AMBIX, Vol. 39, Part 3, November 1992

PHLOGISTON AFTER OXYGEN**

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In conventional interpretations of the Chemical Revolution, the phrase "phlogiston after oxygen" is a contradiction in terms, a droll oxymoron. As Bernard Cohen expressed the standard view recently, echoing James Bryant Conant before him, "the central feature of the Chemical Revolution was the overthrow of the reigning 'phlogistic' theory and its replacement by a theory based on the role of oxygen":[1] that is, one explanation succeeded the other; the two could not coexist. Recently, we have enjoyed several reassessments of the Chemical Revolution.[2] Historians have challenged notions about whether there was a revolution at all—and reconsidered what the problems with the conceptions of acidity, caloric, etc., imply about what exactly Lavoisier achieved. We have learned to focus on the nomenclature and the "doctrine of gases", as some contemporaries called it.[3] Still, an image persists that explanations using oxygen eclipsed those using phlogiston: a view conveyed in such terms as "supplanting", "substitution", "supersession", and "overthrow".[4] That is, we have tended to cast the phlogistic and anti-phlogistic positions—much as Lavoisier and many of the time did—as mutually exclusive rivals, with one ultimately replacing the other. A closer examination of phlogiston after oxygen, however, suggests instead that we cannot portray this episode as an "either-or" conflict or even as linear replacement. Rather, the two theories represented complementary and, ultimately, compatible explanations of combustion.

This observation emerges from adopting a method of "reverse-Whiggism" as a historiographic tool.[5] In this approach, one starts from a former theoretical position, now in disrepute, and follows it forward, rather than backward, through time. More fundamentally, one also allows the antedated perspective to guide and possibly "distort" how one interprets how the history unfolds. Here, I trace the fate of the concept of phlogiston through the Chemical Revolution from the perspective of those who continued to support the doctrine, and defended it even following the 1789 publication of Lavoisier's *Traité.*

Many late defenses of phlogiston may be typified by the position of James Hutton. Though Hutton is more widely known for his geological work, he also pursued chemical inquiries.[6] His less reductionistic, more contextual perspective is especially valuable in revealing the way in which many viewed phlogiston as relevant. Hutton published two dissertations, in 1792 and 1794, where, in direct response to the *Traité*, he staunchly defends the doctrine of phlogiston.[7] At the very outset, however, Hutton lauds Lavoisier's discovery of oxygen. He says that it "is to be ranked among the greatest discoveries in physics", one which "does honor to the present age, and infinite credit to the author".[8] Yet, Hutton maintains, there is still a role for phlogiston. Others, such as Gadolin, Gren, Richter, Crell and Zauschner, like Hutton, also saw a role for both phlogiston and oxygen and used the terms alongside each other, sometimes even when describing combustion.[9] This juxtaposition of beliefs, while paradoxical under canonical views, forms the kernel of a deeper interpretation.

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** A version of this paper was presented at the History of Science Society (U.S.) Midwest Junto, April, 1992. My appreciation to Allen Debus and Robert Siegfried for comments on various drafts.

All these thinkers accepted the existence of a distinct gas that reacted with metals to form calxes: namely, oxygen. They felt, however, "that some important facts, or essential phenomena in the burning of bodies, are not explained in the antiphlogistic theory". When coal burns, for example, Hutton noted:

> There are produced two distinct effects; first, by the oxigenating of the gravitating carbonic substance, there is produced fixed air or carbonic acid in an elastic state. Secondly, in thus changing the nature of coal, there is produced a great quantity of light and heat; it is only this last event, or effect, with regard to which there is any difficulty, or any dispute to be made.

"The present chymists, . . ." Hutton claimed, "must necessarily leave some natural appearances unexplained while they give a most accurate analysis with regard to the gravitating matter of bodies". For Hutton and others, the problem was in assuming that the French principles "should be considered as comprehending all the appearance".[10]

Late defenders of phlogiston were generally interested, instead, in the heat and light of combustion, ignition or reactivity, and other aspects of matter and chemical reactions related to what we would call energy.[11] Hutton, for example, was obsessed, it may be fair to say, with light: how it is produced in inflammation; how it can be "stored" in phosphoretic bodies; how it can sometimes generate heat; how it appears in different colors in burning; how it is transformed by plants into animal fuel; and how it ultimately sustains the planet's habitability. Phlogiston, as a form of fixed light—or what Hutton called a variation of the "solar substance"—was central to his thinking. Though Hutton's own ideas were deeply embedded in his theology, his concerns about light were shared by others.[12] Richter claimed in 1793, for instance: "where light is present, there also is phlogiston!" Gadolin also echoed Hutton's sentiments: "Phlogiston, which is without weight, is the same as the matter of light. . . . I am true to the old theory of phlogiston or the combustible principle".[13] Even Joseph Black, known now as an early supporter of the French system, expressed his reservations to a former student in 1791: "For my part I now, tho I had reluctance first, find the French theory so easy and applicable that I mostly make use of it, tho it must be confessed that it takes almost no notice of light".[14] Black's assent was not unconditional: like others, he withheld support specifically where light was concerned.

