THE THIRTY-SECOND THOMAS HAWKSLEY LECTURE

# The Scientist in War Time

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## INTRODUCTION

At one time it appeared as if my freedom of speech in this lecture would have to be seriously curtailed. For the date of the lecture was fixed, but the end of the war was not. Happily, however, the brilliant efforts of the Allied Forces, supported by one of the outstanding achievements in the history of science, brought it about that the two events took place in the order I could have wished.

I am deeply sensible of the honour paid me by your Institution in inviting me to deliver this, your senior annual, lecture. I have no qualifications as a mechanical engineer, and therefore I cannot deal with a topic within your own special field of interest. Indeed, in one sense, I cannot claim to have any qualification to speak on "The Scientist in War Time", the subject of my lecture; for I have not had an opportunity of working in a laboratory for some years. But it has happened, however, that I have seen perhaps as much as anyone of the general picture of British scientific organization and effort during the war; and it is this good fortune that has emboldened me to speak on the subject.

One further word is needed by way of introduction. I ought at the outset to explain my use of the word "scientist", lest I be misunderstood. I am not going to continue the rather profitless discussions of the difference between an engineer and a scientist. If engineering science is defined, as Southwell has suggested, as "science studied with a view to application" we then have a convenient omnibus term for the great bulk of our technical war effort. For conciseness I shall, however, not employ the term "engineering scientist"; merely the word "scientist".

It is frequently being said that the war which has just ended has been a scientists' war; but I rather think the scientific man would put matters differently. He would say that he has been privileged, as never before, to place his special skill and knowledge at the service of our fighting men. Certainly our achievements in war have been most successful where there has been the closest collaboration between the fighting services, science, and industry.

Science has always had its impact on the nature of warfare. We find Leonardo da Vinci, Galileo, Count Rumford, and others in their time, all directly concerned with scientific aspects of military science. Lavoisier was head of the French State Arsenal where much of his scientific work was done. We ourselves encouraged research on gunpowder because of its potential use in war, and much of the progress of astronomy, including the founding of the Royal Observatory, in the reign of Charles II, sprang from the needs of the Royal Navy. In this connexion it is of special interest to note that Isaac Newton himself realized the need for the scientist to be in a position to grasp, at first hand, the nature of naval requirements. Writing about the year 1692 to Mr. Hawes, Treasurer of Christ's Hospital, on the subject of the better mathematical training of young boys for a life at sea, he said, "I will add, that if instead of sending the observations of seamen to able mathematicians on land, the land would send able mathematicians to sea, it would signify much more to the improvement of navigation and safety of men's lives and estates on that element". In these days when a commander-in-chief in the field will have his own scientific adviser, and when a scientist will often form part of a bombing mission to study new weapons or tactics, this remark of Newton's seems a singularly early and penetrating forecast of things to come.

But not only have scientists, in the past, devoted their attentions to military preparation. It has also been recognized, by penetrating minds, what powerful transformations scientific and technical developments can bring about in military plans, both strategical and tactical. Let me quote from Rear-Admiral A. T. Mahan, the distinguished American naval historian, who, in his classical treatise "The Influence of Sea Power upon History, 1660–1783" (published in 1889), wrote:—

> "He will observe also that changes of tactics have not only taken place *after* changes in weapons, which necessarily is the case, but that the interval between such changes has been unduly long. This doubtless arises from the fact that an improvement of weapons is due to the energy of one or two men, while changes in tactics have to overcome the inertia of a conservative class; but it is a great evil. It can be remedied only by a candid recognition of each change, by careful study of the powers and limitations of the new ship or weapon, and by a consequent adaptation of the method of using it to the qualities it possesses which will constitute its tactics".

I do not know what happened in previous wars. But certainly, in the war that has just ended, we can feel satisfied that the "inertia of a conservative class" has not prevented the rapid revision of tactics demanded by the development of new weapons and instruments. In the case of radiolocation or radar, for example, the nature of the air defensive or offensive has changed almost on the heels of its rapid development. Moreover, as I shall mention later, scientific workers have not only been employed in developing new weapons. They have also, in many cases, assisted their Service colleagues in working out the plans for using them, and have also made objective studies of past operational results, which have served to check these plans.

