X. *Contributions to the History of Explosive Agents.*—Second Memoir.

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Received December 1, 1873,—Read February 5, 1874.

Since the publication of the experiments on the explosion of gun-cotton and other compounds and mixtures by detonation, which are detailed in a memoir submitted by me to the Royal Society in March 1869 *, this matter has received considerable practical development, and has also been made the subject of further scientific investigation, both in England and on the Continent. In continuing my researches into the conditions to be fulfilled for accomplishing the detonation of explosive substances, I have arrived at further results confirmatory of, and additional to, those described in my former memoir. I have also been led to pursue experiments bearing upon this subject in somewhat new directions; and I venture to believe that an account of the results arrived at may possess some value as tending to throw further light upon the behaviour and properties of explosive agents.

The exceptional behaviour which I have described as being exhibited by certain explosive compounds when applied to the development of detonation, in comparison with other substances, to which they were not inferior as regards the force and heat developed by their explosion, has been confirmed by further experiment. It was stated by me that 0·32 grm. (5 grains) of mercuric fulminate, if applied under favourable conditions, suffice to develop the detonation of compressed gun-cotton, that 3·25 grms. (50 grains) of chloride of nitrogen appeared to be the minimum amount by which detonation of gun-cotton could be developed, that 6·5 grms. (100 grains) of iodide of nitrogen failed to produce this result, and that repeated trials with different quantities of nitroglycerine ranging up to 31·2 grms. (1 ounce) did not in any one instance result in the detonation of gun-cotton by that substance, although the mechanical force and heat developed by its explosion were at least fully equal to those brought into operation by corresponding quantities of the most violent of the above explosive agents.

The experiments with nitroglycerine have since been considerably extended by me. Vessels containing 62·4 grms. (2 ounces) and 124·8 grms. (4 ounces) of nitroglycerine have been placed upon disks (weighing 8 ounces) of compressed gun-cotton, and the liquid has been exploded by means of a fulminate-fuse. The only effects of the violent explosion produced were, in each case, the pulverization and dispersion of the mass of gun-cotton, some of the particles being occasionally ignited; but no

* Phil. Trans. vol. clix. p. 489.

symptom of detonation was developed *. Two ounces of nitroglycerine, in the form of dynamite (*i.e.* converted into a plastic mass by admixture with one fourth its weight of Kieselguhr), were also exploded in close contact with a cylinder of compressed gun-cotton; but the same negative result furnished by the preceding experiments was obtained. While, therefore, gun-cotton might be detonated by 0·32 grm. (5 grains) of mercuric fulminate, or by 3·25 grms. (50 grains) of chloride of nitrogen (of which substances only 0·07 grm.,=1 grain, and 0·1 grm.,=1·5 grain, are respectively required to detonate nitroglycerine), it was found not to be detonated even by the explosion in contact with it of 124·8 grms. (4 ounces) of nitroglycerine.

The obvious incompatibility of such results as these with the general conclusion (founded upon extensive and varied experiments with different explosive substances), that the facility with which an explosion accomplishes the detonation of such substances is proportionate to the mechanical force and heat developed by that explosion, led me to suggest that a similarity in character, or synchronism, of the vibrations developed by the explosion of particular substances might operate in favouring the detonation of one of such substances by the initial detonation of a small quantity of another, while, in the absence of such synchronism, a much more powerful initiative detonation, or the application of much greater force, would be needed to effect the detonation of the material operated upon. This view has been favourably regarded by many, as affording a reasonable explanation of the apparently anomalous results above referred to, and appears to have received some support from the results of certain interesting experiments recently instituted by MM. CHAMPION and PELLET † with iodide of nitrogen and one or two other explosive substances. They observed, in the first instance, that the detonation of about 0·03 grm. of iodide of nitrogen at one extremity of a tube 13 mm. diameter and 2·4 metres (and even 7 metres) in length immediately determined the explosion of a similar quantity of the iodide placed at the other extremity. By inserting a pith-ball pendulum into the tube they demonstrated that the concussion transmitted through it was very slight. They also found that the detonation of small quantities of nitroglycerine, mercuric fulminate, or nitroerythrite at one end of the tube exploded the iodide placed at the other extremity; and that if the tube were divided, so as to introduce an interval of 5 or 6 mm. between the two parts, a much more powerful explosion was required to determine the detonation of iodide at the furthest extremity. Some experiments which they made, by attaching small quantities of iodide of nitrogen to the strings of a double-bass and causing these to vibrate, appeared to indicate that only a particular pitch or rapidity of vibration determined the explosion of the iodide, similar results being also obtained with vibrating plates of metal. These, and some other results obtained with the aid of parabolic mirrors, led them to conclude that the

* In *one* instance, among a large number of experiments, the detonation of two ounces of nitroglycerine in contact with a disk of compressed gun-cotton (supported by a wrought-iron plate) furnished a result which appeared to indicate that the gun-cotton had detonated.

† Comptes Rendus, tome lxxv. p. 210.

explosion of a detonating substance must be attributed to a peculiar vibratory motion, differing in character with the constitution and properties of the substance, and acting independently of the concussion and heat developed by an explosion. In a subsequent paper* MM. CHAMPION and PELLET described some experiments in which they compared the effects produced upon a series, or scale, of sensitive flames by explosions of mercuric fulminate and iodide of nitrogen, the quantities of explosive substances and their distance from the flames being varied. The explosion of the fulminate was found to affect certain flames in the scale, leaving others unaffected, at a distance at which a corresponding quantity of iodide of nitrogen produced no effect upon any of the flames. When the distance of the explosion from the flames was reduced, the iodide affected those which represent the highest notes in the scale, while a corresponding experiment with the fulminate acted upon the entire series. By increasing the quantity of iodide used and diminishing its distance from the flames, the whole series was eventually affected by the explosion of that substance. Want of success in attempts to establish a difference between the effects of the explosion of mercuric fulminate and nitroglycerine upon the series of flames was ascribed by the experimenters to the limited range of the series (or of the analyser of vibrations); but they regard their results as having demonstrated that a marked difference exists between the character of vibrations developed by the explosion of iodide of nitrogen and mercuric fulminate, and that the kinds of vibrations developed by a particular explosive substance are modified by an augmentation of the quantity of material exploded, so that a definite relation should be observed between the susceptibility to explosion of the substance (such as gun-cotton or nitroglycerine) operated upon and the quantity of explosive substance required to produce the initiative detonation.

The results described by MM. CHAMPION and PELLET have certainly demonstrated that different explosive agents, detonated under the same conditions, may differ importantly in regard to the character of vibrations which they develop; and their experiments with iodide of nitrogen afford some support to the hypothesis that a particular explosive agent is peculiarly susceptible to the disturbing influences of the class of vibrations which its explosion develops most readily, if not altogether to the exclusion of others. The observation made by them, that iodide of nitrogen, if employed in increased quantities, will develop eventually those vibrations obtained with small quantities of mercuric fulminate, which are not obtained with it when it is employed under the same conditions as the fulminate, is in complete accordance with the facts pointed out by me, that the chloride and iodide of nitrogen will only detonate gun-cotton when employed in very much larger quantities than the requisite amount of fulminate. It still remains, however, to be demonstrated why nitroglycerine, which is so readily detonated by a much smaller quantity of fulminate than has to be used with gun-cotton, and is also susceptible of detonation by small quantities of the latter material, is incapable of detonating gun-cotton, even when employed in comparatively overwhelming quantities.

* Comptes Rendus, t. lxxv. p. 712.

The employment of the iodide of nitrogen in experiments of the kind carried out by MM. CHAMPION and PELLET appears to me open to objection: first, because it is of uncertain composition, and consequently varies very considerably in sensitiveness and stability; secondly, because the quantities employed in experiments can only be approximately estimated, and hence experiments instituted with small quantities cannot possess great accuracy; thirdly, because it is so very readily exploded by vibrations imparted to the air by concussions of all kinds, that its use can scarcely afford much scope as a means of investigating the character and effects of different vibrations.

Hence, in carrying out a series of experiments on the transmission of the concussion or vibration developed by explosions, I have preferred to operate with explosive agents of thoroughly constant composition, and more readily and accurately applicable because less highly susceptible of explosion.

I.—ON THE TRANSMISSION OF DETONATION.

In describing the experiments instituted by them on the detonation of iodide of nitrogen at considerable distances through the medium of tubes, MM. CHAMPION and PELLET allude to an analogous experiment made by M. BARBE with dynamite. I have been unable to find a description of this particular experiment; but Captain TRAUZL, of the Austrian Engineers, has made numerous experiments on the transmission of detonation of a cartridge of dynamite by means of tubes to charges separated from it by considerable distances. A cartridge of dynamite, between 2 and 3 ounces in weight, was inserted into each extremity of an iron tube (a gas-pipe) 6 feet (1·82 m.) long and 1·25 inch (·031 m.) diameter; by the explosion of one of these charges with a detonating fuse, the detonation of the charge at the opposite extremity of the tube was accomplished, the two explosions being apparently simultaneous. A similar result was obtained by employing a much wider tube; and the practically simultaneous detonation of several charges, connected with a long tube by short branch-pipes at a distance of 2 feet from each other, was accomplished by inserting dynamite-cartridges into this long tube over the opening of each branch-tube, and detonating a charge of the material at one extremity of the tube. These interesting results induced me to institute a series of experiments, with the view of more closely examining into the transmission of detonation to widely separated masses of different explosive agents through the medium of tubes. The following is an account of the principal results obtained.

a. *Experiments with compressed gun-cotton.*

The first experiments were made with wrought-iron tubes (gas-pipe), 1·25 inch (·0317 m.) in diameter. One ounce (31·2 grms.) of gun-cotton, in the form of a 1-inch disk, was placed *against* each opening of the tube; the disk at one extremity was exploded by means of an electric detonating fuse. The length of tubes experimented with was gradually reduced from 1·92 metre (6 feet 3 inches) to ·91 metre (3 feet) before any transmission of detonation was obtained; the mass of gun-cotton at the further end was shattered and dispersed, portions of it being sometimes inflamed as the length of the tube used approached 3 feet. With such a tube much of the gun-cotton at the far extremity was scattered in a burning state; but a *partial* detonation of the mass was obtained, as indicated by the shattering of the extremity of the iron tube against which it rested. The experiment was repeated with a tube of the same length (3 feet), the disks of gun-cotton being *just inserted* into each extremity: a partial detonation of the second disk again occurred, portions being dispersed and inflamed. Similar results were obtained with tubes ·760 metre (2 feet 6 inches) long, except that the portion detonated was more considerable, 4 inches of the iron tube being broken up at that extremity. In order to ascertain that the shattering of the tube at the opposite end to that in which the initiative detonation was produced was really due to a partial detonation of the gun-cotton, and not to the check experienced by the rush of gas through the tube upon its encountering the obstacle presented by the disk or plug of gun-cotton, the following experiment was made. A cylindrical plug of wood, fitting *loosely* into the tube, was inserted at one extremity, and a disk of gun-cotton (1 ounce =31·2 grms.) was introduced into the other end and detonated: the wooden plug was entirely broken up into small splinters, which were scattered about, but the end of the tube containing it was not injured. A similar experiment was made with a tube 6 feet 6 inches (2 metres) long, a wooden plug being inserted at one end, and a cartridge of dynamite weighing 2 ounces = 62·4 grms. exploded in the other extremity*: in this case also the wood was reduced to small splinters, but the tube at that end was not injured. The shattering of the tube at the far end in the preceding experiments was therefore conclusive evidence of a detonation of the gun-cotton, or of some

* A remarkable illustration upon a large scale, but analogous to these experiments with tubes, of the work which a wave of gas set in motion by an explosion will accomplish when resistance is opposed to it was furnished by an experiment made a short time back at Portsmouth in reference to the application of compressed gun-cotton to the rapid demolition of fortifications.

Among the old works required to be demolished was an arched "Counterscarp Gallery" of curved form, 250 feet in length, 7 feet wide, and of a total height of 7 feet 4 inches. The arch was of 120° and 18 inches thick; the back wall and part of the arched roof abutted upon solid earth; the front wall was from 5 feet to 5 feet 9 inches thick, and was pierced with nineteen oblong conical openings or "loopholes," the inner dimensions of which were 3 feet 2 inches by 5 inches. Each end of the gallery had a doorway 6 feet high and 2 feet 9 inches wide, provided with a wooden door, outside which was a grating composed of iron bars 1 inch thick, framed together so as to be 4 inches apart.

Three charges of compressed gun-cotton, weighing 20 pounds each, were arranged for simultaneous explosion in this gallery by means of electric detonating fuses; they were quite unconfined, being simply suspended side by side against the outer wall, between two of the loopholes, at a short distance from one extremity of the gallery. By the detonation of these charges the gallery at this end was destroyed to a distance of about 60 feet; and the brickwork was fissured to a much greater distance, the front wall being partly pushed forward up to a length of about 140 feet. At the other end of the gallery, where the wave of gas was checked or brought up, the destruction accompanied by the explosion was nearly equal in extent to that effected at the seat of the charges; the arch of the gallery was destroyed to a distance of about 70 feet, and the front wall was pushed forward to a length of about 80 feet. The bars of the iron grating which closed the entrance into the gallery at this end were twisted up into fantastic shapes, and projected to considerable distances.

portions, at the extremity most distant from the initiative explosion. With tubes 2 feet (·608 m.) in length, the gun-cotton disks being just inserted into each end, perfect detonation by transmission was attained. A variation of the mode of arrangement furnished the same result. One pound of compressed gun-cotton was placed in a pit dug in the ground; one extremity of a tube (1·25 inch in diameter and 2 feet long) was allowed to rest upon it, and was buried in the ground in this vertical position, the earth being firmly rammed round the charge and tube. A perforated disk of gun-cotton, weighing 1 ounce (31·2 grms.), and containing a detonating electric fuse, was just inserted into the open end of the tube, and exploded; the charge at the opposite end of the tube was detonated, a large crater being produced in the ground, and the iron being violently projected to a great height. In a corresponding experiment made with a tube 3 feet (·91 metre) in length, the buried charge was only inflamed by the detonation of 1 ounce of gun-cotton at the upper extremity.

With the employment of 2 *ounces* (62·4 grms.) of compressed gun-cotton as the detonating agent, experiments were made with tubes gradually reduced in length from 6 feet (1·82 metre) to 5 feet (1·53 metre); with such a tube complete detonation of the gun-cotton at the distant extremity was obtained *.

These experiments were subsequently repeated with the employment of stouter wrought-iron tubes, but of the same lengths and diameter (1·25 inch, ·031 m.) as those before used. In these the shattering and opening-up of the tube at the seat of the initiative detonation were less considerable, but increased effects as regards the transmission of detonation were obtained. The detonation of only 0·5 ounce (15·6 grms.) of gun-cotton, inserted into one extremity of a tube 2 feet long, detonated a charge in the opposite extremity—a result which it required 1 ounce (31·2 grms.) to accomplish in the previous experiments, while the latter quantity, employed in the stouter tubes, induced detonation through a tube 3 feet 3 inches (1 metre) long.

Trials were made of wrought-iron tubes only 1 inch (·0254 m.) in diameter, and of similar thickness to those first used in the experiments with the wider tubes; no detonation was transmitted, when the disk of gun-cotton was simply placed *against* the opening of one extremity of the tube, on the detonation of 1 ounce just at or within the other extremity; but when *both* charges were inserted into the extremities, the detonation was transmitted to a distance of 3 feet with the employment of 1 ounce of gun-cotton, while with the wider tube of similar thickness complete detonation was only obtained with certainty at a distance of 2 feet (·608 m.).

In other experiments wrought-iron tubes of larger diameter were used. A stout wrought-iron tube, 1·75 inch (·45 m.) in diameter and 3 feet (·91 m.) in length, had a charge of 3 ounces of gun-cotton (1 inch, ·025 m. diameter) just inserted

* In these experiments, when detonation of the *distant* charge was obtained, the destructive action upon the iron tube was always greatest at that extremity; the sudden obstruction of the wave of gas by the induced detonation was evidently productive of greatly increased destructive effects from the point at which the opposing columns of gas met.

into one extremity; its detonation did not induce that of a disk of the same diameter inserted into the other extremity of the tube; whereas the detonation *was* effected by the explosion of only 1 ounce (31·2 grms.) in the further extremity of a tube the same length and substance, but only 1·25 inch (·031 m.) in diameter. With a tube of the larger diameter (1·75 inch) and 2 feet 3 inches (·684 m.) long, the detonation of 2 ounces of gun-cotton of the above diameter in one extremity induced *partial* detonation in the other extremity. In these experiments the diameter of the tubes was 0·75 inch (·019 m.) larger than that of the disks of gun-cotton inserted in them; had the diameter of the latter corresponded more nearly to that of the tube, detonation would have been effected by transmission through a greater length, as was demonstrated by several experiments; thus 2 ounces of gun-cotton, 1·75 inch (·044 m.) in diameter, detonated in one extremity of a tube 3 feet (·91 m.) long and 2 inches (·05 m.) in diameter, accomplished the detonation of a disk of the same diameter inserted in the other extremity.

Attempts to explode gun-cotton through the medium of tubes of considerably greater width were not successful. Cast-iron tubes, 3 inches (·076 m.) in diameter and of different lengths, from 5 feet (1·52 m.) to 2 feet (·608 m.), were employed, and 2 ounces (62·4 grms.) of gun-cotton were detonated in one extremity; disks 1 inch (·025 m.) in diameter, inserted into the other extremity of these tubes, were not detonated. It appeared probable that the complete shattering and dispersion, on the instant of the explosion, of those portions of the cast-iron tube which were at the seat of the detonation might operate against the effective transmission of the concussion through the tube (and such was demonstrated to be the case in corresponding experiments with dynamite): the experiments were therefore repeated with the employment of *wrought*-iron tubes 2·75 inches (0·069 m.) in diameter, ranging in length from 6 feet 6 inches (2 m.) to 2 feet 10 inches (·858 m.); but only negative results were obtained; the detonation of the charge in one extremity of the tubes shattered the gun-cotton disk in the opposite extremity, inflaming portions, but the latter was in no instance detonated.

A few experiments were made with tubes of different materials, with the view of examining into the influence exerted by such variation upon the transmission of detonation. A tube 1·25 inch (·031 m.) in diameter and 2 feet (·608 m.) long was constructed of several superposed layers of strong brown paper. The detonation of 1 ounce of gun-cotton inserted in one extremity did not accomplish the explosion of gun-cotton in the other end; the disk was dispersed in fragments, some of which were inflamed, and the tube was torn to pieces. Detonation would have been induced with certainty by that quantity of gun-cotton in a thin wrought-iron tube of the above dimensions, and in a stout tube of that material with half the quantity, as already shown. With employment of a lead tube of the given dimensions, but slightly stouter in substance than the thickest wrought-iron tube used, detonation was induced by means of 1 ounce of gun-cotton: the metal composing the tube was opened up and distended into thin sheets at each end by the detonations. The experiments with tubes made of different materials were extended during the progress of this investigation, when silver fulminate was used; the above results, in addition to those obtained with iron tubes differing in strength, indicated, however, that the transmission of detonation is regulated to an important extent, in experiments of some magnitude, by the strength of material composing the tube and the consequent resistance which it opposes locally to the force developed by the initiative detonation.