In Gough's view, "Lavoisier's gravimetric criterion . . . excluded all imponderables from the essential chemical order".[15] Yet the reverse-Whiggish perspective adopted here sensitizes one to features of the outcome of debate that are not defined solely by Lavoisier's lineage. By focusing first on the disagreement itself, rather than the outcome, one ensures a fully symmetrical, or balanced, and therefore more complete account of how the controversy was resolved. One can appreciate, therefore, the translator of the *Method of Chemical Nomenclature*, whose comments resonated with those above:

> . . . Yet we still allow the absolute existence of a phlogiston. It is still the matter of fire, of flame, of light, and of heat, which is liberated in combustion.

While admitting that this matter of fire might, in contrast to Stahl, be liberated from vital air, he insists:

> Yet it is still phlogiston with its most distinguishing attributes. In short, it is still the matter of heat; whether we call it phlogiston, caloric, or in plain English *fire*.[16]

Again, phlogiston was preserved to explain material aspects of heat and, especially, light.

For Hutton, phlogiston was also important in explaining why coal burned and how energy flowed in nature. He noted how plants serve as fuel for animals producing heat and that they must "compose" or generate phlogiston. He acknowledged how plants fix carbon from fixed air and hydrogen from water, while releasing oxygen. But he emphasized that this process was specifically coupled with sunlight, as shown by Ingenhousz.[17] That is, light was essential in understanding the process in plants that was the reverse of combustion.[18] Further, Hutton noted the vegetable origin of coal and how the fixed solar substance (or phlogiston) in plants explained why coal burns.[19] Hutton thus used the new system to explain what we would call the carbon cycle in nature, while insisting that one must also use phlogiston to explain the far more significant process that biologists today would understand as energy flow through an ecosystem.

Not the least of the considerations regarding energy for late phlogistonists was the relationship between phlogiston and electricity. Sudduth has documented occasions starting in 1758 in which electricity had been identified as phlogiston.[20] Electricity was used, for example, as early as 1774 to reduce calxes to their corresponding metals. Others used the concept of phlogiston to suggest experiments, such as burning diamonds by electricity or examining how electricity affected the acid of phosphorus. Sudduth did not, however, highlight how these notions about phlogiston flourished even in the last decade of the century—after the new nomenclature using oxygen had been introduced. Hutton, too, noted the relationship with electricity, and highlighted, for example, how the production of light and heat in forming electric sparks paralled combustion.[21] Senebier, Gren, Peart, Elliot, Weber and Marchand—in addition to the seventeen mentioned by Sudduth, including Leslie and Drew—each postulated some close relationship between phlogiston and electricity. Even as late as 1809, George Gibbes was claiming that "the principle of the negative side of the galvanic apparatus" was phlogiston.[22]

While many acknowledge Lavoisier's contributions based on measurements of mass, therefore, they did not find them complete. Hutton's criticism was particularly strong. The existence of phlogiston, he claimed, was:

> a truth that never can appear to those philosophers, who, with the balance in their hands, refuse to admit into the rank of chymical elements substances which do not ponderate, or which are not cognizable in that manner of estimation.[23]

One can easily appreciate that Lavoisier's work led to the law of constant proportions and then to a coherent system of elements with atomic weights.[24] Yet many persons at the time recognized that the new system did not wholly replace earlier explanations of energy relations in reactions. Though Lavoisier introduced the notion of caloric, many chemists found that it did not productively extend or reorganize the existing concepts of latent heat, heat capacity or phlogiston. Light, also, was listed along with oxygen in the new nomenclature, but for late phlogistionists, their concept went further in underscoring the strong relationship and conversions between light, heat and electricity, and their integrated roles in combustion, calcination and reduction.

There were, of course, those for whom the concepts of oxygen and phlogiston were inevitably contradictory. Priestley, Cavendish and Kirwan—the most noted defenders of phlogiston—all advocated positions that could not be reconciled with the new system of elements. But these three chemists also interpreted phlogiston specifically in terms of gases.