But I think I should add that the achievement of this close partnership of Service man and scientist did not come about as a result of an immediate mutual attraction. Indeed I think each was, at one time, a little suspicious of the other. But it did not take long before it was realized that the scientist could be practical and keep secrets; and that the Service man had something quite essential to contribute, even in technical discussions of projected weapons and techniques. The partnership now is a happy and productive one and, if you draw any moral at all from this lecture, I think it will be that the whole future defence of this country depends on its maintenance.

## THE ORGANIZATION OF SCIENCE FOR DEFENCE

It was, I think, Lord Trenchard who said that it was the task of the technician not only to satisfy Staff requirements, but also to anticipate them. To this end there had been instituted, well before the war, Directorates of Scientific Research in each of the three Service Ministries. Under the supervision of each Director of Research small, but able, groups of scientific workers had been built up, operating in well-equipped laboratories.

But although the magnitude of these scientific organizations was small in pre-war days they proved capable of rapid expansion when required. Just before the war, when danger threatened, there was set up a fourth scientific organization, in the Ministry of Home Security, to cater for Civil Defence. The heads of the four research organizations (Mr. C. S. Wright, Director of Scientific Research, Admiralty; Dr. D. R. Pye, and later

The MS. of this lecture was received at the Institution on 26th November 1945. For the Minutes of Proceedings of the meeting in London on 16th November 1945, at which this Lecture was delivered, see Proc. I.Mech.E., vol. 152, p. 380.

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Mr. B. Lockspeiser, Ministry of Aircraft Production; Dr. H. J. Gough, Director General of Scientific Research and Development, Ministry of Supply; and Sir Reginald Stradling, Chief Scientific Adviser, Ministry of Home Security) have been responsible for the direction of our scientific effort and to them is due the chief credit for its success.

Fortunately, plans for the further mobilization of our scientific man-power had been laid in the year before war broke out. The Royal Society and the Ministry of Labour co-operated in the institution of the scientific section of the Central Register. By the end of July 1939 this section contained particulars of more than 5,000 scientists, and, on the outbreak of war, the recruitment for the defence research establishments began in earnest. Many senior scientists in the universities had, it is true, previously been provisionally engaged for special tasks, but the Register proved particularly useful for filling junior posts. The recruitment of individual scientists did not, however, take place indiscriminately. The safeguarding of the usefulness of teams of research workers was entrusted to the Department of Scientific and Industrial Research, and it was arranged that members of such teams could not be recruited through the Central Register without prior consultation with the Department.

The general policy adopted was to retain research teams in industry practically intact. In the case of university workers, who are generally more accustomed to work alone or in small groups, no such attempt was made. Looking back, this decision seems to me to have proved a wise one. The research establishments of the Services were strengthened by the acquisition of many brilliant individual minds from the universities, while the research teams in industrial firms and research associations retained their striking power as composite units.

As was to be expected, some categories of scientific workers on the Central Register were not in great demand, while others, such as physicists and radio-engineers, were very rapidly exhausted. Mobilization naturally took time and, in a way, it was a good thing that this was so, since the general pattern of research problems and staff needs was by no means clear at the beginning of the war. But with those not enlisted at once there were naturally signs of impatience at not being used. As might have been expected, the war gave rise to more tasks for the physical scientist than for the biological scientist. But in very many cases the latter, nothing daunted, successfully turned himself into the former for the duration of the war. Indeed, one may say that one of the most striking conclusions one can draw from our experience in this matter is that a man with a good scientific training can generally adapt himself very rapidly to work outside his own professional field.

Some of the changes of occupation and subject were rather striking. Before they were required to devote their energies to the development of the atomic bomb, the men who were engaged on nuclear physics in peace time turned their hands with great success to the development of radiolocation equipment. Many biologists turned their hand to operational research. One scientist I know, an authority on crystal structure in peace time, developed into one of our leading experts in the science of civil defence. In yet another case, an authority on building concrete structures became a leading authority on destroying them.

I will permit myself only one or two further observations of a general character. One is to emphasize the great importance team work has played in war-time research. I have already alluded to the collaboration between Service man and scientist; but the same kind of collaboration has been the rule between scientists, often of different professional training, working towards the same objective and also between Government establishments and the research groups of industry. Indeed I would say that the value of any man has depended very largely on his ability to work easily with other people. In this connexion I have noticed that cheerfulness and good humour can be as useful a lubricant in research as in any other form of human activity. Also I think that many scientists have, during the war, been surprised to find that there is as much excitement and satisfaction in applying physical truths as in discovering them.