The almost instantaneous manner in which the detonation appeared to be transmitted from the point of first explosion to the distant mass of gun-cotton, through the medium of tubes, led me to believe that the mechanical condition of the gun-cotton might, under these circumstances, be without effect upon the results obtained. If gun-cotton yarn or wool be struck with a hammer upon an anvil, unless the layer interposed between the support and striking body be very thin, repeated blows are required to accomplish the detonation of any part of it, as the force is mainly expended, in the first instance, in imparting motion to the particles of the mass, which becomes compressed, and thus reduced to a condition in which the particles offer great resistance to mechanical motion before the force applied can develop chemical metamorphosis. For the same reason*, if a fuse charged with mercuric fulminate, to an extent greatly in excess of that required to detonate a mass of compressed gun-cotton, be exploded in the centre of a mass of gun-cotton yarn or wool, freely exposed, or even if a small disk of compressed gun-cotton be detonated in contact with the loose material, the latter will not be detonated, but be simply dispersed in small fragments, with or without inflammation, because the particles of the wool or yarn are not in a condition to oppose resistance to the force applied, which therefore is expended in imparting motion to them. It can be conceived, however, that the blow, or gas-wave, to which a mass composed even of quite loose fibres is opposed may be so sudden in its operation that the particles which it first encounters undergo chemical disintegration before time can operate in causing the force to expend itself in imparting mechanical motion to the mass. In some experiments to be presently described, this action of a sudden blow upon those particles of a compressed mass of gun-cotton (placed so as to be perfectly free to move) which it first encounters will be found conclusively demonstrated (p. 361); but the same kind of action of the gas-wave upon a mass of uncompressed gun-cotton fibre was strikingly illustrated by one or two experiments with wrought-iron tubes of the kind described.

In the first instance, a loosely twisted thread or yarn of gun-cotton was wound pretty firmly into a ball of such size as to fit rather tightly into one extremity of a tube 1·25 inch in diameter and 2 feet (·608 m.) long. The detonation of a 1-ounce (31·2 grms.) disk of gun-cotton in the opposite extremity of the tube induced the detonation of the ball of yarn. Had the latter been in close contact with the detonated disk, freely exposed, it would simply have been scattered, some particles being probably

* Philosophical Transactions, 1869, vol. clix. pp. 497, 498, 501.

inflamed. The experiment was repeated with this difference, that the gun-cotton yarn was inserted into the end of the tube simply in the form of a loose and light plug; in this instance, also, the loose gun-cotton was detonated. The resistance to mechanical motion offered by the mass, supported by the sides of the tube, was sufficient, as opposed to the sudden rush of gas, to ensure the detonation of the loose material. In one experiment a piece of yarn, which formed part of the gun-cotton plug, was allowed to protrude outside the tube; this portion was projected in the air in a burning state, while the plug contained in the extremity of the tube was detonated.

The successive though practically simultaneous detonation of several distinct and somewhat widely separated masses of gun-cotton, through the agency of tubes, affords further demonstration of the great rapidity with which force is transmitted by these means. One or two instances will suffice as illustrations. A tube 1·25 inch (·031 m.) in diameter, 6 feet 6 inches (2 metres) long, had a disk weighing 1 ounce (31·2 grms.) inserted to a distance of 2 feet (·608 m.) from each extremity; similar disks were also just inserted into the openings; thus the tube contained four charges, each one separated from the nearest by a distance of 2 feet. On the detonation of the disk at one extremity only one explosion was heard; but all the charges were detonated, the tube being rent into many pieces.

A tube of the same diameter as the foregoing, but 10 feet in length, had four openings bored into it at intervals of 2 feet, into which were fitted short branch-pipes (1 inch in diameter) at right angles to the main tube. One ounce of gun-cotton was inserted into the latter, opposite each opening, and also into its open ends; half an ounce of gun-cotton was also inserted into the extremity of each branch-pipe. The arrangement therefore included ten distinct charges; those in the main pipe were separated from the nearest by spaces of 2 feet, and those in the branch-pipes were 1 foot distant from the corresponding charge in the long tube. Just as in the preceding experiment, only one sharp explosion was heard when the disk at one extremity of the main tube was detonated; all the disks were exploded, the action being apparently instantaneous. The tubes were rent into many and curiously contorted fragments, which were projected to considerable distances; and small craters were formed, in the ground on which the tube-arrangement rested, at the seat of each charge.

These results rendered it a matter of considerable interest to endeavour to determine the velocity with which detonation is transmitted from mass to mass through the medium of tubes, and to compare it with that at which detonation is transmitted, in open air, by contiguous masses of gun-cotton. The results obtained will be given hereafter *.

* Numerous practical exemplifications of this mode of transmitting detonation have been obtained both with gun-cotton and dynamite; and some decided advantages appear likely to accrue from the application of this mode of exploding charges to certain blasting and mining operations. Thus it is obviously possible, by suitable arrangement of tubes, to fire a number of charges with the practical effect of simultaneous explosions. The Austrian engineers have already availed themselves usefully of this method of firing charges in the application of dynamite to purposes of demolition. Again, it has been demonstrated by the author, in actual

b. *Experiments with dynamite.*

The cartridges used consisted of 2·5 ounces (78 grms.) of dynamite, made up into plastic rolls 4 inches (·1 m.) long and 1 inch (0·025 m.) in diameter, and wrapped in waterproof paper.

The experiments were commenced with wrought-iron tubes 1·25 inch (·031 m.) internal diameter, and 6 feet (1·82 m.) long, a cartridge being just inserted into each end. Detonation was induced, as was the case with a nearly corresponding weight of gun-cotton, when the length of tube intervening between the initiative explosion and the other cartridge was reduced to 5 feet.

Other experiments with dynamite, corresponding to those carried out with gun-cotton in tubes of 1 inch and 1·25 inch diameter, as already described, furnished analogous results. Attempts were made to transmit the detonation developed from a charge of 2·5 ounces (78 grms.) of dynamite through cast-iron tubes 4 inches (·1 m.) in diameter, 5 feet 5 inches (1·64 m.), 3 feet 3 inches (1 m.), and 2 feet 2 inches (·666 m.) in length, the dynamite charges being 2 inches (·025 m.) in diameter. Only negative results were obtained; but on repeating the experiments with *wrought*-iron tubes ·069 m. (2·75 inches) in diameter, the detonation of the above quantity of dynamite produced detonation of a charge of that material in the opposite extremity of this tube, through a length of 5 feet 3 inches (1·59 m.). This was the only indication, but a very decided one, furnished by the tube-experiments, that detonation produced by dynamite is more readily susceptible of transmission to a distant mass of the same material, under severe conditions, than is the case with gun-cotton. The great difference between the results furnished by the cast-iron and wrought-iron tubes with dynamite was most probably due to the circumstance that the former, which were not strong, presented insufficient resistance at the seat of detonation to prevent a great escape of force, the concussion being therefore much less completely transmitted through the tube.

Results quite similar to those described as furnished by gun-cotton, in which detonation was transmitted to a number of distinct and widely separated charges, enclosed in tubes, have been obtained in experiments instituted some time since with dynamite by Captain Trauzl of the Austrian Engineers.

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mining operations, that modifications in the method of charging and firing blast-holes in rock &c. may be introduced with advantage in point of safety and expedition in working. Thus it is unnecessary to insert the fuse, with detonator attached, to the bottom of the blast-hole. After entering the principal part of the charge of gun-cotton or dynamite to the bottom, the remainder, with the fuse attached, may be just inserted a short distance into the hole, and the charge may then be exploded with full effect by firing the fuse; or, in holes of considerable depth in hard rock, the charge of explosive agent may with decided advantage be subdivided, a portion only being inserted to the bottom of the hole, and the remainder at intervals of 1 foot or more, the fuse, with priming charge, being just inserted into the opening as above pointed out.

c. *Experiments with mercuric fulminate.*

The fulminate employed in these experiments to furnish the initiative detonation was enclosed in strong tubes or cases of tinned iron, the openings of which were firmly closed by means of the electric fuse used for exploding the charge. The quantity of fulminate inserted into the opposite extremity of the tubes was, in all instances, 100 grains (6·48 grms.), and was loosely confined by being screwed up in moderately stout paper.

1. *Employment of wrought-iron tubes of* 1·25 *inch* (·031 *m.*) *diameter.*—The explosion of 5 grains (·324 grm.) of the fulminate, in one extremity of a tube 1 foot (·304 m.) in length, detonated the charge which was just inserted in the other extremity; but the detonation produced varied in violence, and it appeared as if 1 foot were about the limit of distance through which detonation was susceptible of transmission under the above conditions, as regards dimensions and force of initiative explosion. The explosion of 10 grammes of the fulminate did not induce detonation through a tube of double the length (2 feet = ·608 m.), and with 15·4 grains (1 grm.) the same negative results were obtained. On inserting the fulminate-fuse, containing 15·4 grains (1 grm.) of the substance, to distances of 6 inches, 3 inches, and 2 inches (·15 m., ·075 m., ·050 m.) into the tube 2 feet long, explosion of the fulminate inserted into the other extremity was always induced; but the effects were those of a violent detonation only when the fuse was inserted to the maximum distance (6 inches), leaving a length of 18 inches (·45 m.) through which detonation was transmitted. When tubes of the same diameter, only 18 inches in length, were employed, the fuse charged with 15·4 grains (1 grm.) of fulminate being just inserted into one extremity, the explosion induced in the other was not so violent as in the preceding experiments when the charges were separated by the same distance, the initiative explosion being, however, produced at some distance (6 inches) inside the tube employed. In these cases the transmission of the concussion was obviously favoured by the circumstance that the tube projected some distance beyond the seat of the initiative detonation, the loss of force by dispersion in other than the desired directions being thereby much reduced. With 23 grains (1·49 grm.) of the fulminate just inserted into one opening of a tube 2 feet (·608 m.) long, detonation was induced at the other extremity; and the same result was obtained with the above quantity of fulminate when tubes 3 feet (·91 m.) long were employed.

2. *With tubes* 1 *inch* (·025 *m.*) *in diameter and* 2 *feet long*, the detonation of 10 grains (·65 grm.) of the fulminate inserted into one extremity produced explosion, though not of a very violent character, at the other end. In one instance, among several experiments with these tubes and the above quantity of fulminate, violent detonation was induced, the conditions of the experiment being evidently just bordering on the limits of those essential to the development of detonation by transmission of the concussion.

Tubes of the same diameter and thickness, 5 feet (1·52 m.) in length, were next employed; the detonation of 20 grains (1·2 grm.) and 23 grains (1·3 grm.) inserted in one extremity did not inflame the fulminate enclosed in paper and placed in the other end; and the detonation of 25 grains (1·62 grm.) also failed in one instance even to produce inflammation; but in other experiments, under apparently the same conditions, the fulminate at the opposite extremity was either inflamed or exploded, though not with the violent action which a perfect *detonation* of the same quantity of fulminate would exert.

It would appear from these and similar results obtained with mercuric fulminate that the amount of the latter required to induce detonation of the same substance, under the conditions described, is generally in direct proportion to the length and diameter of the tube through which detonation is transmitted, except when its length is so reduced as probably to bring the fulminate operated upon within the range of the flash of fire, as well as of the blow given by the initiative explosion.

d. *Experiments with mercuric fulminate and gun-cotton.*

It was shown by me, in my former memoir on Explosive Agents*, that 0·32 grm. (5 grains) of fulminate, enclosed in a thin metal case, was required to develop the detonation of compressed gun-cotton, care being taken to secure *close contact* between it and the detonator. In accordance with the fact demonstrated in that memoir, that the sharpness of a detonation and its consequent power of *developing* detonation in other masses was dependent upon the degree of confinement or the strength of the envelope enclosing the explosive substance, I have since found that only 2 grains (0·13 grm.) of the fulminate are required to detonate compressed gun-cotton *with certainty*, provided the case in which it is enclosed be constructed of stout metal (sheet iron), the detonator being so applied as to be closely surrounded by the mass to be detonated (*i. e.* inserted into a perforation in the piece of compressed gun-cotton). If there is not close contact between the two, a considerable larger proportion of the fulminate, confined as above described, is needed to ensure detonation; and in actual practice, when it may frequently be difficult to ensure close contact of the detonator with even some small portion of the charge to be exploded, it is found advisable to use about 1 gramme (15·45 grains) of the fulminate in the detonating fuse.

In attempts to transmit the detonative force from a confined fulminate-charge (or "detonator") to gun-cotton through the agency of tubes, as in the experiments described, somewhat remarkable results were obtained. Contrary to expectation, it was found impossible to accomplish this result through the medium of a tube 1 inch (·025 m.) in diameter and only 1 foot (·304 m.) in length, by the detonation of even so large a charge as 108 grains (7 grms.) of fulminate inserted into one extremity, the gun-cotton being introduced into the other end. With a charge of 154 grains (10 grms.) only *partial* explosion of the gun-cotton was effected through a tube of

* Philosophical Transactions, 1869, vol. clix. p. 498.

that length and diameter: a perfect detonation was in one instance produced when this charge was used in a tube only 9 inches long; but in others, with tubes of this length and diameter, the detonation was also only partial.

Through a tube only 6 inches long detonation was accomplished by means of 108 grains (7 grms.) of fulminate; but the result was doubtful with 100 grains (6·5 grms.). It therefore appears that in order to accomplish the detonation of gun-cotton through the medium of transmission afforded by a narrow tube, at a distance of not more than 6 inches, it is necessary to use at least fifty times the quantity of fulminate, strongly confined, which is required to ensure detonation when the "detonator" is in *close contact* with the charge. This result presents a marked contrast to the fact demonstrated by the experiments described in the transmission of the detonation of gun-cotton from one mass to another, through the agency of tubes,—that the detonation of 0·5 ounce (14·2 grms.) of compressed gun-cotton will induce that of another mass of gun-cotton if separated from it by a tube, of a particular diameter and thickness, 2 feet in length, the distance which thus separates the two masses being about ninety times greater than that through which the detonation of 0·5 ounce of gun-cotton, exposed in all directions, could accomplish the explosion of another mass of the compressed material.

If, however, the quantity of confined mercuric fulminate employed as the initiative charge be increased not very considerably beyond that (154 grains=10 grms.) which is only just sufficient to detonate gun-cotton through a tube 1 inch (·025 m.) in diameter and 9 inches long, very different results are obtained. 219 grains (0·5 ounce or 14·2 grms.) of confined fulminate were employed, in the first instance, in conjunction with tubes of 1·25 inch (·031 m.) diameter and 2 feet long, and the detonation of gun-cotton inserted in the opposite extremity of the tube was accomplished; on gradually increasing the length of the tubes (of the same diameter) employed, it was found, moreover, that the above quantity of fulminate would induce the detonation, with certainty, of gun-cotton through a tube *five feet* long, in which the same quantity of *compressed gun-cotton* would only induce detonation of the same substance, under the same conditions, through a distance of *two feet* (·608 m.). The power of the fulminate to develop detonation by transmission through considerable distances was still more strikingly demonstrated. Two tubes of the same diameter (1·25 inch) and substance, one of them 5 feet (1·52 m.) and the other 1 foot (·304 m.) long, were placed on the ground end to end, so as to form a channel 6 feet (1·82 m.) long. The two ends of the tubes were brought together as closely as possible, and they were then covered with a piece of paper, over which was heaped a little sand. The confined charge of 0·5 ounce (14 grms.) of fulminate was inserted into the open end of the 1-foot tube, and a disk of gun-cotton into the far extremity of the 5-foot tube. The latter was not detonated, but shattered and partly inflamed by the detonation of the fulminate; but on employing 1 ounce (28 grms.) of fulminate and substituting a tube 2 feet (·608 m.) long for the 1-foot tube, so that the total length of the channel was 7 feet (2·1 m.), the detonation of the gun-cotton was accomplished, although the break in the channel, at the part where the two tubes were placed end to end, must undoubtedly have presented a great outlet of force transmitted, or a serious interruption of the gas-wave.

The observations made by MM. CHAMPION and PELLET, in their experiments on the effects of explosions of different quantities of iodide of nitrogen and mercuric fulminate upon series of sensitive flames, indicated that the vibrations developed by a particular explosive substance varied in character with the quantities exploded; and this appears to receive strong confirmation from the remarkable increase in the power of inducing detonation exhibited by mercuric fulminate, when the quantities detonated exceed certain limits.

On comparing with the foregoing results those obtained by reversing the relative positions of mercuric fulminate and gun-cotton, it was found that the fulminate is susceptible of detonation through considerable distances by comparatively small quantities of gun-cotton. A disk weighing 110 grains (0·25 ounce or 7·1 grms.) inserted in the extremity of a tube 5 feet (1·52 m.) long and 1·25 inch (·031 m.) in diameter, and exploded by means of a small detonating fuse, induced the detonation of the fulminate at the other extremity. The same result was obtained through a tube 7 feet (2·1 m.) long, and even when a channel of this length was constructed by placing two tubes, the one 5 feet and the other 2 feet long, end to end, in the manner already described. It was not practicable to determine the minimum quantity of gun-cotton required to induce the detonation of mercuric fulminate, because the mechanical conditions essential to detonation of the gun-cotton itself cannot be fulfilled with any degree of certainty when smaller quantities than about 100 grains (6·5 grms.) of the material are employed.

e. *Experiments with silver fulminate.*

It was considered desirable to examine into some points connected with the transmission of detonation through the agency of tubes more accurately than was possible with the employment of large metal tubes and considerable quantities of explosive materials; with this view the silver fulminate was selected for purposes of experiment, as being one of the most definite and most manageable explosive compounds of highly sensitive character. In all the experiments, the carefully prepared and dried fulminate was placed in small paper boats, which were inserted into the extremities of the tubes used; the initiative charges were exploded by means of a platinum wire, which was imbedded in the material, and was suddenly raised to a red heat by the current from a sufficiently powerful voltaic battery. It was established, in the first instance, that the explosion of 0·5 grain (·033 grm.) of the fulminate in the manner described, when freely exposed to air, induced the detonation of a corresponding quantity of exposed fulminate with certainty at a distance of 3 inches (·076 m.), but that the attainment of this result was very uncertain when the distance was increased to 4 inches (·1 m.). It was next ascertained, by repeated experiments, that the explosion of 0·6 grain (·038 grm.) of this particular batch of fulminate, inserted into one extremity of a stout (Bohemian) glass tube 3 feet 3 inches (1 metre) long and 0·44 to 0·48 inch (0·011 to 0·012 m.) in diameter, induced, with certainty, the detonation of fulminate inserted into the other extremity of the tube. The result was repeatedly, but not always, obtained by the explosion of 0·5 grain (0·33 grm.) in metre-tubes of the smaller (0·011 m.) diameter. No detonation was induced by employing 0·4 grain (·026 grm.) of this fulminate. As in the case of the larger experiments with gun-cotton &c., an increase in the diameter of the tube was found to reduce the distance at which detonation could be induced; thus 0·6 grain of fulminate exploded in one extremity of a tube 3 feet 3 inches (1 metre) long and 0·7 inch (·018 m.) in diameter did not detonate fulminate in the other extremity, while, as stated, the result was certain when the narrow tubes above described were employed under the same conditions and with portions of the same batch of fulminate. Only a slight increase of effect was obtained by confining the silver fulminate employed as the initiative agent. 0·4 grain (·026 grm.) enclosed in a copper capsule induced detonation through a metre-tube ·0126 m. (0·5 inch) in diameter, though not invariably; that quantity was therefore about on an equality with 0·5 grain (·033 grm.) of the same fulminate exploded without close confinement *.

The explosion of mercuric fulminate enclosed in a stout copper cap was found to be somewhat less effective in inducing detonation of this silver fulminate through tubes than a corresponding amount of the latter substance freely exposed. In one instance 0·5 grain (·033 grm.) of the confined mercury compound induced detonation through a metre-tube of ·0126 m. (0·5 inch) diameter, but in others detonation was only obtained when the tube was reduced to (31·5 inches) 0·8 metre; and in one experiment, although the silver fulminate was exploded, the glass tube at the seat of this explosion was only broken once across, instead of being shattered into small fragments, as in all other instances. It would therefore appear that in this experiment only a partial *detonation* of the silver compound had been developed, a result frequently obtained in the experiments on a larger scale with other explosive agents already described.

Comparative experiments were made on the power of transmitting detonation possessed by tubes of equal diameter and of as nearly the same thickness as could be obtained, but consisting of different materials. The following is a tabulated statement of the results obtained:—

* The silver fulminate, although always prepared with care by precisely the same process, was not always obtained of the same degree of sensitiveness. A particular series of experiments was therefore always made with one and the same batch of material.

TABLE I.