Cavendish and Kirwan equated phlogiston with inflammable air (or hydrogen) and Priestley saw phlogiston as a component determining the "purity" of the air.[25] Yet the notion of phlogiston did not emerge historically from addressing the role of gases in combustion, nor was it essentially linked to such considerations. Siegfried has suggested that once Lavoisier had conceived phlogiston *compositionally* as "negative oxygen", the whole of his new theory of combustion fell neatly into place.[26] But what may have been a productive schemata or heuristic for Lavoisier may not necessarily have applied more universally. Indeed, as noted above, the central role of phlogiston for many may have been "material", but it was wholly separate from compositional questions gauged in terms of mass.

How, then, are we to assess the relationship between phlogistionists and "anti-phlogistonists"? One solution is suggested by a brief comparison of two Dutch chemists: van Marum and van Troostwijk.[27] In the 1780s, the two worked on electricity together, reducing calcined metals by electrical discharge, and even trying to electrify dephlogisticated air; they published their results in 1784 in a phlogistic framework. While they were performing several follow-up experiments, van Marum visted Paris. Soon thereafter, he adopted Lavoisier's system and was subsequently influential in its acceptance in the Netherlands. But while he was "converted", van Marum did not simply reinterpret his electrical experiments in terms of the new nomenclature, nor did he adapt his research, newly taking into account the role of oxygen or caloric. Rather, he abandoned his former work altogether. He turned his attention instead to following Lavoisier's example: synthesizing water, oxidizing mercury, burning hydrogen, phosphorus, oil and carbon, and redesigning apparatus to facilitate the investigation of gases. Although one may be inclined to see van Marum's original work as suddenly outdated or flawed, he nevertheless published it, albeit with a ten-year delay. Van Marum's conversion, therefore, was not conceptually necessary, based on alternative explanations for the same phenomenon. Instead, the reorientation was more deeply cognitive, based on what he viewed as significant or relevant for research or explanation.[28] He switched between aims, problems and potential courses of action, not narrowly between parallel theoretical schemes. Van Troostwijk, by contrast, continued to pursue electricity and maintained a phlogistic perspective, publishing in 1787. In other words, phlogistic and anti-phlogistic were not mutually exclusive conceptually. Rather, they expressed complementary schemes, aimed at different phenomena or different aspects of the same phenomena—and likely pursued by different chemists, each with their own interests.[29]

While phlogiston may have started out in the early eighteenth century merely as a convenient unifying concept for linking calcination and reduction—and the mineral kingdom with plant and animal kingdoms—and while it may have languished as a rather secondary concept in chemist's research for the next several decades,[30] by the end of the century, the concept of phlogiston was again the occasion for much theoretical interpretation of what we would call energy and reduction potential.[31] And it was precisely this aspect that appeared in many defenses of phlogiston following the discovery of oxygen.

The controversy over phlogiston that emerged did exhibit sharply divergent views. But antagonists differed mostly on views of what was relevant and what, exactly, needed to be explained, say, in theory of combustion. Here, multiple, complementary explanations were possible—one using oxygen compositionally, and one using phlogiston (or some equivalent thereof) energetically. The debate was not resolved, therefore, by one theory substituting for another. The respective domains of the two lineages, which had converged on explaining the same phenomenon, had to be articulated and, in some cases, redefined. Specific conceptions of phlogiston, like those of Priestley, Cavendish or Kirwan, that involved gases became awkward or inconsistent in practice, especially in combination with conceptions of oxygen—and were abandoned. But the core notion of phlogiston as a bridge between reduction, calcination and combustion was retained and further developed by others. Oxygen did not wholly replace phlogiston. Rather, as the late defenses of phlogiston show, oxygen displaced phlogiston, limiting acceptable further versions of the concept. At the same time, however, Lavoisier's work also highlighted indirectly how phlogiston explained certain phenomena relating to energy that oxygen and caloric could not.

Historiographic Postscript

More importantly, perhaps, this analysis also suggests a further commentary on the historiography of the Chemical Revolution and, indirectly, of other episodes of scientific change. That is, attention is drawn to the traditional view of replacement, even where the notion of "revolution" itself is qualified.[32] In the conventional model, only one viable explanation of combustion is accepted, debate is cast in "either-or" terms and is seen as resolved by a "winner-take-all" solution.[33] Theories or research traditions are thus seen as successors, and fit into a linear pattern of narrative. The history of phlogiston after oxygen, however, suggests an alternative pattern in which two "competing" explanations may persist when the contexts of each are more finely articulated and thus clearly differentiated.[34] The contrast between "overthrow" and "displacement" interpretations of this episode thus brings to the foregound some of the subtle or hidden themes that permeate our histories. Such themes, of course, form implicit morals,[35] in this case about competition, winners and losers, and the alleged context-independent transcendence of "right" and "wrong". The fate of phlogiston after oxygen, then, understood through a reverse-Whiggish approach, allows us to reflect more deeply on the latent lessons of our narratives and how we tell history.

