Mr. LONGRIDGE desired to add a few explanations. All the formulæ had been reduced to the same notation as his own, which consequently differed somewhat from that given in the text book on Ordnance, issued under the authority of the Secretary of State for War. Professor Barlow's formula was correctly stated in the text book, but Dr. Hart's incorrectly. The plus sign ought to have been put for the minus sign in the latter. Not only had the formula been printed wrongly, but the calculation based upon it was wrong. But the formulæ did not really solve the question. The point to be ascertained was, if there was a cylinder with a given pressure inside, and another pressure outside, what would be the tensile strain induced in the material? The formulæ quoted in the text book did not contain the pressures. The proper formula was given in the Paper: "f_n" represented the internal and "f_{n+1}" was the external pressure; consequently for every ring there was a pair of equations. Then there was another equation, which depended on the modulus of elasticity, which was where the two rings were in contact; so that in the case of a gun with three rings it was necessary to determine three inside and three outside tensions and two normal pressures —eight unknown quantities, and for this there were eight equations. The question was therefore as solvable as any question connected with the building up of a girder. If the modulus of elasticity and the dimensions were known, there was no more difficulty in solving the exact strain at any point in a compound gun built up with rings, than in solving the strain on the upper or lower web of a girder. Unless guns were built on that scientific principle, the same trouble would be experienced as if an engineer were to build any large iron bridge without knowing the formula representing the strains. True, by giving it an enormous strength a bridge might be obtained that would stand a long time; but if the limits of elasticity were passed in any element, the bridge would assuredly, sooner or later, fail. That system had been acted upon in the manufacture of the Woolwich guns. It would be seen by his calculations that at certain portions of the structure, where the strain was beyond the limit of elasticity, a permanent set must occur, and that it must give way at every successive firing until the tube cracked. He desired to take that opportunity of expressing his conviction that the late accident in the "Thunderer" had nothing to do with the Woolwich system. He was certain that Woolwich guns would not burst explosively under any ordinary circumstances. He had an opinion as to what was the cause of the accident, which he could not then enter into; but he was certain that the explosion was not due simply to the structure of the gun. The gun exhibited had been made on the system which he had long advocated. It had been fired in the autumn of 1860, after his first Paper was read, at Southport, and he had since then made experiments with it at the Mauritius. It had been fired many times with heavy charges; it had succeeded perfectly, and there had never been the slightest accident with it. In firing there was no possibility of the slightest escape of gas. He hoped that in the course of the discussion the principle would be considered more than it had been on the previous occasion, when many interesting matters were discussed, but the principle he had brought forward had scarcely been touched.

Colonel J. D. SHAKESPEAR said there were two essential points to be considered, to which all others were secondary in importance. The first point was the exact part where there was the greatest strain on the gun. That point had not hitherto been settled, and he was somewhat surprised to hear Mr. Longridge state that there was an easy formula for calculating it, as it did not appear to him that use had been made of it. Several years ago he had seen it carried out in a rough and ready but practical way. Holes were bored along the first and second reinforces. They were countersunk just sufficiently to steady a 32-lb. shot. The holes were about as large as a good-sized rent. The gun was fired, and it was calculated what height the shot were thrown into the air. By that experiment it was ascertained that the greatest strain on a gun was a few inches in front of the projectile. That seemed to be in accordance with common sense, because the first ounce of a 100-lb. charge would probably move the whole. The greatest strain would take place when the greatest amount of the charge exploded, and that would be some little distance up the bore. He had observed, in his experience, that guns almost invariably burst near the trunnions. If the force of a fowling-piece bursting was in the breech, it would knock a man down; but many persons had a gun burst in their hands, who were absolutely unconscious that such an explosion had taken place; hence it was evident that the violence of the charge was not in the breech. There could be no doubt the principle of placing nearly all the metal of a gun in the breech was a wrong one. The right principle was to place the greatest amount of metal where the strain was—somewhere in advance of the projectile; and he believed that was the intention at Woolwich. With regard to the "Thunderer," it appeared from the drawings in the 'Illustrated London News,' that the tube had broken away immediately in front of the second reinforce, and that was about the point where the end of the projectile would be. With regard to the shrinking of the metal, that was an exceedingly delicate matter. Round a cold tube a bar of iron, almost at white heat, was entwined; it became chilled in contact with the cold iron, and the surface set; the outer surface became set sooner than the inner metal; the two surfaces were hard set, and between them was a soft, spongy metal. It was not possible, therefore, on the principle of shrinking, to get the whole gun homogeneous. With regard to the use of hot water for chilling, it should be remembered that water at 212° was cold in comparison with the heat of the gun. That would always be one of the great difficulties in shrinking guns; yet, considering the number of guns constructed in that way, and the small number of failures, he could not condemn the system. He regretted the absence of Sir William Palliser, who disapproved of the Woolwich plan, but might not approve of this; he had a method of his own, which had been largely carried out in America. He believed there was a large field still open for the construction of heavy artillery. He did not know how the desired result was to be accomplished unless by shrinking, and making the shrinking perfect. In the case of the gun represented in Fig. 9, it appeared that all the metal was in the breech. That gun, he thought, would burst about the letter N, which would be rather in front of the projectile.

Admiral Sir COOPER KEY desired to make a few remarks, as one who had had some experience in the working of heavy guns at sea. He would not follow the Author through his mathematical calculations, but he wished to ask a few questions. If it were possible to calculate the exact tension that the wire required, and if it were possible practically to apply it accurately round a tube, he believed it would make the strongest gun to resist circumferential strain that could be made with equal weight. It certainly carried out the coil principle of making guns, which he considered the best, to an extreme. The smaller the coils, and the more of them, the more reliable the gun would be. There was a point, however, about the proposed gun that he did not like. The Author appeared to think that the longitudinal strength was sufficiently provided for. Admiral Sir Cooper Key imagined that in a 10-inch gun the pressure on the bottom of the bore, in a direction contrary to the path of the shot, would be from 1,200 to 1,500 tons; and it appeared from Fig. 9, that it was intended to take the whole of that strain on four or six bolts. He could not think that would in any way resist the strain. He objected to the use of cast iron, either in the exterior of the gun or for the inner tube. Although the Author had proved that in a 3-inch gun the concussion was not sufficient to damage a tube only ½ an inch in diameter, he felt satisfied that the enormously increased concussion of a heavy gun would be more than any cast iron would stand. He was glad the Author had turned his attention to the breech loading of heavy guns; it was one of the chief requirements of the present day, as guns of great power must be of great length. He should be happy if manufacturers would turn their attention to the best means of providing a good system of breech loading; but he could not say that he liked the Author's plan. The breech piece was only supported by two bars on the small trunnions; and he could not think that such bars, of any size that they could be practically made, would be sufficient to resist the enormous strain at the bottom of the bore in the line of the axis of the gun. In breech loading the convenience and efficiency of the mode of entering the projectile and cartridge were of great importance. A small gun like that exhibited would tip up if the trunnions were properly lubricated, and if just sufficient preponderance were made on the chase end; and the weight of the shot would bring it down again. But in the case of a heavy gun, where the weight on the trunnions would be enormous and the friction necessarily be very great, the shot, placed so close to the trunnions as it must be, could not bring down the heavy breech.

Colonel SHAKESPEAR said the chief difficulty experienced from breech loading on board ship, as well as in casemates, was in connection with the withdrawing of the breech piece, as the men were stifled with the smoke.

General Sir H. LEFROY remarked that no one, at Woolwich or elsewhere, could have any other than a grateful feeling to the Author of the Paper for the ability and mathematical skill he had brought to the investigation of the problems with reference to the expansion of rings or laminæ of metal under tension or compression. It had, however, been well remarked, that the British empire was governed not by logic but by Parliament; and it was equally true that mechanics were governed not by formulæ but by facts. He was far from saying that there was not a substratum of facts in what was contained in the Paper with reference to various moduli. He observed, however, that, in one instance, the Author had taken 24,000 for his modulus, and, shortly after, 13,000.

Mr. LONGRIDGE, interposing, remarked that he had thought it desirable to take a great range, his object in the case quoted being simply to show the effect of varying the modulus.

Sir H. Lefroy continued, that the published works of the officers connected with the Royal Gun Factories were of course fair subjects of criticism, and if they had fallen into mistakes, it was desirable that these should be pointed out. But when it was stated that the rules adopted in those factories and elsewhere were empirical, one was tempted to ask, Why were they empirical? Surely it was not because there was not sufficient mathematical ability at Elswick or at Woolwich to comprehend and apply a formula! The truth was, that experience taught much more than formulæ; and it had shown that the details as to the shrinkage of metals, which were subject to a wide range of variation, were not worth pursuing into a maze of figures. He confessed that he was surprised when he first heard of the practical rule of shrinkage which Sir William Armstrong had adopted; because, in his simplicity, he had imagined that every gun was worked out by formulæ. Since, however, Sir William, and others at the Gun Factories, had discarded formulæ, and had adopted practical rules of thumb, he thought it might be reasonably concluded that they had some justification in doing so. In building a gun, as in building a bridge or any other structure, the engineer looked to three things: first, that the design should not be open to any charge of structural defects; secondly, that the structure should have an excess of strength; and, thirdly, that it should be carried out as cheaply as possible. It was the latter consideration that had led to the preference at the Gun Factories at Woolwich to a small number of thick coils over a larger number of thin coils, which were still preferred at Elswick. The Author, in contrasting the cost of manufacture under the two systems, had charged himself with the exact quantity of metal turned out in the finished 45-ton gun, and he had also put the cost of the metal pure and simple, without anything for the cost of manufacture. There were different kinds of material in the gun—steel wire, solid steel, cast iron, and wrought iron; materials acting differently with different strains, and under different temperatures, and they were all combined in an artificial manner, involving conditions of which they had no experience. How a great coil of steel wire would behave in the tight embrace of a hot iron jacket he did not know. It did not appear to him that the conditions of strength in the proposed structure were such as to warrant the Government in abandoning a well proved system of construction.

Mr. Longridge replied, that there was not the slightest shrinkage; the outer casing was not cast round the inner tube, but was a separate casting, into which the tube was apparently slipped, and it acted only as a sheath, and had nothing to do with the strength of the gun. General Lefroy had fallen into an entire misconception as to the way in which his guns were made, and it would perhaps save time if he briefly explained the method. In the first place he made a tube comparatively thin. For a gun of 20 inches bore the tube would probably be 3 inches or $3\frac{1}{2}$ inches thick. It might either be of cast iron or of steel; that, however, was a question into which he would not enter, simply remarking that his opinion was that cast iron might form the best material. Upon the tube he rolled a coil of wire, $\frac{1}{16}$ inch in diameter, from one end to the other, with a tension varying according to the distance from the breech. It was then rolled back, with another tension gradually increasing. Thus he went backwards and forwards till he obtained the thickness shown at the breech end for a certain distance, gradually decreasing towards the muzzle; the result being that, when the gun was subjected to internal pressure from powder gas, every wire, from the innermost to the outermost, was strained to the same degree. The inner tube had nothing to do with the strength of the gun; it simply transferred the pressure to the wire; and he could so arrange it that the inner tube, 3 inches thick, with a strain of 26 tons or 27 tons per square inch inside, should have no tension at all. That was a matter which must be taken upon trust, as he could not then go through the calculations to prove it. Having completed what was really the essential part of the gun, he had a casting divided through at the point shown in Fig. 9, and held to the breech casting by the bolts. This was intended to preserve the wire from shot or any external injury. The other part, which constituted the main weight of the gun, was like an anvil to receive the blow. The gas check was fitted in the tube; and the bolts held together the two portions of the gun, having nothing to do with the recoil. The recoil was upon the trunnions, and the gun rolled up an inclined plane. In the case of a gun like the one exhibited, the whole recoil was taken up by the side links. At that part the gun had no longitudinal tension. The great principle which he maintained in building breech-loading guns was, that the material that resisted the circumferential strain should have nothing to do with the longitudinal strain. There was a direct strain upon the side rods, which manifestly might be made of any necessary strength. There was no limit to the size which a gun might be made in that way. There was no compound circumferential and longitudinal strain, and no cutting away of the breech. The cast-iron parts were simply protections, and means of getting weight. Weight was necessary in the case of a large gun, on account of the recoil; but he could get weight, employing material at £5 or £6 a ton, that would answer every purpose, and serve as a protection. With regard to formulæ, it should be remembered that if a formula was right it could not differ from facts. All he maintained was, that there should be some formulæ to guide the manufacturers of guns. The Board of Trade had laid down certain limits in the case of bridge building within which the material should be strained; and, in like manner, he thought that in building a gun there should be certain limits beyond which no portion of the gun should be strained; and to ascertain those limits formulæ were necessary. He believed that the formulæ he had given represented, not perhaps with perfect accuracy, but very approximately, the conditions of a gun, and enabled the maker to determine the strain. He did not say, as General Lefroy seemed to imply, that there were no mathematicians at Woolwich; but he believed they had not applied mathematics to the problem in question.

Dr. SIEMENS said the Author complained, and with some reason, that on the occasion of the reading of his previous Paper, nineteen years ago, the discussion had wandered away a good deal from the lines laid down by him. The present Paper presented such clear lines that it was not difficult to keep within them, and he would endeavour to do so. The Paper might be divided into two parts. The first was the critical, and, he might say, destructive part, because the criticisms were such that, if completely borne out, one would almost be afraid to contemplate the result of a general war. The second part was suggestive or constructive. With reference to the criticisms on the Woolwich system, he was ready to admit that the Author was very clear in his mathematical deductions. He had pointed out some error in one of the formulæ used at Woolwich. Passing that over, he thought that the formulæ which were used—those of Professor Barlow and Dr. Hart—were not erroneous in themselves; but, as the Author had shown, were insufficient to meet the case of the strain in every portion of the structure. The Author had from that drawn the conclusion, that in not following out a formula, such as he had presented, the authorities had gone altogether wrong, that the strains by shrinkage which were applied at Woolwich were totally opposed to theory, and that much better results might be obtained in strictly following out the dictates of mathematical reasoning. Mathematics, however good a handmaiden, might be a very dangerous master; and he thought he could show where the