I now turn to consider just a few of the fields of war-time science. In the selection of these I have been, of course, quite embarrassed by the array of material. Moreover my account of even the fraction of this material which I have chosen, mainly because of its scientific interest, cannot pretend to be comprehensive.

### THE ATOMIC BOMB

I do not think that anyone would quarrel with the selection of the atomic bomb as the outstanding result of scientific activity in war time. For, in this case, not only has an outstanding new weapon been developed, but a whole fundamental field of natural knowledge has been advanced simultaneously. Certainly one must call the intensive development of the bomb, from the theoretical prediction of its possibility to its practical realization in two forms, the greatest scientific and technical experiment of all time.

At the risk of repeating much of what has recently been said already, I feel I should draw your attention to a few of the scientific landmarks in this wonderful sequence of events. It was one of the consequences of the Special Theory of Relativity, enunciated by Einstein in 1905, that the two well-known principles, the law of conservation of matter and the law of conservation of energy, were in fact not independently distinct, but that they really should be fused into a more general principle, that of the conservation of *mass plus energy*. For Einstein showed that there was a definite relation existing between the loss (or gain) of mass, and the gain (or loss) of energy. Quantitatively stated Einstein's principle of equivalence runs

$$\delta m = \frac{\delta E}{c^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $\delta m$ is the mass destroyed (or created), $E$ the energy created (or destroyed), and $c$ the velocity of light. Einstein further suggested that an experimental test of this relation might be found in the study of radioactive substances.

The implications of the equivalence relation are most startling, as may be seen by taking an example. Let us suppose that it is possible to annihilate completely 1 kilogram of matter. The resulting energy, according to relation (1), would be equivalent to $2{\cdot}5 \times 10^{10}$ kilowatt-hours, or enough to run all the electricity services of this country for nine months. This may be compared with the energy released by the burning of 1 kilogram of carbon, which produces only 8·5 kilowatt-hours. In the latter reaction, of course, the mass of the products of combustion are practically equal to the mass of the original carbon and oxygen, for Einstein's equation shows us that the loss of mass corresponding to the release of such a small amount of energy would be undetectable by ordinary balance measurements. Still, we believe that an extremely small loss of mass does actually take place.

Now one characteristic of combustion is that it is a kind of chain-reaction, in that, if the process is initiated for a certain number of carbon atoms, the heat thus liberated is sufficient to start up the same process in neighbouring carbon atoms, and so on. To get substantial quantities of energy by a process described by Einstein's equation, we must look for some atomic change which is characterized by an appreciable conversion of mass into energy, and which, when once started, will induce similar transformations to take place in neighbouring atoms. Such an atomic change, we now know, is provided in the process of nuclear fission which was discovered by Hahn and Strassmann, and announced by them in January 1939.

The sequence of experimental discoveries which led to the identification of nuclear fission certainly began in Manchester in 1911 when Rutherford showed that the essentially characteristic thing about an atom was the heart of it—the nucleus, as he called it. The nucleus, which carries a positive charge, is situated in the centre of an atom and its volume occupies only about $10^{-12}$ that of the atom as a whole. It was also Rutherford who, in 1919, first succeeded in causing two nuclei violently to collide so that both of them were changed. This was the first example of nuclear transformation, and it was brought about by bombarding nitrogen nuclei by helium nuclei (i.e. $\alpha$-particles).

Cockcroft and Walton, thirteen years later, gave a verification of the Einstein relation in their pioneer experiment on nuclear transformation, using artificially accelerated protons, for it was found that the energy released just corresponded to the tiny loss of mass in the reaction

$$Li_3{}^7 + H_1{}^1 \rightarrow 2He_2{}^4 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

(Here the mass units are not precisely 7, 1, and 4 as shown in the equation above but actually 7·0165, 1·0076, and 4·0028 respectively, and it will be seen that the total mass on the left-hand side is greater than that on the right-hand side by 0·0185 units.)

But experiments of this kind, in which charged atomic nuclei are speeded up to act as projectiles, are subject to two limitations. It is found that successful nuclear hits are disappointingly few (of the order of one in a million) and the nuclear projectiles lose a lot of energy uselessly in colliding with the electrons in the bombarded material. Moreover the reaction is not self-propagating.