Nature of tube.	Dimensions. Diameter.	Thickness.	Length.	Initiative charge exploded in one extremity (*silver fulminate*).	Result.	Remarks.
	″ mm.	″ mm.	″ m.	grn. grm.		
Glass (Bohemian)	0·48=12	{0·049=1·24 / 0·058=1·47}	39 =1	0·5=0·032	Detonation induced.	The glass tubes were always shattered to small fragments to about 0·2 m. (7·9 inches) beyond the seat of the initiative detonation.
„ „	„ „	„ „	„ „	„ „	No detonation.	
„ „	0·5 =14	0·049=1·24	39 =1	0·6=0·039	Detonation induced.	Several times repeated with the same result.
„ „	0·5 =14	{0·049=1·24 / 0·058=1·47}	33 =	0·4=0·027	No detonation.	„ „ „ „
Pewter	0·5 =14	{0·042=1·07 / 0·049=1·24}	39 =1	1 =0·065	„ „	The pewter tubes were always deeply indented, but not opened up, at the seat of the initiative detonation. When detonation was induced at the opposite end, the latter was always torn open, and the metal much distended.
„	„ „	„ „	35·5=0·9	„ „	„ „	
„	„ „	„ „	„ „	„ „	Detonation.	
„	„ „	„ „	31·5=0·8	„ „	„	Several times repeated with the same result.
Pewter, bent in the centre pretty sharply at right angles.	„ „	„ „	31·5=0·8 (total length).	1 =0·065	„	Tubes of the same length, bent into different curves, were previously tried with the same result.
Brass	0·5 =14	0·042=1·24	39 =1	1 = „	No detonation.	The brass tubes were not even indented at the seat of the explosion.
„	„ „	„ „	29·6=0·75	„ „	„ „	
„	„ „	„ „	23·7=0·6	„ „	Detonation.	
Paper	0·5 =14	0·058=1·47	39 =1	1 =0·065	No detonation.	The length of the tube was gradually reduced to 0·5 m.
„	„ „	„ „	19·7=0·5	„ „	„ „	The tube was torn at the seat of detonation to the length of about 1 inch.
„	„ „	„ „	11·8=0·3	„ „	Partial detonation.	There was an explosion, but with comparatively little destructive effect.
Vulcanized india-rubber.	„ „	0·058=1·47	39 =1	1 =0·065	No detonation.	The india-rubber was not torn in any one instance at the seat of the initiative explosion.
„ „	„ „	„ „	19·7=0·5	„ „	„ „	
„ „	„ „	„ „	15·8=0·4	„ „	Detonation.	

The following points are indicated by the foregoing tabulated results:—

(1) Detonation was transmitted through glass tubes with very much greater facility than through tubes, of corresponding diameter and thickness, of any of the other materials tried. Employing nearly double the quantity of silver fulminate required to induce detonation with certainty through the glass tubes, it was only possible to obtain a similar result through a pewter tube 0·8 m. (31·5 inches) long, a brass tube 0·6 m. (23·7 inches) long, an india-rubber tube 0·4 m. (15·8 inches) long, and a paper tube 0·3 m. (11·8 inches) long.

(2) The difference in the results obtained was not ascribable to a difference in the escape of force on the instant of explosion at the seat of the initiative detonation, in consequence of the fracture of the tube, nor to the expenditure of force in work done upon the tube at that point, since the glass tubes were always destroyed by the first explosion to a very much greater extent than any of the others; and the brass tube, which was in no way injured at the seat of the explosion, did not transmit detonation to so great a distance as the pewter tubes, which were always deeply indented.

(3) The transmission of detonation would not appear to have been favoured by the sonorosity, or the pitch, of the tube employed, as the sonorous brass tube was not found to favour transmission of the detonation to the same extent as the pewter tube. This was corroborated by some special experiments with glass tubes, of the same dimensions as those described in the Table. A coating consisting of two layers of bibulous paper was firmly attached throughout by means of gum to the exterior of one of the metre-tubes; but the same result was obtained with it by the explosion of silver fulminate as with the uncoated tube. Another tube had pieces of tightly fitting india-rubber tubing placed upon the outside, until its sonorosity was reduced to a very low pitch; but, when used in this condition, it transmitted the detonation, developed by 0·6 grain of fulminate, as readily as the naked tubes.

The principal if not the only cause of the great difference exhibited, in power of transmitting detonation, by these tubes composed of different materials appears to have been satisfactorily demonstrated by some experiments which will be presently described.

II.—INTERFERENCE WITH THE TRANSMISSION OF DETONATION BY TUBES.

Attempts have been made by me, and with some success, to demonstrate by experiment that when the limit of distance has been reached to which a tube of a particular diameter will transmit the force developed by a detonation, of a particular kind or magnitude, with sufficient completeness to induce detonation at the most distant part of the channel, the interposition of impediments in the path of the gas-wave, so slight as to be apparently incapable of opposing the transmission of force to any important extent, will effectually interfere with the development of detonation. Some examples of the experiments instituted in this direction, in which mercuric fulminate and silver fulminate were employed to produce the initiative detonation, are given in Table II. (p. 354).

The quoted experiments with iron tubes demonstrated that the interposition of a small loose plug of tow, or, better still, of finely carded cotton-wool, between the initiative detonation and the charge of explosive substance inserted into the opposite end of the tube will protect the latter from detonation under circumstances which, in the absence of the plug of loose material, just fulfil the conditions essential to detonation. The violence of the concussion or blow sustained by the substance while exposed to the action of the detonation, before motion is imparted to the entire mass by the rush of gas, is strikingly demonstrated by the following circumstance. The crystals of mercuric fulminate, which were *quite loosely* confined in thin paper, were found to be more or less completely crushed or pulverized on recovering the small packets (which were not exploded, but only projected to a considerable distance), when the tuft of wool had been interposed between them and the detonation produced at the other extremity of the tube.

In witnessing these experiments it was difficult to realize that the slight resistance

Table II.

No. of experiment.	Description of tube used.		Initiative detonator inserted into one extremity.	Explosive material inserted into the other extremity.	Obstacle interposed in the path of the gas-wave.	Result.
	Wrought-iron gas-pipe.					
	Length.	Diameter.				
1.	1 foot = ·3 m.	1″·25 = ·026 m.	5 grns. (·32 grm.) of mercuric fulminate confined in case of sheet-tin.	Mercuric fulminate, loosely wrapped in thin paper.	None	Detonation *induced*; tube shattered.
2.	„ „	„ „	„ „ „	„ „ „	None	Explosion of the loose fulminate, but no destructive effect upon the tube.
3.	„ „	„ „	„ „ „	„ „ „	A small plug of tow, sufficient to completely prevent the passage of light through the tube.	The loose fulminate was simply inflamed.
4.	„ „	„ „	„ „ „	„ „ „	„ „ „	The same as in preceding experiment.
5.	„ „	„ „	„ „ „	„ „ „	A thinner plug of tow admitting the passage of light in several places.	Detonation induced.
6.	5 feet = 1·5 m.	1″ = ·025 m.	25 grns. (1·6 grm.) „	„ „ „	None	Detonation, but apparently only partial; destructive effect not great.
7.	„ „	„ „	„ „ „	„ „ „	Plug of finely carded cotton-wool sufficient to prevent passage of light.	No inflammation. The small package of fulminate was projected to a considerable distance, and the *loosely* confined crystals were pulverized by the force of the initiative detonation.
8.	„ „	„ „	„ „ „ (the detonator inserted to a distance of 6 inches into the end of the tube, which had been cracked in the previous experiment).	„ „ „	Small plug of carded cotton-wool	Same as above.
9.	{2 ft. 6 in.} = ·77 m.	1″·25 = ·026 m.	15·5 grns. (1 grm.) mercuric fulminate, confined as usual, inserted into one extremity of tube.	„ „ „	None	Detonation, but apparently only partial; very little destructive effect. Experiment repeated, with the same result.
10.	„ „	„ „	„ „ „	„ „ „	Small plug of carded cotton-wool	No inflammation. The crystals of fulminate were crushed to powder. Experiment repeated, with the same result; in a third similar experiment the same result was produced as without the plug of cotton.
11.	6 in. = ·15 m.	1″ = ·025 m.	108 grns. (7 grms.) „	Disk of compressed gun-cotton.	None	Detonation induced.
12.	„ „	„ „	„ „ „	„ „ „	Plug of carded cotton-wool inserted so as to obstruct the passage of light.	The gun-cotton was dispersed.
	Bohemian glass.					
13.	39 in. = 1 m.	{0″·44 = 0·011 m. 0″·48 = 0·012 m.}	0·5 grn. (0·032 grm.) of silver fulminate placed in an open paper boat, exploded by heated platinum wire.	0·5 grn. (0·032 grm.) of the same silver fulminate in open paper boat.	None	Detonation induced, but not invariably, in repetitions of the experiments with corresponding quantities of the same fulminate.
14.	„ „	„ „	0·6 grn. (0·039 grm.) of the same fulminate applied in the same way.	„ „ „	None	Detonation induced, and the experiment several times repeated with the same result.
15.	39″ = 1 m.	0″·44 = 0·011 m.	0·6 grn. (0·039 grm.) „	„ „ „	A diaphragm of thin bibulous paper inserted into the tube halfway between the two charges of fulminate.	No detonation induced. The fulminate in the far extremity of the tube was blown away, and the paper diaphragm was torn in several pieces, which were projected to a distance of 0·2 m. along the tube.
16.	„ „	„ „	1 grn. (0·065 grm.) „	„ „ „	„ „ „ „	No detonation. The fragments of the diaphragm were projected further towards the distant opening of the tube.
17.	„ „	„ „	1·5 grn. (0·097 grm.) „	„ „ „	„ „ „ „	No detonation. The diaphragm was very much broken up.
18.	„ „	„ „	2 grns. (0·13 grm.) „	„ „ „	„ „ „ „	No detonation. A very considerable length of the tube was shattered by the initiative charge.
19.	„ „	„ „	3 grns. (0·195 grm.) „	„ „ „	„ „ „ „	In this instance the tube was shattered by the initiative detonation to a length of about 0·6 m., and therefore beyond the seat of the paper diaphragm.
20.	„ „	„ „	0·6 grn. (0·039 grm.) of a different batch of silver fulminate applied in the same way.	„ „ „	None	No detonation. This fulminate was decidedly less sensitive than that used in the preceding experiments.
21.	„ „	„ „	0·7 grn. (0·045 grm.) of this fulminate „ „	„ „ „	None	Detonation.
22.	„ „	„ „	0·6 grn. (0·039 grm.) „	„ „ „	No diaphragm, but the interior surface of the tube was coated throughout with a thin lining of French chalk, which was made to adhere to the glass by means of thin gum-mucilage.	No detonation; the looser portions of the French chalk lining were blown out of the tube.
23.	31″·2 = 0·8 m. (same tube as in experiment 22).	„ „	1 grn. (0·065 grm.) „	„ „ „		No detonation; further portions of French chalk were blown out of the tube.
24.	19″·5 = 0·5 m. (same tube as in experiment 23).	„ „	0·6 grn. (0·039 grm.) „	„ „ „		No detonation.
25.	14″ = 0·36 m. (same tube as in experiment 24).	„ „	0·6 grn. (0·039 grm.) „	„ „ „		No detonation.

which the very light tuft of wool opposes to the transmission of force through the tube could modify its action to the extent described; the experiments with silver fulminate detailed in Table II. appear, however, to demonstrate conclusively that a slight retardation of the velocity of the gas-wave, or the expenditure of force in overcoming what appears to be only minute obstacles to the unimpeded transmission of the wave, suffices to interfere most materially with the transmission of detonation.

The interposition of a loosely fitting diaphragm of thin unsized paper between the "detonator" of silver fulminate and a charge of that substance inserted into the other extremity of a glass tube of a particular diameter and 1 metre long, prevented the transmission of detonation through the tube of that length until the quantity of fulminate employed as the initiative "detonator" was about five times that required, of the same fulminate, to transmit detonation under the same conditions, but with omission of the paper diaphragm. But it is not only by such an expenditure of force as is involved in overcoming the resistance which the latter opposes to the free passage of the gas-wave that the transmission of detonation is greatly impeded; the retardation in velocity which the gas-column may sustain in consequence of the friction established between it and particles of a fine powder attached to the sides of the glass tube will also greatly reduce the distance through which detonation of any given description and magnitude will be transmitted. In experiment 22 (in the foregoing Table) much of the French chalk, which was loosely attached to the interior of the tube, was carried away by the rush of gas; and a similar result, though to a diminished extent, was observed in experiments 23 and 24: yet the roughness of the interior surface of the tube was still sufficient, in experiment 25, to prevent the detonation of 0·6 grain (0·039 grm.) of silver fulminate from detonating the fulminate in the opposite extremity of the tube only 14 inches (0·36 metre) long; while a corresponding amount of the same batch of fulminate induced detonation through a glass tube of the same diameter, 35 inches (0·9 metre) long, presenting the usual smooth inner surface.

Discrepancies which were not unfrequently observed in results obtained with wrought-iron tubes in the experiments upon a larger scale with mercuric fulminate and with gun-cotton, were now clearly traceable to differences in the degree of roughness of the inner surface of the tubes, and to the consequent variation in the resistance opposed by those surfaces to the passage of the gas-wave. Moreover, the above results obtained with the glass tube coated inside with powder suggested some experiments which clearly demonstrated that the great difference observed (as shown in Table I.) in the transmission of detonation by tubes consisting of different materials was, at any rate chiefly, ascribable to the resistance which the inner surfaces of those tubes opposed to the free rush of gas through them. A paper tube was constructed of the same dimensions and thickness as those employed in the preceding experiments, but the inner surface consisted of glazed paper instead of ordinary brown paper. The interior of this tube was not uniformly smooth throughout like the ordinary glass tubes used; but still it presented a marked difference to the paper tubes with rough interior used in the first instance, as regards the readiness with which it transmitted detonation. One grain (·065 grm.) of the fulminate, when detonated in one extremity of the tube 0·9 metre (35 inches) long, induced the detonation of fulminate in the other extremity; whereas a similar result was only obtained with paper tubes 0·3 metre (12 inches) long, the interior surfaces being composed of the comparatively rough brown paper. Again, a piece of brass tube, of the same description as that employed in the preceding experiments, the inner surface being dull and somewhat rough, was brightly polished inside. In this condition the tube transmitted detonation, developed by 1 grain (·065 grm.) of silver fulminate, through a length of 36 inches (0·93 metre); whereas in the original condition, with the somewhat rough interior, it only transmitted the detonation developed by 1 grain (·065 grm.) of the same batch of fulminate, with certainty, through a length of 19 inches (0·5 metre).

The tubes of paper and of brass may therefore be considered to have been placed nearly on an equality with glass tubes of the same dimensions, as regards their power of transmitting detonation, by employing them with smooth interior surfaces. It may not be impossible that the slight superiority of the glass tubes in their power of transmitting detonation may still have been entirely due to the establishment of less friction between their inner surfaces and the gas-wave.

The surfaces of the pewter tubes approached in smoothness those of the glass tubes; and it will be seen (by reference to Table I.) that these tubes did not differ from each other considerably as regards the facility with which detonation was transmitted through them. Several attempts were made to impart a smooth interior to the india-rubber tubes by coating them with varnishes of considerable body; no very satisfactory result was obtained; but the smoothest of the varnished tubes afforded decided indications that the transmission of detonation was favoured, though only to a comparatively slight extent, by the diminution in roughness of the interior. In some experiments one extremity of the tubes was lined with sheet copper just at the seat of the initiative detonation, but the results were not at all affected thereby. The conclusion appears warranted, that with india-rubber tubes the effect of the detonation upon the *material* composing the tube operates in a manner decidedly antagonistic to the transmission of detonation: one cause of this is, no doubt, the comparative readiness with which the *sides* of the tubes yield to the pressure of the gas-wave, and the consequent considerable lateral expenditure of force. The particles of the tube appeared themselves to be set in violent and irregular motion by the explosion; the tubes were always thrown into contortions, and violently jerked out of position, by the initiative detonation *; while with tubes of other materials only those portions were projected which were actually destroyed by the explosions, the tube itself remaining undisturbed.

* In some of the experiments these tubes were strongly attached to boards by means of strappings of wire placed at short intervals; but the results were not affected thereby.

III.—CONCLUSIONS REGARDING THE TRANSMISSION OF DETONATION BY TUBES.

The results which have been described on the transmission of detonation by tubes appear to have established the following points:—

1. The distance to which detonation may be transmitted through the agency of a tube to a distinct mass of explosive substance is regulated by the following conditions:—

(*a*) By the nature and the quantity of the substance employed as the initiative detonator, and by the nature of the substance to be detonated, but not by the quantity of the latter, nor by the mechanical condition in which it is exposed to the action of the detonation.

(*b*) By the relation which the *diameter* of the "detonator," and of the charge to be detonated bear to the diameter of the tube employed.

(*c*) By the strength of the material composing the tube, and the consequent resistance which it offers to the lateral transmission of the force developed at the instant that detonation is produced. This condition does not appear to affect appreciably the results produced by detonation on a small scale, but its influence becomes apparent in larger operations.

(*d*) By the degree of roughness of the tube employed for transmitting detonation, or, in other words, by the amount of resistance opposed to the gas-wave and the amount of force consequently expended in overcoming the friction between the gas and the sides of the tube, or other impediments introduced into the latter.

(*e*) By the degree of completeness of the channel, and by the positions assigned to the "detonator" and the charge to be detonated. It need scarcely be pointed out that if the tube be fissured, or much enlarged either at the seat of detonation or at any other part (*e. g.* if injured by the effects of a previous detonation), or if even a very slight break in continuity exists in the tube, the extent to which force is transmitted must be proportionately diminished. It is also obvious that if the detonator, or the charge to be detonated, be placed against the opening of the tube instead of being inserted into the extremity, the conditions are comparatively unfavourable to the development of detonation by transmission; on the other hand, if the detonator be introduced some distance into the tube instead of being simply inserted into one opening, the loss of force by lateral dispersion is considerably reduced, if not altogether obviated, and the gas-wave consequently retains detonative power at an increased distance from the starting-point.

2. The nature (apart from strength or power to resist opening up or disintegration) of the material composing the tube through which detonation is transmitted generally appears to exert no important influence upon the result obtained, so far as could be determined by the experiments described. At any rate the effects produced by differences with respect to smoothness of the interior of the tubes far outweigh those which may prove to be traceable to differences in the nature of material of which the tubes consist.

3. The results furnished by mercuric fulminate, when applied to the detonation of gun-cotton through tubes, showed that the effects produced by the detonation of a particular substance upon other explosive bodies may vary very importantly with the quantity of material detonated. Thus, when mercuric fulminate was employed in as large a quantity as 10 grms., it did not detonate gun-cotton with certainty through a tube ·225 m. (9 inches) long and ·025 m. (1 inch) in diameter, and 7 grms. were required to develop detonation through a tube ·15 m. (6 inches) long; but double that quantity (14 grms. = 0·5 ounce) transmitted detonation to gun-cotton through a tube 1·52 m. (60 inches) long. The latter result (*i. e.* when an initiative detonation of sufficient magnitude was developed) demonstrated that gun-cotton is much more susceptible of detonation at a distance, through the medium of a tube, by mercuric fulminate than by gun-cotton itself, as 14 grms. of the latter would only have developed the detonation of gun-cotton through about one fifth the distance under the same conditions; but when the detonation of *smaller* quantities of fulminate was applied, the result was reversed, the sensitiveness of gun-cotton to detonation by the fulminate being diminished to a remarkable extent. Thus the amount of the latter required to transmit detonation through a tube ·31 m. (12 inches) long was more than two thirds the quantity required for transmission of detonation to gun-cotton five times that distance, and about eighty times the quantity required to develop detonation when applied in close contact with the gun-cotton.

4. The experiments with gun-cotton and mercuric fulminate furnished, moreover, another instance, analogous to that of nitroglycerine and gun-cotton, of a want of reciprocity in the sensitiveness of two explosive agents to the concussions or vibrations which they develop. 10 grms. of the fulminate would not always develop detonation of gun-cotton through a tube ·31 m. (12 inches) long and ·025 m. (1 inch) in diameter, and 14 grms. were required to induce detonation through a distance of 5 feet; while 7 grms. of gun-cotton amply sufficed to develop the detonation of fulminate through a tube of the same diameter but 2·1 m. (7 feet) long, and having moreover a complete break in its continuity. Both nitroglycerine and mercuric fulminate are therefore far more susceptible of detonation by gun-cotton than the latter is prone to detonation by the vibrations which they develop.

