A Short History of Combustion

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"What if I am, in some way, only a sophisticated fire that has acquired the ability to regulate its rate of combustion and to hoard its fuel in order to see and walk?" mused anthropologist Loren Eiseley some fifty years ago.[1] Of late, such incendiary thinking has cooled. Fossil-fueled climate change and the ashen surrender of rainforests to plantation farming have not been kind to the appreciation of fire. Neither has the long association of the enclosed flame of the hearth with attachment and rootedness—or as we now see it, with domestic confinement and drudgery. But terrestrial flame rarely stays down for long, for this is a fire planet, and we are a fire species.[2] And if we are to engage effectively with the current ecological and energy predicament, we would do well to face up to fire in all its transformative possibility.

A few decades ago, historian Theodore Wertime drew attention to "the often forgotten but massive effects of man's re-shaping of earthy materials by fire."[3] Wertime was not referring to the use of fossil-fueled machinery to hammer, stamp, or extrude preformed materials into new shapes and forms. Nor was he talking about any of the other uses made of combustible hydrocarbons. What interested Wertime was the much longer history of using heat directly to transmute matter from one state to another: to turn lime into plaster, clay into earthenware, mineral ores into metals, silica into glass. Around these transformations, he reminds us, arose ancient and enduring artisanal traditions. Rather than seeing these crafts as separate and distinct, Wertime proposes that we view them together—as multiple and often integrated expressions of a 10,000-year spree of experimentation that he and other fire-oriented thinkers refer to as "pyrotechnology."[4]

Pyrotechnology, as defined by metallurgist J. E. Rehder, is “the generation, control, and application of heat, which at sufficient temperatures can alter the properties and compositions of all materials.”[5] Over hundreds of generations, fire-wielding artisans gradually climbed a ladder of heat, rising from the modest 100 °C at which roasted gypsum produces plaster of paris, to the baking of clays at around 500 °C, up to 1100 °C for the smelting of copper and gold, just beyond the 1500 °C mark for extracting iron from its ores, and on to 1600 °C plus for fusing silica into glass. The key to these advances was the enclosure of fire in purpose-built chambers. As kiln and furnace technology developed, artisans both attained higher temperatures and increased their ability to control and modulate heat. In this context, Wertime reflects, “early smiths viewed not one element at a single temperature, but the whole world of matter on an ascending scale of heat.”[6]

Returning to our own era, it is important to keep in mind that it takes a tightly sealed and robust casing to contain the concentrated energy of fossilized hydrocarbons when they are ignited and to channel their explosive power into useful work. Without the fire-smelted metals produced by a much earlier pyrotechnology, there would be no viable way of corralling the force of combusting fossil biomass. And without the very capacity to capture and intensify fire in an enclosed space, there would be no boilers, motors, or turbines. A great deal has been said about the emergence of Industrial Age heat engines, and a lot is still being said about their cumulative contribution to social globalization and changing planetary conditions. Beyond the specialist domains of metallurgical or pyrotechnical scholarship, however, the significance of the much earlier enclosure of fire—and the multitude of ways in which it was set to work—has been largely eclipsed by the scale and impact of mechanized combustion.

From the perspective of the planet itself, however, that initial containment of fire—the chambering and intensification of open-air flame—may well represent a critical juncture. The Earth, environmental historian Stephen Pyne likes to remind us, is a fire planet.[7] One of the four classical “elements,” along with air, water, and earth, fire turns up in many philosophies and worldviews as an essential component of the universe. In fact, Pyne points out, the Earth is the only astronomical body in the solar system where fire is found. And even at the galactic scale, fire may turn out to be a rarity.

Technically speaking, fire is a reaction rather than an element or substance. “Fire” is the common term for rapid or chain-reaction combustion, “combustion” being the reaction in which chemical energy is converted into thermal energy. As such, it is just one among a number of possible conversions of the various energies—electromagnetic, chemical, thermal, kinetic, electrical, nuclear, and gravitational—from one into another.[8] Combustion, then, is a particular type of conversion in which energy held in the atomic bonds of a fuel is released through oxidation—a reaction with oxygen or an oxygen-rich compound—resulting in the release of heat and the formation of new chemical bonds.