Author had made mathematics his master. He had given his idea of a gun constructed on the Woolwich principle—a 9-inch gun. There was a steel tube of 8 inches thickness of side, around which he shrank iron to a thickness of 28 inches, with a shrinkage exceeding that usually given at Woolwich, namely, of 1 in 1,000. Dr. Siemens knew from experiments of his own that a shrinkage of 1 in 1,000 meant a strain of 12 tons per square inch. If the shrinkage was 1 in 1,000 upon the inner diameter, there would be a strain of 12 tons upon the inner surface of the coil. That in itself presented a very good strain for a material such as iron. If, however, round a tube of 8 inches inside, 28 inches of iron were shrunk in such a way as to put the whole into tensions varying in elastic strain inversely as the diameter, what would be the result? That the strain on 28 inches would be opposed by the 8 inches; that the area of the outer metal would be resisted by the lesser area forming the side of the lining. The Author, in all his calculations, spoke only of what would take place when the powder pressure of 24 tons to the inch was applied; he did not say what would be the case when the shrinkage pressure was applied in the first instance. That shrinkage pressure would undoubtedly have the effect of crushing or deforming the tube permanently. The tube would be no more able to resist such an amount of shrinkage pressure than if it did not exist at all; and therefore such shrinkage as was contemplated by Mr. Longridge could not practically be applied. The Author had criticised rather severely some remarks in the Woolwich reports. Referring to the statement that in "guns of present construction the heavy breech coil compresses the steel barrel to such an extent that the latter becomes in some instances as much as $\frac{1}{100}$th of an inch smaller in diameter during the process of shrinking," the Author had remarked, "It is difficult to imagine a more complete confusion of ideas than that which pervades this sentence" (*ante*, p. 8). Dr. Siemens believed the statements in the official report were perfectly consistent, not with mathematical, but with engineering or physical facts. It would, he maintained, be impossible to give such shrinkage to the mass of iron surrounding the inner tube as would leave that mass of metal under a sufficient tension to take its full proportion of work when an inner pressure was applied equal to 24 tons to the square inch. But suppose that the inner tube could be made strong enough to resist such a pressure, the use of the gun had then to be considered, and the result of the first few rounds. Shrinkage would then again take place, but upon the wrong side of the gun; that was to say, expansion by heat would occur inside the gun, which would still farther increase the strain upon the inner tube; and if it was able to resist the crushing pressure in the first instance, the heating of the inner tube would greatly augment the strain. He thought that was the reason why men, like Sir William Armstrong and the Woolwich authorities, who well knew what they were about, had not ventured to give that distribution of strain by shrinkage which mathematical reasoning would lead them to adopt. The Author would probably admit that the mathematical knowledge which he brought forward nineteen years ago would not have remained idle for so long a time if it could have been advantageously applied; but Dr. Siemens was clearly of opinion that in the construction of the Woolwich guns it was impossible to apply that reasoning properly. But the Author did not really intend to make a gun by shrinking on iron rings upon a steel core; he had brought forward a construction of his own, which had something very pleasing to recommend it at first sight. He took a lining tube, and bound upon it several layers of wire, increasing and varying the strain of the wire in such a way that when the inner pressure—the maximum powder pressure—was applied, each portion of the material bore the same amount of tensile strain. There again, however, the Author had not contemplated, or, at all events, had not brought forward, the result of the crushing action of that amount of binding force upon a comparatively small tube. The tube was made of cast-iron, which resisted compression better than extension, and to that extent the construction might be very proper; but the powder pressure in heating the tube would, he apprehended, work a change in the tensions, the same as it would do in the iron coils, either causing the wires to be overstrained, or the tube to be crushed under that strain. The question was, however, whether it would be possible to put the material into any more satisfactory form. When the powder pressure acted, artillerists would like to distribute the force uniformly over the material; but they had to contend with the different portions under the two conditions of rest and of action from within. One great drawback to the Author's proposed system, which he himself admitted, was that he had a resistance against bursting strain without resistance in the longitudinal direction. The Author remedied that by putting a very heavy mass into the breech piece of the gun, connecting that heavy mass with a protecting tube which did nothing towards resisting the bursting strain of the gun. This was a great drawback to that mode of construction. The amount of metal which actually resisted the bursting strain was probably not more than one-third of the total weight of the gun, the other two-thirds being used for a totally different purpose—to resist recoil and longitudinal action. Why should a wire coil be used? Was metal in the form of wire susceptible under ordinary circumstances of bearing any greater resistance than solid metal? Certainly not. The same strain per inch could be resisted by solid material. In the case of wire there was certainly this advantage, that inasmuch as the iron of commerce was a mixture, or concrete, of the metal iron and a glassy substance called cinder, if that glassy substance were mixed in an irregular way with the iron it would give no tensile strength at all; but inasmuch as the layers of glass were drawn out in a longitudinal direction, they did less harm than they would do if mixed promiscuously; and for that reason wire gave a larger resisting strain than solid metal. That, however, was not the case with steel. Steel wire resisted no better than solid steel. On the contrary, steel wire, while resisting no better per square inch, would give less elongation than solid steel; but the Author would say, "You cannot, with solid steel, distribute your strains in the manner I tell you to do; there ought to be more strain near the outer layers, and less towards the inside of the gun." But there again he thought the steel maker would not be at a loss. If it was desired to distribute a compressive strain on the inner surface of the ring and a tensile strain on the outer surface, could that not be obtained in any other way than by cutting the whole thing up into wire and winding it round, thereby losing all the advantage of longitudinal resistance? He thought it was quite possible. If a cylindrical mass of steel were heated in a furnace to redness, and then, while the steel was in the furnace, a cooling action was applied inside—say, a spray of water—would immediately cause a solid tube to be formed inside the mass of what was called set or cold metal. The inner diameter would remain the same, because it was governed by the general mass of the tube. The metal would shrink, not in the direction of the diameter, but in the direction of the thickness of the tube, which thickness would become less. If the cooling action went on while the outside was at its full temperature, layer after layer of metal would be formed at a gradually reducing temperature, all of which would be, under those conditions, in a state of perfect rest and equilibrium. After some time, perhaps an hour, there would be an outside temperature of say 600° Cent., and at the inside 100° Cent. The coil being taken out of the furnace and allowed to cool, the result would naturally be that in each layer a tension would be formed proportionate to the relative temperatures. The contraction on the outer surface would be very great, and it would act as shrinkage upon the rest. The shrinkage of the surrounding layers would be less and less, and the total result would be a tension which might be represented by a diagram showing a maximum positive strain near the outside of the gun, and a maximum negative strain in the metal nearest the inside of the gun, the neutral axis being somewhere midway between the two. The explosive action of gunpowder upon such a tube would cause the internal negative pressure to be transferred into a positive pressure; it would act on the larger diameter in a less and less degree; and, when the full pressure was acting, there would be a field of compression which might possibly be represented by a diagram showing equal positive tension throughout the mass. In that way it would be possible to obtain, by means of a single ring, all the advantages which the Author claimed for his wire system, with the additional advantage of having strength in all directions, it being unnecessary to amplify the gun after all the required strength was obtained, by two or three times the amount of dead weight. He believed that an inner tube would always be necessary; but it should not be a resisting tube. A tube of hard metal, surrounded by comparatively weak metal, appeared to him to be a great mistake, which was shared both by the Woolwich system and by the plan proposed by the Author. The inner tube should be of metal that accommodated itself entirely to the outer tube and to the necessities of the gun. It should be extra mild steel, which would expand or extend 30 per cent. without break in its continuity. Any hard metal, such as hard steel or cast iron, would be subject to such action and reaction as to bring about its final destruction; whereas a lining of metal that was like putty in its constitution, coupled with great strength, was, in his opinion, the proper lining of a gun surrounded, not by a series of rings, but by one ring or tube, in which the strains were in the first instance so arranged as to give each portion of the metal an equal strength when the maximum powder-gas pressure was applied.

Mr. Homersham thought Dr. Siemens was mistaken in stating that sections of steel wire would only bear the same tension as a section of bar steel of the same area. He had had occasion some years ago to try a great many experiments upon the tension of wire, and an equal area of steel wire drawn $\frac{1}{16}$ of an inch diameter stood considerably more than double the tension of bar steel. When steel was tempered by hardening in oil before being drawn into wire, then it had more than double the strength of bar steel of the same area. All the best pianoforte wires were so made.

Dr. SIEMENS observed that he had made a great many experiments with steel in the form of wire and in the solid state. He had not, perhaps, explained as fully as he ought to have done what he meant with regard to wire being no stronger than solid metal. In speaking of steel wire he supposed it to be annealed wire, that had not been subjected to any hardening process; but if the wire were cold-drawn, or oil-hardened, its elastic range would certainly be greatly increased. Any kind of steel, the mildest and the hardest, yielded in the same manner and to the same extent by applying the same amount of weight per square inch. The only difference between hard and strong and weak steel was, that the weak or mild steel came sooner to the limit of its elasticity. If it was desired to compare steel wire with steel in bulk, the steel in bulk should be put into a similar aggregate condition. Sir Joseph Whitworth could produce steel to bear a strain of 80 tons or more in the bulk after he had oil-hardened it; and Dr. Siemens knew from experience that it was exceedingly difficult to get steel wire, even when oil-hardened, that could be depended upon to resist more than 80 tons per square inch; occasionally 100 tons, or even 110 tons, might be reached in very thin wire, owing to great success in the mode of hardening. In order to make a fair comparison, a metal in the form of wire should be compared with metal in bulk subjected to analogous processes, when it would be found that the absolute tensile strength was nearly the same, whereas the solid steel had generally the advantage of elongating to a greater extent than wire, before rupture took place.

Dr. HOPKINSON said he would not occupy time in expressing the agreement which he felt with the Author in his adoption of a deductive method in discussing this problem, but would at once proceed to point out one or two things in which he thought the detail of his work was open to a slight criticism. He had verified the Author's equations, with the exception of the last. In arriving at that equation the Author had considered a ring of material, and had remarked that that ring was under a circumferential tension; and he inferred that it would be extended by an amount represented by that tension, multiplied by the length of the ring and divided by the modulus of elasticity. That would be perfectly true if the only stress acting upon the material were the circumferential stress; but with that there was a radial compression, and also a stress parallel with the axis of the gun, the last being no doubt small in comparison with the others. Taking those into consideration, the accurate expression for the extension of a ring length l would be $\frac{T\,l}{K} + \frac{f\,l}{K'} - \frac{Z\,l}{K'}$, where T, f, and Z were respectively the circumferential tension, the radial pressure, and the tension parallel to the axis; instead of $\frac{T\,l}{K}$ as assumed by the Author. K′ was a constant for the material. According to Wertheim K′ = 3 K for several metals. Assuming this, he would correct the Author's calculation for the 4½-inch gun, as follows. The tension of the interior of the steel tube, instead of being 16·97 tons, would be 18·2 tons. The tension of the interior iron ring would be diminished by about ½ ton. The amount of correction was very small, and did not materially affect the results. The point was one which was easily set right, but that was not the case with the other point to which he would refer. In testing a rod of any material by direct tension, its limit of elasticity was said to be reached when it began to take a permanent set. If, in addition to the tension, there was a lateral compression, it was a question whether it would take a permanent set with the same longitudinal stress as before. So far as he knew, no experiments had ever been tried upon that point. It had, however, an application to the theory of guns. It was generally thought that a press cylinder or gun would begin to give way just when the maximum tension in the material was equal to the limit of elasticity, and it was tacitly assumed that the compressive stress perpendicular to that tension would not affect the result. He did not think that anything of the kind should be assumed. The ordinary results of testing by pure tensile stress ought not, he thought, to be applied to cases in which there was also a lateral stress. The same consideration applied to many other cases. In the shell of a boiler, for instance, there was not only a circumferential tension, but a longitudinal tension, which ought to be considered in any calculation as to the probable pressure at which a boiler would burst. It appeared to him that that was a subject deserving investigation; and until more was known about it, it was impossible to say definitely what the real tendency to break at any point of such a structure might be.

Mr. HADDAN observed, that the Author had quoted Barlow's formula for the diffusion of light, and so applied it to guns as to show that a gun might be made stronger by weakening it, as he did, 90 per cent. on the outside. All gunmakers were, however, agreed that the bore was the weakest part, its strength depending on the tensile value of the metal, not on its thickness. Dr.

Siemens, he believed, had made steel capable of resisting 100 tons pressure on the square inch, and others had reached 60, 70, or 80 tons; but in the case of the "Thunderer" explosion, details of which he had in his hand, the bursting strain exerted was even there equal to 350 tons on the square inch. But if, as he thought, the accident happened by expansion and contraction (for which no allowance was made in any gun that he had ever heard of), it was equal to an expansive energy of 120 tons per square inch on that portion of the bore exposed to heat. The character of the broken section in no way indicated a burst necessarily longitudinal in direction, but indicated a transverse or shearing strain. It appeared to him to be begging the question to acknowledge that a gun could not be made that would not burst. Such a gun could be made if the bore was so arranged that it was not opposed nakedly to the powder-pressure and heat. It had been sought to provide against the weakness of the bore—as metal sufficiently strong could not be manufactured—by the use of pebble powder. The advantage of pebble powder was obtained by so enlarging the area of the charge that its effort was spread over a larger surface longitudinally, while it might be better effected transversely without chambering. The gun possessed a larger margin of safety by diminishing the pressure on the bore from 35 or 40 tons per square inch to about 16 tons. It was inconvenient, however, to have a charge 5 or 7 feet long, as in the case of the 81-ton gun, when a charge of equal energy could be put in the trousers pocket. It would be seen by the diagram (Fig. 1) that he had evaded the difficulty in question, so that the metal, instead of having the requisite 200 tons pressure per square inch to resist, was subject to a strain of only 40 tons. A gun to be safe ought to be prepared to resist a stress of at least 200 tons per square inch in the bore. The Author had explained, that when a gun was in a state of rest, a certain portion of the gun, say the area between A and N, was in compression and the rest in tension, but that when an explosion took place they offered mutual resistance. Thus as there were two rings, one of compression and the other of tension, there must always be a neutral circle where there was rest, and that point was at N, Fig. 1. If the compression ring could be suppressed altogether, and something put in its place that was perfectly inert, the area of resistance offered to the charge would be increased in the proportion of the areas of N to A, so that the pressure at N would be very moderate indeed, in fact reduced to the average. Compression area might therefore as well be omitted, for he did not believe a durable or safe gun possible which converted + into − strains.

every time the gun was fired. As the metal of the present guns did not average 50 tons tensile strength, though it was necessary to make it resist a strain of 200 tons, the desired result could only be effected by an expedient. The space between the fictitious or inner bore, A, and the real bore, B, was to be filled in by, say, com-

FIG. 1.

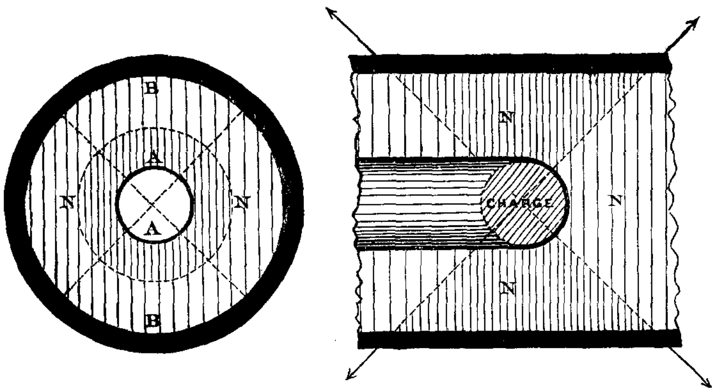


Diagram of 9-inch gun.

A, fictitious bore, pressure = 200 tons per square inch.
B, actual bore, pressure = 40 tons per square inch.
N, neutral circle in an iron gun.
N, non-conductor in Mr. Haddan's gun.