In 1932 the ideal projectile for effecting nuclear transformation was identified by Chadwick. This was the neutron which, because it is uncharged, can pass quite freely past other nuclei, and enter relatively freely any nucleus which it happens to hit head-on. It was soon found by Fermi, in Italy, that all manner of nuclear transformations could be made to take place by bombarding the nuclei of various elements with neutrons. Usually, however, the change was small, resulting in the emission of $\gamma$-radiation or in an increase of mass number by unity, followed by the emission of an electron. But in the case of uranium, Hahn and Strassmann found that one of the products of this reaction was an isotope of the element barium which has an atomic number and mass about half that of uranium. Immediately afterwards, Frisch and Meitner pointed out that this could only mean that, when uranium was bombarded with neutrons, the nucleus actually split into two parts of roughly equal mass. This process was termed "nuclear fission". Moreover, Frisch, working in Bohr's laboratory at Copenhagen, demonstrated the intense energies associated with the fragments of the fission.

In Fig. 1, Plate 1,* are shown pictures of the fission of uranium, almost taken in the act. They were taken by Bøggild, Brostrøm, and Lauritsen, also working in Bohr's laboratory. The uranium, which was exposed to neutron bombardment, was placed as a thin layer on an aluminium or mica foil, which was stretched across a Wilson cloud chamber filled with a mixture of argon and other gases. The foil crosses the picture almost vertically. The small ionization tracks are due to nuclei of the chamber gas driven forward by the neutrons. But we see also two intensely ionized tracks originating from a uranium fission. These are due to the two fission fragments which, of course, travel out from the scene of the atomic explosion in opposite directions.

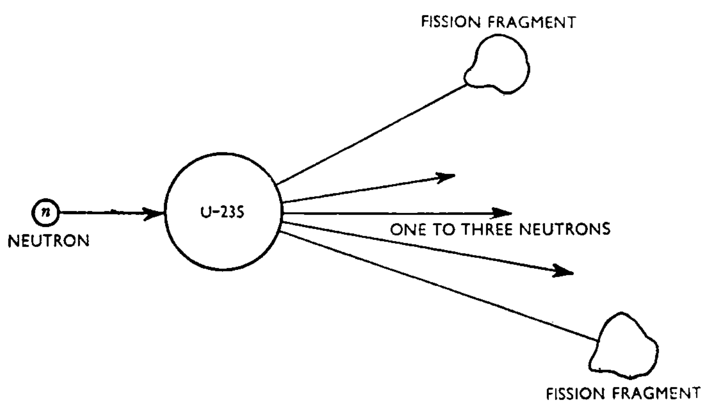



Fig. 2. Liberation of Neutrons on Fission of Uranium

Very shortly afterwards, in the spring of 1939, Joliot and his co-workers, Halban and Kowarski, demonstrated the further fact that the fission of the uranium nucleus is accompanied by the liberation of a few neutrons, as illustrated in Fig. 2. Similar experiments were conducted about the same time in America confirming that more than one neutron is produced for each fission of an uranium nucleus.

This result immediately directed attention to the possibility of a nuclear chain reaction, such as is illustrated in Fig. 3, in