In order to have fire, the essential components are fuel, free oxygen, and a means of ignition. The sun, by this logic, is not on fire. It is actually carrying out a process of nuclear fusion—a completely different kind of energy conversion that happens to share with fire the production of heat and light. Elsewhere scattered across the solar system can be found the requisite ingredients of fire: Mars has traces of oxygen, Saturn’s icy moon Titan has plentiful fuel in the form of methane, while the gas giant Jupiter is frequented by the kindling spark of lightning. But as Pyne notes, it is solely on Earth that all three constituents come together, and it is only on the surface of this planet that the necessary inflammatory components gel into a workable unity.[9]

It is biological life that is the Earth’s crucial mechanism for assembling combustion. Terrestrial fire and organic life have a shared and inverse chemistry: life forms capable of photosynthesis convert the thermal energy of the sun into carbon compounds rich in chemical energy, then fire feeds on this carbon-based organic matter and in the process transmutes it back into thermal energy.[10] The combustion side of this reaction needs oxygen. On our planet, oxygen in the necessary atmospheric concentration was first produced by marine phytoplankton as a by-product of photosynthesis. But marine life is not well positioned to catch fire. It took the colonization of the Earth's landmasses by vascular plants to bring biological life into an oxygenated environment where it could become fuel—where carbon-plumped tissues and fibers could be exposed to the spark of lightning, volcanism, or friction. Presciently, Russian geochemist Vladimir Vernadsky, one of the first scientists to view the Earth as a single integrated system, describes terrestrial plant life as "green fire."[11]

For some four hundred million years, land-based life and earthly fire evolved together, rafting on slow-moving continents, ebbing and flowing with changes in global climate, and gradually diversifying. As an evolutionary stimulus, fire has tended to select for species or communities that are tolerant of, or positively disposed toward, further fire. In this way, fire effected a positive feedback cycle at the planetary or geophysical scale—drawing the Earth system toward heightened combustibility.[12]

Eventually, but by no means inevitably, these geophysical and evolutionary processes gave rise to a living creature capable of handling fire, a being with the ability to proliferate combustion, first accidentally and then intentionally. The emergence of fire-handling hominids at some point in the lower Pleistocene epoch—perhaps a million or a million and a half years ago—can be seen as a turning point not only in human evolution but also in the planet's history. As Pyne intones, "a uniquely fire creature became bonded to a uniquely fire planet."[13] But he adds the telling proviso that "*the Earth did not get quite what it supposed.*"[14]

First appropriated, later manufactured, fire made it possible for the genus *Homo* to inhabit zones, regions, and niches that would otherwise have been forbidding. Human use of combustion accelerated the spread and diversification of terrestrial flame—encouraging the emergence of new "species" of fire. Eventually, much of the Earth's land area was worked into a mosaic of adjoining, overlapping, or intermingling fire-scapes. In the process, a great many human communities became experts at what has recently come to be called "broadcast" or “prescribed” burning: the intentional application of fire as a means of managing a grassland, scrub, or forest environment.

Deploying fire in a living environment is inevitably an inexact and changeable process. Every fire and each fire season represents a unique combination of fuel loads, biota, topography, moisture, and weather conditions—an expression of the shifting, indeterminate relationship among these ingredients.[15] Because climate is itself variable at every scale, and because biological life continues to evolve, the application of flames to the living world is an experiment that never ceases.

Fire provides humans with warmth, light, and a communal gathering point. It can help prise open dense forest – making it more accessible to humans and other large animals . Flame purges ecosystems of pests and pathogens. It keeps away predators. Judicious deployment of fire in a landscape reproduces the effects of natural and rejuvenating disturbance. It strips away acidic humus, coats the ground in fertile ash, and promotes new plant growth. By accelerating the circulation of nutrients and multiplying edge zones, fire can jolt an ecosystem into new levels of productivity and stimulate biological diversification.[16] Applying heat to comestible organic matter—cooking—can greatly improve a food’s nutrient value or render usable what was previously indigestible. Over time, targeted application of fire selects for species that are of value to human communities, in this way gradually increasing the carrying capacity of a landscape.