NOTE.—The real bore is coned, to equilibrate the pressure.

pressed paper, which was inert, and did not, like metal, carry its expansive energy with it. The paper rolls used by calenderers were harder and denser than steel. It might appear a paradox, but it was none the less true, that a thick gun was weakest with regard to expansion, and strongest with regard to pressure. There were, therefore, these two contradictory elements in the gun, and the question was how to meet them; he believed by insulation. He had not seen in any gun provision for expansion and contraction, although even at atmospheric changes of temperature the force of expansion was one half the force of the powder, say 9½ tons. The steel tube had proved the necessity for providing for expansion by being elongated some inches out of the muzzle. He could not agree with the Author's method of calculating circumferential stress, just as if the gun was composed of a series of non-coherent 1-inch discs split in half and hinged. He could not see why Barlow's theory should not be equally applied longitudinally as transversely, in fact, spherically—or rather, hemi-spherically; the hemispheres being separated according to the length of the charge, as shown by dotted lines and arrows upon the diagram, where the charge was drawn spherically simply for illustration. The Author's calculation would apply if the gun were a cylinder open at both ends and the whole of the bore exposed to the maximum pressure simultaneously, as if it were filled with powder; whereas, both ends were practically closed, and the pressure was concentrated on a portion only of the bore. Mr. Haddan believed, judging from well-known punching experiments, and also with the ogival-headed shot, that in a manner analogous to the distribution of pressure through sand, &c., metals also transmitted pressure through their mass at angles, varying with their molecular structure. The non-conducting lining would enable a weak metal to successfully resist any exaggerated strain required, whether hot or cold, provided the area exposed to the force could be sufficiently enlarged to obtain the same result as in foundations. The other advantages of insulation were: It enabled gun-cotton, or concentrated and more portable charges, to be used without risk to the gun, since, without diluting the charge with air spaces, the same result was obtained, but radially, as attempted by chambering, in lieu of longitudinally. There was no waste of gas-power, from radiation or condensation. The heaviest gun could be constructed in loosely-fitting pieces and built up *in sitû*. Flaws were not of consequence, except in the insulator, so that larger guns than even the 100-ton were not a remote contingency. Re-tubing could be performed in the field. The insulating tube could be supplied to existing artillery without reducing the calibre; and breech-loaders became feasible when the movable parts were not subject to heat. With reference to the "Thunderer" explosion, he would merely say that he had, previous to receipt of data, published in 'Iron,' of the 22nd February, an exposition of his theory of shearing the gun by heat. He calculated that the heat derived from the explosion of the double charge would expand the bore 0·37 inch. It had been established that there was a radial increase of 0·34 inch in the diameter of the bore at the point of rupture. The rupture took place precisely at the spot where the gas-check of the leading shot rested; and he thought, that if the shot hesitated to move for an appreciable time after the gas-check was expanded, then the heat in rear thereof would have been about 1,400°; in contradiction to 35° of temperature forward. The antagonistic forces requisite to shear the cross-section of 13·4 square inches were here explained, by the irresistible force of heat expansion; in this case = 350,000 tons. The gas-check gave the knife-edge or shear, which no amount of pressure could have done, since the rule, that the limit of continued resistance in a cylinder was measured by the tensile strength of the metal, was only true circumferentially, and would have manifested itself in longitudinal ripping, as in a boiler.

Commander W. DAWSON, R.N., said that great strides had been made within living memory in the art of gun manufacture, not by soldiers or sailors, but by civilians, and chiefly by civil engineers. He gathered from the Paper that it was desired to raise the art of manufacturing guns into a science. The system of construction hitherto adopted had been a kind of rule of thumb. With a certain quantity of metal to be manufactured into a gun, it was left to experience to determine what the length of the gun should be, the size of the bore, the dimensions of the projectile, and the charge of gunpowder. Guns were built by very practical and distinguished men, but they did not pretend to construct them on any scientific principle. The Author had quoted a book to which the Secretary of State for War had put his name; but it should be remembered that that book had been written by certain young gentlemen who had come straight from the Academy at Woolwich, and not by Sir William Armstrong, or by any of the gun manufacturers. The fact was, the guns were built first and the mathematical formulæ found afterwards. What ought artillerists to exchange for the rule of thumb that had hitherto been adopted? The formulæ of mathematicians? Which mathematicians were they to follow? The Author had pointed out that Professor Barlow had said one thing, Dr. Hart another, and he another; and, since the discussion had commenced, two or three mathematicians had suggested other formulæ. Should gun-making stand still until mathematicians had determined the right algebraical expression? He had great respect for mathematicians, but he agreed with Dr. Siemens that mathematics, while a good servant, might be a very bad master. All the formulæ to which reference had been made were very well, if the values of the different letters could be obtained; but if those values were not ascertained by experimental data, the formulæ were simply so much juggling with letters of the alphabet. Of course the Woolwich system was theoretically wrong, and no one knew that better than the constructors of the guns. But they were perhaps practically the best available in the present state of metallurgical knowledge. A hard steel tube was put inside, and soft metal outside. What could be worse than that? Of course the soft metal outside expanded much more than the tough steel inside, and if it was overstrained it would get the "set" first. It was, however, necessary to look at such matters practically. If wrought iron were put inside heavy ordnance, as in Sir William Palliser's system for light guns, what would happen? It would not stand the erosion, and the interior of the bore would be guttered and soon destroyed. It might be said, "Why not put on steel jackets outside?" As far as he had been able to gather from the progress made of late, makers were constantly improving the manufacture of steel, so that probably in a few years they would be able so to manipulate steel as to produce any amount of ductility, or tensile strength, or any other quality, that might be required. He looked forward to the possibility of putting outside, not wrought-iron jackets, but steel jackets. It might be said that the plan had been already tried; and so it had. In Krupp's guns a steel jacket was used. It could not be urged that the Germans knew nothing of war, and never fought; or that they were a spendthrift nation, who liked to pay double the necessary price for their weapons. At all events, *primâ facie*, the expensive Krupp guns, which were steel, and were bought in preference to coil guns by every nation on the continent except France, had something in their favour. He had not read much on the subject of late, but a few years since he read a defence of the Woolwich system, based upon an attack on the Krupp system, and it ended in his being nearly converted the other way. The Author had described a gun which he did not wish to criticise unduly, because he felt most grateful, as a sailor, to civilians who devoted attention to subjects of this kind, and it was to them that the nation had to look for future progress. But looking at the gun, he did not know how the dead weight at the breech was going to hold on to the barrel when the gun was fired with heavy charges. The chase of the gun appeared not to have sufficient strength, and it had not been prepared for the accident of a double charge. It had hardly strength enough for a single charge. The weight ought to be carried farther forward. A space of 10 feet was occupied by the two charges in the "Thunderer's" 38-ton gun, and there was only $6\frac{1}{2}$ feet of free space. He had not been able to understand from the Paper how the gun was to be practically constructed, or how the tensile strain was to be equably applied. If the plan were of value, he should have thought that during nineteen years some talented engineer would have applied the process to strengthening the cylinders of steam engines. Reference had been made to the explosion of the 38-ton gun on the "Thunderer." It so happened that six years ago he had read, at the Royal United Service Institution, a Paper upon that very gun,[1] and he had traced certain injuries, not to the gun itself, but to the shot within it. He had during two or three years examined a great number of shot that had been recovered after being fired, and had found on the studs, which were alone supposed to touch the gun, certain marks which ought not to be there if the shot had come out fair and straight from the gun. They were wedge-shaped, or misshapen in various other ways. He was not allowed to see the guns themselves, being a sailor, and not a soldier, and he accordingly examined the published official reports with regard to the position of the marks inside the guns, and ascertained that a large number of the guns were injured by their own shot in coming out. The majority of these injuries took place not, as might be imagined, in the powder-chamber, but in the portion of the gun traversed by the shot—in most cases within 10 or 12 inches of the seat of the shot—and these "cracks," "burrs," and other marks in the bore, were directly traceable to the studs; in fact the marks within the gun and the marks on the studs agreed. It was no wonder then that English guns had "decidedly the lowest velocities," according to the official reports from Woolwich. When two similar guns were fired with similar shot and similar charges, and one shot came out at a maximum speed and the other at a reduced speed, what was the cause? The same force was developed in the powder chamber, and applied to the base of the two projectiles, but when the two shot came out of their bores they came out with different energies. It was evident that the differences of the momentum of the two escaping shot represented the force or power absorbed within the gun, in making the marks, and in injuring its own shot and the gun itself. Certain 400-lb. common shell were found to have their walls compressed by the studs wedging between the shell and the bore, and these walls had to be strengthened by reducing their powder capacity. Another thing he had observed was, that there was no relation between the powder pressure in the chamber and the velocity with which the shot came out of the gun. On the contrary, there was a difference of from 20 tons to 60 tons pressure per square inch on the base of the projectile, and yet the shot came out with the same velocity as before; or sometimes it was reversed, and it came out with less velocity when there was a high pressure on its base than it did when there was a low pressure in the chamber. These were facts, taken from the published reports, and it was upon them that he had examined the position of the injuries

[1] *Vide* Journal of the Royal United Service Institution, vol. xvii., p. 1.

on piles of recovered projectiles and in the reports on damaged guns, and had based the strictures he had made six years ago, on the gun that had now failed. His belief was, that whatever fault existed was not in the gun nor in the gunpowder, but in the shot, the exit of which from the bore was obstructed by the wriggling motion incidental to its being balanced on two points nearly under the centre, and to its having a rifle-bearing of less than 1 inch in each groove. The explosion in the "Thunderer" was not the first that had occurred. A 68-pounder of Sir William Palliser's construction had exploded, and Captain Dawson had endeavoured to discover the reason. He believed that the powder charge had only a secondary part in that explosion. The accident had nothing to do with the construction of that gun, for the gun was stronger than it was before; the sole cause was the wriggling of the studded shot in its effort to escape from the charge. The peculiar way in which the shot was balanced, in unstable equilibrium upon two points, prevented it sliding out as if on rails. Two bronze guns were exploded in India during experiments, and the marks within them were noted as the firing proceeded. Those marks were clearly shown to have been made in front of the seat of the studs by the studs, and not by the powder. When the accident on board the "Thunderer" was first reported in England, one of the causes assigned was, that there was an air space in the gun, and some authorities stated that that would burst the gun. In his experience as a naval officer he had had the responsible charge of firing from eight thousand to ten thousand heavy shot of the period, and he was quite sure that several hundred of them must have been fired with a space between the shot and the cartridge. It was difficult to get a heavy gun out in a rolling ship without a jar, which shifted the shot from its place; but he had never heard of a gun exploding, or any serious injury happening, from that cause. It was found by experiment, that if a gun were inclined 14° the shot would slip out a certain distance; and a roll of 14° for a ship was nothing, so that such a slip must be of frequent occurrence. He did not believe that an air space would lead to an explosion; but, if it were otherwise, it was disgraceful that he should be left in ignorance of the fact—that having had the firing of so many heavy guns under his charge, he should never have been told of this danger. It was often wanted to explode enemy's guns, and it was not known how to do it; so that the discovery that a little air was all that was wanted to destroy captured guns might be really useful. Another reason had been recently given, that there were two charges in the gun, of the united weight of 195 lbs. of powder and 1,315 lbs. of shot. Many persons might think that that circumstance was rather astounding, but it was a thing that must have frequently happened before. When fifty or sixty guns were being fired close together, it was difficult to tell whether one particular gun had gone off or not, so that in former naval actions many guns must have been so treated. The occurrence happened sometimes even in ordinary quiet target practice, and he had observed it in his own personal experience. On one occasion, when firing on board an eighty-gun ship, as he went along the battery he noticed that the rammer of a gun was not inserted to the proper distance, and he called out, "Not home." The captain of the gun replied, "Yes, it is home." Captain Dawson looked in, and found the gun was half full of charges. A worm was then brought, and three charges were pulled out, the fourth having been about to be put in. What would have happened if the gun had been fired with the four charges? There would have been a little kick, and that would have been the end of it. It was one of the old cast-iron guns, that were nowadays despised. The reason why no harm would have been done was, that there was no shot in the gun. It was the shot that did the mischief. If, however the shot could be made to glide away from its seat without wriggling, no mischief would be done: the gases would escape, and no explosion would take place. Whether the "Thunderer's" 38-ton gun exploded by detonation or not, the chances of its doing so would have been much lessened, if the shot could have slipped out of the way on rails with ease, instead of having to give several preliminary wriggles before starting fair. When investigating the question a few years ago, he had been puzzled at finding that a 10-inch gun, which had been boasted about a good deal at Woolwich, had been fired a great many rounds without being battered to pieces by its own studded shot, like other Woolwich guns. He found on inquiry that the studs had been clipped off the shot, so that their whole length rested upon the bore and they were able to come out freely, and the gun at the end of the firing was almost as good as it was on the day when it was made. The great evil of English guns was the extremely low velocity of the projectiles when fired, so that they hit very weak blows. Whilst the German guns had been subjected to the rough usages of war, the English heavy guns had never been tried in action except once, or in any way similar to a naval action. The only case was that of the "Shah" and the "Huascar." The "Huascar" was an ironclad, with as thin sides as the old "Warrior." After firing 16 tons of shot and about 431 rounds at her, the result was that one man on board the "Huascar" was killed. It should always be remembered that fifty shot had to be fired for one effective hit.[1] That was the practical way in which the question should be regarded. A gun was wanted that would fire fifty rounds in as short a time as possible, so as to make the one effective hit quickly, before the enemy could make his hit. Of course the gun got heated; then the interior expanded and the exterior expanded, and if the exterior did not expand at the same rate as the interior, but took a "set" sooner, the evil complained of would occur.

Admiral SELWYN thought the Author had shown quite sufficient energy and determination, and *primâ facie* argument, to justify him in seeking and obtaining, what all such matters deserved, an experimental trial. When it was stated that a gun could be built for one quarter of the cost of the existing guns, a good case was made out for a trial of the system. Guns of 100 tons had been sold to the Government for £16,000 each by Sir William Armstrong, and the nation would certainly desire to economise in that direction. He was not, as a sailor, competent to decide upon the question of the tensile strain into which a coil of wire would be thrown by the discharge of powder inside it; but he could hardly believe that an engineer would tell him that an effect might be greater than its cause. If the pressure gauges had shown an extreme pressure of from 24 to 27 tons per square inch, he did not see how the wire could get a greater pressure from any other source. Powder gas was made under certain conditions; it gave a fair record of its pressure wherever it found anything to crush; and he believed the authorities at Woolwich were satisfied that that strain under

[1] The old rule was, "The weight of the gun in shot to kill one man," or two effective hits per hundred shot fired. The shot fired at the "Huascar" were:

"Shah" fired	32 projectiles of	250 lbs. from	12½-ton guns =	3½ tons.
,, ,,	149 ,,	100 ,,	6½ ,, ,, =	6½ ,,
,, ,,	60 ,,	64 ,,	3½ ,, ,, =	1½ ,,
	241 ,,			11½ ,,
"Amethyst"	190 ,,	64 ,,	3½ ,, ,, =	5½ ,,
Total . .	431 ,,		Total . .	16 ,,

The range varied from 300 to 2,000 yards. The firing was spread over 2½ hours. Four 250 lbs. projectiles, two 100 lbs. projectiles, and four of the 64 lbs. projectiles struck the hull of the "Huascar," = 10 shots out of 431, *i.e.*, better than the ordinary rule of discharges, 2 per cent., or one hit in fifty. There were two perforations of the hull, and one man was killed and one wounded by these 431 projectiles.—W. D.