5. When the conditions essential to the transmission of detonation are only on the verge of being fulfilled, or when some slight accidental impediment has arisen, a result is frequently produced which is intermediate between the sudden explosion distinguished as detonation, and simple mechanical disintegration and dispersion of the material (accompanied occasionally by inflammation of the particles).

IV.—DEVELOPMENT OF DETONATION, AS DISTINGUISHED FROM EXPLOSION.

In the preceding experiments many instances occurred in which the mass of gun-cotton operated upon was exploded with comparatively little destructive effect, portions being at the same time dispersed and occasionally inflamed. Similarly, the mercuric fulminate, which was exposed to the concussion of a distant detonation transmitted through a tube, was frequently exploded in a manner quite distinct from the violent detonation developed in other instances. It has even occurred that the silver fulminate, which under all ordinary conditions detonates violently even when only one particle of a mass is subjected to a sufficient disturbing influence, has been exploded without the usual development of force by the transmitted effect of a detonation of mercuric fulminate; that is, the extremity of the glass tube into which a particular quantity of the silver compound has been inserted was simply broken once across, the paper boat in which the fulminate rested being only partly destroyed, instead of their being reduced to small fragments, as was usually the case with the same quantity of the substance.

In all these instances the violence of the concussion transmitted was obviously only just bordering upon that required for the development of detonation; and it appears most probable that only some small proportion of the mass of fulminate or gun-cotton was in a condition or position favourable to the operation of the explosive force transmitted through the tube. The remainder of the mass would then be dispersed by the gases developed from the detonated portion; in some instances the particles would be inflamed at the moment of their dispersion, in others they would even escape ignition. The latter appears to be always the case when gun-cotton is exploded by a blow from a hammer or falling weight. However carefully the arrangements are adjusted with a view to distribute such a blow uniformly over the entire mass struck, the concentration of a preponderance of the force applied upon some portion or portions of the entire mass appears almost inevitable; hence only a small proportion is actually detonated, the remainder being instantaneously dispersed by the gases suddenly generated while the weight is resting upon the support. This was well illustrated by the results of some very carefully conducted experiments, in which cylindrical masses of compressed gun-cotton, all of the same dimensions and density (1 inch diameter and 1 inch thick), were placed on and between two smooth brass plates upon a flat anvil, adjusted in a level position, and were submitted in that position to the blow of a falling weight (of 50 lb.), the striking surface of which was properly levelled and maintained in its adjusted position during the descent of the weight by means of guides. The small cylinder of gun-cotton (which had been originally produced by submitting the pulped material to a pressure of four tons on the square inch) was reduced to one third its original length by the fall of the weight from a height of 3 feet, but no detonation was produced; with a four-foot fall of the weight on another cylinder, a slight detonation was produced, but the principal portion of the gun-cotton was scattered; the results were quite similar in further experiments, in which the height of fall of the weight was raised by increments of 1 foot to 10 feet: the detonations were somewhat sharper when the weight fell from 12 feet and upwards; but in every instance, even when the weight was allowed to fall from the maximum available height (39 feet), only a small proportion of the gun-cotton was detonated, the remainder being violently dispersed in a finely divided condition. Similar results were obtained in operating upon small slabs of gun-cotton ·0025 metre (0·1 inch) thick and ·025 m. (1 inch) square, which were placed between smooth and level bronze plates, and subjected to blows from a falling weight.

In some experiments made with the object of investigating, from a new direction, the action of a blow in producing explosion, some slabs and disks of compressed gun-cotton of different weights and thicknesses were fired at from a Martini-Henry rifle at distances ranging from 120 to 300 feet. In these experiments the impact of the bullet determined, in a few instances, the complete explosion of the mass; but in others, when circumstances combined to diminish the detonative power of the blow, a comparatively slight explosion was produced, and the greater portion of the mass fired at was violently scattered in small particles, which sometimes were inflamed. The complete or partial explosion of the mass of compressed gun-cotton was effected either when the thickness of the mass which was freely suspended in air was sufficient to cause it to oppose more or less effectual resistance to the penetrative power of the rifle-bullet, or when the slab of gun-cotton fired at rested closely against an iron plate. In the one case, the particles of gun-cotton actually struck by the projectile were effectually prevented from yielding to motion or mechanical dispersion at the *moment* of impact, by the support which the considerable surrounding mass of gun-cotton afforded them; in the other instance, the rigid iron support, or backing, of the thinner masses of gun-cotton operated in a similar way in causing the effects of the blow to be concentrated upon, or confined to, the portions of gun-cotton actually struck by the bullet. Hence the effect of its impact was in both instances quite similar to that of a blow from a hammer applied to some portion of a piece of compressed gun-cotton placed upon an anvil; the particles struck by the hammer are prevented from taking up the motion of the striking body by the rigid support or anvil; chemical disintegration or explosion consequently takes place instead of mechanical dispersion, which would occur if less resistance were afforded to the motion of the hammer or projectile. At the instant of explosion the particles of matter which are undergoing transformation are confined between the striking body and the support (whether the latter be of metal or of gun-cotton); the resulting gas suddenly generated therefore escapes under great pressure, and scatters the contiguous particles of gun-cotton, sometimes even before these, or any large proportion of them, can become inflamed. In rare instances, as above stated, the explosion of the entire mass of gun-cotton followed upon the impact of the bullet; such an explosion did not, however, give rise to the sudden development of force (and consequent destructive effects) obtained by the *detonation* of similar or even much smaller quantities of gun-cotton, as was demonstrated by placing the masses fired at upon iron plates, which remained uninjured, but would have been indented or fractured had the gun-cotton been detonated in the usual way when in contact with them. These comparatively feeble but complete explosions of the gun-cotton masses were most probably due to some very exceptional peculiarities in the physical condition of the disks or slabs, which favoured the transmission of ignition from the point where explosion was produced by the blow to the whole of the surrounding portions of gun-cotton at the instant when they were undergoing dispersion. The resulting transformation of the solid into gas, though sufficiently rapid to produce the oral effect of an explosion, must be very gradual as compared to that which attends a detonation, and the destructive effects exerted must in consequence be comparatively unimportant*.

The manner in which resistance to mechanical motion favours the chemical disintegration or explosion of the portions of a compact mass of gun-cotton which is subjected to a blow, as from the impact of a bullet, was conclusively demonstrated by a series of experiments with gun-cotton disks of the same density and diameter, but differing in thickness, and therefore in weight. These disks had strings fastened round their circumference by which they were freely suspended; they were fired at from a Martini-Henry rifle with hardened lead bullets, the marksman being stationed at a distance of 100 yards from the gun-cotton which served as a target. Disks which weighed 4 ounces and 8 ounces were perforated by the bullet, not a particle of the gun-cotton being even ignited, and these results were repeatedly obtained. Disks weighing 12 ounces were inflamed when struck by the bullet, but not exploded; whilst disks weighing 16 ounces, fired at under the same conditions, were exploded, portions being, in some instances, dispersed in a burning state. The resistance opposed to the flight of the bullet, even by the 8-ounce disks, was insufficient to cause such retardation of the projectile during its penetration of the mass as to develop sufficient heat to inflame the gun-cotton; with the 12-ounce disk the resistance to motion offered by the particles in the bullet sufficed, during the penetration of the mass, to develop the heat necessary for its ignition; while the penetration of the bullet was opposed by the mass of the 16-ounce disk to a sufficient extent to cause the operation of the force conveyed by the projectile to be concentrated, at the instant of impact, upon the particles immediately in front of it, which therefore were suddenly transformed into gas or exploded.

By attaching a piece of soft wood, 0·4 inch thick, to one of the faces of a disk weighing 8 ounces, which was suspended as in the former experiments, the surface being fired at from a distance of 100 yards, the flight of the bullet was so far retarded by the resistance which the wood opposed in the first instance, that its subsequent penetration of the gun-cotton was effected comparatively slowly, and the heat developed by the further retardation of the bullet inflamed the gun-cotton, while in former experiments with unprotected disks of the same size these were perforated without any instance of ignition.

Wooden boxes containing compressed gun-cotton, both loosely and closely packed, have been repeatedly fired at from rifles; generally the contents of the box were inflamed, but in no instance was an explosion produced. Similar packages containing

* An interesting confirmation of this difference between explosion and detonation was obtained in subsequent experiments made with the view of determining the rate at which detonation is transmitted through tubes, which are described in the concluding portion of this Memoir.

dynamite or other nitroglycerine preparations were always violently exploded by being fired at, nitroglycerine being much more readily susceptible of detonation by a blow.

V.—INFLUENCE OF DILUTION, BY SOLIDS AND BY LIQUIDS, ON THE SUSCEPTIBILITY OF EXPLOSIVE COMPOUNDS TO DETONATION.

It has been pointed out in my former memoir (p. 513) that solid explosive mixtures, consisting of one or more readily oxidizable substances intimately incorporated with an oxidizing agent, are less readily susceptible of detonation than explosive compounds, and that the readiness with which their violent explosion can be developed through the agency of an initiative detonation is in direct proportion to their sensitiveness to explosion by percussion. Mixtures consisting of a powerful oxidizing agent (*e. g.* potassium chlorate) and a substance which is *per se* already endowed with explosive properties approach (if they are not quite equal) to gun-cotton and even to nitroglycerine, in the readiness with which their detonation may be effected; thus an intimate mixture of potassium picrate and potassium chlorate, in which the latter salt exists in the proportion required for the perfect oxidation of the former, may under favourable conditions be detonated by means of almost as small an amount of mercuric fulminate as the minimum required to detonate compressed gun-cotton*.

a. *Dilution with inert solids and with solid oxidizing agents.*

The extent to which the susceptibility to detonation of the more violent explosive compounds is affected by their intimate mixture with non-explosive substances is regulated partly by the physical or mechanical condition of the substance, and partly by the nature of the material with which it is mixed. Nitroglycerine may be very largely diluted by admixture with perfectly inert solid materials without diminution of its sensitiveness to detonation. Thus the preparation to which its inventor, A. NOBEL, gave the name of *dynamite*, and which consists of nitroglycerine diluted with about one third its weight of the very bulky infusorial silica known as "Kieselguhr," whereby it is converted into a plastic material, requires no more powerful initiative explosion to ensure its detonation than the undiluted liquid: other preparations of similar nature, based upon NOBEL'S original idea of employing solid materials as media for the convenient application of nitroglycerine (and of which some contain not more than 20 per cent. of the explosive liquid), are not less sensitive to detonation. This is obviously due to the liquid nature of nitroglycerine, which permits of its being highly diluted with solid material, without isolation of different portions of the explosive by inert or much less explosive material. In the most diluted mixtures of this kind, provided they are not very carelessly prepared, each particle of the diluent is coated with a film of nitroglycerine, so that there is no break in continuity of the explosive agent in the

* ABEL "On Explosive Agents," Phil. Trans. 1869, vol. clix. p. 513. Very interesting results have also been attained in a similar direction by Dr. SPRENGEL (*vide* Journal of Chemical Society, 1873).

mixture; hence when the initiative detonator is surrounded by such a mass it is in contact at all points with some portion of the nitroglycerine, and the latter is in continuous connexion throughout; detonation is consequently as readily established and transmitted through the mass as though it consisted entirely of nitroglycerine.

The case is different when a *solid* explosive compound is diluted with solid inert material. In an intimate mixture of the finely divided substances there must obviously be complete separation of the particles of the explosive at a number of points proportionate to the extent of dilution and to the state of division; a condition of things may therefore arise, within comparatively narrow limits, when the establishment or transmission of detonation is impeded, either by a diminution of the extent of contact between the exploding substance itself and the initiative detonator, or by the barrier which the interposed non-explosive particles oppose to the transmission of detonation, or by both causes. In some experiments made with intimate mixtures of mercuric fulminate and French chalk (selected for the purpose as being a bulky material), it was found impossible to detonate mixtures containing more than one fifth part by weight of the diluent by means of one grain (·065 grm.) of mercuric fulminate confined in a copper capsule and exploded in close contact with the mixtures; that quantity, similarly confined, sufficed to detonate undiluted fulminate through a tube 8 inches (·2 m.) long and 0·5 inch (·013 m.) in diameter. A mixture of four parts of fulminate and one of French chalk was exploded, without destructive effect, by the grain of confined fulminate fired in contact with it; when the diluent was reduced to one eleventh, the mixture detonated under these conditions, and it was also found to be detonated through a pewter tube 8 inches (·2 m.) long, like the undiluted fulminate. In this mixture the fulminate particles were no longer sufficiently separated to effect their ready detonation.

If an intimate mixture of finely divided particles of sensitive solid explosive compound and an inert solid diluent be compressed into compact masses, the mixture is considerably more susceptible of detonation than if it were in the loose condition; in this respect it resembles the undiluted material; indeed, so far as has been ascertained by experiments with gun-cotton, dilution may under these conditions be carried to a considerable extent, with little reduction in the sensitiveness of the material to detonation, provided the diluent consists partly or entirely of a soluble salt, as will be presently shown.

Intimate mixtures of finely divided gun-cotton with *solid oxidizing agents*, converted into compact and very homogeneous masses by compression while wet and subsequent desiccation, furnished interesting results when compared with pure compressed gun-cotton in regard to their susceptibility to detonation. Pure trinitrocellulose requires for the complete oxidation of its carbon the provision of 24·24 of oxygen for every hundred parts, in addition to that which its composition includes. This proportion of oxygen would be furnished by the admixture with that compound of 61·2 parts of potassium nitrate, 51·5 parts of sodium nitrate, or 61·8 parts of potassium chlorate. Gun-cotton, when prepared with the greatest care upon a manufacturing scale according to the system now practised, contains not less than seven per cent. of lower nitro-compounds, so that even somewhat larger proportions than those specified of the above named salts would be required to completely burn the oxidizable elements. In order, therefore, to obtain the maximum amount of work from a given quantity of gun-cotton, that substance should be supplied with the additional oxygen capable of being furnished by even somewhat higher proportions than those named of the well-known oxidizing salts. Gun-cotton thus largely diluted with saline matter presents the form of very hard masses of uniform structure, with no tendency to lamination, if the salt is intimately incorporated with the finely divided or pulped fibre, and converted by powerful compression, with the aid of a saturated solution of the particular salt used, into masses of cylindrical or other forms, which are afterwards dried.

A careful comparison of the susceptibility to detonation of these compressed mixtures of gun-cotton and oxidizing salts, with that of simple compressed gun-cotton, has shown them to be on an equality with the latter in this respect. Detonators containing only 1 grain (·065 grm.) of mercuric fulminate, when inserted so as to fit tightly into perforations in cylinders consisting of ordinary gun-cotton and of the mixtures above described, never developed detonation by their explosion; the compressed masses were scattered; in the case of the simple gun-cotton ignition sometimes occurred, and always when the potassium-chlorate mixtures were tried; no instance of ignition occurred with cylinders of the "nitrate" mixtures. When detonators containing 2 grains (·13 grm.) of fulminate were employed in the same way, not only the pure gun-cotton cylinders, but also those consisting of the "nitrate" and "chlorate" mixtures were invariably detonated.

To compare with the foregoing results, some compressed cylinders, quite similar in density and hardness to those of the "nitrate" and "chlorate" mixtures, were prepared by substituting an inert salt (potassium *chloride*) for the other salts in corresponding proportions. The detonation of these could not be accomplished by means of detonators containing 2 grains of mercuric fulminate, which sufficed in the preceding experiments; but they were exploded with certainty by means of 3 grains (·192 grm.) of the fulminate.

The conclusions deduced from these results are as follows:—

1. Gun-cotton may be largely diluted with a non-explosive and perfectly inert solid substance with but little diminution of its sensitiveness, provided the mixture is in the mechanical condition most favourable to its detonation. If the explosive compound is thoroughly incorporated with a soluble salt, the mixture being then compressed into compact masses with the aid of the solvent (water) and dried, the material is obtained in a condition of greater rigidity, and therefore in a form more readily susceptible to the detonating effect of a small charge of fulminate, than can be attained by submitting the undiluted gun-cotton to considerable greater compression, because the crystallization of the salt, upon evaporation of the solvent, cements the particles composing the mass most intimately together. Hence the reduction in sensitiveness, due to the dilution of the explosive compound, is nearly counterbalanced by the greater rigidity imparted to the mass.

2. When the solid substance with which gun-cotton is diluted consists of an oxidizing agent, the predisposition to chemical reaction between the two substances so far increases the susceptibility to detonation that, operating in conjunction with the effect of the soluble salt in imparting rigidity to the mixture, it renders the latter quite as sensitive to the detonating action of the minimum fulminate-charge as undiluted gun-cotton is when in a highly compressed condition. Some indication that the most powerful oxidizing agent furnishes, under these conditions, the material most susceptible of explosion was afforded by the circumstance that the fuses containing only one grain of fulminate invariably inflamed fragments of the "chlorate" cylinders by their explosion, while the "nitrate" cylinders were always scattered without ignition*.

* Soon after the discovery of gun-cotton, attempts were made to increase the explosive force of that substance by impregnating it with solid oxidizing agents, such as potassium nitrate; but the quantity of the salt which could be introduced into preparations of gun-cotton by the only practical mode of treatment (namely, by impregnating these with a saturated solution and evaporating the water) was too small to render such treatment of any decisive practical value. The system of reducing gun-cotton to a fine state of division has afforded the means of readily incorporating this substance with the somewhat large proportion of saltpetre or analogous source of oxygen required for fully oxidizing the whole of the carbon in trinitrocellulose, and I have been successful in obtaining results of considerable practical importance in this direction. The general mode of producing "nitrate" or "chlorate" preparations of gun-cotton is as follows:—The requisite proportion of oxidizing agent, reduced to a very fine powder, is intimately mixed with the finely divided gun-cotton, with the aid of a saturated solution of the particular salt employed, and the mixture is granulated or compressed into any desired form by the usual pressure. Care is taken to make due allowance for the fluctuations in the amount of salt held dissolved by the water, consequent upon any change of temperature in the latter during the manufacturing operation, as well as for the extra amount of salt which will be deposited in the product by the evaporation of the solution left in it after the pressing or granulating. The products obtained in this way, especially when compressed, form very hard masses, which are much less liable to break up or dust when roughly handled than ordinary compressed gun-cotton. The gradual evaporation of the water from them during the drying process causes part of the salt to crystallize throughout the mass, and thus the particles composing it become so firmly cemented together, that the application of considerably less pressure than is required to produce very compact cakes of gun-cotton suffices to furnish masses decidedly superior in hardness and compactness. The cakes or granules, when dry, are found to have become coated with a hard film of the salt, which acts as an additional protective against mechanical injury, and also renders them less readily inflammable than simple compressed gun-cotton. It has been, moreover, conclusively demonstrated, by several experiments continued for considerable periods, that these preparations sustain continuous exposure to elevated temperatures without appreciable development of chemical change for much longer periods than the undiluted gun-cotton; the distribution of saline matter throughout the mass operates protectively by impeding the transmission and consequent further development of any minute change established by protracted exposure to heat in some particle of the mass of gun-cotton, which, however carefully prepared, cannot be absolutely uniform throughout in point of purity.

Although the attainment of the maximum work from a *given weight* of gun-cotton demands the supply of oxygen sufficient for the complete oxidation of the carbon, and although, therefore, the products obtained by incorporating gun-cotton with the full theoretical requirement of a chlorate or nitrate will develop considerably more explosive force than an equal weight of the simple gun-cotton, the most advantageous results are obtained, in actual practice, by employing somewhat less than the full theoretical proportions of the oxidizing agent.

