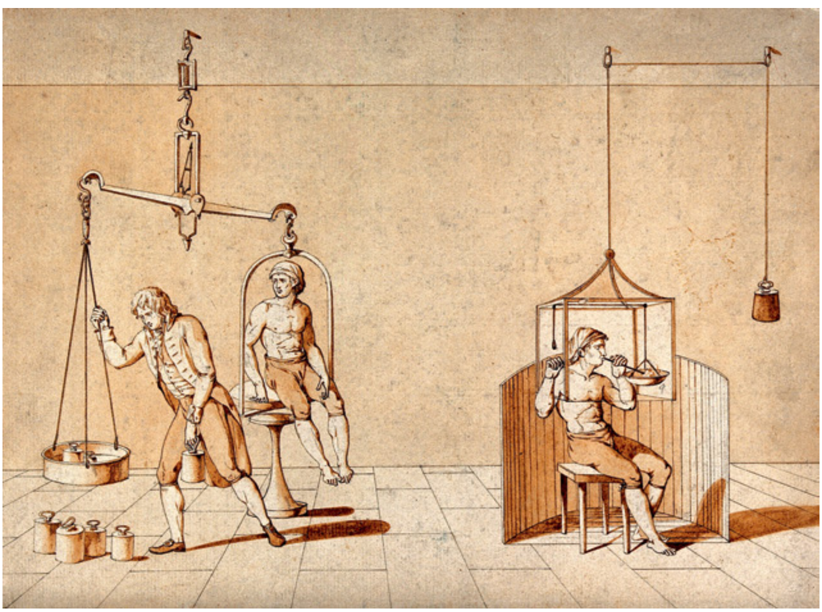

Figure 8. A man being weighed on a large set of scales (ca. 1790) (Wellcome Library).

as the two other drawings by Madame Lavoisier, for – as in Figures 4 and 6 – the only man without a wig (Gillan?) in Figure 7 is taking the pulse of the subject sitting in the barrel (Séguin), while in Figure 8 we see a woman who could not be anyone other than Madame Lavoisier making a record of the experiment. The body of the man sitting in the barrel and the one sitting on the balance closely resemble the subjects portrayed in Madame Lavoisier's known drawings. The floor also appears to be identical in all four pictures and the roof is low, as would be expected in an attic. The two men with wigs who appear in Figure 7 seem to correspond to the assistants in the respiration experiments and, if my identification of the man in the centre of the scene in Figures 4 and 6 as Lavoisier is correct, he would correspond to the man dictating to Madame Lavoisier in Figure 7. It is true that his features are unlike those in the known portraits of Lavoisier, but the face of the woman does not resemble that of Madame Lavoisier either. This is quite understandable because, as I shall argue below, the drawings were meant to illustrate a scientific text and should not be considered primarily in an aesthetic light.

The first drawing (Fig. 7) shows Séguin sitting in barrel filled with water and exhaling through a pipe into a dish that probably contained limewater, which would have precipitated out any carbon dioxide in the form of chalk, thus allowing Lavoisier to weigh the quantity of exhaled carbon dioxide. The seal created where the glass canopy came into contact with the water in the barrel prevented new air from entering the canopy and into the subject's lungs. The man on the right seems to be collecting air from the canopy into a jar, although the purpose of this operation remains obscure to me. The consumption of oxygen by the subject could be quantified by monitoring the increase in the amount of the water in the canopy and measuring the oxygen content of the air in the canopy using an eudiometer.[42]

The second drawing (Fig. 8) shows a cross-section of the barrel in which Séguin was sitting and the scale that was used during the experiment. Séguin was weighed before and after each experiment in order to measure the quantity of hydrogen consumed during respiration. This was quantified by subtracting Séguin's final weight plus the quantity of carbon dioxide precipitated in lime from his initial weight.

The use of such a large balance recalls the quantitative experiments on transpiration described by Santorio Santorio in his *De statica medicina* (1612) (Fig. 9), and Lavoisier and Séguin certainly must have studied his

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[42] I thank Johann Peter Prinz for sharing with me his views on this point.