ordinary conditions was not practically exceeded in a gun. Sir Joseph Whitworth had made a gun of solid steel, in which he could burn away the whole charge through the touch-hole, the gun being plugged up. It was time attention should be paid to making guns stronger and of better metal; and, if the Author had been able to advance from two laws which were not applicable to the case to a law which was applicable, being only subject to a slight error of 3 or 4 tons, such a great theoretical advantage ought to be received with pleasure by gun manufacturers. There was a time when strong guns bore the pressure and the number of fires required from them with perfect stability. The bursting of an iron gun was rare, unless there was some extraordinary maltreatment. A new mode was then discovered of rifling guns, and thereby getting greater accuracy and a longer range with a smaller diameter and greater length of shot; but it was ascertained that, in order to produce the rotation of the elongated projectile as well as its projection, without greatly increased strain, there had to be a less powder charge; and indeed, even with less powder charge, strains were set up which could not be met by built-up guns. The powder was then changed for one resembling the weakest powders made in China and in India. It was good enough for its purpose, because it burnt over a long time, and in a long gun it answered very well. The guns next had to be made longer in consequence of the weak powder, and then it became necessary to enlarge the casemates to receive the longer gun. It was next ascertained, according to the late report of the Artillery Committee, that unless the gun was washed out carefully after every round, the shot tended to jam up against the fouling. If the guns were stronger, good powder could be used, and they might be shorter, and there would be no smoke in the casemates, which led to the abandonment of breech-loading artillery for ships thirty to forty years ago. He remembered seeing the first gun of that kind tried, and it filled the whole deck with a peculiar kind of smoke. When the breech of the gun was opened in the confined space after firing, the draught of air set up changed the carbonic acid gas, which would be the result of perfect combustion, to carbonic oxide gas—probably because the oxygen coming in took up some of the unburnt carbon remaining in the gun, and thus made CO instead of CO^2—which was of a very stifling nature. There was another reason for not using bad powder. It had been discovered that the same kind of powder would not do for more than two or three kinds of guns; that one kind was required for a mortar, another for a howitzer, another for a long gun, and so on. That of itself introduced objectionable complexity into the subject of powder supply in action. Sometimes, again, the whole charge ignited, while at other times many grains were unignited, and that caused a difference of range. All those were results of abandoning correct principles. The best materials should be employed for making powder gas, and the authorities ought not to be induced, by any deficiency in the machine in which the gas was used, to give up the manufacture of it from the best materials, and in the manner most calculated to produce perfect combustion. With regard to the closure of the bore, to which reference had been made: some years ago his attention had been drawn to a clever use of the cylindrical wedge by Major Penrice, who showed that, by taking a cylinder about the size of the shot belonging to a gun, and dividing it into three wedges, the base of the central wedge being towards the powder, no explosion of powder could drive that out of the bore; there was an irremovable wedge against powder impact, but a perfectly removable one against the slightest push. Thus the whole longitudinal strain was transformed into circumferential strain if there was radial strength enough, and there should be no necessity for the rather cumbrous machinery that had been brought forward. He did not find fault with it, as some had done, because he doubted whether the tensile strain could be properly calculated on the connecting bars outside. He had no doubt that the Author had calculated the tensile strain on his bars sufficiently accurately to dispose of the question. It was important to have as light a gun as possible. People said, "If you have a light gun you will have a heavy recoil." Colonel Moncrieff had shown an accurate and scientific mode of doing away with that objection. He had utilised the recoil, instead of allowing it to destroy the carriage, by making it bring down the gun into cover. He did not fear firing with the lightest gun that could be given to him. It was in a scientific direction that the objection was to be removed, just as the objection to bad powder was to be removed by increasing the strength of the gun, in whatever manner. No doubt solid steel guns would be more cheaply manufactured than with almost any other material. He did not know whether Dr. Siemens could produce a gun of solid cast steel, tempered as he had described, and as Captain Rodman had first described for cast-iron guns, at the same price as the Author had spoken of. But, even if that could be done, he saw no objection to having experiments with the Author's system; and he was quite sure that, when the House of Commons and the nation thoroughly understood that money spent in experiments on those subjects, under proper supervision and advice, was the cheapest and wisest expenditure, complaints would no longer be made by so many inventors that they could not get their principles worked out to the bitter end. Engineers, who well knew how much they owed to experiments conducted by members of their own body at great expense to themselves, and how the nation had benefited by them, would, he hoped, always be advocates of liberal votes for experiments. He was sorry to hear the Author say that he had no longer any other than a scientific interest in the question, because he knew that any invention in which only a scientific interest was felt was like an orphan child. Nobody put any money in it, because there was nothing to be got out of it. So many discussions on different systems would not have been heard in the Institution of Civil Engineers, if it had not been felt by the speakers that they had a property in the inventions, and that they could do something, better than anybody else could do it. That was a stimulus which he longed to see applied throughout the nation—a stimulus which would produce new industries, new trade and commerce; and, as soon as reasonable protection could be given to inventions, which were the seed-corn of industry, it would be found that England would not be behind America in its powers of production.

Captain Noble observed, through the Secretary, that with many of the Author's theoretical views he concurred. As far as he remembered, the formulæ he used were deduced (in an able memorandum by Mr. Brooks, which formed part of the Author's former Paper) from the expression for the strength of cylinders or hoops in common use; and these formulæ, or similar ones, no doubt underlaid the principles upon which all built-up ordnance of the present day was constructed. He could not, however, agree that the description given by the Author of the Armstrong mode of construction was at all in accordance either with the views or the practice prevailing at the Elswick works. In all cases when a gun had to be designed, the maximum pressure to which it was to be subjected was first determined. The dimensions and shrinkages of the coils were then fixed, the calculated shrinkages being greatly modified by the results of a long series of experiments carried on during many years, chiefly by Sir W. Armstrong personally. Rightly or wrongly, proof had, it was believed, been obtained that, with the shrinkages applied, greater strength was got than would be the case were the guns made in accordance with the rules recommended by the Author. He was also unable to concur in the view, that there was any ground for supposing that by the explosion of a charge of powder in a gun, that gun was strained to double the extent it would be were the same pressure gradually applied. As far as he knew, in almost all cases where material had failed under the employment of suddenly applied strains, such failure had, in his opinion, been chiefly due, not to the suddenness of the application, but to the fact that, from the *modus agendi*, energy in one form or another had been generated, so that, in addition to the ordinary strain, the material had had to bear the extra strain arising from this cause. So far from thinking that a gun, under the actual circumstances, would only stand half of what it would do were the pressure applied more gradually, he believed that many guns, owing to the almost infinitesimal time during which the highest pressures acted, withstood pressures that would undoubtedly cause their failure were such pressures of longer duration. As regarded the mode of manufacture for which the Author contended, he might mention that the same idea was independently proposed by the late Mr. Brunel, when attention first began to be directed to rifled ordnance, and that he asked Sir William Armstrong to construct a gun on this principle. The work was commenced, and would have been carried out had not Mr. Brunel countermanded the order, on hearing that a patent had been taken out by the Author for the same thing. It was afterwards found that a still earlier patent had been taken out by Captain Blakely; and he had been informed that a gun was made and tried in America on the same principle, under the direction of Professor Treadwell. Attention had been frequently given to the subject at Elswick, but the advantage of the system had been considered much more questionable on practical than on theoretical grounds.

Mr. Canet said, in the course of the discussion mathematicians had been taunted with being unable to agree amongst themselves as to the accuracy of the various formulæ propounded for giving the strength of a tube subjected to an internal pressure, and therefore it was argued that mathematics had nothing to do with the construction of ordnance, and that the well-known rule of thumb was the only safe guide. He could not agree with this, as it was not disputed that Professor Barlow's law was only approximate; but, if no notice were taken of the valuable indications given by theory, it would not be possible to judge accurately of the strength of guns of various systems of construction, which he considered was the subject under discussion; and the manufacture of ordnance would go on as at present, every manufacturer pretending to make the most reliable guns. The strength of cylinders had been fully investigated for the first time by Monsieur Lamé, who gave its true theory in his "Leçons sur la Théorie Mathématique de l'Elasticité des corps solides." From this theory was deduced the following formula, for the internal equilibrium of a cylinder subjected to interior and exterior pressures f_o and f_1,

$$t = f_o \times \frac{\rho^2}{y^2} \times \frac{R^2 + y^2}{R^2 - \rho^2} - f_1 \times \frac{R^2}{y^2} \times \frac{\rho^2 + y^2}{R^2 - \rho^2}. \quad . \quad . \quad (1)$$

In order to avoid confusion he had kept the same notation as the Author. This formula depended upon the admission that the metal forming the cylinder was equally elastic at every point of its mass, and in every direction—in other words, that the metal was homogeneous; so that, if the formula could not be applied to a metal, it would not be the fault of the formula but of the metal itself, which was not as perfect as was admitted in the formula. But, even in this case, the problem had been solved by an able officer, General Virgile, of the French artillery. He had assumed in his calculations three moduli of elasticity, varying according as the metal was taken radially, circumferentially, or longitudinally, thus allowing for all the variations that were likely to be found in practice. This involved long calculations, and for practical purposes formula (1) was sufficient. The Author, in his calculations of the strength of a gun, had taken a certain definite shrinkage, a certain interior pressure, and a certain modulus of elasticity. Should these three elements of the calculation not exist in the gun under consideration in the precise form that the Author had assumed, the calculations would have to be re-made. It was, for these reasons, difficult to compare one system of construction with another, in following the Author's method of calculation. But this could be done, he thought, simply as follows. It was obvious that in a gun no part ought to be strained, before and during explosion, beyond the elastic limit of the metal of which it was composed. If this condition was not fulfilled, the gun would be injured permanently at each round fired, and failure would be imminent. It was equally obvious that, to get the maximum resistance out of a built-up gun when the interior pressure reached a certain point, the interior surface of every layer or section of which the gun was composed (which was the part of each layer or section most strained) should be stretched at the same time up to its elastic limit. He therefore called the strength of a gun the maximum pressure per square inch that could be exerted in the bore without straining any part of the gun beyond its elastic limit, the shrinkage being disposed during manufacture so as to make each layer or section work to the utmost whilst the structure was under that pressure; and he had assumed in his calculations that these conditions had been fulfilled. To have

Q 2

the internal normal pressure at the inner surface of the $(n+1)$th ring, let in equation (1)

$$t = T_n$$
$$f_o = f_n \qquad f_1 = f_{n+1}$$
$$\rho = R_n \qquad R = R_{n+1},$$

then

$$f_n = T_n \frac{R_n{}^2{}_{+1} - R_n{}^2}{R^2{}_{n+1} + R_n{}^2} + \frac{2 f_{n+1} R_n{}^2{}_{+1}}{R_n{}^2{}_{+1} + R_n{}^2} \quad . \quad . \quad . \quad (2)$$

R_n and R_{n+1} were the radii of contact of the ring under consideration; T_n was the elastic limit of the metal of the ring; and f_n the normal pressure on the interior surface of the ring.

For the last ring, $f_{n+1} = 0$.

From equation (2) it would be easy to calculate f_n, then f_{n-1}, then f_{n-2} . . . . f_o.

He had made these calculations for several guns, taking for the elastic and ultimate stress of steel the figures given in Table I.

TABLE I.

—	Stress per Square Inch.	
	Elastic.	Ultimate.
	Tons.	Tons.
Wrought iron used at Woolwich	11	22
Oil-tempered steel for tubes	25	50
" " jackets reheated and cooled in oil.	21	40
" " " " " " atmosphere	18	35
Soft steel for exterior rings	16	32

These materials were used at the London Ordnance Works, with which he was connected, and the results quoted were obtained by direct experiment. The solid 10-inch guns, of cast iron, wrought iron, and steel, given for comparison, were supposed to be made of the same dimensions as the Woolwich gun. The 80-pounder B.L., 10-inch and 12-inch built-up steel guns, were of the construction originally adopted by the late Captain Blakely, R.A.,[1] and now manufactured by Mr. Vavasseur, M. Inst. C.E.

[1] Captain Blakely was, he believed, the first to construct built-up guns of steel. In the Exhibition of 1862 he exhibited several built-up steel guns. One, made at Liverpool, was of 8 inches bore; another, of 6 inches bore, was made by Mr. Vavasseur; while all the guns exhibited by Mr. Krupp were made of solid forgings, and had even the trunnions forged on.—G.C.

They consisted of a tube, jacket, and one or two layers of steel rings according to the calibre. He had selected these guns because they were those with which he was best acquainted.

It was easy to demonstrate mathematically that a sudden strain was equivalent in effect to double a steady strain of the same amount. On the other hand, Mr. Kirkaldy found by experiment that the effect of a sudden strain was equal to 81·5 per cent. of a steady pull. This depended, of course, upon the suddenness of the application. It seemed obvious that in a gun the strain was applied more suddenly than could be done in experiments, so that a strain of 81·5 per cent. was too much, and of 50 per cent., which was the theoretical amount, too little. In taking a mean between the two, say 66 per cent., or $\frac{2}{3}$, he would probably be nearer the truth, and the figures of the fourth column of Table II. had been so calculated. They showed clearly the maximum pressure that could be used,

TABLE II.

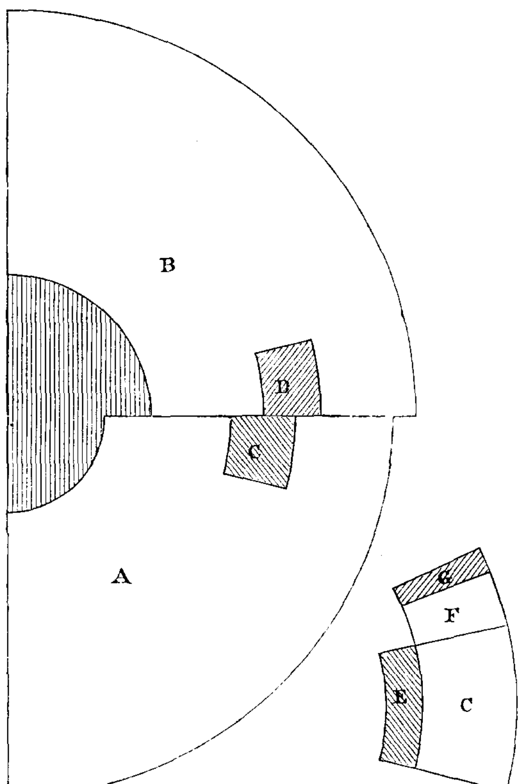
—	Greatest Diameter over Chamber.	Weight of Gun.	Strength of Gun per Square Inch in bore.		Initial Compression of Bore per Square Inch.
			Statical.	Dynamical.	
	Inches.	Tons.	Tons.	Tons.	Tons.
9-pounder gun, Woolwich construction, mark II. . . .	9·75	0·4	19·94	13·3	+ 0.9
Same gun, built up with steel .	„	„	29·17	19·4	−10·3
80-pounder B.L. built-up steel gun, Vavasseur construction .	22·5	4·0	34·32	22·9	−15·6
7-inch gun, 90 cwt., Woolwich construction, mark I. . . .	26·0	4·5	26·21	17·5	− 5·3
Same gun, built up with steel .	„	„	35·60	23·7	−16·3
10-inch solid cast-iron gun . .	45·0	18·0	5·44	3·6	0
„ „ wrought-iron gun.	„	„	9·97	6·6	0
„ „ steel gun . . .	„	„	14·50	9·6	0
„ gun, Woolwich construction, mark I.	„	„	23·84	16·0	− 1·3
10-inch gun, Woolwich construction, mark II.	„	„	28·62	19·1	− 6·6
10-inch built-up steel gun, Vavasseur construction . . .	41·0	16·3	39·74	26·5	−19·8
12-inch 38-ton gun, Woolwich construction	57·5	38·0	30·82	20·5	− 8·6
12-inch built-up steel gun, Vavasseur construction . . .	45·0	27·0	36·13	24·1	−16·7
80-ton gun, Woolwich construction	72·0	80·0	28·49	19·0	− 6·5