Comparing the explosive action of *equal weights* of compressed gun-cotton and of the "nitrate" mixture prepared with the full proportion of the oxidizing agent (in which, therefore, about 38 per cent. of gun-cotton is

The identity in behaviour of the "nitrated" and "chlorated" preparations of gun-cotton, and of the ordinary material, when subjected to the detonative effect of mercuric fulminate, rendered it interesting to compare the behaviour of these materials when in contact with exploding nitroglycerine. Equal quantities of the several preparations (4 oz.) were employed in all these experiments. The disks (3 inches in diameter) were placed upon wrought-iron plates, all of equal dimensions and resting upon a firm anvil hollow in the centre. The nitroglycerine was contained in glass beakers which were placed upon the disks, and the detonating fuse was immersed in the centre of the nitroglycerine. The development of detonation was recorded by the indentation and cracking of the plate. When the explosion of the nitroglycerine simply dispersed the disk upon which it was placed, or only *exploded* the latter (as was several times the case in the course of these trials), no destructive action was recorded upon the plates which served as supports. The interposition of the disk of gun-cotton between the nitroglycerine charge and the plate served to protect the latter from injury, the force of the exploding nitroglycerine being to a great extent expended in pulverizing and dispersing the disk. Only in one instance, among several experiments, did 2 ounces of nitroglycerine develop the detonation of compressed gun-cotton; that quantity of the liquid detonated both "nitrated" and "chlorated" gun-cotton with certainty. One ounce of

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replaced by the salt), the increased work performed by the 62 parts of gun-cotton, with the aid of the oxidizing agent, will be found not quite equal to that obtained from the one hundred parts of pure gun-cotton; in other words, the loss of force due to the replacement of about one third of the gun-cotton by the salt used is not fully compensated for by the extra work obtained from the remaining two thirds of gun-cotton resulting from its complete oxidation. If, however, about three fourths of the theoretical amount of the salt be employed (referring specially to the potassium or sodium nitrate), the resulting products will perform fully the amount of work obtained from a corresponding weight of the undiluted gun-cotton; and as nearly one third of gun-cotton has been replaced in them by material of about one sixth its cost, a considerable advantage is gained in point of economy.

When equal volumes of highly compressed gun-cotton and of the "nitrate" or "chlorate" mixture, similarly compressed, are compared, the explosive force of the latter is much the most considerable. "Chlorated" gun-cotton is decidedly more violent in its action than the "nitrated" preparations; but it is more costly, on account of the comparatively high price of the salt, and because a larger proportion of the chlorate is required to furnish the requisite proportion of oxygen. It is, moreover, very susceptible of ignition by friction or percussion, and is therefore comparatively dangerous. For these reasons it does not compare favourably with the "nitrated" preparations. Of these, the mixtures with potassium nitrate are somewhat the most readily prepared; they, moreover, have but little if any more tendency to absorb moisture than pure compressed gun-cotton. The considerable advantage which the "nitrated" gun-cotton possesses in point both of cost and of power (especially when compared with equal volumes of compressed gun-cotton), added to the fact that it is as readily susceptible of ignition by detonation and possesses other valuable properties above pointed out, render it highly probable that this preparation of gun-cotton will be largely substituted for the ordinary compressed material in many of its applications. The circumstance that carbonic oxide, produced in considerable amount upon the explosion of trinitrocellulose, is present in the products of explosion of nitrated material in scarcely higher proportion than it exists in those of gunpowder, appears likely to remove the objection against the employment of gun-cotton in military mines, which arose from the large quantity of carbonic oxide developed when heavy charges of gun-cotton were exploded.

nitroglycerine, which in no instance detonated compressed gun-cotton, produced detonation of those materials in three out of four instances; in the fourth, with nitrated gun-cotton, the latter was exploded, but there was no destructive effect exerted upon the iron plate. Results similar to the latter were always obtained when 0·75 ounce and 0·5 ounce of nitroglycerine were employed; with these quantities ordinary compressed gun-cotton was never exploded; the disks were simply dispersed in minute fragments. It appears conclusively established by these experiments that the compressed mixtures of gun-cotton with potassium chlorate and potassium nitrate, prepared in the manner described, are decidedly more sensitive to detonation by nitroglycerine than gun-cotton itself in a highly compressed condition. In order to ascertain whether this difference was ascribable to difference in structure, *i. e.* to the greater hardness and rigidity of the gun-cotton preparations containing a large proportion of saline matter, some disks were prepared of an intimate mixture of finely divided gun-cotton and of the inert salt potassium chloride; the proportion of ingredients used corresponded to those existing in the "chlorated" and "nitrated" gun-cotton, and the same method of manufacture and extent of compression were adopted. Two ounces of nitroglycerine produced partial detonation of this material; a few finely divided fragments were recovered, but the iron plate sustained some, though comparatively little, injury. One ounce of nitroglycerine exploded the chloride mixture only partially, some portions escaping ignition; no indication whatever of the development of detonation was obtained with the employment of this quantity, while in the majority of instances the "chlorate" and "nitrate" mixtures were detonated by a corresponding quantity of the liquid.

It appears, therefore, that the ignition or explosion of the gun-cotton by the detonation of nitroglycerine is to some extent promoted or facilitated by the greater resistance which the material opposes to disintegration by the blow, consequent upon the increased rigidity which its incorporation with the salt imparts to it, but that the undoubtedly greater susceptibility to detonation of the "nitrate" and "chlorate" mixtures by nitroglycerine is chiefly due to some predisposing influence exerted by the oxidizing agent, arising perhaps out of the tendency to violent chemical reaction between it and the gun-cotton, when the conditions favourable to chemical activity are suddenly fulfilled.

b. *Dilution by inert liquids.*

If gun-cotton is diluted by impregnation with a *liquid* substance, or with a body solid at ordinary temperatures which is introduced into the mass in a liquid state, its sensitiveness to detonation is reduced to a far greater extent than by a corresponding weight of a solid substance incorporated *as such* with the gun-cotton. The obvious cause of this is just the converse of that which operates in preventing the reduction of sensitiveness to detonation of nitroglycerine by its considerable dilution with an inert solid. In the latter case, the explosive material envelopes the diluent, and occupies the spaces intervening between its particles; the continuity of the explosive material is consequently preserved throughout the mixture, and detonation is therefore readily established and transmitted: while in the other case the *diluent*, which is liquid, or is at any rate first applied in the liquid state, envelopes each particle of the solid explosive agent, so that a complete casing (or film) of inert material surrounds each, isolating it from its neighbours; even therefore if the amount of diluent applied is only small, it must oppose comparatively great resistance to the transmission of detonation throughout the mass, either if it remain in the liquid condition or if it afterwards solidifies*.

If the dilution or impregnation with a liquid be carried to the full extent, the diluent will, in the case of gun-cotton, penetrate, at any rate to some extent, to the interior of the small particles of hollow fibre composing the compressed mass, and the deadening effect will thus be greatly increased.

Experiments have been made with the view of ascertaining how small a proportion of water, distributed through compressed gun-cotton, interferes with its detonation by the ordinary means employed in practice; *i. e.* by exploding a fuse containing about 15 grains (1 grm.) of mercuric fulminate, confined in a sheet-tin tube in contact with it. Cakes of gun-cotton of known weight were kept upon supports in a small chamber, the bottom of which was covered with a layer of tow, thoroughly wetted with water; their increase of weight, due to absorption of moisture, and their susceptibility to detonation were periodically ascertained. When 3 per cent. over and above the normal proportion (2 per cent.) of water had been absorbed, the detonation of the cakes was doubtful. Other specimens which were impregnated with oil, or soaked in melted fat until the latter had penetrated to the centre of the mass, could not be detonated by the explosion of the usual "detonator" (containing about 1 grm. of fulminate) firmly imbedded in them. The explosion of the freely exposed damp gun-cotton was, however, accomplished by greatly increasing the strength of the detonator (*i. e.* by employing a large amount of confined mercuric fulminate); and it occurred to my assistant, Mr. E. O. Brown, to apply the detonation of dry gun-cotton itself to the development of the explosive force of the compressed material when in a moist or wet state.

Gun-cotton, immediately on removal from the press, in which the wet pulp has been submitted to a pressure of not less than four tons on the square inch, retains about 15 per cent. of water. In this condition it cannot be burned by the simple application of fire to its surface, nor can it be detonated except by the employment of a fulminate "detonator" of very considerable power; but if a piece of air-dry compressed gun-cotton, weighing about 0·5 ounce (14 grms.), be placed *in contact* with it and detonated by means of two or three grains of confined mercuric fulminate, the moist gun-cotton is

* In the attempts made by me and by Mr. E. C. Prentice, a few years ago, to moderate the rapidity of explosion of gun-cotton sufficiently for its safe application to propulsive purposes, the most successful results were obtained by uniformly impregnating the compressed explosive agent with solid substances (*e.g.* india-rubber, collodion, paraffine, or stearine) applied with the aid of solvents which, on evaporation, deposit the diluent in the form of a film, continuous throughout the mass and completely enveloping each particle of gun-cotton. The rapidity with which explosion extends through a mass may be regulated to a considerable nicety by varying the strength of the solution of diluent employed or the thickness of the layer deposited between the particles.

violently exploded with absolute certainty. If the compressed material be soaked in water until thoroughly saturated with the liquid (in which case it will absorb about 35 per cent.), or if it be similarly saturated with oil or any other liquid, it may still be detonated, provided a sufficient quantity of dry gun-cotton be exploded in contact with it. In a series of experiments instituted with gun-cotton containing precise quantities of water, it was found that a compact cylinder of the air-dry material weighing 100 grains (6·5 grms.) sufficed to develop the detonation of compressed gun-cotton containing as much as 17 per cent. of water, provided it was detonated in close contact with some portion of the moist mass. Occasional failures occurred, however; and when the proportion of moisture was increased to 20 per cent., double the quantity of dry gun-cotton (200 grains=13 grms.) did not suffice to develop detonation, the result being certain only when about one ounce (28 grms.) of dry material was employed as the initiative detonator. When the gun-cotton had absorbed the maximum amount of water (30–35 per cent.) its detonation could not be absolutely relied upon with the employment of less than about four ounces (112 grms.) of air-dry gun-cotton applied in close contact.

On comparing the susceptibility of moist or wet compressed gun-cotton to detonation by confined mercuric fulminate and by dry compressed gun-cotton, freely exposed and exploded by means of the usual "detonator," the results were decidedly in favour of gun-cotton as the initiative agent. Thus with 12 per cent. of water the moist substance was only detonated once in seven experiments by a "detonator" containing 100 grains (6·5 grms.) of fulminate, whereas no failure ever occurred in detonating gun-cotton, containing that proportion of water, with 100 grains of the air-dry material; moveover the latter sufficed to produce detonation when the proportion of water amounted to 17 per cent., whereas this result could not be obtained with 150 grains (9·75 grms.) of fulminate, and appeared to be certain only when the detonating charge was about 200 grains (13 grms.).

The transmission of detonation from dry gun-cotton to a moist disk, through the agency of a tube, appears to take place, so far as two or three experiments showed, with the same facility as though the mass to be detonated were dry. One ounce of gun-cotton, exploded in one extremity of wrought-iron tubes 1·25 inch (·031 m.) diameter and 2 feet (·608 m.) long, induced the detonation of moist disks, containing 15 per cent. of water, inserted in the other extremity; and with a stronger tube of the same dimensions the detonation was, in one instance, transmitted to a distance of 3 feet. These results are quite parallel to those obtained with dry gun-cotton.

The propagation of the detonation of moist gun-cotton from one mass to another in open air, the pieces being ranged in a row, *in contact* with each other, takes place apparently with as much facility as with the dry material, provided the piece *first* detonated contain not less water than the others to which detonation is to be transmitted*; but this is not the case if even very small spaces be allowed to intervene between the individual masses, as i shown by the following experiments.

* For an interesting result bearing on this point see page 382 (footnote).

Four 9-ounce (280·8 grms.) disks of gun-cotton, containing about 30 per cent. of water, were placed on either side of a similar disk of air-dry gun-cotton, with spaces of 1 inch (·025 m.) intervening between it and them. The detonation established by the dry disk was only transmitted to the nearest on each side, the others were broken up and scattered by the explosion. With a row of pieces of air-dry compressed gun-cotton, 28 feet long, the disks used being 3 inches (0·75 m.) in diameter and ranging in weight from 2 to 2·5 ounces (56 to 70 grms.), and the *contact being continuous* throughout, detonation, when established at one extremity, continued to a distance of 42 feet (12·76 m.), the entire length of the train. In another experiment, similar in all respects, except that the disks employed ranged in weight from 2·5 to 2·7 ounces and were saturated with water, detonation extended likewise to the entire length of the train; the destructive effect, and the velocity with which the detonation travelled, being the same at the end as at the commencement. When disks of the same diameter, but of even higher density and of greater weight (consisting of 4·5 ounces of air-dry gun-cotton), were employed, saturated with water (containing about 30 per cent.) and arranged with intervening spaces of 0·5 inch (·013 m.), the detonation being established by the explosion of a 9-ounce (280·8 grms.) disk in contact with the first of the train, only two of the wet disks were detonated. In a second precisely similar experiment, except that the initiative detonation was produced by the explosion of 18 ounces (561·6 grms.) of dry gun-cotton, only the first five spaced disks were detonated; and in a third experiment, with disks of the same weight and containing the same amount of moisture, but separated only by intervals of 0·25 inch (·0062 m.), ten disks were detonated, 9 ounces of dry gun-cotton being used as the initiative detonator. It appears, therefore, that contact of the distinct masses is essential to the transmission of detonation through any considerable number, by wet gun-cotton, in open air. It has also been established by experiment that the same condition is essential, even when the wet gun-cotton is confined, unless the strength of confinement is sufficient to resist the destructive action of the initiative detonation.

It has been amply demonstrated by careful experiments that the gun-cotton preparations which have been described just now as "nitrated" and "chlorated" may be as readily detonated in the moist state as ordinary compressed gun-cotton, and under the same conditions. These preparations absorb less water, as might have been anticipated, than the comparatively porous masses of gun-cotton itself, even in its most highly compressed condition. The cakes of nitrated gun-cotton, when removed from the press, contain not more than about 8 per cent. of water, and the maximum amount which they will absorb does not exceed 28 per cent.

Numerous comparative experiments on a small and large scale have been instituted with moist and wet gun-cotton, both in the ordinary and "nitrated" forms, with the object of ascertaining whether the mechanical effects of its detonation differ from those obtained with these materials in the air-dry condition; and no evidence whatever has been obtained of a falling off in the work done by gun-cotton (or by the "nitrated" preparations) when employed wet. It appears, therefore, that the diminution in the expansion of the gases generated, consequent upon the expenditure of heat in the conversion of water into vapour, must be counterbalanced by the additional volume of vapour which the water furnishes. Indications were, however, obtained, in the comparative experiments with large charges, that when gun-cotton (or the nitrated material) is employed in the wet state its detonation is somewhat sharper or more sudden than when used dry; and this is in accordance with the previous observation, that the less susceptible a mass of given explosive material is of compression, when submitted to the action of a sufficient initiative detonation, the more readily will detonation be transmitted, and the more sudden will the transformation take place from solid to gas and vapour. Hence, when the air is replaced by water, in a mass of compressed or nitrated gun-cotton, the transmission of detonation, when once established, is favoured by the increased resistance of the particles to mechanical motion*. The conclusions drawn from the behaviour of wet gun-cotton in practical trials on a large scale were subsequently confirmed in an interesting manner by the results of experiments on the rate with which detonation is transmitted by dry and wet gun-cotton.

The change in structure which a mass of wet compressed gun-cotton sustains when its temperature is sufficiently reduced to freeze the water, affects its susceptibility to detonation in a remarkable, though readily explicable, manner. When the water is crystallized, the particles of gun-cotton are no longer uniformly and completely enclosed in the diluent; but the dilution becomes similar in character to that of the mixtures of gun-cotton with soluble (crystallized) salts which have been described, and the wet gun-cotton (or rather gun-cotton diluted with solid water) becomes readily detonated by the ordinary means employed for exploding the air-dry substance. Thus gun-cotton cylinders in the moist condition in which they were removed from the hydraulic press, and others which had afterwards been soaked in water when frozen and reduced in temperature to $-9^\circ{\cdot}4$ C. (17° F.), were found to be exploded with certainty by the fulminate-"detonators" ordinarily used for exploding dry gun-cotton.

Mercuric fulminate, and also the mixture of that substance with potassium chlorate and antimony tersulphide, which is employed in percussion-caps, were found to be readily detonated through the agency of dry confined fulminate when they were mixed with water in sufficiently large proportion to convert them into pasty masses. In the first instance, 5 grains (·325 grm.) of dry fulminate, enclosed in a capsule of sheet-tin, were found to detonate the wet fulminate and "cap-composition" when surrounded by these.

* In some recent submarine experiments, in which means were employed for accurately measuring the comparative force exerted by different explosions, produced under corresponding conditions (as to depth of submersion, confinement of charge, &c.), some gun-cotton of lower compactness than usual was found to furnish a somewhat low result when detonated in the dry state, but gave a decidedly high result when thoroughly saturated with water. In this case the comparatively porous gun-cotton, when its pores were filled up by water, was in a condition most favourable for sudden detonation.

It was afterwards found that a "detonator" containing 3 grains (·195 grm.) of dry fulminate would not explode the wet fulminate or "cap-composition" when fired at a distance of 2 inches (·05 m.) from them, but did so with certainty at a distance of 1·5 inch (·031 m.). When, instead of exploding the dry fulminate confined in a capsule or tube of sheet-tin, it was detonated by a sharp blow from a hammer (a naval "gun-hammer" being used for the purpose), the wet substance was detonated when just in contact with 5 grains (·32 grm.) of dry fulminate thus exploded; but it failed to detonate when removed to a distance of 0·25 inch (·0063 m.). The detonation produced by means of the hammer was therefore much less violent than when the same or a smaller quantity of *closely confined* fulminate was exploded*, no doubt because particles of the latter escape detonation by the falling hammer, being dispelled by the rush of gas from the portions first exploded.

Finely divided gun-cotton, made up into a paste or pulp with water, is not susceptible of explosion under conditions far more favourable than those just pointed out, which determine the detonation of wet mercuric fulminate. Wet gun-cotton pulp was placed in a cylinder of sheet-zinc open at the upper end; a disk of compressed gun-cotton, coated with waterproofing material, and fitted with an ordinary "detonator" (10 grains of mercuric fulminate enclosed in a tube of stout sheet-tin), was inserted into the pulp, so as to be completely surrounded by it. The explosion of this disk only dispersed the pulp, scattering the fragments of the zinc cylinder. This experiment was repeated with the same result; and no other effect was obtained when disks weighing 2 ounces (62·4 grms.) were detonated in the centre of the pulp, which was employed with various proportions of water. Very different effects were, however, produced by a simple modification of the manner of carrying out these experiments, as will be presently seen.

VI.—EMPLOYMENT OF WATER AS A MEANS OF TRANSMITTING DETONATION, AND OF APPLYING THE FORCE DEVELOPED BY EXPLOSION.

In experiments made upon the employment of wet compressed gun-cotton in submarine mines, the charges being enclosed in stout cases of wrought iron, it was demonstrated not only that gun-cotton containing 30 per cent. of water might be thus as efficiently applied as the dry substance, but also that it is possible to detonate masses of wet compressed gun-cotton, surrounding the dry initiative charge, when the interstices between the individual masses are filled up with water. The slight compressibility of the liquid does obviously not present an impediment to the sufficiently sudden transmission of the force, developed by detonation, to closely contiguous masses of gun-cotton and to others surrounding these, if the individual masses are separated from each other only partly and by small quantities of water. Provided the escape of force by transmission through the water be retarded, at the instant of the first detonation,

* The wet fulminate in close proximity to the dry material, which was detonated by a hammer or in a capsule, was always dispersed by the detonation; but it was collected by a receptacle surrounding the charge, and was thus proved not to have been exploded.

either by the resistance which the material of the case offers in which the gun-cotton disks are confined, or by the pressure of a considerable column of water, the detonation of wet compressed gun-cotton, immersed in water and separated from the initiative detonator and surrounding masses by thin layers of the liquid, can be accomplished with certainty. Results fully equal to those obtained with wet charges enclosed in stout metal cases have been furnished by charges closely packed together and confined round the initiative detonator by means of a case of thin sheet-tin, or a bag, or even by a simple fishing-net (being thus freely exposed to the surrounding water), provided they are immersed in water to a considerable depth. Charges of wet gun-cotton arranged similar to these, but in which the individual masses were not firmly enough held together, thus allowing of greater water-spaces between them here and there, and greater liability to movement, or which were submerged to comparatively small depths, failed to be detonated, even when comparatively large initiative charges of dry gun-cotton were employed, the wet disks being simply dispersed by the explosion.