It is more than just the organic world that fire transforms. Over the course of hundreds of thousand of years of manipulating fire, humans slowly gleaned knowledge of what flames could do to other materials. Just as fire softened flesh and fiber , they discovered, it also hardened wood, cracked rock, and baked clay: “what began with meat and tubers eventually fed bone, stone, sand, metal, liquids, wood, whatever might be found, into the transmuting flames.”[17] At different times and in many different places, experienced fire users eventually worked out that by enclosing fire, they could concentrate, control, and intensify its metamorphic effects.

The earliest known purpose-built chambers for fire are the kilns uncovered at the Dolní Věstonice and Pavlov sites in today's Czech Republic. Here, along with many sculpted animal forms, a number of the now famous voluptuous "Venus" figurines have been unearthed. These artefacts and the kilns in which they were fired have been dated at around 25,000 BP, which locates them deep in the last Pleistocene Ice Age. Analysis suggests that all the baked earth forms were hand-shaped out of wind-blown loess soil. Many were moistened with mammoth fat and strengthened with powdered bone—perhaps the earliest known example of humans deliberately combining materials to form a compound with novel properties.[18]

With the waning of the last Ice Age and the multi-sited emergence of agricultural production, the rudimentary kilns that first appeared at Dolní Věstonice burgeoned into full-blown "fiery furnaces." From out of these proliferating fire chambers came the very stuff of which "civilized" life was and is composed—ceramics, plaster, cement, metal, concrete, and glass—together with a multitude of techniques for molding, throwing, casting, extruding, and melding these materials into functional forms. But long before the pyrotechnic arts radiated outward across the ancient world, there was Dolní Věstonice, and the site today offers a tantalising glimpse of what may have propelled the earliest enclosure of flame.

What we might expect to see in a tiny cluster of settlements huddled within sight and wind chill of the great northern ice caps is evidence of fire being set to the hardscrabble work of daily survival. Unsurprisingly, communal hearths appear to be a focus of cooking and keeping warm. However, excavations at Dolní Věstonice and Pavlov reveal no trace of earthenware vessels and in fact no fired object of any discernible utility. Instead, what turns up in and around the kilns looks more like the residue of bursts of exorbitant creativity. Mingled with the celebrated "finished works" are balls and tubules, pellets and pinchings, body parts and amorphous shapes, incomplete and fractured figures—a teeming sea of fragments amounting to over 10,000 distinct fired forms. Given the clear indicators of ceramic skill, archaeologists speculate that this artefactual superabundance is less an archive of failed and/or successful efforts in the course of evolving competence than it is a sign that creative endeavor among the humans here was performative, that the very act of partaking in the fiery transmutation of earthy matter was somehow valued over and above any physical outputs.[19]

As pyrotechnic skills developed twelve, fifteen, or twenty thousand years closer to our own time, a multitude of uses were found for the products of fiery furnaces. Agricultural produce was stored, prepared, and served in ceramic vessels, water cisterns and channels were lined in brick and mortar, and metals provided hard edges for cutting through soil, wood, flesh, and stone. Alongside its contribution to early urban infrastructure, baked clay furnished the first medium for writing. As well as being cast into measures and tokens of value, metals were forged into the weapons with which these hoardable objects could be guarded or expropriated.

Like the effects of fire on living landscapes, the impacts of pyrotechnic products on social systems are too diverse, too prodigious, and too entangled to tease out into clear cause-effect relations. Just as a prairie fire shakes up an ecosystem, the chambered flame and its outputs seem to jolt social systems to new levels of productivity. And just as the presence of certain metals triggers and stimulates organic processes, the shimmering new products of pyrotechnology appear to excite social existence. As Wertime observes of the emergence of smelted metals: “They became catalysts of social life for men even as they had been catalysts of energy exchanges for cells in the biological organism.” [20]

Eventually, entire empires in the ancient world were staked on the distribution and use of metallic ores.[21] While human trade may have drawn metal tools, weapons, and currencies into self-reinforcing circuits of production and exchange—developments whose final destinies we may still have before us—this tells us little of those objects’ origins and the initial impetus to make them.