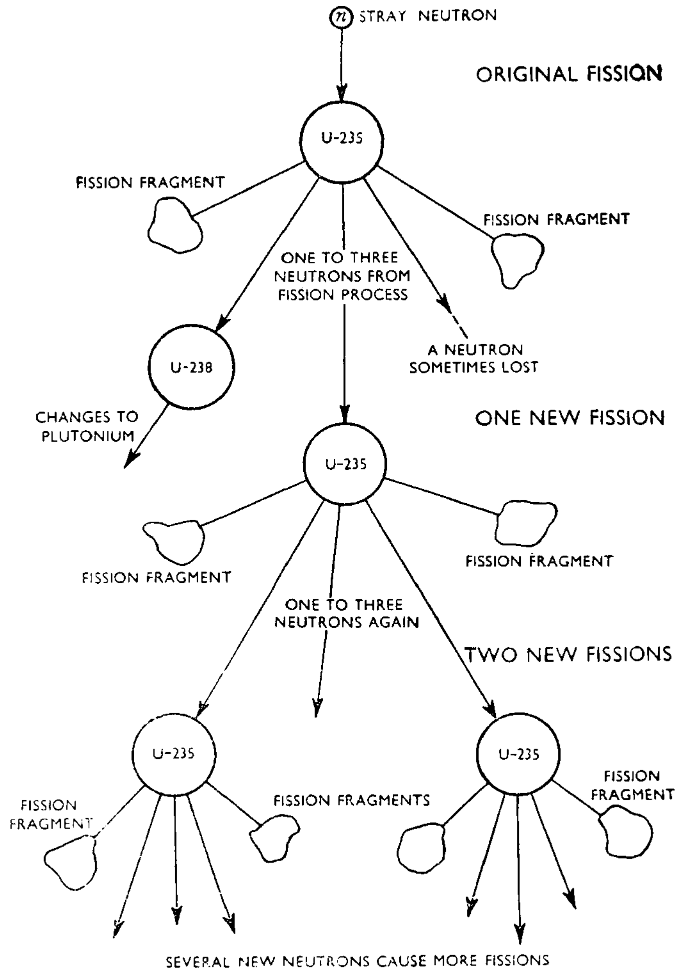



Fig. 3. Nuclear Chain Reaction

Schematic diagram of chain reaction from fission, neglecting effect of neutron speed. In an explosive reaction the number of neutrons multiplies indefinitely. In a controlled reaction the number of neutrons builds up to a certain level and then remains constant.

which the process is continued and multiplied. Here we see at once the essential feature of an energy-releasing avalanche and thus the idea of a bomb.

It has been found, however, that such a process can only take place in the isotope of uranium which has an atomic weight of 235 and in a newly discovered element, plutonium, which has an atomic weight 239. Bombs can therefore be made of both

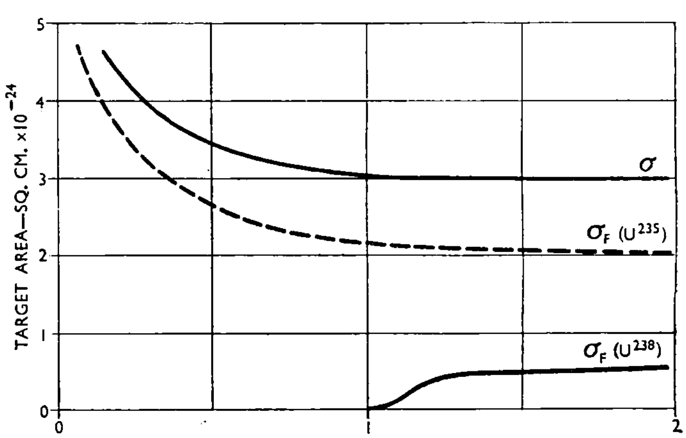



Fig. 4. Relation between Target Area and Energy of Incident Neutron

* Bøggild, J. K., Brostrøm, K. J., and Lauritsen, T., *Mathematisk-fysiske Meddelelser* (Copenhagen), 1940, vol. 18, No. 4, "Cloud Chamber Studies of Fission Fragment Tracks".

these materials, and I shall therefore say a few more words about each.

(*a*) *Uranium 235.* Experiments have shown that the probability of fission taking place when a neutron collides with a uranium nucleus various enormously with the speed of the bombarding neutron. Actually we express this probability in terms of what is called the equivalent target area of the uranium nucleus for the process in question. In Fig. 4* is shown approximately the relation between the target area for fission, $\sigma_F$, as a function of the energy of the incident neutron. We note that $\sigma_F$ for U(235) increases as the velocity of the neutron is reduced. We also note that $\sigma_F$ for U(238) is never large and becomes zero below a certain neutron speed. Now the U(235) isotope of uranium is present in uranium found in nature only to the extent of 0·7 per cent. As a result it can be shown that no chain reaction will develop in ordinary uranium metal. Even if fission were started, most of the neutrons would be scattered inelastically by the U(238) atoms. As a result, their velocity would be rapidly reduced below the value for which the fission of U(238) can take place.

In U(235), on the other hand, neutrons will cause fission in the majority of cases even if they have suffered a few collisions previously. The neutrons can therefore multiply, and an explosion can take place.

Such a chain reaction can, however, only develop in an amount of active material large enough to prevent too many of the neutrons from escaping. Here we see a marked contrast with the ordinary chain process of combustion, where the combustion of one molecule ignites *adjacent* molecules. In uranium, a neutron chain reaction is propagated by neutrons which, due to their great penetrating power, travel through hundreds of millions of atoms before they strike another nucleus and initiate a further fission. In order to sustain a neutron chain reaction, the system must therefore exceed a certain minimum critical size. The linear dimensions of a critical system must be comparable to the mean free path of neutrons in U-metal, which is about 5 cm.