The suddenness and completeness with which detonation was transmitted through small water-spaces, in the experiments with iron cases, suggested to my mind the possibility of applying water as a vehicle for the efficient employment of small detonating charges for bursting or breaking up cast-iron shells into numerous, and comparatively uniform, fragments, thus applying a shell or hollow projectile, of the most simple construction, to fulfil the functions of the comparatively complicated shrapnel or segment shells. The results furnished by experiments in this direction are interesting, and may prove of practical importance; they are fairly represented by the examples given in Table III. (p. 374). The shells experimented with were exploded by electric agency, being placed in a capacious iron chamber, or cell, lined with oak, specially constructed to admit of the collection of fragments of shells after their explosion. The charge of explosive material, fitted with the fulminate-fuse by which it was detonated, was either enclosed in a cylinder of thin sheet-iron or (in the case of gun-cotton charges) simply coated with waterproofing material; it was attached to the screw-plug of the shell, so that, when this was inserted and screwed into its place, the bursting-charge was fixed in the centre of the shell, being surrounded in the latter on all sides either by air or water. The fine wires by which the detonating fuse was fired were passed through a small opening in the screw-plug, which was then filled up with cement, so that the shell, when fitted, was closed as securely as possible. In subsequent experiments, in which the shells were fired from guns, the bursting-charges were fitted to the base of the concussion-fuse used in the service, so that the shells were absolutely closed when the fuse and charge were screwed into position.

These results afford interesting demonstration of the power possessed by water to transmit, uniformly in all directions, the force developed by an explosion, the destructive effect being proportionate not merely to the amount of explosive agent used, but also to the suddenness of the concussion imparted to the water by the explosion. They showed, besides, that a very slight flaw in the continuity of the resistance opposed in

TABLE III.

No. of expt.	Nature and weight of shell.	Nature of bursting-charge.	Shell, how filled.	Number of fragments furnished by the explosion.	Portion of the shell not recovered, broken up into very minute fragments.	Remarks.
	diam. lb. oz.	oz. grms.				
1.	Spherical shell 5½″ 16 3	Gunpowder........... 13 =368·54	The shell entirely filled with the explosive agent.	19 (2 fragments under 1 oz.) ...	None.	
2.	,, ,, ,, 16 1	,, ... 13 =368·54	,, ,, ,,	18 (1 fragment ,, ,,) ...	None.	
3.	,, ,, ,, 16 ½	,, ... 1·12= 31·75	Charge contained in the cylinder surrounded by water.	8 (2 fragments ,, ,,) ...	None.	
4.	,, ,, ,, ,,	,, ... 1·12= 31·75	Shell filled with water, charge in tin cylinder surrounded by the water.	None. The water and gases escaped through the small perforation containing the fuse-wires.	....	A repetition of this experiment furnished the same result.
5.	,, ,, ,, 16 1½	Picric powder......... 1 = 28·24	Charge in central tin cylinder, shell filled with water.	89 (37 fragments under 1 oz.)	1·5 oz.=42·51 grms.	
6.	,, ,, 5 12 1	Gun-cotton cylinder. 0·5 = 14·17	Cylinder fixed in centre of empty shell.	28 (3 ,, ,, ,,)	None.	
7.	,, ,, ,, ,,	,, ,, 0·5 = 14·17	Shell filled with water; charge surrounded by it.	254 (181 ,, ,, ,,)	2·75=77·94 grms. }	{ Repetitions of these experiments furnished corroborative results.
8.	,, ,, ,, ,,	,, ,, 0·25= 7·08	,, ,, ,,	141 (68 ,, ,, ,,)	None .... }	
9.	16-pounder rifle-shell (cylindro-conoidal), weight 14 lb. 15 oz.	Gunpowder........... 16 =453·59	Entirely filled with the bursting-charge.	29 (2 ,, ,, ,,)	None.	
10.	,, ,, ,,	,, ... 16 =453·59	,, ,, ,,	32 (7 ,, ,, ,,)	None.	
11.	,, ,, ,,	Gun-cotton cylinder. 1 = 28·34	Cylinder in the centre of the empty shell.	53 (16 ,, ,, ,,)	2·75 oz.=77·94 grms.	
12.	,, ,, ,,	,, ,, 1 = 28·34	Shell filled with water, cylinder surrounded by it.	300 (236 ,, ,, ,,)	2 lb. 1 oz.=953·52 grms......	A repetition furnished a similar result.
13.	,, ,, ,,	,, ,, 0·5 = 14·17	Cylinder in the centre of empty shell.	25 (9 ,, ,, ,,)	2·5 oz.=70·85 grms.	
14.	,, ,, ,,	,, ,, 0·5 = 14·17	Shell filled with water, the charge surrounded by it.	165 (87 ,, ,, ,,)	None	A repetition furnished a similar result.
15.	,, ,, ,,	,, ,, 0·25= 7·08	Charge placed in the centre of empty shell.	None. The gas escaped through the small perforation containing the fuse-wires.		
16.	,, ,, ,,	,, ,, 0·25= 7·08	The shell filled with water enclosing the charge.	121 (57 fragments under 1 oz.)	None .... }	Repetitions of these experiments furnished corroborative results.
17.	,, ,, ,,	Picric powder......... 15 =425·24	The shell entirely filled with the explosive agent.	52 (8 ,, ,, ,,)	2 lb. 14 oz.=1304·07 grms. }	
18.	,, ,, ,,	,, ,, ... 2 = 56·68	The shell filled with water, which surrounded the charge enclosed in a tin cylinder.	138 (71 ,, ,, ,,)	1 lb.=453·59 grms. .... }	

all directions to the water (*i. e.* the existence of a very small vent which permits of an escape of water at the instant when explosion was established) sufficed to protect the shell against rupture, if the explosion in the latter was not of very sudden nature. Thus, on several occasions, 1·12 ounce of fine-grain powder, when exploded by means of a fulminate-fuse in a small shell filled with water, failed to burst the latter, the water and gases finding their escape through the very small opening in the fuse-plug which received the firing wires, and the luting of which did not offer any effectual resistance; but even when less than one fourth that quantity (0·25 ounce=7·8 grms.) of gun-cotton was detonated under the same conditions in shells of the same size, no instance occurred in which the shell escaped being broken into a large number of pieces, the suddenness with which the force was developed and transmitted by the water leaving no time for the small vent to exert any decisive influence upon the results.

It should be stated that the disintegration of the shells by 1 ounce, and even $\frac{1}{2}$ ounce of gun-cotton, through the agency of water (as shown in Table III.), is far too complete to be of practical value, as the large number of very small fragments produced would be of no use as missiles. The fragments furnished by employing only 0·25 ounce of gun-cotton in the particular sizes of shells used were of much more serviceable nature. Even with this very small charge the shells were not merely burst into very numerous fragments, but these were also projected with considerable force.

The powerful effects obtained in those shell-experiments in which gun-cotton was employed, and the fact that detonation was transmitted from one mass of compressed gun-cotton to another through small water-spaces under the conditions described at page 372, led me to attempt the transmission of detonation from one mass of gun-cotton or dynamite to another in a tube, with the intervention of water. The tubes (of wrought iron, 1·25 and 1 inch in diameter) were fixed in a vertical position; the lower extremities were closed with plugs of wood and of clay, and in some instances with strong metal screw-caps; the gun-cotton or dynamite was placed at this extremity, and the initiative charge, consisting of 2 ounces of compressed gun-cotton or of dynamite, enclosed in waterproof material, was just immersed in the water at the upper extremity and was detonated in that position. The distance between the two charges of explosive material was reduced to 2 feet without detonation being transmitted; and it was evident that, under the conditions fulfilled by these experiments, the intervening column of water, even if much reduced in length, must act as a protective to the submerged explosive charge, the force being mainly expended in the opposite direction, where comparatively little resistance was opposed to it.

Other experiments, to which I was led by the remarkable effects produced in detonating small charges of gun-cotton in shells filled with water, furnished interesting and important results. In developing detonation in a perfectly closed and sufficiently strong vessel, which is completely filled with water (in addition to the small detonative charge), the resistance offered by the water, *at the instant* of detonation, may be regarded as similar to that which would be presented by a perfectly solid mass. Similarly if, instead of water only, the strong vessel be completely filled with a mixture of a solid substance (*e. g.* a fine powder or a fibre reduced to a fine state of division) and water, such a mixture should also, at the instant of detonation, behave as a very compact solid with reference to the resistance it opposes, at the instant of explosion, to the detonating charge which it encloses. If this be so, then a mixture of even the most finely divided gun-cotton fibre with water, if enclosed in a strong receptacle, such as a shell, should be in a condition readily susceptible of detonation, because, at the instant of explosion of the initiative charge, the particles of gun-cotton offer great resistance to mechanical motion. The correctness of this conclusion has been fully established by experiments, which have demonstrated that, while it is indispensable to employ gun-cotton in a very compact or highly compressed form in order to ensure its detonation under all other conditions, it may, if enclosed in strong vessels, such as shells, be employed with equal efficiency in a finely divided state, provided the spaces between the particles be *completely* occupied by water, the small detonating charge being immersed in the aqueous mixture. The following experimental illustrations of this will serve to compare with the shell-experiments given in Table III.

Spherical cast-iron shells $5\frac{1}{2}$ inches (·138 m.) in diameter, and weighing about 16 lb., were filled with mixtures of finely divided gun-cotton, or pulp, and water. In some instances the pulp (containing no more water than remained in it after thorough drainage in a centrifugal machine) was firmly rammed into the shell, a central cavity being formed in the mass to receive the "primer" of dry gun-cotton; water was then poured in, so as to fill the shell completely, and ample time was allowed for it to soak thoroughly into the rammed pulp and expel the air retained by the latter. The "primer," which consisted of a cylinder of air-dry gun-cotton weighing 1 ounce (31·2 grms.), fitted on to the ordinary "detonator," and coated with waterproofing material, was then inserted into the cavity provided for it (displacing part of the water contained in the latter). It was attached to the screw-plug, as in the experiments given in Table III., by which the shell was closed as perfectly as possible when the loading was completed. In other experiments the pulp was mixed with water to the consistency of thick paste, and poured into the shell in this state; in others it was introduced in a still more dilute condition, the fitting of the shell being completed, in all cases, as above described. The shells thus loaded were broken up by the explosion of the detonator into a very large number of fragments, of which from 350 to 400 were recoverable, a considerable proportion of the shell being, however, almost pulverized and buried in the oak casing of the chamber. Many of the larger fragments were also driven into the hard wood with great violence, being very difficult to extract; and the effects (both as regards disintegration and violent dispersion) furnished by from 2 to 4 ounces of gun-cotton used in this way were far greater than those produced with the full charge (about 1 lb.) of gunpowder.

These experiments conclusively demonstrated that gun-cotton in a fine state of division may be exploded by detonation, with certainty, when mixed with water in different degrees of dilution, provided such mixtures be enclosed in a receptacle of sufficient strength. The detonation of 2 ounces of compressed gun-cotton, immersed in such mixtures, was without effect upon them when they were only partially confined; but 1 ounce applied in the same way developed detonation when the mixtures were completely confined in the cast-iron shells. This result is not attained by the employment of only 0·5 ounce of compressed gun-cotton as the detonator; but more sensitive explosive agents than gun-cotton are susceptible of detonation, under the same conditions, by much smaller initiative charges. Thus 2 ounces of mercuric fulminate, placed in a 16 Pr. cylindro-conoidal shell, which was then filled up with water, was detonated by means of about 15 grains (1 grm.) of the fulminate confined in a sheet-tin case. Although the loose fulminate was in a small heap at the bottom of the shell, being separated from the lower extremity of the detonating tube (attached to the screw-plug of the shell) by a water-space of 0·75 inch (0·018 m.), the shell was very uniformly broken up; 170 fragments were collected in the chamber, and 1 lb. 11 oz. (842·4 grms.) were not recovered, being dispersed in minute fragments.

The susceptibility of gun-cotton (and of other explosive bodies) to detonation in shells, when employed in admixture with water, as described, appears to have afforded the means of overcoming the hitherto insurmountable difficulty of employing violent but comparatively sensitive explosive agents in shells, with safety to the gun from which these are fired. Various plans have been devised, but hitherto without success, for preventing charges of gun-cotton, in shells, from being exploded through the agency of the concussion to which the latter are subjected when fired from a gun, and the attempted application of nitroglycerine-preparations in shells has failed for the same reason. But mixtures of gun-cotton with water may be fired from guns in shells with absolute freedom from liability to premature explosion; and it is now no longer doubtful that the desideratum of a simple and safe system of applying the violently destructive effects of gun-cotton in shells will be attained as soon as a safe adaptation of the mercuric detonating arrangement to the fuse of the shell has been perfected.

VII.—ON THE VELOCITY OF DETONATION, OR THE RATE AT WHICH DETONATION IS TRANSMITTED.

The very satisfactory results obtained by the Government Committee on explosive substances in employing the chronoscope, devised by Captain A. NOBLE, F.R.S., for determining the time occupied by a projectile in traversing different intervals in the bore of a gun, led me to avail myself of this instrument for estimating the velocity with which detonation is propagated or transmitted under various conditions. The construction and mode of using this chronoscope have been described in the preliminary Report of the Committee on Explosions issued by the War Office in February 1870. A few words may serve to give a sufficient explanation of the instrument for present purposes. A series of thin metal disks (36 inches in circumference), the edges of which are covered with white paper coated with lamp-black, are fixed upon one common shaft, which is driven at high speed by means of a falling weight, continually wound up, and a series of very accurately constructed multiplying-wheels. The speed usually attained by these disks (the precise rate of which is ascertained by means of a stop-clock) is about 1000 inches per second linear velocity at their circumference; so that 1 inch of the latter, travelling at that rate, represents the one-thousandth part of a second; and as, in reading off the records obtained, 1 inch is divided into a thousand parts by the vernier used, a linear representation is thus obtained of intervals of time as minute as the one-millionth part of a second. The uniformity of rotation of the disks during the duration of an experiment is ascertained by a series of observations of the speed, by means of the stop-clock. Each revolving disk is brought into connexion with one of the secondary wires of an induction-coil, and the other wire is attached to an insulated discharger, fixed opposite the edge of its corresponding disk, and adjusted so that its point is just clear of the latter. If, therefore, the primary circuit of any one of the induction-coils is interrupted (*e. g.* by suddenly severing the conducting-wire) the induced current must leap across, at that instant, from the discharger to the circumference of the disk, and will produce a small but distinct white spot on the blackened paper. As all the disks revolve with the same velocity, it is obvious that if the primary circuits of their respective coils be simultaneously interrupted, the spots produced by the discharge of the secondary currents on all the disks will be in a straight line, but that, if they be successively interrupted, the spots on the several disks will form a curve, varying in character with the intervals of time which have elapsed between the successive development of the respective secondary currents. In using this chronoscope to measure the rate of progression of a projectile in a gun's bore, the shot is made to sever the primary wires of the coils which it passes in succession, by means of cutters which slightly project in the bore, and which it therefore brings to bear upon the wires as it passes over them. In applying the instrument to the measurement of the speed of detonation in open air, or of the rate of its transmission through tubes, the only difference in the *modus operandi* consisted in the manner of effecting the rupture of the primary wires.

The disks of gun-cotton used in the experiments for determining the rate at which detonation is propagated in open air were ranged in a row or train upon the ground (or, rather, upon the level surface presented by a support of very thin narrow deal board); they consisted generally of disks 3 inches in diameter, varying somewhat in thickness in different experiments; they were either ranged in a continuous row, each disk touching the one on either side, or with equal spaces intervening between them. At the commencement of the row, or train, the wire forming the primary circuit of the coil connected with the first chronoscope-disk was tightly stretched across the part where detonation was to be first established. To facilitate the sudden severance of the circuit by the explosion, this part was composed of a fine copper wire, insulated by means of a silk covering, which was held in close contact with the gun-cotton surface, across which it was stretched by being fastened round the insulated heads of two hookstaples driven into the ground on either side of the piece of gun-cotton. The circuit-wire of the coil belonging to the last (eighth) chronoscope-disk was similarly fixed across the further extremity of the train, and the other wires were stretched across different parts at intervals of 1, 2, 4, and 6 feet in different experiments.

In determining the velocity of transmission of detonation through tubes, wrought-iron gas-pipe of 1·25 inch (·031 m.) diameter was used; these pipes had very small perforations bored into them at the desired intervals, so that the fine insulated wires could be passed transversely through the centre of the tube at those points. The wires were rigidly stretched by being wound round staples on each side of the tube, and the small disks of gun-cotton to which, and by which, detonation was to be transmitted were inserted into the tubes so as to be in close contact with the wires*.

a. *Detonation of dry gun-cotton, arranged in continuous rows.*

The first three results obtained with continuous rows or trains of gun-cotton disks laid on their flat sides, exhibited considerable want of uniformity, *i. e.* the rate at which velocity was transmitted from one point to another (through distances of 1–4 feet, ·304 to 1·216 m.) appeared to vary considerably in different parts of one and the same train, as well as in different experiments; but this was evidently due to the employment of too stout a wire as the means of severing the circuit by the explosion. A much finer wire was therefore substituted for it; but even with the employment of the finest procurable insulated wire, stretched as tightly as possible across the gun-cotton disks, it was obviously impossible to avoid very slight variations in the degree of rapidity with which the wires were broken by the detonation. Making allowance for this source of error, it will be evident from the following example that, in a continuous row of 170 disks (3 inches, =·075 m., in diameter and about 0·9 inch, =·0225 m., thick, and of the average weight of 2·6 ounces, 81·1 grms.), the detonation, measured at intervals of 6 feet in a length of 42 feet (=12·76 m.), was transmitted with uniform velocity; the measurement at the far extremity of the train was practically identical with the rate at which detonation was transmitted through the first 6 feet.

				Rate of progression of the detonation per second.		
Between	0′	and	6′	=17466	feet	(5309·664 m.).
,,	6′	,,	12′	=16815	,,	(5111·761 ,,).
,,	12′	,,	18′	=17972	,,	(5463·488 ,,).
,,	18′	,,	24′	=16252	,,	(4940·608 ,,).
,,	24′	,,	30′	=17511	,,	(5323·344 ,,).
,,	30′	,,	36′	=16099	,,	(4829·70 ,,).
,,	36′	,,	42′	=17738	,,	(5321·45 ,,).

Mean=17122 feet=5136·60 m.

* In carrying on these experiments I have received valuable assistance, at different times, from Captain Singer, R.N., Major Maitland, R.A., and Captains W. H. Noble and Jones, R.A.

In an earlier experiment with the same description of disks, the mean velocity with which detonation was transmitted along a train 30 feet (9·12 m.) in length, the rate of travel being measured at intervals of four feet, was 16,871 feet (=5061·3 m.) per second; the rate of travel in the first four feet was 18,527 (=5558·1 m.), and in the last four feet 18,442 feet (5532·6 m.) per second. A third similar experiment gave a mean velocity of 18,234 feet (5470·2 m.) per second.

In these experiments the separate 3-inch disks were just touching each other at two points of their circumference. The average weight of gun-cotton disks used was 2·6 ounces, =10·4 oz. per foot (324·48 grms. per ·304 m.) of the train. In another experiment a continuous train of *uniform* dimensions throughout was constructed of solid cylinders 1·25 inch (·031 m.) in diameter and 1·5 inch (·038 m.) long, which were laid on their sides, with the ends of each one in close contact with one end of another cylinder, so that the entire train was in the form of a continuous cylinder weighing 8 ounces per foot (249·6 grms. per ·307 m.). The mean rate of transmission of detonation in this experiment was 18,868 feet (5660·4 m.); the rate of travel in the first four feet was 18,180 (5454 m.), and in last four feet 18,950 feet (5685 m.) per second.