Anticipating the late 1980s speculation about the artefacts of Dolní Věstonice, pyrotechnology scholars have long insisted that when it came to transmuting the materials of the Earth, allure and enchantment preceded utility and function. In the words of metallurgical historian Robert Forbes: “Metal made its first impression as a fascinating luxury from which evolved a need.”[22] Materials scientist Cyril Smith makes a related point, taking a broader gauge approach to artisanal work:

> Nearly all the industrially useful properties of matter and ways of shaping materials had their origins in the decorative arts…. [T]he making of ornaments from copper and iron certainly precedes their use in weaponry, just as baked clay figurines come before the useful pot. Alloys come from jewellery and the metal-casting industry began as sculpture.[23]

How pyrotechnic artisans came to an understanding of the pathways of transformation involved in their arts has long intrigued researchers. So dramatic are the changes involved in many of the crafts—the transmutation from soggy clay to impermeable ceramics, from crumbly ore to lustrous metal—it would have been impossible to foresee the outcome of subjecting a given matter to furnace heat. Alongside speculation on the role of accident and serendipity, scholars conjecture about the importance of curiosity, of ceaseless experimentation for no purpose other than the pleasure of probing the potentiality of the material world. For Smith, himself a practicing metallurgist, at the core of artisanal discovery is “creative participatory joy,” the long, slow acquisition of pyrotechnic skill that emerges out of “a rich and varied sensual experience of the kind that comes directly from play with minerals, fire, and colors.”[24]

Such is the exquisite detail and sheer beauty of many early pyrotechnic products that they are still breathtaking thousands of years later. However much chance or pleasure or ceaseless probing played a part in initiating this heat-driven morphogenesis, the processes themselves evolved into disciplined engagements with the determinate physico-chemical conditions of the material world. In the words of Wertime:

> Although they might have been launched as innocent and isolated skills, the pyrotechnic crafts in the years between 10,000 BC and 2000 BC became formidable industrial "disciplines," entailing the most severe chemical controls on daily operations.[25]

With its homemade kilns, its unstandardized fuels, and its ores and earths of variable consistency, pyrotechnology—for the greater part of its history—was always going to be a matter of tacit knowledge rather than an exact science. Not only is it necessary for the enclosed air to reach the right temperature, its correct chemical concentration is also crucial, for it is often "impurities" in the gas atmosphere of the kiln that serve as catalysts for the requisite thermochemical reactions.

Smith drives home the point that the pyrotechnic arts were characterized by their dealings with "aggregates and assemblies" of matter, or with a real world inconsistency and irregularity that until very recently was too complex even for the physical sciences to adequately analyze.[26] In this regard, the relationship between iron and steel is paradigmatic—and pivotal. For over 3,000 years, artisans were familiar with the wondrous transmutation through which iron's relative weakness gave way after intense heating to the tensile strength of steel. But knowing how was not the same as knowing why. From Aristotle's *Meteorologia* in the third century BCE through to Vannoccio Biringuccio's treatise *Pirotechnia* in the sixteenth century, steel's superior strength was assumed to result from its being a purified form of iron. It was not until the revolutionary developments in chemistry in the late eighteenth century that it became clear that it was the presence of carbon in the smelting process—more in the manner of an impurity—that made the vital difference.

Used as a fuel, usually in the form of charcoal, carbon was ubiquitous in the long history of working with metals. Only after Antoine-Laurent de Lavoisier had arrived at an understanding of the elemental properties of both oxygen and carbon—and their centrality to the process of combustion—was it possible to decipher carbon's precise contribution to the production of steel. As Smith observes, "It was during the excitement over the discovery of the new gases and their reaction…that the role of carbon in distinguishing steel from iron was realized."[27] Lavoisier's unpacking of combustion into a chemical reaction involving oxygen and carbon opened the way to a recognition that for thousands of years metalworkers—through their use of carbon-based fuel—had been introducing carbon into their furnaces without knowing its essential role. Functioning as a reducing agent, carbon helps separate metallic iron from its ores, but it is as an alloying element—which serves to prevent dislocations in the lattice-like atomic structure of iron—that carbon plays a crucial role in the transformation of iron to steel.

"The Chemical revolution under the leadership of Lavoisier inevitably brought with it a simplification of the understanding of the various forms of iron and steel," Smith observes, before going on to show how this reduction of the process to its essentials contributed to greater control over the production of steel.[28] At the same time, Smith points to a vital informational flow in the other direction, suggesting that the practical knowledge of the metalworker played a part in the identification of carbon, just as the know-how of ceramicists, glassmakers, and metallurgists contributed more generally to the scientific understanding of the chemical and thermal behavior of minerals.[29] In the broader picture, conceiving of combustion in terms of its chemical composition and precise reactive pathways did much to strip the mystery out of fire and its morphogenetic effects. By the same logic, Lavoisier's thermochemistry—the new understanding of combustion in terms of measurable exchanges of energy—prepared the way for the laws of thermodynamics.