according to the system of construction, without injuring the gun permanently at each round. If greater pressures than those indicated for each gun were used, in order to obtain greater effects, then the life of the gun was limited to a certain number of rounds. Having found the strength of a gun, the next thing was to see that, in its initial state, the interior surface of the bore was not compressed to such a point as to be injured; and it was this condition that limited the strength of any gun. It was highly probable that the compression necessary to injure the tube of a gun was very great. The experiments made in crushing pieces of metal, that were allowed to give way laterally, did not certainly apply to cylinders that remained similar to themselves when under pressure. The results of his calculations were embodied in Table II. He found that the initial compression of the bore of the 9-pounder Woolwich gun was positive. By this expression he wished to convey the idea, not that the bore of the gun was in a state of initial tension, but that, with the proportions of steel and wrought iron adopted, it was impossible, on the basis of his calculations, to obtain the maximum amount of resistance from the materials employed; therefore the gun was slightly weaker than a solid gun made of the same steel as the tube. But if a steel jacket was substituted for the wrought-iron coil, the strength was greatly increased, and the gun would probably be able to stand well with any charge of powder, as it was easy in field guns to keep the pressure of the gases under 15 tons per square inch. He quite agreed with a previous speaker, that the Author had made an omission in not taking into consideration the lateral deformation of a cylinder when under pressure and submitted at the same time to a longitudinal strain; but the question of the shrinkage had not the importance that had been attached to it by the Author—on the condition, however, that the shrinkage was not less than that which was given by the theory, and not so great as to bring the outer layer on the point of breaking. Supposing it was so in the 10-inch Woolwich gun, mark II., and that the interior pressure was equal at each round to the strength of the gun, viz., 19 tons, too great a shrinkage meant that there was more tension on the outer rings than was wanted; consequently the rings would be strained beyond their elastic limit; they would be stretched permanently at each round, and the shrinkage would decrease accordingly till the gun was theoretically perfect. And if from that moment the pressure was kept under 19 tons, the gun would stand for ever, as far as the *tangential strength* was concerned; but if the interior pressure was above 19 tons, the injury would go on with the firing, till the tube, not receiving a proper amount of support from the external coils, failed by cracking. A gun of any construction subjected to an interior pressure greater than its strength, as explained, must ultimately fail. This was so well understood by the French, that it was a rule with them to test to destruction a gun of every calibre or system of construction that had been approved of for the service. They found experimentally the number of rounds that it would stand in actual practice, and therefore, when a gun issued for service had fired the number of rounds considered consistent with safety, it was withdrawn and condemned. If it was necessary to have guns of greater power of internal resistance than those shown in Table II., an increased thickness of metal must be added to the walls of the gun, or a stronger metal must be used, or a different system of construction—such, for instance, as that proposed by the Author—must be adopted. As to the question of heat, it did not at all affect the principles of building up; but simply increased the tension of the outer rings. Table II. showed the great difference in the strength of guns made of iron and steel, or entirely of steel. It was a curious fact that steel as a material for guns had been adopted in nearly every European country except England, where the manufacture of that metal was the best. Steel guns were now used by France, Germany, and Russia, also by Italy for field guns. The guns of the French navy had long been made of cast iron and steel. The theory proved what was already known by practice, that these guns were inefficient to resist high internal pressure, and, notwithstanding their great cheapness, and the alleged variable quality of steel made by French manufacturers—probably due to their want of experience in the manufacture of the large masses required for this purpose—guns built up entirely of the metal had been adopted for some time.

It might, perhaps, be interesting to mention, that wire guns had been experimented upon by the French Government. The system tried was that proposed by Captain Schultz, of the French Artillery. Four guns were made—two field guns of 3·15 inches bore, and two $7\frac{1}{2}$-inch guns, one lined with steel and the other with cast-iron. One of the field guns had fired, up to the time of the information he had received, 433 rounds, with projectiles weighing from 17·6 lbs. to 30·8 lbs., the initial velocity ranging from 1510 feet for the heaviest projectile, to 1887 feet for the lightest. The $7\frac{1}{2}$-inch gun lined with cast iron fired nearly 300 rounds. After the experiments no enlargement could be detected in the powder chamber. In Captain Schultz's design for a 24 centimètres ($9\frac{1}{2}$ inches) gun, there were over the chamber 34 rows of ·0945-inch steel wire, and 17 rows only in front of the trunnions. The breech mechanism, which was on the French system, was put into a separate breech-block connected with the trunnion hoop by twelve 4·4-inch steel bolts. The general dimensions of the gun were given in the drawing he exhibited. It would, he thought, be conceded by all, that guns must be built up; and if each layer of wire was considered as a steel tube whose tension could be regulated and varied at will, the system of construction to which the Author had invited attention seemed to provide tubes far stronger than any that had yet been made; and so far as practice had gone it showed that those guns were as strong as theory said they must be. When it was considered that steel wire was equal to an elastic stress of 80 tons, and a breaking strain of 120 tons per square inch, guns of this construction must have a great future before them.

Mr. Imray said that was the third discussion he had attended at the Institution on the same subject. The first discussion was twenty years ago, when wrought-iron guns were scarcely thought about; the second turned very much upon the question whether guns ought to be of cast iron or of wrought iron; and now, at the third discussion, cast iron seemed to be altogether ignored. The members of the Institution and the country were greatly indebted to the Author for calling the attention of the engineers of England to the question of artillery. There was no doubt of the fact that the present wrought-iron guns used in the English navy were not trusted by the sailors. After the terrible catastrophe that had recently happened, most of them felt that they would be safer outside the turret than inside. That was certainly an alarming state of things. At the time of the previous discussion, a commission was appointed by the Government of the United States to visit all the arsenals and factories throughout the Continent, in order to ascertain what was being done. After careful investigation of the proceedings at Woolwich, Elswick, and elsewhere, the commission recommended the United States Government to keep to their old cast-iron guns. The result was, that American ships were now armed with cast-iron guns of 12, 15, and 20 inches calibre, some of them delivering a blow twice as hard as any that could be given by wrought-iron guns. One of those guns, a 15-inch one, had been tried for endurance, and, after being fired 1800 rounds, was as good as ever. In the face of such facts it became a serious question whether the Government was right in making wrought-iron guns. Many persons had believed that the strain upon the interior of a gun was determined by the tensile strain of the metal of which it consisted. That was certainly a fallacy. That was not an occasion on which to enter into any discussion or calculation of what those strains were; but he might mention that, taking a strain of 20 tons upon the square inch inside a 12-inch gun, the utmost tensile strain that could be put upon the interior lining was 13 tons. Now it was well known that good cast-iron would stand 13 tons, and that with the present powders there was no such strain as 20 tons put upon the interior of a gun. He might be permitted to direct attention to a diagram, Fig. 2. The lower

Fig. 2.



part, A, represented part of the section of the gun before it was fired, and the upper part, B, showed the conditions of the parts at the time it was fired, of course much exaggerated. Taking the element of the metal of the gun as marked at C and D, that element was subject to three actions: first, it was compressed in itself; secondly, it was moved outward to an amount which was determined by the compression of all the metal outside; and thirdly, the circumference so pressed outwards had to be extended in proportion to the outward movement. Those three actions were what told upon every element of the metal. Looking at the enlarged figure below, and taking C to represent that element of the metal before it was subjected to the pressure, it would be found that by mere compression to the amount marked by the inner part E, without any tensile force at all, a certain amount of the metal would be spread out lengthwise, as shown by F; therefore the tensile strain was not what was due to the total extension of the element, but only the extra extension marked at G—the quantity by which that must be extended more than the metal compressed into it would give. Adopting that mode of computation, he arrived at the result he had mentioned, that the strain inside the gun was not so great as might be imagined. That accounted for the fact that cast-iron guns had served, and still served, better than almost any guns that had been used. He did not think that for that reason the manufacture of guns should be confined to cast-iron. At all events, it taught that the metal constituting a gun ought to be continuous; there should be no breaches of continuity from the inside to the outside. When there was a breach of continuity, what happened? The two metals, however intimately joined by shrinkage, were in two different states: the outside of the inner metal was under compression, and the inside of the outer metal was under extension; and the result was, that every time the gun was fired the inner metal struck a blow upon the outer, so that a continual loosening and degradation took place, which in time would be so serious that the whole strength would be in the inner metal, without calling to aid the outer metal at all. Such were the serious consequences that had followed in some of those guns. Another curious fact was, that up to the time when wrought iron began to be introduced the British had exclusively cast-iron guns; the largest were 68-pounders, and not one of them was known to burst under extreme strain. They stood remarkably well. Of the last 3,000 guns delivered at the Arsenal, only seven burst on proving; the rest stood, and did service. In the American war only cast-iron guns were used; they were made with great rapidity, many of them of inferior metal and with bad workmanship; and only one Dahlgren gun gave way during the whole war; but a number of Parrott guns had given way. With those known facts, it was a serious question, for the country and for engineers, whether the present system of building up guns was right. He agreed with Dr. Siemens, that better material than cast iron should be used. If steel could be got, let it be had by all means; also the lining tube—not to take any strain, but merely to form a part that could be renewed when it was worn or cracked, and another substituted. He could not help thinking that engineers ought to give as much attention as possible to the theory of the question, in order to ascertain whether they were on the right or on the wrong tack in the employment of the present expensive system.

Mr. P. M. PARSONS said the Paper contained, first, a criticism of the Woolwich guns, and then a description of a gun which the Author considered would be superior. He proposed first to remark upon the Author's own system. Two formulæ had been given in the Paper, one by Professor Barlow and the other by Dr. Hart, and they disagreed considerably. It was very unsatisfactory for a practical man to find two formulæ by eminent mathematicians disagreeing to such an extent, and the idea of taking as the true result something between the two appeared to him absurd. Either Professor Barlow's formula was right and Dr. Hart's wrong, or the reverse, or they might both be wrong. They could not both be right, and to take anything between the two was childish. The difference between them consisted in the bases on which the calculation was commenced. Professor Barlow assumed that the metal was merely stretched, that there was no compression, that although a cylinder might alter its form the cross-sectional area of the cylinder would always remain the same; whereas Dr. Hart assumed that the metal was compressed, and that the compression was about the same as the extension. In the case of a tube that was stretched, all the metal was in tension, and it could not be compressed unless the metal was forced into itself, so that the specific gravity would be increased; and that appeared to him to be impossible. He thought Professor Barlow's formula was the correct one. He had always resorted to it, and had found that in practice the results agreed with the theory. The Author having founded his calculation upon a wrong formula, his criticism of the Woolwich guns must be erroneous. The principle of his own gun would not be, of course, affected, but merely the different strains or tension of wire, and so on, which could be adjusted when the right formula was adopted. It appeared to him that the building up of a gun by strengthening the tube by tension was bad. If a gun could be made in such a way that each ring or tube should take the strain due to it, without putting any initial tension upon it, or just a little to satisfy the different elasticities of the metals, as was done in his own guns, having a reinforced steel tube surrounded with a cast-iron jacket without any initial tension, that would be much better than attempting to compress the internal tube to the necessary extent by an extensible metal outside. The Author's gun had an inner tube, as in the case of all guns which were built up, and he gave the choice of steel or cast iron. He hoped the Author would abandon cast iron altogether, because he was sure that it would be useless. If a rifled gun with an interior bore of cast iron were fired with heavy charges, it would be soon cut to pieces. Moreover, a cast-iron tube of such size would never bear the pressure of so great an amount of steel wire wound round it: the tube would be crushed, and it would be of no use when subjected to alternate compression and tension caused by firing heavy charges. Taking a steel tube to begin with, there was no doubt that to wind wire round it with a proper amount of tension, each layer receiving its due share, would be the most economical way of applying the material to get direct strength out of it. If instead of that the steel was tempered in oil as much strength could be obtained, but a little more material would be required. From 25 to 30 per cent. more material would be needed in hoops of the ordinary size to get the same strength as in the Author's system, and that would only amount to an addition of about 5 per cent. on the total weight of the gun. Then the question arose whether all that complication paid, and whether the tempered-steel tube would not be more economical, and much easier to apply. One important defect in the proposed gun was the want of longitudinal strength in the inner tube. The Author evidently thought that there was no longitudinal strain upon the inner tube, or that the strain, whatever it might be, was taken up by putting a mass of cast iron at the breech end. That was an idea from which he totally dissented. If a gun tube had a projectile screwed into the bore, and a charge was ignited between it and the end of the bore, it would be admitted that, in addition to the circumferential strain, a longitudinal strain would be set up tending to pull the tube in two; but the same strain would occur if the projectile was free to move forward to almost the same extent. The hold on the tube would then be made up of, first, the pull of the projectile due to the rifling; secondly, the friction of the wad driven against the side of the bore, or, if no wad were employed, the friction of the gas rushing between the projectile and the bore; thirdly, the friction of the gas rushing forward against the whole surface of the bore behind the projectile—the two last amounting to about the same as if a solid copper cylinder, fitting tightly into the bore, were being drawn out at the same velocity. There was nothing in the Author's gun to resist that strain except the strength of the tube itself. The wire would be no good, and the cast-iron casing was so thin that it would be of no use even if it laid hold of the tube; but the wire being continued all along to the muzzle, the cast-iron casing only abutted against it at the muzzle, and would be of no assistance to resist the strain set up at the breech end. If the mass of iron were taken away from the breech, and distributed round the exterior so as to bring the longitudinal strength of the cast iron to the tube, the gun, he believed, would be considerably improved. As a proof that the Author's idea of the longitudinal strain was erroneous, in a 12-inch gun there was a pressure at the moment of explosion of upwards of 4,000 tons, tending to blow the gun backwards. If the whole of that pressure were exerted in sending the gun back, it would be blown to the other side of the turret, whereas it was under complete control by the compressors and the weight of the gun. In a small-bore rifle the pressure set up inside was about 2 tons to the inch, which would give a pressure of 700 lbs. on the end of the bore, and if that pressure were effective in forcing back the rifle, no one would be able to fire it from the shoulder. The actual pressure of the recoil was only about 30 or 40 lbs., showing that a large portion of the pressure was absorbed in pulling the barrel forward. He should have been glad if the Author had entered into some of the practical details of the construction of his gun. There were difficulties that had occurred to him, which probably had been considered and overcome. In the 150-ton gun there would be about 32 tons of steel wire. Of course it could not all be drawn in one piece; it must have joints; and if there were joints there must be weak points, and if there were any weak points the whole thing would fail. With regard to the Author's criticism of the Woolwich gun, as it was based upon an incorrect formula, a great deal of what he had said was not applicable. Mr. Parsons was not there to defend the Woolwich guns; he did not agree as to the correctness of the principle upon which they were constructed, and there were many practical points in them which he condemned. But he thought the Author was in error in supposing that the officers in the Gun Factory were guided by the text book he had referred to in putting on the coils. There was plenty of mechanical and mathematical ability at Woolwich, and he believed all the coils were put on at a proper tension, or as nearly as they possibly could be by any mechanical engineer. It was hardly fair to assume that they were put on by one hard and fast rule. He had himself always assumed, in his criticisms, that the tubes and coils were put on with a proper amount of tension, so as to get the utmost amount of strength out of the metal. But when that was done, he still found that the Woolwich guns were not up to the mark for calibres above 9 inches. At the reading of Mr. Britten's Paper, in 1872, he had stated that he had calculated the strength of the guns from 9 to 12 inches.[1] The 9-inch gun would bear a strain of 24 tons to the inch when the metals were strained up to the elastic limit, and the 12-inch gun would bear a strain of about 28 tons. In calculating the pressure as indicated by the pressure gauge, and the respective weights of the projectiles per square inch of bore, he found that, while the pressure in the 9-inch gun was 24 tons, in the 12-inch it was 36 tons. There was an increase of only 15 per cent. in the strength, whereas there was an increase of 57 per cent. in the strain. Therefore, if the 9-inch gun was only just strong enough the 12-inch gun must be too weak. That appeared to have been the case in the "Thunderer" gun, and he believed that a certain action was going on in the tube at that part which caused the gun to give way, which he would endeavour to explain. If the circumferential strength of the "Thunderer" 38-ton gun were calculated, it would be found that at the breech and C coil it would be about 28 tons per square inch at the elastic limit of the metals, taking the wrought iron at 10 tons, and the tempered steel tube at 28 tons per square inch. Of this the tube contributed about 10 tons, and the wrought-iron coils about 18 tons. If the circumferential strength at the point where the C coil ended was also calculated, it would be found that the strength suddenly dropped to 18 tons, of which the tube as before contributed 10 tons, and the B coil only 8 tons; and if the longitudinal strength of these two parts of the gun were also calculated, it would be found that, if the strength of the part surrounded by the C coil was represented by 100, the part beyond, owing to the halving together of the breech and B coils, would only amount to 22, or, taking the tube into account, as 100 to 44. There occurred, therefore, at this point a serious and sudden diminution of the support afforded to the inner tube, sufficient to account for its rupture even with ordinary charges; and the more so that, owing to the use of pebble powder, the maximum pressure would probably be developed when the projectile arrived about

