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SOME EARLY EXPERIMENTS ON IGNITION BY RADIATION

by

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That burning glasses could produce ignition was known to Greeks, Romans, Chinese and Arabs[1,2,3]. Crombie[4] quotes Grosseteste (d.1253)

"if a concave mirror were held to the sun, it would reflect the rays to one point, the 'locus combustionis', where wool or tow placed at that point would be set alight."

It must have been a powerful mirror since it is difficult to set wool on fire. Leonardo[5] (1452-1519) commented on both the properties of burning mirrors and their effects as did Paracelsus[6] (c.1493-1541).

Kepler[7] (1571-1630) reported that black bodies are more easily heated since they take up more light. He also[8] introduced the concept 'focus' into geometrical optics.

Mersenne[9] (1588-1648) found that a green willow branch would be ignited immediately by a burning glass although the hottest furnace would only do so after some time. It is possible to produce an intensity of radiation greater than 10 cal $cm^{-2}s^{-1}$ from such mirrors and ignition of wet wood does not take more than a second or two. In the hottest furnace Mersenne might have had available, the rate of heat transfer would not exceed 5 cal $cm^{-2}s^{-1}$.

Another early attempt to quantify the subject is noted by Smith and Forbes[10] who say that Glauber (1604-70) related the amount of heat concentrated to the diameter of the mirror. A mirror of one span in diameter burns wood, of two spans melts tin, lead or bismuth, and of four or five spans melts gold and silver and softens iron sufficiently for forging. They add that Robert Hooke (1635-1703) developed this concept further, and proposed to use the size of the aperture as a quantitative index of the degree of heat necessary to produce an effect.

Such an index would not, however, be adequate for mirrors of different focal lengths, where the same aperture would deliver different intensities of radiation at the focus; the intensity would vary with the intensity of the sun in an undetected way.

Azout[11] combines the work of Kepler and Hooke and promises to show that about 50 times as much light (i.e. radiant heat) as we have on Earth is necessary to burn bodies if they are black and 450 times as much for white and so observing the intermediate proportions between these two for burning bodies of other colours". Taking a value for the sun's radiation at the earth's surface of 1.4 cal $cm^{-2}min^{-1}$ this gives a value for the critical intensity for spontaneous ignition of about 1 cal $cm^{-2}s^{-1}$ for black materials, a remarkably accurate value, although the figure for white materials appears rather too large[12]. In a later passage, Azout suggests trying to find whether smaller apertures are needed in the tropics to obtain the same effects, so presumably his results were obtained using different aperture sizes.

Boyle (1627-91) makes numerous references to burning glasses[13].

"Ordinary burning glasses such as are wont to be used to light tobacco, will not in a great while burn, or so much discolour, a sheet of white paper".

Boyle goes on to say white bodies reflect the most of any.

Galileo's pupils and disciples of the Accademia del Cimento in Florence[14] carried out a comprehensive series of experiments. In one passage they write "of a dark colour upon which the Fire has an easie effect." A later passage adds "Likewise paper, and fine white holland*, when exposed flat to the Reverberatory of a large Concave, at length Fires: wherefore 'tis a mistake, that the light will not inflame any white bodies, as is generally thought; indeed, they take fire with more difficulty than coloured bodies, and it may be with a small concave or lens they will not fire". In another, under the title "Of Firing Bodies with a Burning Glass", they write "The light refracted by a crystal lens, or reflected by a burning (burnished) concave will not fire spirits of wine though made opaque by a tincture. Amongst other combustible matters, gunpowder fires upon the uniting of the rays of a lens or concave but the perfumed pastils, etc., ... melt but will never take fire". This is, of course, a limitation of this method of igniting materials, many melt before they are hot enough to be ignited.

Tschirnhaus used lenses as well as mirrors. One of these had a focal length of 12 feet and at the focus the image was 1½ inches in diameter[15]; by using a second lens he produced a much smaller and more intense image. With it, he carried out a comprehensive series of experiments, including two on ignition:

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*A form of linen

1. Every sort of wood, let it be ever so hard, or ever so green, nay, tho' it be soaked in water, will catch fire in a moment.
2. When you expose to it in summer any tender wood, such as fir, under water it does not seem to change it (i.e. the wood) on the outside, but when it (i.e. the wood) is cleft in two, it is found burnt within to a coal.