Thermodynamics, it has often been noted, emerged from an era in which a new kind of machine was becoming central to social life. The context is explicit in the title of French engineer and physicist Sadi Carnot's 1824 monograph *Reflections on the Motive Power of Fire and on Machines Fitted to Develop That Power*, a text that proved pivotal to the later formulation of the laws of thermodynamics. In the heat engines of the Industrial Age, what I have been referring to as chambered fire took on new forms and functions. Fire still transformed "earthy materials" used as fuel, but the primary intention was no longer to play upon all the metamorphic possibilities that inhere in matter. It instead was to obtain motive force: to generate the energy to turn a crank arm, pump a piston, and power a hammer or pile driver. And increasingly it was this mechanical or kinetic exertion that came to define "work," which Carnot concisely—and narrowly—described as "weight lifted through a height."

Much has been said about the dramatic upsurge in socially available energy that came with the new capacity of heat engines to convert fossil hydrocarbons into motive force. But just as Smith sees the breakthrough application of Lavoisier's novel theory of combustion to the production of iron and steel as a *simplification* of the transmutations in question, so too might we view this literally explosive increase in mechanical energy—and its growing centrality to social and cultural life—as a *contraction* in the way heat is used and understood. As physicist Ilya Prigogine and historian of science Isabelle Stengers observe:

> Fire transforms matter; fire leads to chemical reactions, to processes such as melting and evaporation. Fire makes fuel burn and release heat. Out of all this common knowledge, nineteenth century science concentrated on the single fact that combustion produces heat and that heat may lead to an increase in volume; as a result combustion produces work.[30]

Even as they gesture at the reductiveness of this "single fact," what Prigogine and Stengers really want to show us is how the thermodynamic understanding of energy pries open the closed mechanistic world of Newtonian physics and leads the way to a much more dynamic understanding of matter-energy. So, too, when philosopher Michel Serres writes about the conjoined arrival of heat engines and the laws of thermodynamics, he wants to impress upon us how innovations in energy use allowed industry to break out of the lumbering circuits of wind, water flow, muscle, and the immutable clutches of gravity. “What is the Industrial Revolution?” asks Serres. “A revolution operating on *matter*…. [A] sudden change is imposed on the raw elements: fire replaces air and water in order to transform the earth.”[31]

But why take the “frozen orbits” of Newton’s cosmos as the point of comparison to the world of novel “igneous machines” and the new laws of heat and work they embody?[32] Or for that matter, why take trudging oxen and trickling water as the baseline for measuring what the industrial engine achieves? By no stretch of the imagination could be it said that the world into which industrial fire thrust itself was lacking heat energy or igneous potentiality. And only in the narrow sense of driving crank arms and pulleys could it be claimed that “fire replaces air and water.”

To imagine that boilers and steam engines transformed a clockwork Newtonian universe is to project backwards from the burgeoning transformative force of the industrial heat engine and to find, unsurprisingly, a world that turns on comparably monotonous and predictable powers. But things look very different if we start with a planet of fire, a million-plus years of experimental broadcast burning, or a multi-millennial binge of pyrotechnic creativity. Neither Lavoisier’s thermochemistry nor classical thermodynamics could come close to capturing the complexities involved in any “real world” combustive event, not only because these theories hewed to an imaginary of systems perfectly sealed from their environment, but also because they could only handle small numbers of pure and idealized elements. By contrast, every torching of a living landscape fuses a unique and unfathomable array of ingredients, just as every kiln firing folds into a single event a bustling complement of inconstant temperatures, gaseous impurities, mineral aggregations, and structural imperfections.