[1] *Vide* Minutes of Proceedings Inst. C.E., vol. xxxiv., p. 257.

that point. The tube would be subjected to undue expansion, which would injuriously strain it circumferentially, and that expansion would set up a shearing action between that part of the tube thus unduly expanded and that part of the tube prevented from expanding by the superior support of 10 tons per square inch afforded to it by the C coil. At the same time, at this very point, it would be subjected to a greater longitudinal strain than in any other part of its length from the greatly diminished strength of the outer coils occurring at the same point. Whether or not the disaster on board the "Thunderer" was immediately caused by a double charge, it was evident to him that these guns were constitutionally weak, and would all burst after firing a certain number of rounds with battering charges. The question then was, what was to be done with those guns. He had said long ago that the only way to strengthen them was to put on an additional hoop of steel, by which they might be brought up to from 28 to 40 or 45 tons per square inch; but in that case it would be better to do away with wrought iron altogether, and put on a cast-iron jacket, as then the guns, even if overloaded, would not burst explosively. This was proved by the test of his converted 68-pounder gun, which fired 163 rounds with charges of R. L. G. powder 20 per cent. heavier than the two charges, combined, which were supposed to have burst the "Thunderer" gun,[1] in proportion to the weight of gun, and besides these, two charges, which were 50 per cent. greater. All that had occurred was this: the inner tube expanded slightly beyond its elastic limit, but well within its breaking limit, and this was sufficient to burst the cast-iron casing, which quietly opened, showing a crack from the trunnions to the breech, thus giving palpable warning to cease firing, which warning being attended to, no explosive burst took place.

Mr. E. A. Cowper could not agree with the statement in the Paper: "It is generally admitted that a sudden change is equivalent in effect to double the amount of a steady strain, so that in the present case the effect would be equal to a steady strain of 55·06 tons per square inch." He did not believe that that was practically the case, nor generally admitted. If a weight came suddenly upon a piece of iron there was a certain small amount of excess of strain, due to that fall. In order to explain his meaning he had suspended a piece of indiarubber with a weight at the bottom. It would be seen that when the weight was put

[1] *Vide* "Report of the Committee appointed to inquire into the cause of the bursting of one of the 38-ton guns in the turret of H.M.S. 'Thunderer;' with Minutes of Proceedings, 24th January to 13th February, 1879," &c. London. Folio. 1879.

on steadily it carried the indiarubber down to a certain point, while if it were put on suddenly it went down lower, by the force of the momentum of the falling weight. That was the case of a falling weight; but it did not apply to a gun, where there was no falling weight. There was pebble powder lying close to the side walls of the gun. There was as much powder gas at the sides as in the middle; the gas neither moved from the centre to the sides nor from the sides to the centre. When the powder was fired, there was an elastic pressure against the sides of the gun, but there was no weight or motion, except at a speed due to the gradual burning of large pebble powder. Quick burning sporting powder gave greater speed and a greater strain. There was practically no momentum if he were to blow air into an indiarubber ball. Every time the ball was blown into, it expanded a little, but there was no momentum. He did not believe that there was anything like a double strain on the metal due to the strain coming on at the speed it did with pebble-powder. If that were the case, all the guns made on that principle would have burst long ago. It would not have been a question of degree of endurance; they would have burst at the first round. As a matter of fact, the Woolwich guns did not burst. It was all very well to calculate, and to say that they must; the fact was, they did not. They had been made to burst by way of experiment, but those in actual service did not give way. The guns were much heated inside with quick firing, and he did not think that point had been sufficiently investigated. He did not know of any exact experiments to ascertain the precise temperatures, and strains upon the rings and inside tube. The thinner the inner tube, the less it would bear the compression of hoops shrunk upon it; if the inner tube were much hotter than the hoops, the compression would be very severe indeed; and the thinner the hoops were, and the greater their number, and the thinner the tube, the greater would be the effect. In a Woolwich gun, of course the solid metal conducted better than a greater number of hoops would do, and therefore the difference in strain was not so great. However a gun might be sponged, or water sent into it at great pressure, it was impossible to prevent the heat from getting through the body of the gun; and the hoops outside the steel lining would be very hot, and it was impossible to get at them. He could not agree with what had been said as to the increase in pitch. He had made the first rifling machine for Mr. Lancaster. The first rifled guns used in service were employed in the Crimean war; they were 68-pounders, and were of cast-iron. Mr. Lancaster wished to have a considerable increase in the pitch; Mr. Cowper endeavoured to persuade him not to have it, and he now thought, as then, that an increase in pitch was wrong. A shot would increase in rotation as it increased in rapidity of motion forwards; when there was a great increase of pitch, the shot was apt to pull off the muzzle of the gun—a result which he had himself seen in several guns.

Captain R. A. E. Scott, R.N., said that Mr. Cowper's statement with reference to the increased twist was certainly true; and he might have added, that as slower-burning powders were being used there was no reason for rifling the guns with an increasing twist. One point, he thought, had been rather under-estimated, namely, the waves of pressure. Mr. Cowper appeared to think that there was no sudden wave of pressure in the gun. But in the trial of 7-inch guns (the rear end of the inner tubes of which were made circular) the rebound of the powder gases was so great after striking against the shot, that they positively bored through the breech-end of the inner tube. All the tubes were partly bored through at an early date, and the tube that was most bored into was that of the gun firing the expanding shot. In fifty rounds the inner tube of this gun was nearly cut through. The Paper was a very able one, and there was every reason for calling attention at the present time to the whole system of artillery. The Author thought that the present service guns were not strong enough—that they were so near the limit of their strength that a little more would burst them. He did not quite agree in this view, but concurred in what Captain Noble had said as to the suddenness of the pressure, and the short time it acted upon the inner part of the gun, admitting of a much greater strain than would really burst it if the shot were detained longer. But it was obvious that as the gun was so near its limit of elasticity, everything that tended to check the projectile in issuing out of the bore ought to be avoided. The projectile might be checked by indentation or erosion of the bore, by the fouling of the gun, or by an unequal yielding of the studs. The first effect of the pressure was, to crush the lower studs and push the service projectile down to the bottom of the bore. It was there shoved along, just as anything might be dragged over a dirty road; but if the shot had long flanges it would rise, centre itself, and run smoothly out of the bore. In an experiment which had been made with a smooth-bore cylindrical shot and a rifled one, the rifled shot went out of the gun at a greater velocity, and apparently more easily; but at that time the pressures were not measured. The Author had proposed a gun of very great strength. Without giving an opinion as to whether the wire system was the best possible, he had no doubt that for new guns it would be desirable to have the great strength which wire would afford. He did not wish to criticise the details of the proposed plan, though many who had some knowledge of practical gunmaking could probably dispose of the solid portion of the metal in a better way. For himself, he had no fondness for cast iron. Notwithstanding what had been said as to the American guns firing heavy charges, the reports which had been received here showed that the charges for rifled guns were very low, and that the reason why the Dahlgren guns had not burst was, that they were not rifled. The smooth bore did not require the same strength as the rifled gun. The Parrott guns were not made of bad metal, but through being rifled they cracked and blew their muzzles off. It was scarcely correct to say that wrought-iron English guns had not burst. He recollected the "Shunt" gun bursting with a powder charge one-quarter the weight of the shot, and he was present when a 12-ton gun blew out its breech. He observed that the Author, in the case of the 150-ton gun, proposed a muzzle-loader, and in that he fully concurred. His experiments, however, were made with the breech-loader. In the details of this gun, as well as in the details of its carriage, he thought there was a good deal that was not quite practical. But though he had not an intimate knowledge of metals, he had been immediately concerned with the mounting of guns, and so could assure the Author that it was necessary to have a high carriage in order to obtain room for sufficient elevation and depression, as well as for the appliances for working the guns. The carriages used at the present time, including those in the after turret of the "Thunderer," on which 35-ton guns were mounted, were as low as they could well be made. If they were lower, the gear would have to be out of sight. The whole subject was a national one, and if it increased the safety of the crew or the power of the ship they ought to have breech-loaders. But the facts of the case did not bear out this. The experience with Prussian guns, firing 6 lbs. of powder, afforded no criterion as to the results of firing 150 lbs., 200 lbs., 250 lbs., and sometimes 400 lbs. of powder. A breech-piece would have to be enormously heavy to withstand such charges. The mechanism would occupy a great space, and there would be immense difficulty in handling it. But was it necessary to adopt breech loading at all? He was confident that it was not. Several turret vessels were provided with 18-ton muzzle-loading guns; the "Glatton," "Monarch," and "Hotspur," with 25-ton guns; the "Devastation" with

35-ton guns; and in the after-turret of the "Thunderer," 35-ton guns. Then it would be asked, "Why did the accident occur in the 'Thunderer'?" Simply because the loaders of the fore-turret were out of sight. It was true that there were fewer men inside; but the fact had not been sufficiently understood that the loaders were outside, so that the turret officer could not see what they were doing. Having mounted the muzzle-loading guns above-mentioned, he might be permitted to say that no accident had happened with any of them. It was true that the system of hand power and hand loading was alone used, but there was not the slightest difficulty in applying steam gear also, and falling back upon the hand gear if a valve or other appliance should fail. Although 35-ton guns were now mounted in the after-turret of the "Thunderer" there would be no difficulty in putting in 38-ton guns and loading them in the same way. Those who had practical knowledge of the working of heavy guns on board ship had foreseen the danger of loading from the lower deck, and he believed that the accident had occurred just as the Committee had reported. As to muzzle loading by the ordinary method, there were advantages in it which had been much overlooked, apart from its security. In firing, the gun was usually slightly elevated, and when it recoiled, it was loaded at once from the muzzle without any alteration of the elevation. The present pebble powder gave an enormous mass of dense smoke. The result would be that the enemy could not be seen; and hence, if the elevation had to be changed for the purpose of loading, the next shot would be likely to fail. This was an important point in favour of muzzle loading. He did not think that a large breech-loading gun would be found to be safe in the hurry of close action at night; nor did he think that the experiments about to be carried on in Prussia would convey any correct criterion as to the safety of the plan. A 72-ton breech-loading gun might be worked in daylight, and no accident might occur; but in a turret, men could not see well, and the officer would need a hundred eyes to overlook what was done, so as to prevent accident, with a breech-loading apparatus. Prussian naval officers had told him that they had great difficulty in keeping the breech of their heavy guns tight, and that they preferred muzzle loaders. He believed the present British service guns were good and serviceable, and would be safe if existing obstructions were removed, so that the shot might glide steadily out of the bore. With regard to the inner tube, if it were made thinner he did not know but it would stand better. His own experience was, that the thinner the tubes the stronger they were in proportion; and he believed if a tube were drawn with rifling in it, it would be still better. He did not think any solid metal could be adopted which would be superior to Sir Joseph Whitworth's compressed steel; and therefore either this alone, or in combination with wire, was the direction which should be pursued in making new guns. He did not see much force in the arguments that had been advanced against the Author's wire system.

Mr. W. H. BARLOW, Vice-President, said it might be thought that the Author's ingenious specimen of a wire gun had been put forward at the Institution as a complete novelty, but it was not so. When at the Philadelphia International Exhibition of 1876, he saw exhibited a specimen of the Woodbridge gun, made on the same principle. The gun was described in the report of Major W. H. Noble, R.A., a judge of that department. It appeared that the Woodbridge gun was not altogether a new one,[1] as it was said to date as far back as 1850. In 1865 a trial was made of a 2½-inch gun which demonstrated its great strength and endurance, and another trial was made in 1872. He had not heard how the gun shown at the Exhibition had behaved. He desired to mention these facts in order that it might not be thought that the Institution was unaware of the existence of such guns.