The latter effect is only explicable in terms of self-heating of the solid; that is, if the external heating were continued for some length of time, it would start chemical reactions within the solid which would produce charring <u>inside</u>.

Both Boerhaave (1668-1738)[16] and Musschenbroek (1692-1761)[17] give detailed accounts of the results of experiments using burning glasses.

Musschenbroek first gives examples showing that black coloured materials heat up more quickly and to a greater extent than lighter and brighter materials[18].

> "If one takes bodies of the same material, the same volume and similar in all other respects, and that may be coloured or dyed white, red, yellow, green, blue, purple or black; if one then exposes them equally to the sun then the whites will be those which take the longest to heat up and will heat up less than the others; the reds will heat up a little more, the others more again, each following the range of colours that we have given; and of these bodies it will be the black which heats up the quickest. That can be proved by the fact that when clothing is hung on a line, the blacks dry much more quickly than the white and at the same time become much hotter".

The principal innovation of the passage is in the first part of the sentence which separates out the effect of colour from other properties. He did not have a firm grasp of the principle for he writes[19] "Black bodies ignite sooner than bodies of other colours" and gives as an example, <u>black</u> charcoal is easier to ignite than <u>white</u> wood. He is here confusing colour changes with basic chemical changes in the wood.

Musschenbroek then attempts to prove that a black body absorbs all the radiation that falls on it and points out that the mirror surface must itself be reflecting:

"I have said that black bodies on which light falls reflect practically nothing but they absorb nearly everything which is why they become as hot in so short a time. One can prove this by the aid of a concave mirror which has been blackened by a flame; when exposed to the sun it will not reflect the light towards the focus and a thermometer which approaches the focus will not become very hot but the mirror itself will heat up very quickly. Mr. Boyle having made a great burning mirror of black marble could never make a piece of wood catch fire at the focus although he exposed the mirror for a long time to rays from the sun. White (shiny ?) bodies, on the contrary, reflect nearly all the light which falls on them and it is for this reason that the best burnished mirrors are those which are made of a white metal".

He fails to make it clear that the surface must be smooth.

He distinguishes 'chaleur' from 'feu' where we should only use the one term 'heat', 'feu' being a property near to the concept of 'phlogiston' and describes the ignition process[19].

"But fire separates from the rest of the mass the grossest of this nourishment, such parts as are aqueous, saline, oleagineous and earthy escape, carrying with them a little fire and forming another fluid which is visible called smoke. But when the same parts become volatile in larger quantities and this action is accompanied with much heat, they form what we call flame (spontaneous ignition) in coming away from the bodies to which they have until now adhered. Consequently smoke is not very different from flame and it can easily be converted into flame by bringing to it a little heat, for when a fire smokes very much it can easily be made to flame with a burning match (pilot ignition)".

Boerhaave[20] attempts to calculate the concentrating power of a certain mirror and finds that there should be 7396 times as much 'Fire' at the focus than usual; he says that some allowance must be made for the mirror not being perfectly reflecting nor perfectly focussed. In spite of Boerhaave's straightforward calculation, viz, the heat is more effective because it has been concentrated, he later argues[21] that the concentration of the rays of heat increases the particles' effectiveness many times. In the sense that there are threshold effects, this is true, but Boerhaave is really arguing that one particles of 'fire' become more effective in themselves.

Buffon[22] (1707-1788) noted that not only do black surfaces absorb more light than white ones, but that rough surfaces absorb more than smooth ones. He showed that burning mirrors were more powerful, i.e. could produce a higher rate of heating, than both reverberatory and bellows furnaces[23].

The work of the eighteenth century had shown the effect of surface absorptivity on ignition time but had not succeeded in elucidating which other thermal properties were involved, although it was recognised that there were others. Attempts had also been made to quantify the results in terms of a factor of so many times the intensity of radiation of the sun, and accurate descriptions of the ignition process had been given. It would have been profitable to have read their work before modern research work began.

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