Science, until very recently, may have averted its gaze from the more complex dynamics of combustion, but that hardly disqualifies fire as a vital and productive presence in the social worlds into which a new generation of heat engines was thrust. For all the increase in force achieved by machines that could set the combustive power of fossil hydrocarbons to work, it is crucial to remember that converting heat into mechanical or kinetic energy—Carnot's "weight lifted through a height"—is but one of many kinds of work. For most of its four hundred million-year history on this planet, and especially over the span of time it has been put into play by curious and expressive hominids, combustion has been a great deal more than a means of shunting lumpen objects from here to there.[33]

Fire in the real world, we have seen, is an assemblage that only came together through the complex dynamics of biological life and its reengagement with other aspects of the geophysics of the Earth and cosmos. Rather than mere motion, it is metamorphosis—transformation from one physical state to another—that is fire's forte. As Pyne puts it, "Fire remains, above all, the great transmuter."[34] By this logic, even the creative outburst engendered by the original chambering of fire and its application to selected materials might be seen as a kind of narrowing or constriction of its metamorphic potentiality: this concentration of fire's power is attained through temporarily severing flame from its wider, more complex, and more tumultuous manifestation in the open field. Indeed, the word "focus" itself comes from the same Latin word for "the domestic hearth," the primordial site of fire's isolation and containment.

The Industrial Age heat engine, I have been arguing, might best be seen as another focusing, an even tighter corralling, and a further constriction of fire's transmuting force—a qualitative forfeiture that earns a massive quantitative dividend in prime moving power. What has since been learned, as classic thermodynamics has itself morphed into a full-bodied engagement with open, complex, and non-equilibrium systems, is that industrialism's monstrous amplification of fire's power is triggering all kinds of transformations in the Earth system. As the thermochemical reactions within the industrial engine export heat to the world beyond, it has become clear, many existing forms of order in the wider environment are being perturbed or broken down.

One of the changes we are already starting to see on a warming Earth is more wildfires. “Fire,” warns Pyne, “appears more profusely during times of rapid and extreme climatic change.”[35] As a species, we need to ask, as we are arriving at this juncture in the Earth’s history, whether or not we want a full complement of pyrotechnic capacities. Recent centuries have not been kind to the different species of fire or to the diversity and richness of fire-tending know-how. Many traditional practices in the pyrotechnic management of living landscapes came under duress during periods of colonization, when they found themselves in competition with novel and destructive deployments of fire intent on clearing the way for new kinds of agriculture. And then again, because the blanket prohibitions on burning that were later introduced to arrest these waves of destruction failed to distinguish between the crude new fires and those that had been kindled over many generations.

The enclosed and closely tended flames of the artisan are no safer from suppression. “The great technologies that began 10,000 years ago can still be found in altered form in the bazaars and workshops of Afghanistan, Iran, Turkey, Ceylon, India, Thailand, and China,” affirms Wertime.[36] But Wertime was writing more than forty years ago. Over the intervening decades, the globalization of industrial and post-industrial production has been muscling out a multitude of smaller scale and localized pyrotechnic manufactories. And as the fires of the small foundry or pottery works are quenched, so too are ancient skills quietly extinguished.[37]

None of this is good news if we wish to explore alternate pathways through and beyond this era during which a minority of the Earth’s human population have invested deeply in the prime moving operations of fossil-fueled heat engines. The ongoing attenuation and disappearance of pyrotechnic practice is even worse news when we consider possible transformations in the biosphere and Earth system. In a rapidly changing Earth system—on what remains, ineluctably, a fire planet—the transmuting force of fire will continue to work its experiments on us and other life forms, as it has done for the last four hundred million years. The onus will be on us as fire-handling hominids to experiment, in turn, with whatever blend of pyric play, discipline, and desperation we can conjure up.

Already there are proposals to intentionally intervene in climate systems at the planetary scale. But we need to think long and hard about vaulting ambitions to collectively modulate the heat of an entire astronomical body at time when a great many of our communities lack the skill to fire a clay pot, let alone a piece of bronze jewelry or a high tensile steel saber. This is a moment when decisions need to be made about whether we continue to extinguish the many hard-won ways of working with fire or commit to preserving and proliferating combustive practices and species of fire.

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[1] Loren Eiseley, "The Last Neanderthal," in *The Star Thrower* (New York: Harcourt Brace Jovanovich, 1978), 151.

[2] See Stephen Pyne, *World Fire: The Culture of Fire on Earth* (Seattle: University of Washington Press, 1997), 3.