The velocities of the neutrons are of the order of magnitude of $10^9$ cm. per sec. and the time required for neutrons to form a new generation is therefore about $10^{-8}$ second. Now in order to produce the fission of an appreciable fraction of all the active nuclei present, a family tree of about 70 to 80 generations will be needed, and the time for the avalanche to develop fully must therefore very approximately be of the order of a millionth of a second. We therefore see that, to get an explosive system, we must assemble the subcritical parts, to form a supercritical mass, in a time which is so brief that the system is assembled before a stray neutron has struck it and the explosion has developed.

The complete "nuclear combustion" of 1,000 grams of active material would liberate the same amount of energy as the use of about 20,000 tons of "T.N.T.". As the energy is liberated, however, the system tends to expand, and thus becomes more transparent to the passage of neutrons. A stage will therefore be reached when the reaction can no longer sustain itself. Thus we cannot count on the utilization of all the active material.

It will readily be seen that the reaction efficiency depends on two factors: (a) the rate of expansion, and (b) the rate at which the reaction proceeds. For systems of only slightly supercritical size, where a small expansion is sufficient to stop the reaction, only a very low efficiency can be expected. On the other hand, for systems of several times the critical size, the efficiency can be very greatly increased.

(*b*) *Plutonium* (*239*). Although a fast neutron chain reaction, such as takes place in a U(235) bomb, cannot develop in ordinary uranium metal, it is possible, by adding materials to the system which slow down the neutrons, to produce a chain reaction without first separating the isotopes. This arises from the fact that, for very slow neutrons, as is illustrated in Fig. 4, the fission cross-section of U(235) is sufficiently greater than the capture cross-section of U(238) as to compensate for relative rarity of the former isotope, so that fission in U(235) is more probable than capture by U(238). Materials used for slowing down neutrons, by way of repeated collisions, are called *moderators*. They must not capture neutrons and, in order to be effective, must be of low atomic weight. The most suitable materials are thus heavy water, beryllium, and carbon (graphite). Hydrogen would obviously be appropriate, so far as its atomic weight is concerned, but, unfortunately, it absorbs neutrons and is therefore unsuitable.

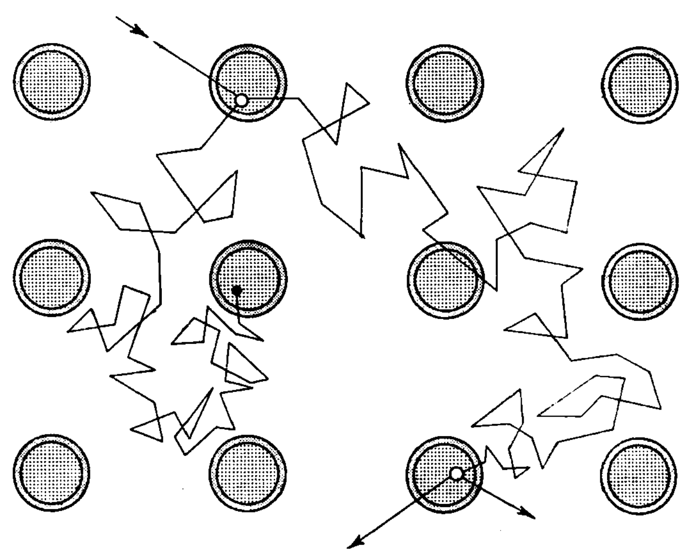


Fig. 5. Diagrammatic Arrangement of a Graphite Pile

In Fig. 5 is shown a cross-section of a possible arrangement of a so-called "pile" for producing slow-neutron chain reactions. Rods of uranium are placed in graphite, and the diagram illustrates the life histories of two neutrons which initially were ejected, with high speeds, from a uranium U(235) fission. Both are slowed down by repeated collisions with carbon atoms, but one is captured by U(238), whereas the other produces a U(235) fission which helps to sustain the reaction. Both of such processes are of interest, for the absorption of a slow neutron by

* In Fig. 4 is also shown the total equivalent cross-section of the uranium nucleus for all collisions which lead (initially) to the capture of a nucleus and thus the formation of a compound system. Bohr has given a most illuminating theory to account for neutron capture and the subsequent events, in that it relates such events to well-known physical processes. According to this theory, when a neutron strikes a heavy nucleus a compound system is first formed, with an excitation energy which is equal to the kinetic energy of the neutron together with the energy with which the neutron is bound to the nucleus. The excitation energy of the compound system will be distributed over the various degrees of freedom, very much like the energy of a heated body, and the final outcome of the reaction will depend on the different ways in which the system may get rid of its energy or disintegrate.