In order to ascertain whether the rate of transmission of detonation would be affected by a very considerable reduction in the amount of compressed gun-cotton included in a given length of the train, cylinders of 0·9 inch (·019 m.) diameter were arranged in a continuous row, as in the preceding experiment; their weight corresponded to 3 ounces (93 grms.) per foot (0·304 m.) of the train, or less than one third that of the disks used in the first experiments (and it corresponded to the weight of nitroglycerine used in an experiment to be presently described). In one experiment with these small disks the mean velocity of detonation was =18,546 feet (5638 m.) per second; in another it corresponded to 20,000 feet (6080 m.) per second. It will be seen that in these, and also in the preceding experiments with larger cylinders placed end to end, the velocity of transmission was higher than when the large disks were employed which rested on their broad surfaces, and only presented to each other comparatively small points of contact at their circumference. It was to be expected that the rapidity of detonation would be promoted by increasing the contact surfaces of the individual masses, and thus rendering the train as nearly as possible continuous. The individual records of velocities obtained at the different parts of the train (24 feet, =7·296 m., long) composed of the very small disks of gun-cotton presented greater variations than in the other experiments with larger masses; this was no doubt caused by a greater variation in the degree of suddenness with which the wires were fractured, by the comparatively less violent explosions.

In the second experiment with the very small disks, about one half of the train was constructed of cylinders having a central perforation of 0·25 inch (0·006 m.) diameter, those which composed the first half being perfectly solid. There were indications of a somewhat more rapid transmission of the detonation along the perforated part of the train.

The foregoing experiments demonstrate that the rate at which detonation is transmitted from mass to mass of dry compressed gun-cotton (the individual masses being in actual contact with each other) is between seventeen and twenty thousand feet (5168 m. and 6080 m.) per second, and that the rapidity of transmission is affected by the compactness or rigidity of the masses of gun-cotton, but not importantly by a difference in the form and arrangement of the individual masses of gun-cotton, nor by very considerable variations in their weight.

b. *Detonation of dry gun-cotton, with spaces intervening between the masses.*

A few experiments were made for the purpose of ascertaining to what extent the rate of transmission of detonation was affected by leaving small spaces between masses of compressed gun-cotton of a particular size, the spaces being insufficient to arrest detonation. Disks 3 inches in diameter, and ranging in weight between 2·3 and 2·6 ounces (71·76 to 81·1 grms.), were placed in a line with intervening spaces of 0·5 inch (·013 m.) between each disk. The train was 28 feet (8·51 m.) long, but the detonation stopped short at 22 feet, there being at this point a somewhat light and comparatively spongy disk. The mean velocity of the detonation was =16,935 feet (5080·5 m.) per second, the rate of transmission being 15,606 feet (4681·8 m.) per second in the first four feet, and 16,573 (4971·9 m.) in the last four feet of the train. A second experiment with the same description of disks, selected so as to present no great difference in weight and compactness, the disks being placed, as before, 0·5 inch (·013 m.) apart, in a row 28 feet (8·51 m.) long, gave results closely agreeing with the above, the entire train being, however, detonated in this instance. The mean velocity of the detonation was =16,776 (5032·8 m.), the rate of transmission being 15,676 feet (4702·8 m.) per second in the first four feet and 16,218 (4865·4 m.) in the last four. The observations recorded of the progress of detonation along the last 16 feet of this train afforded an excellent illustration of the uniformity of the rate of transmission, even if the disks are spaced, and of the accuracy attainable by the method of observation employed.

	Rate of transmission of detonation per second.
Between 12′ and 16′	=16,815 feet (5044·5 m.).
" 16′ " 20′	=16,692 " (5007·6 ").
" 20′ " 24′	=16,634 " (4990·2 ").
" 24′ " 28′	=16,218 " (4865·4 ").

In a third experiment, with a row of disks of the same dimensions as the foregoing, but the weight of which ranged between 3·75 (117 grms.) and 4 ounces (124·8 grms.), they were separated from each other by spaces of 0·75 inch (·0189 m.). Detonation was transmitted more rapidly than by the lighter disks (2·7 ounces=84·24 grms.), which were separated by spaces of 0·5 inch (·013 m.); the rate of travel in the last four feet happened to be identical with that in the first four, but the records obtained in the intermediate distances exhibited more considerable fluctuations than usual, as though the uniformity of the rate of transmission were affected by the increased spaces which were allowed to intervene between the masses of gun-cotton. The fluctuations may, however, have been due in part to *slight* differences in the spaces, combined with small variations in the weight of the disks. The mean velocity of the detonation was =17,478 feet (5243·4 m.) per second. It would appear from these results with spaced disks that the separation of masses of compressed gun-cotton from each other by spaces insufficient to arrest detonation may retard the rate at which this is transmitted from mass to mass, the extent of such retardation being of course determined by the relation between the size of the individual masses and the extent of spaces intervening between them. The separation of masses of about 2·5 ounces (78 grms.) from each other by spaces of 0·5 inch (·013 m.) had a decided and uniform retarding effect upon the rate of travel of the detonation; but with masses at least a third larger, the further increase, by one third, of the space intervening between them did not maintain a similar uniform retardation in the rate of travel, although there were indications of such retardation at some points along the train or row of spaced disks.

c. *Detonation of moist and wet gun-cotton.*

Gun-cotton disks containing about 15 per cent. of water, ranged in a continuous row (the *dry* disks weighing the same as those used in previous experiments), were found to transmit detonation with the same velocity as the dry material; there appeared, indeed, some indication that the rate of travel was a little higher, the results obtained being *all* equal to the *highest* furnished by dry gun-cotton of the same density. Thus in one experiment the rate of travel in the first four feet was 18,416 (5524·8 m.), and in the last four 18,340 feet (5502 m.) per second, the mean velocity being =18,375 (5512·5 m.) per second. In the last 12 feet of the train the following rates were recorded:—

	Rate of travel of detonation per second.
Between 16′ and 20′	=18,880 feet (5664 m.).
,, 20′ ,, 24′	=18,416 ,, (5524·8 ,,).
,, 24′ ,, 28′	=18,040 ,, (5502 ,,).

In another experiment the mean velocity was =18,581 feet (5574·30 m.) per second, and in a third 18,433 feet (5529·9 m.) per second.

With gun-cotton disks which were *saturated* with water (containing about 30 per cent.), but in other respects similar to those used in the former experiments, the rate of transmission of detonation was *decidedly higher* than with the dry disks. In one experiment, with a train 30 feet long, the mean velocity of transmission was =19,213 feet (5763·9 m.) per second; and the records from which the mean result was derived included one*

* An interesting example was obtained, in the course of these experiments, of the manner in which the behaviour of gun-cotton, when exposed to the action of a detonation, as also the character of its detonation, is liable to be modified by a variation in the proportion of water with which it is impregnated. A number of disks ranging in weight from 2·5 to 2·7 ounces (78·0 to 84·24 grms.) when air-dry contained some of them

which had obviously been affected by some slight retardation in the breaking of the wire. The following were the recorded rates of travel:—

	Rate of transmission of detonation per second.
Between 0′ and 4′	=19,751 feet (5925·3 m.).
,, 4′ ,, 8′	=19,751 ,, (5925·3 ,,).
,, 8′ ,, 12′	=19,006 ,, (5701·8 ,,).
,, 12′ ,, 16′	=20,281 ,, (6084·3 ,,).
,, 16′ ,, 20′	=18,928 ,, (5678·4 ,,).
,, 20′ ,, 24′	=17,608 ,, (5282·4 ,,).
,, 24′ ,, 28′	=19,169 ,, (5750·7 ,,).

In another experiment the mean velocity was 19,664 feet (5899·20 m.) per second. The following records were obtained at 6-feet intervals, with a train of the wet disks 36 feet long:—

	Rate of travel of the detonation per second.
Between 0′ and 6′	=22,574 feet (6772·7 m.).
,, 6′ ,, 12′	=18,404 ,, (5521·2 ,,).
,, 12′ ,, 18′	=19,916 ,, (5974·8 ,,).
,, 18′ ,, 24′	=20,036 ,, (6010·8 ,,).
,, 24′ ,, 30′	=19,516 ,, (5854·8 ,,).
,, 30′ ,, 36′	=19,240 ,, (5772·0 ,,).
Mean velocity	=19,948 ,, (5984·4 ,,).

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about 15, others 30 per cent. of water; they were arranged in a continuous train, of which the first 25 feet consisted entirely of the least wet disks, the remainder being composed of those saturated with water. When detonation was established (by means of an 8-ounce disk of dry gun-cotton), it was transmitted from disk to disk, in the first 25 feet, at a rate of 18,000 feet per second, but was arrested by the first disk containing the higher proportion of water, which, besides the two next following, was shattered and dispersed by the explosion. It has been shown that the detonation of gun-cotton containing 30 per cent. of water could not be accomplished by the employment of less than about 4 ounces of gun-cotton as the initiative detonator; in the above experiment, therefore, in which the train consisted of disks weighing only about 2·75 ounces (85·8 grms.), the detonation being transmitted by each disk to the one next in succession, it was consistent with former experiment that the last of those disks in the train which contained 15 per cent. of water should fail to transmit detonation to the first of the disks containing 30 per cent., although they were in contact. But in other experiments with trains which consisted *entirely* of disks containing 30 per cent. of water, and weighing only between 2·5 (78·0 grms.) and 2·7 ounces (84·24 grms.), detonation, established by means of an 8-ounce dry disk, was transmitted, without fail, throughout the longest trains experimented with (45 feet), provided the disks were in contact. Detonation was therefore transmitted to gun-cotton saturated with water by disks which contained *the same proportion of water*, but which were far too small to have produced this result had they been dry, or had they contained only 15 per cent. of water. These apparently anomalous results appear to indicate that the *quality* of detonation developed by gun-cotton is modified by the proportion of water which the latter contains.

These results demonstrate conclusively that when compressed gun-cotton is saturated with water, so that the air in the mass is replaced entirely by the comparatively incompressible liquid, detonation is transmitted at a decidedly more rapid rate than with equally compact dry gun-cotton.

d. *Detonation of nitrated gun-cotton.*

The considerable amount of a nitrate required to completely utilize the oxidizable constituents of gun-cotton should naturally tend to reduce the rapidity of explosion of that substance, when employed in the form of a mixture with any proportion of saltpetre approaching the theoretical requirement. Results obtained by the detonation of "nitrated" gun-cotton, in practical experiments, afforded decided evidence of less rapid action, which was confirmed by determinations of the rate at which detonation is transmitted along trains of the nitrated material. The disks employed were 3 inches (0·078 m.) in diameter, containing about two thirds the theoretical requirement of saltpetre (namely, 38 per cent.), and weighed about 4 ounces each. The mean velocity of detonation was =15,981 feet (4794·38 m.) per second, the rate of transmission generally ranging between 15,500 (4650 m.) and 16,000 feet (4800 m.) per second; it was therefore about 2000 feet per second below that of ordinary air-dry compressed gun-cotton.

e. *Detonation of dynamite.*

The material used in these experiments was that known as NOBEL'S dynamite (No. 1), and consisted of an intimate mixture of about seventy-three parts of nitroglycerine with twenty-seven parts of Kieselguhr*, made up into cylindrical cartridges 0·5 inch (0·013 m.) in diameter, and 3 inches (0·078 m.) long, by being firmly pressed into wrappers of stout parchment-paper. Thus prepared it resembles stiff clay, not sufficiently wet to be very plastic. The paper envelopes were removed from the cartridges for the purpose of these experiments, and the cylindrical masses (the average weight of which was 2·3 ounces =71·76 grms.) were placed end to end and pressed together; in this way perfectly continuous trains of dynamite, 30 feet and 42 feet (9·12 and 12·76 m.) long, were prepared; detonation was established by means of the ordinary "detonator" used with gun-cotton, which was inserted into a small cartridge of dynamite or a disk of gun-cotton, and placed upon one extremity of the train. The rate at which detonation was propagated was recorded at intervals of 4 feet and 6 feet (1·21 and 1·82 m.) along the trains; the mean velocities observed were 19,536 feet (5938·24 m.) and 21,592 feet (6563·96 m.) per second. As with gun-cotton, the rate of progression of the detonation was as high at the end of the longest train as at the commencement, and at one part of each of the trains it attained a velocity of 24,000 feet (7296 m.). These numbers show that the velocity with which detonation is transmitted by the plastic nitroglycerine mixture is decidedly higher than with dry compressed gun-cotton.

* The dynamite was obtained from the factory of the British Dynamite Company, near Glasgow, which has recently been established to meet the demands for NOBEL'S nitroglycerine preparations in the country.

Careful comparative submarine experiments, in which the explosive force was measured by the effects produced on crusher-gauges, have indicated that this dynamite (*i. e.* nitroglycerine diluted with one third its weight of inert material) is about equal, and sometimes a little inferior, in power to gun-cotton; but in open-air experiments (*e. g.* explosion of freely exposed charges against walls or timber) the dynamite has been observed to be sharper and somewhat more local in its action. These observations harmonize with the results of the velocity-determinations with the freely exposed trains.

Dynamite was, however, found to behave very differently from compressed gun-cotton when spaces were allowed to intervene between the masses composing a charge which is detonated in open air. It will be remembered that with pieces of gun-cotton 3 inches (0·076 m.) in diameter, weighing about 2·5 ounces (78 grms.) each, which were placed in a row with intervals of 0·5 inch (·013 m.), detonation was transmitted with a velocity ranging between 16,000 and 17,000 feet (4864 and 5168 m.) per second, and therefore not greatly inferior to the mean rate at which detonation was transmitted by similar disks arranged in continuous rows. But when charges of some of the *dynamite*, which had transmitted detonation at a rate of from 19,000 to 21,00 feet (5776 to 6384 m.), the cartridges forming a continuous row, were separated from each other by spaces of 0·5 inch (·013 m.), which were left at the same intervals as in the trains of gun-cotton (the weight of the individual masses of both substances being nearly alike), the mean rate of progression of the detonation was only 6239 feet (1896·65 m.) per second, or less than one third of the *lowest* velocity observed in the experiments with *continuous* trains of dynamite. The trustworthiness of this result was conclusively demonstrated by the uniformity of the observed velocities at different parts of a long train of the spaced dynamite cartridges, as is shown by the following numbers:—

				Rate of progression of the detonation per second.
Between	0′	and	4′	=6591 feet (2003·66 m.).
„	4′	„	8′	=6133 „ (1864·43 „).
„	8′	„	12′	=6159 „ (1872·23 „).
„	12′	„	16′	=6394 „ (1943·77 „).
„	16′	„	20′	=6552 „ (1991·80 „).
„	20′	„	24′	=5789 „ (1759·85 „).
„	24′	„	28′	=6059 „ (1841·93 „).

f. *Detonation of nitroglycerine.*

The quantity of nitroglycerine at my disposal for these experiments was limited to a few pounds; it was therefore necessary to devise arrangements for the attainment of trustworthy results with comparatively small quantities of material. V-shaped troughs, 14 feet long and about 2 inches deep in the centre, were constructed of thin sheet-metal, and the insulated wires at intervals of 2 feet were passed through, and cemented into, small perforations in the sides of the trough, sufficiently near to the bottom to ensure their being covered by the nitroglycerine. In the first experiment the trough was filled to about one third its depth with the liquid, and the initiative detonation was developed at one extremity by means of a dynamite cartridge (and detonator) partly immersed in the nitroglycerine. Although pains were taken to fix the trough uniformly level upon the ground, there was a slight unavoidable elevation at one part—about 9 feet distant from the point of first detonation; the layer of nitroglycerine was at this point about half the depth of the remainder, and this sufficed to arrest detonation, which had been transmitted up to that part of the train at a rate of from 5200 to 6000 feet per second, the mean velocity being 5573 feet (1794 m.) per second. The layer or train of nitroglycerine used weighed 20 ounces (624 grms.), being at the rate of 1·4 ounce (43·68 grms.) per foot of the layer or train. In the next experiment a layer of fully double the depth was used (weighing about 3 ounces =93·6 grms.) per foot; the detonation proceeded along the entire length of the trough with undiminished velocity, which was, however, not higher than when the smaller quantity of nitroglycerine was employed, the mean rate of its progression being 5305 feet (1612 m.) per second, and the maximum rate, at any part, 5994 feet (1822 m.). The quantity of nitroglycerine employed, in a given length of the train, in this last experiment corresponded to that used in the two gun-cotton experiments, in which the smallest cylinders (=3 ounces per foot) were used, arranged in a continuous row, the rate of travel of the detonation ranging between 18,500 and 20,600 feet (5624 and 6262 m.) per second.

The very low results furnished by nitroglycerine, when detonated in open air, are obviously due to the physical peculiarity (*i. e.* to the liquid nature) of this explosive agent, the transmission of detonation being greatly retarded by the tendency of the liquid particles to escape from the blow of the detonation. In the first experiment it was demonstrated that when the mass of liquid subjected to the detonation was sufficiently reduced in quantity, it was actually dispersed, or made to yield so completely to the blow, that detonation was arrested while being transmitted at a rate of 5500 feet (1672 m.) per second. The very high velocity with which detonation may be transmitted by nitroglycerine, when that substance is in a condition or position enabling it to resist mechanical dispersion, was demonstrated by the results obtained with dynamite employed in the form of compressed cartridges. On the other hand, the remarkable manner in which the velocity of detonation of the latter was reduced by introducing such spaces between the cartridges as had no retarding effect upon the detonation of corresponding masses of the rigid gun-cotton, demonstrated that the somewhat plastic nature of the explosive material, and its consequent tendency to yield to force, affected the transmission of detonation very decisively when the conditions were not such as to ensure its transmission continuously from particle to particle.

These results confirm in an interesting manner the conclusions arrived at from experiments in various other directions, regarding the influence exerted by the physical character or mechanical condition of an explosive body upon its susceptibility to detonation.

The comparatively limited quantities of nitroglycerine at my command have compelled me to suspend for a time further experiments with that substance; I hope, however, at some future time to have the opportunity of determining the rate at which detonation is transmitted by *confined* nitroglycerine, and of comparing it with gun-cotton under the same conditions, as well as with other explosive agents.

g. *Transmission of detonation by tubes.*

Several experiments were made for the purpose of comparing the rate of transmission of detonation by gun-cotton disks arranged as described in the foregoing, and by widely separated masses, through the agency of tubes. The mode of operating was as follows:—Iron gas-pipes, clean inside, and either 1·25 or 1·5 inch (1·031 or ·037 m.) diameter, had pairs of small holes drilled into them at intervals of 2 feet (·608 m.) and 3 feet 3 inches (1 metre) from each other, sufficiently large just to admit of the insertion of the fine insulated wire, and so placed that the latter, when thrust through both, was stretched across the interior of the tubes at its centre and at right angles to its length, being tightly secured to pegs fixed in the ground on either side of the tube. Disks of suitable dimensions to fit the tube were inserted, so that two, weighing together 1·5 ounce (46·8 grms.), were placed against each wire. In the wider (1·5 inch, ·037 m.) tubes the charges and wires were 2 feet apart, and in the 1·25 inch (·031 m.) tube they were 3 feet 3 inches (1 m.) from each other. The initiative detonation was produced at one end of the tubes by means of 2 ounces of gun-cotton. The rate at which it was transmitted from the starting-point (or initiative explosion) to the first charge in the tube was somewhat variable, ranging between 10,000 (3000 m.) and 13,000 (3900 m.) feet per second; the subsequent transmission along the tubes, from charge to charge, proceeded at a tolerably uniform, but considerably reduced rate, the average being 6000 feet (1800 m.) per second. The following is an example of the observations recorded, with employment of a tube 1·5 inch (·037 m.) diameter, the charges being separated by intervals of 2 feet:—

	Rate of transmission in feet per second.
From the initiative detonation to the charge 2 feet distant	9922 (2976·6 m.).
From the charge at 2 feet to that at 4 feet	=6693 (2607·9 „).
„ „ 4 „ „ 6 „	=5320 (1596·0 „).
„ „ 6 „ „ 8 „	=6957 (2087·1 „).
„ „ 8 „ „ 10 „	=6854 (2056·2 „).
„ „ 10 „ „ 12 „	=5648 (1694·4 „).
„ „ 12 „ „ 14 „	=5246 (1573·8 „).