Figure 9. The scale invented by Santorio Santorio to weigh the loss of fluids during transpiration, in an engraving of 1710.

work and methodology. Lavoisier's scale was probably lost, for it is not conserved in the collection of scientific instruments at the Musée des Arts et Métiers in Paris, but a description of its parts and its accuracy can be found in Séguin's *Second mémoire sur la transpiration* published in 1814.

Unfortunately, in the absence of an explanatory text the precise scientific content of Madame Lavoisier's drawings remains open to interpretation. However, the recently discovered drawings in the Wellcome Library offer important clues as to their purpose and destination. In Figure 7, to the right of the canopy the inscription *fig. 1ere* (abbreviation for "figure première") in Lavoisier's hand is clearly visible and there are letters indicating various parts of the apparatus: the canopy (H), a small tube? (K), and the barrel (A). The fact that the figure is numbered and its parts are labelled with letters suggests that Lavoisier had contemplated a series of illustrations depicting his experiments on respiration, as well as explanatory captions or references in the text to the various parts of the apparatus. This drawing therefore was intended for publication, most probably in the *Mémoires de physique et de chimie*, which Lavoisier was working on with Séguin in 1793.

The illustrations differ significantly from those in the *Traité*, because they are not mere diagrams of instruments; they show participants using complicated apparatuses in actual experiments. As I have already pointed out, this iconography is consistent with the imagery to be seen in other engravings, such as that of the optical pyrometer, which we know were meant to be published in the same work. These works by Madame Lavoisier were no doubt preparatory drawings, not yet ready for publication in a scientific text, but the new evidence presented here establishes a plausible context to explain how they were produced.

Conclusion

Antoine-Laurent Lavoisier's theory of respiration constituted a fundamental pillar in the new chemistry, but he was beginning to sketch a comprehensive outline of its principles at a stage in his life when he was deeply engaged in, and then after 1793 personally threatened by, the political events that were engulfing France. In this fraught situation Lavoisier found an indispensable assistant in Armand Séguin, who designed most of the experiments that were presented before the Académie des Sciences in the autumn of 1791 and the spring of 1792. The results of their work were revolutionary and Lavoisier realized how urgent it was to make them known to the scientific community. Therefore, together with Séguin he worked in haste to prepare them for publication in what would have been one of his most important works, the *Mémoires de physique et chimie*. Unfortunately, due to the bankruptcy of his friend Dupont's printing works the project had to be suspended, and the planned volumes remained incomplete and unbound. What is more, the *Mémoires* were supposed to have been published with several engraved plates that would have added greatly to their scientific value, and Madame Lavoisier's drawings of her husband's pioneering experiments on respiration represent four preparatory sketches for these illustrations.

After Lavoisier's execution on May 8, 1794, the manuscripts and laboratory notebooks connected with these experiments probably remained in the hands of Séguin, who published the results in a series of papers, the last of which appeared in 1814. In 1796, when Madame Lavoisier was given back all of her husband's belongings, including the unbound volumes of what survived of the *Mémoires de physique et de chimie*, she invited Séguin to write an introduction to the work and requested Dupont to advise her as to the best way to publish them.

Madame Lavoisier, however, refused to acknowledge the contribution of Séguin to the all-important experiments on respiration and decided to exclude him from any future projects involving her husband's work. It is not clear whether in 1796 the two actually discussed the possible publication of the *Mémoires* (and illustrations) on respiration and transpiration, but I believe it is no coincidence that their quarrel exploded on the issue of the authorship of these crucial scientific papers, for which Madame Lavoisier wished her husband to receive exclusive credit. It was only in 1805 that Madame Lavoisier placed in circulation a restricted number of copies of the *Mémoires* and her brief preface omitted any reference either to Séguin or to the illustrations (in which he featured as a participant), thus contributing to subvert her husband's true intentions and his planned strategy to communicate his last discoveries.