Notes and References

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3. R. Siegfried and B. J. Dobbs, "Composition: A Neglected Aspect of the Chemical Revolution," *Annals of Science*, **24** (1968), 275–93; T. H. Levere, "Lavoisier: Language, Instruments, and the Chemical Revolution," in T. H. Levere and W. R. Shea, eds., *Nature, Experiment, and the Sciences* (Dordrecht: Kluwer Academic, 1990), pp. 207–23.
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5. Here, I follow the claim that historians should be as explicit as scientists in documenting the "materials and methods" of their investigations. Historical work, in this view, is guided by various historiographic models of interpretation, which both generate and shape the product of historical inquiry. The view also reflects the

critiques of sociologists who promote a reflexive posture [*e.g.*, S. Woolgar, ed. *Knowledge and Reflexivity: New Frontiers in the Sociology of Knowledge* (London: Sage, 1988)]. "Reverse Whiggism", as once such method or model, is closely allied with a principle of empirical symmetry, which complements the Strong Programme's principle of sociological symmetry [*e.g.*, D. Bloor, *Knowledge and Social Imagery* (London: Routledge and Kegan Paul, 1976)]. The principle of empirical symmetry asserts that both "true" and "false" beliefs (or "right" and "wrong" claims) may be articulated as interpretations of empirical data. For further discussion and examples of empirical symmetry and reverse Whiggism, see D. Allchin, "Resolving Disagreement in Science: The Ox-Phos Controversy, 1961–1977", Ph.D. dissertation, Committee on the Conceptual Foundations of Science, Univ. of Chicago, 1991, esp. pp. 11–14, 21–25.

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9. See J. D. Partington and D. McKie, "Historical Studies on the Phlogiston Theory, III–IV," *Annals of Science*, **3** (1938), 336–71 and **4** (1939), 112–49; Part IV, on pp. 125–26, 131–35, 136–39, 145, 146.
10. "Phlogiston," *op. cit.* (7), pp. 173, 204–5; "Light, Heat and Fire," *op. cit.* (7), pp. 153–54.
11. On reactivity as the central problem of Guyton de Morveau, see E. M. Melhado, "Oxygen, Phlogiston and Caloric: The Case of Guyton," *Hist. Stud. Phys. Sci.*, **13** (1983), 311–334; for a general discussion of the roles of heat and light, see J. R. Partington and D. McKie, "Historical Studies," *op. cit.* (9), Part III.
12. D. Allchin, "Hutton," *op. cit.* (6).
13. See J. R. Partington and D. McKie, "Historical Studies, IV," *op. cit.* (9), pp. 126, 131.
14. W. Ramsay, *The Life and Letters of Joseph Black, M.D.* (London: Constable, 1918), pp. 97–98; C. E. Perrin, "A Reluctant Catalyst: Joseph Black and the Edinburgh Reception of Lavoisier's Chemistry," *Ambix*, **29** (1982), 141–76, on p. 164n.; J. Black, *Lectures on the Elements of Chemistry*, James Robison, ed., **1** (Edinburgh 1803), p. 550.
15. J. B. Gough, "Lavoisier and the Fulfillment of the Stahlian Revolution," *Osiris*, **4** (1988), 15–33, on pp. 17–18.
16. James St. John, 1788, quoted in J. R. Partington and D. McKie, "Historical Studies, III," *op. cit.* (9), pp. 339–40.
17. Hutton, "Phlogiston," *op. cit.*, (7), Part II, Chap. 3.
18. This view was shared by others—for example, Leslie [see J. R. Partington and D. McKie, "Historical Studies, III," *op. cit.* (9), 345].
19. Hutton, "Light, Heat and Fire," *op. cit.* (7), pp. 198–99; *idem*, *Theory of the Earth*, **1** (Edinburgh, 1795), Chap. VIII.
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21. J. Hutton, "Physical Dissertations on the Powers of Matter and Appearances of Bodies," Part III in *Dissertations*, *op. cit.* (7), in Diss, VII, Chap 4; "Ligh, Heat and Fire," *op. cit.* pp. 48, 143, 224–26.
22. J. R. Partington and D. McKie, "Historical Studies, III," *op. cit.* (9), pp. 345, 352, and "IV," pp. 119, 123, 125, 137.
23. Hutton, "Phlogiston," *op. cit.* (7), p. 207.
24. R. Siegfried and B. J. Dobbs, *op. cit.* (3).
25. J. McEvoy, *op. cit.* (2).
26. R. Siegfried, "Lavoisier and the Phlogistic Connection," *Ambix*, **36** (1989), 31–40.
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