There would appear to be some indication of a falling off in the rapidity of transmission in this experiment towards the end of the tube, but this was not borne out by other results with tubes of the same length.

In one experiment, with a tube of 1·5 inch (·037 m.) diameter, charges of only 1 ounce of gun-cotton were placed in the tube at intervals of 2 feet. The results obtained in the first 6 feet of the tube corresponded with those furnished by tubes of the same dimensions, when charges of 1·5 ounce (46·8 grms.) were employed; but the fourth and succeeding charges, though they exploded, did not detonate, no destructive effect being produced upon the tube; the wires were, however, severed by the explosions, and the records obtained indicated that the rate at which the *explosion* was transmitted from charge to charge, through the last three intervals of 2 feet each, was only between 1500 and 1800 feet (450 m. and 540 m.) per second.

It appears from the experiments with tubes that, when the relations between the amount of explosive agent, the diameter of the tube, and the space or length of tube intervening between the charges are such as to ensure the transmission of *detonation*, the rate of its transmission is about one third of that at which it travels, in open air, along a *continuous* mass, or row of masses, of the same material in the same condition.

VIII.—ON CIRCUMSTANCES WHICH INFLUENCE THE BEHAVIOUR OF EXPLOSIVE AGENTS WHEN EXPOSED TO HIGH TEMPERATURES.

In my former memoir on explosive agents I discussed* incidentally the influence of an accumulation of heat in a mass of gun-cotton in promoting violent explosion or detonation, if through any cause the materials become ignited, an influence which equally affects other explosive agents. This point has acquired much additional importance since the publication of that Paper, in consequence of its probable bearing upon the violent explosions which occurred at the Gun-cotton Works at Stowmarket in August 1871, and of the possibility thereby rendered manifest that violent explosions of gun-cotton, or other substances of analogous properties, may occur under circumstances which until lately were not considered to involve hazard.

The fact that the previous application of heat to an explosive agent increases the violence with which this will explode when flame, or a sufficiently powerful source of heat, is applied, admits of ready demonstration by simple experiments. Thus, if a small quantity of gun-cotton, wool, or thread be inserted and lightly pressed down into a test-tube, and ignited by application of a hot wire to the gun-cotton, or of a sufficient source of heat to the exterior of the tube, it will simply flash into flame rapidly, with but little indication of explosive violence; but if it be previously exposed to a heat of 90° to 100° C., until it has attained that temperature throughout, its ignition, while at that temperature, will be attended by decided evidence of greater explosive energy.

* Phil. Trans. 1869, vol. clix. pp. 495–6.

A small piece of compressed gun-cotton, similarly inserted in a tube, and ignited, while at the ordinary temperature, by platinum wire which was heated by an electric current, burned slowly, almost with the appearance of smouldering; but when another fragment was ignited in the same way, after having been raised for some time to 100° C., and while still heated to that temperature, it exploded with considerable violence and shattered the tube. The cause of this great difference in behaviour is evidently due in part to the circumstance that comparatively little heat had to be expended at the instant of ignition in raising the entire mass to the exploding point, and in part to the state of chemical tension, or predisposition to chemical change, into which the particles of the gun-cotton had passed by their continued submission to heat. Similar effects have been readily obtained by exposing gunpowder and other explosive agents to sufficient heat previous to their ignition.

In the case of a substance like gunpowder or mercuric fulminate, the mechanical condition (granulated or crystallized form) of which favours the rapid penetration of heat or flame throughout a mass, an explosion, of violence proportionate to the quantity which is ignited, must inevitably result from the inflammation of any portion. The circumstance that masses of compressed gun-cotton simply burn rapidly from the exterior to the centre, if ignited, imparts to this material at first sight an appearance of comparative safety (or of non-liability to violent explosiveness under ordinary conditions of exposure to flame or to an igniting temperature), which experience has shown to be in great measure delusive, inasmuch as it is true only so far as regards comparatively small quantities (a few hundred pounds) of the material, and is even then, to a considerable extent, dependent upon the circumstances under which the material is exposed to heat. This has been conclusively demonstrated by some experiments upon a considerable scale which have been carried out by the Government Committees on Explosive Agents and on Gun-cotton, of which the following is a brief account.

Single boxes of stout wood (0·75 inch in thickness) strongly made, filled with disks of compressed gun-cotton (28 lb. in each) and firmly closed with screws, have been surrounded by inflammable material, the burning of which exposed the case and its contents to considerable heat, eventually igniting it, and causing the box to burn fiercely. In every instance the gun-cotton in the box became inflamed after a few minutes and burned fiercely, the entire quantity being consumed in two or three seconds; but no explosion was brought about in any instance, and the box in which the gun-cotton was confined was only partially forced open by the pressure developed from within. Eight boxes of the same kind, each containing 28 lb. of gun-cotton, were afterwards placed in the centre of a pile of similar boxes, filled with earth to the same weight, and the contents of the innermost box in the heap were ignited by an electric fuse. They burned fiercely, and the flame penetrated to the gun-cotton in one other box; but in neither instance was an explosion produced, and the pile of boxes was scarcely disturbed; the remaining six which contained gun-cotton were charred but not otherwise injured. Another more severe experiment, in which one of the inner boxes composing the heap was coated with tar and covered with wood shavings, these being afterwards set fire to, furnished a similar result; no explosion followed the eventual ignition of the gun-cotton contained in this and another box. These results were considered at the time to afford satisfactory proof that if even considerable quantities of gun-cotton, in the form of compactly compressed, homogeneous masses, were ignited when confined in strong wooden boxes, no explosion would occur, the gun-cotton merely burning rapidly; and that if such packages of compressed gun-cotton were exposed to the effects of fire from without, some portion must be inflamed by access of fire, and the combustion of the mass thus brought about before it can be raised to the temperature of explosion. Subsequent experiments, however, clearly demonstrated that the results above described must be considered *in relation to the quantity* of gun-cotton by which they are furnished, as well as to the degree of its confinement when subjected to the action of heat or fire. In the experiments just described, the largest quantity of gun-cotton employed was 224 lb. (contained in eight pakages); but some very different results were obtained in somewhat similar experiments conducted in each instance with three times that quantity (viz. 672 lb.) of gun-cotton. That amount of material, packed in 24 boxes of the kind used in the preceding trials, was, in the first instance, placed upon two tables in a light wooden shed; a heap of shavings and wood chips was then kindled immediately beneath the two piles of boxes, of which two were left partly open. The gun-cotton inflamed after the lapse of eight minutes, and continued to burn with increasing violence for about six seconds, when a powerful explosion occurred, the shed being blown to pieces and a deep crater formed in the ground. It was estimated, from comparative experiments with packages of gun-cotton purposely detonated, that the explosion occurred when only a small proportion had burned. In a second similar experiment the nature of the building only was varied, the 672 lb. of gun-cotton being placed (in boxes upon tables, and, surrounded by inflammable material) in a strongly built brick magazine. In this instance also a violent explosion occurred after the gun-cotton had been burning, with increasing fierceness, for nine seconds. A third periment, conducted with an equal quantity of gun-cotton, was made for the purpose of ascertaining whether the result would be influenced by confining it less strongly. The 672 lb. were therefore packed in twenty-four deal boxes of lighter construction than those before used ($\frac{3}{8}$ inch instead of $\frac{3}{4}$ inch deal, and more lightly fastened together), and these were placed in light wooden sheds, the other details of the experiment being as before. The gun-cotton became inflamed about 36 minutes after the fire had been kindled in the hut, and burned fiercely for about 15 seconds; having subsided for a short time, there was a second burst of flame, and the gun-cotton was entirely burnt about 48 minutes after the first ignition, there being no explosion in this instance. A repetition of the experiment furnished the same negative result.

An experiment, similar to the first of the foregoing, was made some time afterwards with NOBEL'S dynamite (the mixture of nitroglycerine and Kieselguhr). 672 lb. of this material (containing about 500 lb. of nitroglycerine), enclosed in twelve stout wooden packages, were placed upon tables in a light wooden building (8·5 feet square by 6·5 feet high), and a heap of inflammable material was placed between the tables. It was somewhat difficult to determine the precise time after the fire was first kindled in the building when the dynamite commenced burning, as the change in the appearance of the flame was less characteristic or sudden than with gun-cotton as observed from a distance. The rapidly increasing fierceness of the flame, however, about five minutes after the fire was kindled, showed that the nitroglycerine was burning; and after the lapse of ten minutes a violent explosion occurred, fragments of the wooden structure were thrown to great distances, and a large crater was formed in the ground.

These experiments, conducted with 672 lb. of gun-cotton and with 500 lb. of nitroglycerine in the form of dynamite, placed in confined spaces, demonstrated that if some portion of the explosive substance is ignited, the remainder of the material being pretty strongly confined, the very rapid increase in the intensity of the heat developed may soon combine to raise some portion of the *still confined* explosive to the inflaming point, and that then, the mass being already in a heated condition, the inflammation may proceed with such rapidity as to develop the pressure essential for establishing explosion while the substance is confined, which explosion would be instantaneously transmitted to the contents of the surrounding packages. It was also satisfactorily demonstrated that with equal quantities of explosive material confined in packages, a difference in the *strength* of confinement of the substance is productive of an important difference when the material is exposed to fire. The weaker the packages the more readily they are opened up by pressure from within; hence, when some portion of the contents of a box of light structure becomes raised to the inflaming-point, the pressure developed by the ignition is not sustained to a sufficient extent or for a sufficient time to bring about explosion. It need, however, be scarcely pointed out that the safeguard against explosion thus presented, in the case of compressed gun-cotton or of a nitroglycerine preparation, by the employment of packages of light structure, must be limited by the *quantity* of explosive material exposed to fire. Thus it is very probable that, although no explosion resulted from the exposure to fire and ultimate burning of 6 cwt. of gun-cotton contained in packages of light structure, while explosion was produced in experimenting with a similar quantity in strong packages, the difference in the strength of the boxes might not have ensured safety against explosion with a much larger quantity. Indeed it may be presumed that, if the quantity be sufficient, no further confinement than that afforded by the outer portions of a large pile of disks of compressed gun-cotton, or cartridges of dynamite, would be required, after the burning had proceeded for a sufficient time, for determining the explosion of some portion of the interior of the mass, in consequence of the resistance opposed to the escape of gas from the confined or inner portions to which the fire had reached.

The results furnished by the experiments just described were similar in their character, and the conditions which determined them, to those noticed on the occasion of the accident at the Stowmarket Gun-cotton Works in August 1871. The ignition of some portion of the gun-cotton contained in one of three closely adjacent wooden store-sheds or magazines, containing together about 13 tons of the material, was unquestionably due primarily to the spontaneous decomposition of some very impure material, the existence of which in one of those stores was clearly demonstrated in the subsequent inquiry. This, and the gun-cotton stored with it, was packed in strong boxes of the same kind as those used in the above experiments. Several unusually hot days had preceded that of the explosion, and the contents of the boxes, confined in these wooden store-sheds, which they filled almost completely, must have become very warm throughout. A large volume of flame, apparently enveloping these sheds, was described by eye-witnesses at a considerable distance as having been observed for a short but very distinct interval previous to the explosion; and there appears no doubt that the ignition of some portion of gun-cotton must have been immediately followed by the inflammation of the entire contents of one box, the flame rapidly penetrating to other boxes, and in a very brief space of time determining the explosion of some portion of the confined gun-cotton in the manner already described. The explosion not only of the entire contents of the one shed but also of the two in close proximity was the inevitable result, the small brick partitions which separated the sheds from each other affording no impediment to the almost instantaneous transmission of the explosion. Among the buildings which were ignited by the flame, or burning *débris* from this principal explosion, there were two small store-houses or packing-sheds, containing gun-cotton packed in a number of boxes of very light construction as compared with the packing-cases already alluded to: these sheds and their contents were entirely consumed without any explosion. But there was a third of the same kind which contained some of the strong boxes filled with gun-cotton, and this, after having been some considerable time in flames, exploded with great violence.

In my Memoir "On the Stability of Gun-cotton"* I demonstrated by numerous experiments and by the results of observations upon a large scale, and extending over some considerable time, that water acts as a most perfect preservative of gun-cotton even under most severe conditions of exposure to heat, and that the material may be preserved for indefinite periods either in a moist state or completely immersed in water, without the slightest change, either chemical or physical, even if the damp or wet gun-cotton be continually exposed to daylight. The correctness of those statements has been fully confirmed by the further and extensive experience of the last five years. Not only have the samples which formed the subject of my former experiments been preserved and found unchanged upon recent examination, but several hundred pounds have been preserved in the damp state for the past seven years, and many thousand pounds in the form of compressed disks have been stored wet for more than two years. Not the slightest symptom of change has been observed in any single instance; and as the substance may thus be preserved in a perfectly uninflammable condition, this

* Phil. Trans. 1867, vol. clvii. p. 233.

method of storing gun-cotton in large quantities has been adopted by the Government, as tending to simplify very greatly the precautions needed in preserving large supplies of the material.

Some experiments have been made with the object of determining as accurately as possible the minimum percentage of water which would deprive compressed gun-cotton of its power of inflaming when brought into contact with a red-hot body. Some disks which contained about 15 per cent. of water were exposed to air in a room where they parted very slowly with the water by natural evaporation. Their weight was determined at the commencement of the experiment, and their power of inflaming was tested by pressing a red-hot iron rod in contact with one of their surfaces for a second or two, their weight being noted just before each trial. As a small proportion of the gun-cotton and water was vaporized each time the hot iron was applied, the weight of the disk was redetermined after each experiment. A period was at length reached at which the surface of the gun-cotton was inflamed, though not instantaneously, the flame spreading slowly from the point of contact with the source of heat, and being readily extinguished by a puff of breath. The proportion of water remaining in the disk when this point had been reached was 9·3 per cent. A disk which, though it smouldered slightly on the surface where the heated iron was applied, did not inflame, was found at that period to contain 10·7 per cent of water.

When removed from the mould of the hydraulic press in which the finely divided gun-cotton or pulp has been converted into homogeneous and very compact masses (of about the density of water) by the application of a pressure of about six tons upon the square inch, the material contains about 15 per cent. of water. In this condition it may be thrown on to a fire or held in a flame without exhibiting any tendency to burn; the material may be perforated by means of a red-hot iron, or with a drilling-tool, and the hard masses may with perfect safety be cut into slices by means of circular saws revolving with great rapidity. If placed upon a fire and allowed to remain there, a feeble and transparent flame passes over the surface from time to time as the exterior becomes sufficiently dry to inflame, and in this way a piece of compressed gun-cotton may be allowed to burn away very gradually indeed. In the same way a hank of gun-cotton yarn or a handful of the pulped material, which, after removal from the centrifugal wringing-machine used in the purifying operations, retains about 20 per cent. of water, burns away very slowly if thrown upon a fire and allowed to remain there. Boxes in which the damp material was packed have been exposed singly to fierce fires until the box itself has been burnt through, but the gun-cotton has only been charred or has burned slowly wherever, and as soon as, it has become sufficiently dry upon the surface to be inflammable. When conducting the large-scale experiments on the burning of dry gun-cotton, it was considered desirable to institute a similar experiment with the moist material for the purpose of ascertaining whether its long-continued exposure to fire when closely packed might result in the development of conditions favourable to the explosion of some portion. 6 cwt. (672 lb.) of compressed gun-cotton containing about 20 per cent. of water was packed in the strong wooden boxes already described, which were placed upon tables in a light wooden shed. They were then surrounded by wooden shavings and chips, which were fired with the aid of some coal-tar naphtha. Eighteen minutes after the fire had been kindled, the shed itself was in flames, and not long afterwards the boxes could be seen burning upon the ground, the supports having been destroyed by the fire. The heap continued to burn for about three quarters of an hour, by which time the whole of the gun-cotton and woodwork had disappeared. At no stage during the experiments was any flame visible which could be positively identified as that of burning gun-cotton.

The apparent immunity of compressed gun-cotton, if sufficiently moist, from any tendency to explode when submitted in considerable quantities to the prolonged effects of a high temperature, needed confirmation by experiments upon a still larger scale and of a more severe nature, before it could be considered satisfactorily demonstrated that the conditions essential for developing the detonation of moist gun-cotton, namely the sufficient desiccation and subsequent detonation of some portion of the highly heated substance, might not possibly be brought about during the prolonged exposure of a great quantity to powerful heat. Two large experiments have therefore recently been instituted by the Government Committee on Gun-cotton, of which the following is a brief account:—Two small arched buildings, or magazines, were very strongly constructed of concrete and brickwork, the walls being 2 feet thick and the arched roofs 9 inches thick. Each magazine was provided with a wooden door, and with a staging 1 foot 8 inches high, which consisted of four brickwork pillars with pieces of railway-bar joining the two on each side together and supporting broad cross bars of wrought iron. In one magazine a tank of the dimensions now used for storing wet gun-cotton in, and constructed of stout pine coated internally with a pitch-composition, was placed upon the staging, and 4480 disks (or 2240 lb.) of gun-cotton were packed into it, the lid of the tank being then securely screwed down. A similar quantity of gun-cotton, packed in eighty stout and tightly closed boxes, each holding 28 lb., was placed in the other building, the boxes being piled on the staging as close together as possible. The gun-cotton, in both experiments, contained about 30 parts of water to 100 of the dry material. A large quantity of wood shavings and other inflammable materials was placed under the staging and round the gun-cotton packages in each magazine and set fire to, the doors being left ajar. The entire contents of both buildings had burned away, without any explosion, in rather less than two hours. The heat to which the gun-cotton, or portions of it, had been exposed was very great, as was demonstrated by the condition of the buildings, and the distortion of some of the wrought-iron bars, when the conflagration had subsided. The brilliant yellow flame characteristic of the burning of a mass of gun-cotton was not observed at any period throughout the experiment; but about one hour after the fires were kindled, considerable volumes of a pale yellow lambent flame, occasionally exhibiting a greenish tinge, issued from the doors. In the case of the magazine which contained the gun-cotton in separate boxes, there were frequent increased outbursts of the flame, apparently caused by the successive fall of boxes from the staging into the fire beneath. When a tuft of gun-cotton wool is placed in a capacious vessel (*e. g.* a large glass beaker) and ignited, the flash of bright yellow flame first observed is followed by a pale yellow lambent flame, of the character above described, which lasts for a distinct interval, and is due to the burning of the inflammable gaseous products as air enters the vessel, the slight greenish tinge being caused by the presence of small quantities of nitrogen-oxides. The flame observed to issue from the magazines was quite similar to this, and was evidently produced by the burning of the gases gradually developed from the wet gun-cotton.

These last experiments demonstrate conclusively that even very severe exposure to heat of large packages or heaps of distinct masses of compressed gun-cotton, saturated, or nearly so, with water, is not attended by risk of explosion. Just as in smaller experiments, when the proportion of water has been expelled from the surface of the heated gun-cotton to the extent to reduce it to about 10 per cent., those portions of the mass burn quietly with a weak flame accompanied by the development of inflammable gas. No accumulation of dry or even of *nearly* dry gun-cotton can consequently take place, and no portion of the gun-cotton can be raised to the exploding temperature.

As compressed gun-cotton may, by employment of simple appliances, be made to exert its full explosive force when thoroughly saturated with water, and as it may therefore be applied in that condition to many of its more important uses, the non-liability of wet gun-cotton to explosion by simple exposure to heat, at any rate in such large quantities as have been experimented with, is a matter of considerable practical importance. The material may be easily preserved in store in an uninflammable condition, and employed at once in that state almost as readily, and with quite as much effect, as if it were dry; its storage in the wet state appears, moreover, to be an absolute safeguard against change, even when doubts exist as to the substance having been thoroughly purified. Therefore, although many years must still elapse before general confidence in the stability of *dry* gun-cotton is well established, very simple means now exist for dealing with this material as extensively as with gunpowder, and with unquestionably greater safety.