[3] Theodore Wertime, "The Furnace Versus the Goat: The Pyrotechnologic Industries and Mediterranean Deforestation in Antiquity," *Journal of Field Archaeology* 10, no. 4 (1983): 446.

[4] Theodore Wertime, "Pyrotechnology: Man's First Industrial Uses of Fire," *American Scientist* 61, no. 6 (1973): 670–82.

[5] J. E. Rehder, *The Mastery and Uses of Fire in Antiquity* (Montreal: McGill Queens University Press, 2000), 3.

[6] Theodore Wertime, "Man's First Encounters with Metallurgy," *Science* 146, no. 3649 (1964): 1264.

[7] Stephen Pyne, "Maintaining Focus: An Introduction to Anthropogenic Fire," *Chemosphere* 29, no. 5 (1994): 889–911.

[8] Vaclav Smil, *Energy* (Oxford, UK: Oneworld, 2006), 10.

[9] Pyne, *World Fire*, 3.

[10] Stephen Pyne, *Tending Fire: Coping with America's Wildland Fires* (Washington, DC: Island Press, 2004), 21.

[11] Cited in Dorion Sagan and Eric Schneider, "The Pleasure of Change," in Lynn Margulis and Dorion Sagan, *Dazzle Gradually: Reflections on the Nature of Nature* (White River Junction, VT: Chelsea Green Publishing, 2007), 231.

[12] Pyne, "Maintaining Focus," 890.

[13] Pyne, "Maintaining Focus," 889.

[14] Stephen Pyne, *Fire: A Brief History* (Seattle: University of Washington Press, 2001), 26.

[15] Stephen Pyne, *Burning Bush: A Fire History of Australia* (New York: Henry Holt, 1998), 33.

[16] Stephen Pyne, *Vestal Fire* (Seattle: University of Washington Press, 1997), 233, 250.

[17] Lydia Pyne and Stephen Pyne, *The Last Lost World: Ice Ages, Human Origins, and the Invention of the Pleistocene* (New York: Penguin Books, 2012), 99.

[18] Don Hitchcock, "Dolni Vestonice and Pavlov sites," http://www.donsmaps.com/dolnivi.html (accessed August 20, 2015).

[19] P. B. Vandiver, O. Soffer, B. Klima, and J. Svoboda, "The Origins of Ceramic Technology at Dolni Věstonice, Czechoslovakia," *Science* 246, no. 4933 (1989): 1002–8.

[20] Wertime, "Pyrotechnology," 680.

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[21] Jack Goody, *Metals, Culture and Capitalism: An Essay on the Origins of the Modern World* (Cambridge: Cambridge University Press, 2012), 80–1.

[22] Robert Forbes, *Metallurgy in Antiquity* (Leiden: E. J. Brill, 1959), 11.

[23] Cyril S. Smith, *A Search for Structure: Selected Essays on Science, Art, and History* (Cambridge, MA: MIT Press, 1981), 242.

[24] Smith, *Search for Structure*, 305, 203.

[25] Wertime, "Pyrotechnology," 670.

[26] Smith, *Search for Structure*, 49, 54, 191–4.

[27] Smith, *Search for Structure*, 34.

[28] Smith, *Search for Structure*, 43, 48.

[29] Smith, *Search for Structure*, 50, 76.

[30] Ilya Prigogine and Isabelle Stengers, *Order Out of Chaos: Man's New Dialogue with Nature* (New York: Bantam Books, 1984), 102.

[31] Michel Serres, "Turner Translates Carnot," in *Hermes: Literature, Science, Philosophy* (Baltimore: John Hopkins University Press, 1983), 56.

[32] Luis Fernández-Galiano, *Fire and Memory: On Architecture and Energy* (Cambridge, MA: MIT Press, 2000), 51.

[33] N. Clark and K. Yusoff, "Combustion and Society: A Fire-centred History of Energy Use," *Theory, Culture & Society* 31 no. 5 (2014): 203–26.

[34] Pyne, *Fire*, 120.

[35] Pyne, "Maintaining Focus," 890.

[36] Wertime, "Pyrotechnology," 682.

[37] Clark and Yusoff, "Combustion and Society," 222–3; N. Clark, "Fiery Arts: Pyrotechnology and the Political Aesthetics of the Anthropocene," *GeoHumanities,* forthcoming 2016.