Mr. LONGRIDGE, in reply, observed that the principle he advocated had been brought before the Institution by himself eighteen years ago. The breech-loading gun now exhibited was made and fired in 1860; and in 1867, in a Paper which he had sent to the Institution, but which was not read, there was an exact description of the gun, with drawings. Questions of priority were never satisfactory, and he did not wish to enter into them. His object in bringing the matter again before the Institution was not to advocate anything new, because his propositions were much what they were nineteen years ago, but he had carried them out into a practical form. The objections then raised were not against the principle, but as to the impossibility of giving a practical form to his proposals. He had again brought the subject forward in order to show that it was not simply a scheme which had entered into his brain, but that he had considered all the necessary details. It was not simply a matter of theory; but, like all true theories, a matter which could be easily and economically reduced to practice. Several speakers had referred to the subject of formulæ. General Sir John Lefroy did not dis-

[1] *Vide* 'Reports on the Philadelphia International Exhibition of 1876,' vol. i., p. 159. London, 8vo., 1877.

pute that formulæ were of some use; but he said that at Woolwich facts were preferred to formulæ, "that mechanics were governed, not by formulæ, but by facts," and that "experience taught much more than formulæ." He begged to differ from Sir John Lefroy. Formulæ could be nothing but an expression in symbolical language of absolute truth. If a formula was not that, it was a false formula; either the mathematics were wrong, or the data which were the constants in the formula were wrong. It had been said that half-a-dozen formulæ had been brought forward, but in truth there were only two. One was that of Professor Barlow, which any one who examined it could see was wrong, because he assumed the area of the ring to be constant. His own formula, Dr. Hart's, M. Lamé's, and Dr. Hopkinson's, were identical. Dr. Hopkinson had kindly pointed out that he had omitted to take one element into consideration. When there was a tensile force and at the same time a normal compressive force, there was a tension arising out of the latter which he had not taken into account. To have done so would have complicated the formula, and he felt that the effect would be inconsiderable. He was much pleased, however, that Dr. Hopkinson had worked it out to the rigid formula; and the result was that, instead of a tension, in an extreme case, of 17 tons, he had found the tension to be $18\frac{1}{4}$ tons. Guns might, of course, be calculated upon that more exact formula, but the labour of calculation would be much increased without materially altering the result. Sir John Lefroy had stated that the guns at Woolwich were quite perfect; and other speakers, especially Mr. Cowper, had repeated the statement. He had for a long time kept a list of Woolwich guns which had their tubes split; he had, unfortunately, lost it; but, by way of an appeal to facts, he would refer to an extract from the Quarterly Report of the proceedings of the department of the Director of Artillery, minute 34,636, 16 : 3 : 77. The Superintendent of the Royal Gun Factory reports "that, on examination of 30 : 12 : 76 of the experimental 80-ton gun, it was found that the steel tube was cracked, the split being in one of the rifle grooves; widest at 70 inches from bottom of bore, about the position of maximum pressure, and extending about 15 inches along the groove in both directions. An incipient crack appears in the opposite groove. He will forward a more detailed report." Two months afterwards the Director of Artillery forwarded the foregoing Report to the Secretary of State for War, remarking "that the crack is unfortunate, but shows the great strength of the structure. The gun has fired one hundred and sixty-six rounds, and, although the tube cracked, the gun itself has not given at all. The experimental 35-ton gun had a split tube after sixty-eight rounds, and the gun was fired in that condition for five rounds, and, although the crack increased, the gun itself showed no signs of damage. The gun was designed to pierce a 20-inch plate at 1000 yards. It was calculated that this gun, with a 16-inch calibre, firing 300 lbs. of powder and 1,700 lbs. projectile, would effect this. The experiments point out that this effect will be obtained. The Explosive Committee, finding that an addition to the charge greatly increased the power of the gun without giving any great increase of strain, proceeded to fire the gun with much increased charges, so that sixty-nine out of one hundred and sixty-six rounds have been fired with 370 lbs. of powder. The Director of Artillery has no reason to doubt that this is the cause of damage. Valuable information has been obtained, and the gun has shown great strength and endurance." After some further rounds, he continues: "Third crack discovered. Thinks gun is slowly breaking up." That was one of the facts upon which, he presumed, Sir John Lefroy relied to defend the system of Woolwich construction. It was a fact that might have been predicted by any person who had made the calculations upon the assumption that the statements in the text book as to the shrinkage of 1 in 1,000 were correct. It had been stated that that text book was not worked by at Woolwich, and that it had been drawn up by two or three young gentlemen who had just left the Royal Military Academy. On the contrary, it was a book published by order of the [Secretary of State for War. The previous edition had been written by Captain Stoney and Captain Jones—one the Assistant Superintendent, and the other Captain Instructor, in the Royal Gun Factory. The present edition was written by Major John F. Owen, Captain Instructor in the Royal Gun Factory; and it also was published by order of the Secretary of State for War. The book professed to give an exact account of the work at Woolwich. Major Owen was not a young man who had just left the Royal Military Academy, but one of the gentlemen recently sent to Malta to report upon the "Thunderer" gun. The book was only published last year, and it ought to be accepted as evidence of what was done at Woolwich. If it had not been so he should not have brought the book before the members. It had been urged against his own proposal that he had not put the heavy material of the gun in the right place. He had tried to explain that there could be no longitudinal strain upon the inner tube of the gun; but it appeared that he had failed to make himself intelligible, at any rate to Mr. Parsons; because, although Fig. 9 showed that the breech was closed, not by a solid tube, but by a plug free to move, only abutting against the iron, Mr. Parsons persisted in saying that the strain must come upon the tube itself, and would blow the breech out, whereas there was no strain whatever. By removing the four bolts and applying pressure, the breech plug could be pushed out of the tube altogether. It was exactly the same in the breech-loading gun exhibited. There was no strain on the chase, except a compressive strain, due to the action of the shot, which was very slight, tending to force the chase of the gun forward. It had been stated that it was impossible, according to his plan, to give sufficient longitudinal strength. On the contrary, this was a simple matter; there were two solid side rods which could be made of any desired strength. In the case of a large gun he proposed to make them of steel plates laid side by side. One speaker had stated, that there was a weight of 4,000 tons acting upon the breech; if it were 10,000 tons, all that would be needed was to make the side rods of a sufficient area so as to give no more than 3 tons or 4 tons per square inch. That was easy and simple, and it avoided all the complication of strain which Dr. Hopkinson had pointed out as arising wherever an attempt was made to have two strains at right angles in the same piece of iron. In large breech-loading guns that would be found a serious matter. Dr. Siemens said, "One great drawback to the Author's proposed system, which he himself admitted, was that he had a resistance against bursting strain without resistance in the longitudinal direction." The Author did not admit this to be a disadvantage; instead of a drawback, it was a great advantage, as the system, especially for large breech-loading guns, afforded facility of construction and safety. He would now refer to other criticisms of Dr. Siemens. If Dr. Siemens were right in his conclusions, his objections would be very serious; but he thought he could show that Dr. Siemens was entirely wrong. He had misrepresented (not intentionally) that he had, in giving his idea of a gun constructed on the Woolwich principle, referred to a 9-inch gun with a tube 8 inches thick, and with 28 inches of iron outside. It would be seen from the Paper that it was not a 9-inch but a 16-inch gun. The gun was not such a gun as he would propose to make; but, his object was to show that a gun could be made with the same number of hoops as a Woolwich gun, and yet no hoop would be strained more than 10 tons per square inch. Dr. Siemens had mistaken the radius of the bore for the thickness of the tube: the radius was 8 inches, the thickness 6·39 inches. The iron outside the two tubes was 28 inches. Fig. 6 showed the exact tensions, both before and during explosion. The compressive strain was not confined to the steel tube; it extended to the steel tube and to the first iron tube, and it was exactly balanced by the tension of the outer tube. Dr. Siemens and other speakers seemed to think that necessarily the whole compression must be thrust upon the inner tube; but that was a mistake. It was an error to suppose that the great tension he would put on would crush the inner tube. He could put any compression or tension upon it that he liked. In the case of the large 150-ton gun which he had proposed, the cast iron would never be under more than 12 tons compression. When it was fired it would not have more than 3 tons tension, yet it would stand an internal pressure of 24 tons to the square inch. He could not then stop to demonstrate it, but if anyone would examine the formula he would see that it was so. He had not said, as alleged by Dr. Siemens, that a shrinkage of 1 in 1000 was not sufficient for such a gun, but that the shrinkage was a governing factor, a most important one, and that it must depend upon the modulus of elasticity of the materials, and the dimensions of the rings. A gunmaker might say, "I will make a gun with a shrinkage of 1 in 1000;" but then the rings must be proportioned to that shrinkage, and that could not be done without a formula. He had referred to a sentence in the text book, with regard to which he had said it was difficult to imagine a more complete confusion of ideas than that which pervaded it. Dr. Siemens, in his criticism, had alluded to the wrong sentence, namely, that "guns of present construction, ... during the process of shrinking." There was no confusion of ideas in that sentence, and it was not that to which he referred. The sentence which he had criticised was: "Much will depend upon the thickness and strength of the coil to be shrunk on, for the heavier it is the tighter will be its grip, and the more will the inner parts be compressed and supported; whereas a thin weak coil would probably suffer from over tension." It was of that sentence he had said "a more complete confusion of ideas could not exist;" and he still maintained it. He next came to another objection which, if Dr. Siemens were correct, would certainly be serious, although it might be provided against. Dr. Siemens seemed to think that by the heating of the gun after firing all the tensions would be thrust adrift and destroyed. That was an error arising from a misapprehension of the cause of the heating of the guns. It was not caused, or only to a small extent, by the combustion of the powder. Even assuming the powder-flame to be at a temperature of 5000°—which was the outside it had ever been taken at—and that it was in contact with the chase of the gun during the whole time the shot was in it, say $\frac{1}{100}$ second—which was also beyond the mark—the total amount of heat absorbed would be $\frac{15}{100}$ unit per square foot acting upon about a ton of metal in a large gun; consequently it was impossible that the heating could arise from the flame: it arose from the sudden state of tension into which the material was thrown. If a bullet was squeezed in a vice it would become hotter. If mechanical energy was employed in any way in compressing material, heat was produced. The heating of the guns, therefore, was not appreciably due to the flame, but to the severe tension produced in the material. That was the point on which his gun had so great an advantage over others. The tensions became at the end uniform throughout. The guns could be made so that when they were hot they were absolutely perfect with regard to their tensions, and when they were not hot they were slightly weaker than they would otherwise be. He had calculated that weakness, and it was inconsiderable. With regard to Dr. Siemens' proposal, he could not think that it was practical. Possibly Dr. Siemens had in his mind the Rodman gun, which was cooled from the inside when in a fluid state. He had proposed to make a cylinder gun, to put it in a furnace, to raise it to a high temperature, about 600° Centigrade, and then to cool it in the inside to 60°. He had no hesitation in saying that in the case of a 12-, 18-, or 20-inch gun that was physically impossible. If air were sent through it at zero, the internal surface would never be below 579°; if cooled with water at freezing point, it would not be ever below 500°. The material could only give off a certain amount of heat from the inside, and it took a certain amount of heat from the outside, which was three or four times as large. But even if the proposal could be carried out, what would happen? The gun might be kept ten hours in the furnace; and no doubt, while the cooling was going on, and the outside was hot, there would be a varying strain throughout the gun. But when it was taken out to cool (it could not be cooled from the inside right through, as in the Rodman gun), what would happen? The gun would go back to the original condition: the 12-inch bore which was expanded would go back to 12 inches; the 24-inch bore to 24 inches. He therefore maintained that Dr. Siemens' plan was physically impossible. If it were possible, he would only arrive at an approximation, and then at an enormous expense.

He would now briefly refer to the remarks of Captain Noble. In the first place, he desired to give all credit and honour to his friend Mr. Charles Henry Brooks, who had made all the mathematical calculations for him. That fact had been stated in his former Paper, and he did not refer to it again because he thought it was so well known. Captain Noble stated that he agreed with a great many of the theoretical views in the Paper, but he could not agree that the description of the procedure at Elswick ought to be regarded as correct. Mr. Longridge had given no description of it; he had not said a word about Elswick except what was extracted from the Woolwich text book to which he had referred. He presumed that the writers knew what was going on at Elswick; if not, they ought to apologise to Elswick. Captain Noble had stated that calculations were made at Elswick at the present time. It would be in the recollection of many members that Sir William Armstrong, nineteen years ago, said there was no attempt at making calculations; but at present it appeared they were made. Captain Noble stated that the calculated shrinkages were greatly modified by the results of a long series of experiments. He protested against that as utterly unscientific. If the formulæ were right, the shrinkages must be the right ones, and it was impossible to strengthen the gun by departing from those shrinkages. He was glad, however, to find that rules were now applied at Elswick. He believed that the Elswick guns were far superior to the Woolwich guns, because at Woolwich the authorities had made a far greater departure from theory, and in fact had set all theoretical considerations at naught.

The remarks made by Mr. Canet were exceedingly valuable. He had evidently thoroughly studied the subject, and he had shown that his formula was identical with M. Lamé's. Mr. Canet's calculations appeared to be generally right, and it was gratifying to find that the formulæ had been practically and successfully applied in France. He had heard that statement several years ago; and he had since been informed that the guns (7- and 9-inch) had been successful, and that it was possible the French Government might adopt the system with larger guns. With regard to the suddenness of a strain, he believed that it had a considerable effect. Mr. Cowper was in error in imagining that, because the space in which a weight acted was not great, there could not be any momentum. He forgot that, although the space was exceedingly minute, there was a space, and the velocity was enormous. He forgot that the strain was applied in about $\frac{1}{600}$, or $\frac{1}{700}$ second, and that the velocity of the wave pressure was above 20,000 feet per second in steel. It was not a question as to whether the space moved through could be seen with the eye; there was velocity and pressure, and consequently energy. No doubt the law of increased strain existed to a certain extent, but to what extent he could not say. In his calculations, though he mentioned the law he had not taken advantage of it in his criticisms upon the Woolwich guns, but he had taken the simple statical strain, putting aside altogether the increased strain due to the suddenness of the application of the pressure. He would only add that, although he had no longer anything but a scientific interest in the matter (which was perhaps the best interest a man could take in it), nothing would please him more than to see his ideas brought into practice in this country. The theory had never been disputed, and no real practical objections had been made to his proposals in the form in which he had submitted them.

Mr. Barlow, Vice-President, observed, through the Secretary, that the Author, in his concluding remarks, made a statement not contained in the Paper itself, namely, that the late Professor Barlow was wrong in the formula he gave for strains generated in cylinders by internal pressure, the Author's opinion being based on the supposition that the specific gravity of metal underwent alteration under strain. A bar extended by tension undoubtedly diminished in sectional area. Whether the diminution of sectional area was such as to maintain the specific gravity without alteration had not been ascertained. There were no experiments, so far as he knew, which established the fact that any alteration of specific gravity arose from strain, even in the case of a simple strain like that of direct tension. But supposing, for argument sake, that tensile strain might, to a small extent, decrease the specific gravity, compression ought, by the same reasoning, to increase it. In the case of the gun both these forces or strains were operating; each lamina conveyed its action to the next one outside it, by pressure acting in lines radiating from the centre; and therefore, while the strains arising in the circumferential lines were tensile, those acting in the radial lines were compressive, so that as regarded the question of specific gravity they would counteract each other. It appeared, therefore, that there was no sufficient reason given for pronouncing Professor Barlow's formula to be wrong.

Colonel Shakespear remarked, through the Secretary, that, without expressing an opinion on the merits of the Author's mode

Nature of Gun.		Length of Bore.		Charge.
		Inches.	Calibres.	lbs.
English muzzle-loading rifled guns . . .	12-inch of 35 tons . . .	162½	13·5	110·0
	12 „ 25 „ . . .	145	12·0	85·0
	11 „ 25 „ . . .	145	13·2	85·0
	10 „ 18 „ . . .	145½	14·5	70·0
	9 „ 12 „ . . .	125	13·9	50·0
	8 „ 9 „ . . .	..	14·8	35·0
	7 „ 7 „ . . .	126	18·0	36·0
	7 „ 6½ „ . . .	..	15·9	30·0
German breech-loading rifled guns . . .	14 „ 56 „ . . .	270	19·3	253·0
	12 „ 36 „ . . .	227	19·0	132·0
	11 „ 27 „ . . .	207	19·0	132·0
	10 „ 22 „ . . .	225	22·5	104·0
	10 „ 18 „ . . .	174	17·0	104·0
	9 „ 15 „ . . .	178	20·5	60·0
	9 „ 14 „ . . .	157	17·0	60·0
	8 „ 10 „ . . .	163	22·0	37·5
	8 „ 9 „ . . .	119	14·0	33·0
	7 „ 5½ „ . . .	149	21·9	26·5
	7 „ 5 „ . . .	131	19·3	22·0
	7 „ 4 „ . . .	135	19·5	..
French breech-loading rifled guns . . .	13·4 „ 48 „ . . .	..	13·4	..
	12·6 „ 38 „ . . .	204	16·6	139·0
	11 „ 20 „ . . .	167	15·4	53·0
	11 „ 22 „ . . .	194	18·0	88·2
	11 „ . . .	..	..	92·0
	9 „ 14 „ . . .	165	17·5	35·0
	9 „ 14 „ . . .	165	17·5	62·0
	9 „ 11 „ . . .	165	17·5	84·0
	8 „ 8 „ . . .	138	18·0	18·0
	8 „ 8 „ . . .	138	18·0	33·0
Russian breech-loading rifled guns . . .	12 „ 40 „ . . .	204	17·0	113·0
	11 „ 27 „ . . .	187	17·0	82·0
	9 „ 14 „ . . .	152	17·0	47·0

Weight of Projectile.	Muzzle Velocity.	Velocity at 1,000 Yards.	Muzzle Energy.	Energy at 1,000 Yards.	—
lbs.	Feet per Second.	Feet per Second.	Foot tons.	Foot tons.	
700	1,300	1,196	8,200	6,946	Rifled on Woolwich system; nine grooves; twist increasing from 0 to 1 in 35 calibres.
600	1,300	1,179	7,030	5,780	Two patterns; nine grooves; twist 1 in 100 to 1 in 50 calibres.
535	1,315	1,199	6,415	5,335	One thick coil over breech; nine grooves; increasing from 0 to 1 in 35 calibres.
400	1,364	1,228	5,160	4,185	Two coils over breech; seven grooves; increasing from 1 in 100 to 1 in 40 calibres.
250	1,420	1,236	3,496	2,648	Five patterns of this gun, all with six grooves.
180	1,413	1,213	2,492	1,837	Armstrong construction; three grooves.
115	1,561	..	..	..	
115	1,525	1,261	1,855	1,268	
1,157	1,665	1,550	22,330	19,270	Steel.
650	1,525	1,385	10,510	8,672	"
520	1,640	1,483	9,699	7,934	"
414	1,575	1,410	7,112	5,706	"
414	1,509	1,362	6,553	5,322	"
306	1,502	1,330	4,786	3,753	"
306	1,476	1,309	4,622	3,633	"
217	1,394	1,223	2,925	2,253	"
206	1,312	1,127	2,458	1,830	"
119	1,509	1,280	1,876	1,351	"
119	1,411	1,202	1,643	1,191	"
..	..	..	..	..	"
..	..	..	..	..	New experimental steel.
770	1,371	1,257	10,057	8,433	Cast iron and steel.
476	1,188	1,046	4,659	3,610	" "
476	1,378	1,247	6,275	5,130	" "
476	1,525	1,377	7,671	6,259	Steel.
317	1,188	1,027	3,103	2,317	Cast iron and steel.
317	1,427	1,265	4,575	3,517	" "
300	1,558	1,370	5,057	3,903	" "
165	1,168	991	998	718	" "
165	1,486	1,272	2,533	1,881	" "
650	1,398	1,275	8,830	7,325	Steel.
495	1,360	1,229	6,346	5,182	"
270	1,541	1,181	3,365	2,612	"

of construction, the statement in a tabular form (preceding pages, 252 and 253), from authentic documents, relative to the heavy artillery of England, Germany, France, and Russia, showed that the former country was behind hand; for it would be seen that whilst a shot from the German 12-inch gun of 36 tons had a velocity of 1,385 feet per second after it had gone 1,000 yards, the corresponding English gun—the 12-inch of 35 tons—only had a muzzle velocity of 1,300 feet per second: and as regarded the energy of the shot after a flight of 1,000 yards, the figures were thus:—Germany, 8,672 foot-tons; France, 8,433; Russia, 7,325; and England, only 6,946 foot-tons.

The above were the principal known guns; but Italy, Austria, and Turkey had powerful guns; whilst China and Japan were adopting, and possibly making in their own workshops, a powerful artillery after European pattern. America had adopted the "Palliser" system of construction. Indeed, all the nations of the earth were busy on their artillery. Italy seemed to prefer muzzle-loading guns on the Armstrong system, and had the largest gun of all, and which had been made at Elswick, viz., a 100-ton gun; but this gun, as well as the English 81-ton gun, was still experimental. The following results had been obtained with them: The 100-ton gun, with a charge of 500 lbs. of Italian powder, and a projectile of 2,000 lbs., gave a muzzle energy of 38,000 foot-tons; and with 463 lbs. of English powder, a muzzle velocity of 1,627 feet per second; and energy, 36,700 foot-tons. The 81-ton gun, with a charge of 423 lbs., and projectile of 1,700 lbs., gave a muzzle velocity of 1,620 feet per second; at 1,000 yards, of 1,518 feet per second; and a muzzle energy of 29,935 foot-tons. Both the above were muzzle loaders. The table showed that length of bore was necessary to velocity. The projectile of a breech loader being larger than the bore, centred itself in the bore, whereas with the muzzle loader that was not so. This disadvantage to the latter had been overcome by the introduction of "gas-checks." Mounted as guns were at present, muzzle loading had the advantage in rapidity of fire. The only practical advantage breech loaders had over muzzle loaders was, that less space was required for loading; hence breech loaders could be generally the longer, to the more profitable consumption of heavy charges. Land-service guns might be of any length, but at sea space was limited.

Dr. SIEMENS explained, through the Secretary, that the Author in his reply had stated that Dr. Siemens had mistaken the radius of his normal gun with hoops for the thickness of the inner tube; and in this he was perfectly right. But, considering that the radius of the hypothetical gun was 8 inches, and the thickness of the inner tube 6·3902 inches, the correction only served to strengthen the argument to the effect that under the shrinking system there was danger of crushing the inner tube by the tensile strain of the greater mass of metal composing the hoops. True, the Author maintained that the shrinkage of succeeding layers of hoops might be so regulated that the first layer would habitually be under compression, and thus aid the inner tube to resist compression. He had not overlooked this possibility, but endeavoured to prove that such nice adjustment of original tensions in the different parts constituting the guns would be upset, and rendered illusory, on account of the heating of the inner tube by the act of firing the gun. The Author admitted this portion of the argument, but said that it was based upon a misapprehension of the cause of heat in firing guns. The products of combustion of the gunpowder, though taken at a temperature of 5,000°, would not, he asserted, communicate more than one unit of heat to every square foot of inner gun-surface during the short interval of $\frac{1}{100}$ second when the heat would be active in firing, an amount of heat which would certainly be inappreciable in its effect upon the large mass of the gun. But in order to account for the great heat undoubtedly produced in firing, he ascribed it to the compressive action communicated to every portion of the fabric in firing. So far from agreeing with this view, Dr. Siemens ventured to assert that not a single unit of heat would be set up in the body of the gun by such compressive action, so long as the metal was not strained beyond its elastic limit. The elastic action of a watch-spring would not give rise to heat, although the continued bending of a non-elastic wire through the same angles of range would cause it to heat rapidly. In the one case the work expended in bending the spring was recovered, and in the other it was lost, and its equivalent of heat put into its place. He maintained that all the heat produced in firing a gun was due to the heated products of combustion, and that the Author misapprehended entirely the amount of heat taken up by a metallic surface from a dense current of highly heated material even in so short an interval as $\frac{1}{100}$ second. The heat produced by successive firing must indeed cause strains in the gun far exceeding those originally created by shrinkage, because every 130° Fahrenheit must produce in an iron or a steel cylinder under confinement a strain of 12 tons per square inch; and it was well known that a few shots would suffice to produce that degree of temperature in the inner tube, unless powerful means of internal cooling were resorted to. The

Author's criticism of the mode proposed by him of distributing the strains in massive hoops or cylinders, in such a way as to make them capable of resisting a maximum of bursting strain, was based upon the same misapprehension of the heating, or, in this case, cooling, effect of a dense and active current upon metallic surfaces. If water were to be the medium employed, and the tube was of a temperature below that at which actual contact was prevented by spheroidal condition, the innermost surface of the cylinder under operation would almost instantaneously assume the temperature of the cooling current, the heat-absorbing action of which would be limited only by the conductivity of the metal itself limiting the inflow of heat toward the centre. This cooling action would be kept up until the whole mass was cooled from within. The conditions of varying tension aimed at could not be realised unless the temperature of the external surface was kept up to the last; and in this respect the plan here proposed differed essentially from that followed by Captain Rodman in cooling his cast-iron guns, which metal was moreover much less susceptible than steel to the mode of treatment, owing to its short elastic range.

Mr. Robert Wilson observed, through the Secretary, that the principle upon which the Author's formula was based was that steel and iron were ductile, and elongated when subjected to tensile stress. One element had, however, been overlooked by the Author, without which the property of ductility could not be brought into play. This was the element of time. The formula was approximately correct theoretically for hollow cylinders subjected to a steady hydraulic or steam pressure, where the tension increased gradually from zero, and allowed time for the exercise of ductility. But he considered the Author was in error when he assumed that the formula was equally applicable to the strength of cylinders exposed to a great pressure very suddenly applied, where there was no time for the exercise of ductility, or for each layer in the thickness to take its share of the pressure, as was implied in the formula. In addition to the sudden circumferential pressure exerted by a large charge of gunpowder, there were also still more severe local pressures. In the experiments with the 10-inch gun,[1] it was found that these local pressures were as great as 63 tons per square inch. They acted like blows, and their energy was mainly expended upon the inner surface of the tubes, without producing any great circumferential pressure upon the outer surface or the coils beyond. In the Paper the Author only once

[1] *Vide* Philosophical Transactions of the Royal Society, 1875, p. 49.

mentioned that the explosion pressure was sudden, and that its effect might be double that of a steady pressure; but he did not appear to see that it affected the very principle upon which this formula was founded, and not merely the relative value of the terms and factors in the formula. The Author censured the Woolwich and Elswick gunmakers for not using his formula. This censure and his reasonings were based upon two assumptions: 1st. That guns always failed from longitudinal fracture of the tube. Now this assumption was not borne out by facts, as solid, coiled, and tubed guns, of cast iron, wrought iron, bronze, and steel, had failed by fracture transversely near the breech, and not always longitudinally, in this country, on the Continent, and in the United States. 2nd. That the longitudinal fractures were always and only due to circumferential tension, exerted by the pressure of the gases. Now this was opposed both to experience and theory, for the severe local pressures, which acted like blows on the inner surface of the tube, were more trying to the resistance of the material than the steady strains assumed by the Author. Sir W. Armstrong, in his evidence before the 35-Ton Gun Committee, stated that his guns failed always in the tube, and that the steel tubes failed from the shock, the jar, or the concussion. He did not appear to consider the circumferential stress at all. It was probable that most of the fractures found in steel tubes were the development of the surface cracks produced by the local blows of the explosion, and by the great and sudden changes of temperature to which the inner surface of the tube was exposed. The temperature of the gases was about 4,000° Fahrenheit. Although the time to which the metal was exposed to this high temperature was infinitesimal, and although the quantity of heat was small notwithstanding its intensity, the heat had been found sufficient to account for the melting of the soft particles of metal in bronze and cast-iron guns. It was therefore not unreasonable to conclude that the severe local pressures or shocks acting upon steel tubes exposed to a high temperature were sufficient to start the surface cracks found in the steel tubes of large guns. It appeared to him that no strengthening of the tubes by shrinking on coils, or coiling on wire with any degree of tension according to the formula, which was only intended to meet the case of a steady and gradually applied load, would prevent the formation of these surface cracks. When a surface crack was once started, no matter how, either longitudinally or transversely, the jarring and shocks to which the tubes were subjected at every discharge would inevitably cause the crack to extend in a homogeneous metal like steel or cast iron, and ultimately bring about complete fracture. The homogeneity of ductile steel rendered it in some respects much superior to wrought iron as a constructive material. Yet it was this very homogeneity that rendered steel so unsuitable when it could not be guaranteed against incipient fractures in positions where it was exposed to shocks, jars, concussion, or vibration. In wrought iron an incipient fracture would often alter its course, or stop altogether at the first cinder, or break in the structure it met with, and it was but little affected by subsequent jarring; but in steel, no matter how ductile, a crack once begun was sure to extend rapidly by jarring till complete fracture ensued. However, owing to its superior resistance to detrusion, abrasion, and erosion, steel was, on the whole, the best material for gun tubes; and as it could not be expected soon to meet with a better material, the best should be made of the material. It appeared to him that any attempt to increase the life of large guns should be in the direction of cushioning the blow given by the explosion of the powder. This could probably be done by leaving a sufficient air space all round the charge; and with suitable powder this cushioning need in no way reduce the velocity of the shot, but might actually be made to increase it. In order to carry this out properly, recourse, however, must be had to breech loaders. In seeking to devise a remedy for the failure of the steel tube of large guns, it appeared to him that the Author had ignored the cause or causes to which the failure in the first place was due. He would apply an external remedy, where only an internal remedy could reach the root of the malady. In applying mathematics to the solution of any question on the strength of materials, there was nothing so misleading as figures, excepting facts; and for this reason—it was extremely difficult to get at all the facts which went to the making up of a problem; and when all the facts were ascertained, it was still more difficult to "condition" them (so to speak), and to assign to each its proper position and value.

Mr. Longridge replied, through the Secretary, that Mr. Barlow's observation respecting Professor Barlow's formula did not convince him that he was in error in pronouncing that formula to be wrong. It was a mathematical question, and he was content to leave it as it was, supported as he was by such authorities as M. Lamé, Dr. Hart, and Dr. Hopkinson. As regarded Dr. Siemens' explanation, he regretted that that gentleman should repeat his assertion about the hypothetical 16-inch gun. If he had looked at Fig. 6 he would have seen how erroneous such an assertion was. To make the matter perfectly clear, the following table showed the strains in this gun before and during explosion, with an internal pressure of 24 tons per square inch:

—		Before Explosion.	During Explosion.
Steel tube	Inner surface	− 9·946	10·000
	Outer "	− 6·510	− 1·734
First ring	Inner "	− 1·110	10·000
	Outer "	− 1·933	2·121
Second ring	Inner "	5·966	10·000
	Outer "	3·352	5·620

So far from there being any fear of crushing the inner tube, it would be seen that it was never under a compression greater than 10 tons per square inch. Dr. Siemens repeated his assertion about the destruction of the tensions by heating, and said that the Author admitted this portion of the argument. He did nothing of the kind. What he did say was this: "If Dr. Siemens were right in his conclusions, his objection would be very serious; but he thought he could show that Dr. Siemens was entirely wrong." He still adhered to that statement. With reference to the question of heating, he could not accept Dr. Siemens' dicta. Did Dr. Siemens mean to assert that if a steel anvil was struck with heavy blows from a steel hammer, both being elastic, and receiving no permanent deformation, no heat would be evolved? If so, he made an assertion which he might easily satisfy himself was contrary to fact. Neither could he accept Dr. Siemens' assertions about the quantity of heat that would be absorbed into the body of the gun from the powder gases, nor about the cooling a cylinder from the inside, under the conditions proposed by Dr. Siemens. With all respect, he must formally deny the correctness of such assertions, and hold by every iota of what he said in his general reply, based as it was upon such authorities as Rumford, Peclet, and Cauchy. Finally, he would repeat, that this question of heating had long ago had his careful attention, that it could be practically met without difficulty, and especially in the wire system of construction.