After a neutron has been absorbed by a uranium nucleus three possibilities arise:—

(i) The neutron may be captured and the excess energy liberated in the form of a photon. According to Bohr's theory we can regard this process as analogous to ordinary heat radiation. But, as the effective temperature of the compound nucleus is high, the quanta of electromagnetic radiation emitted are of high energy ($\gamma$-rays).

(ii) A neutron may escape from the compound system. As a result of the accidental energy fluctuations within the compound system, sufficient energy may be acquired by a neutron at the surface of the system to permit it to overcome the attraction of the nuclear forces and so escape. This process is analogous to the well-known phenomenon of evaporation.

(iii) The compound system may undergo fission. This process entails a deformation of the nucleus sufficiently large to reach a state of instability, in which the electrostatic repulsion between the protons in the nucleus just counterbalance the attractive nuclear forces which act as a kind of surface tension. The result is that the compound nucleus undergoes fission and splits into two fragments of comparable charges and masses with energies of about 100 MeV each. Since such deformations are due to accidental fluctuations of the energy within the compound nucleus the fission process proceeds in a manner similar to a monomolecular chemical reaction.

U(238) leads to the formation of plutonium, Pu(239), by way of the following reactions:—

$$U_{92}{}^{238}+n_0{}^1 \rightarrow U_{92}{}^{239} \quad . \; . \; . \; . \; . \; . \; . \quad \text{(i)}$$

$$U_{92}{}^{239} \xrightarrow[\text{23 mins.}]{} Np_{93}{}^{239}+e_{-1}{}^0 \quad . \; . \; . \quad \text{(ii)}$$

$$Np_{93}{}^{239} \underset{\text{2·3 days}}{=} Pu_{94}{}^{239}+e_{-1}{}^0 \quad . \; . \; . \quad \text{(iii)}$$

Such piles have been used for the production of Pu(239) and, as was predicted by Bohr's theory of nuclear transformations, this element has been found to have much the same properties with regard to fission as U(235), and thus can be used in a bomb. In a graphite pile of this kind a great amount of heat is generated as a result of the fission of U(235), which may be regarded as the main source of the supply of neutrons.

We can make a rough guess as regards the order of magnitude of the heat production in a pile of this kind. Let us suppose, for example, that, to produce one atom of plutonium, it is necessary to produce about one fission. Therefore, for a production of 1,000 grams of plutonium per day, we must have about

$$\frac{4\times 6\times 10^{23}}{24\times 60\times 60} = \tfrac{1}{3}\times 10^{20} \text{ fissions per second.}$$

Now since the release of energy in a single fission is about $3\times 10^{-4}$ erg, the rate of energy production is consequently approximately $10^{16}$ ergs per second, or 1,000,000 kW.

It should, however, be stressed that, in order to achieve chain reactions in ordinary uranium metal in a pile, great care must be taken to secure the necessary neutron economy. No materials which absorb neutrons can be used in the structure of the piles, and therefore all materials used must be of a high degree of purity. The plutonium is formed in the uranium rods and is extracted from them chemically, from time to time. The major technical problem connected with the construction of a pile is, however, that of cooling. This can be achieved by surrounding the uranium rods with tubes of running water, as shown in Fig. 5.*

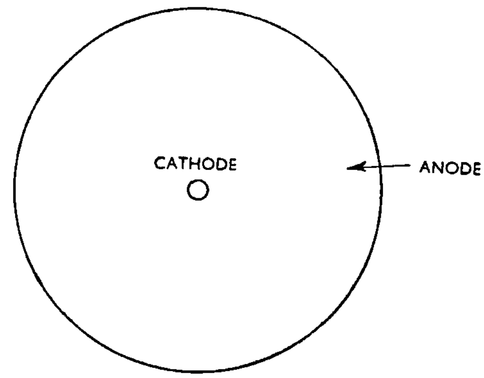
The operation of the pile can always be prevented from getting out of control by inserting in it some material which absorbs neutrons strongly. Such a material is cadmium. A "poker" of cadmium can therefore be used to control the "burning" of the U(235). In this case we therefore poke the pile to discourage, and not encourage, heat production!

## RADAR

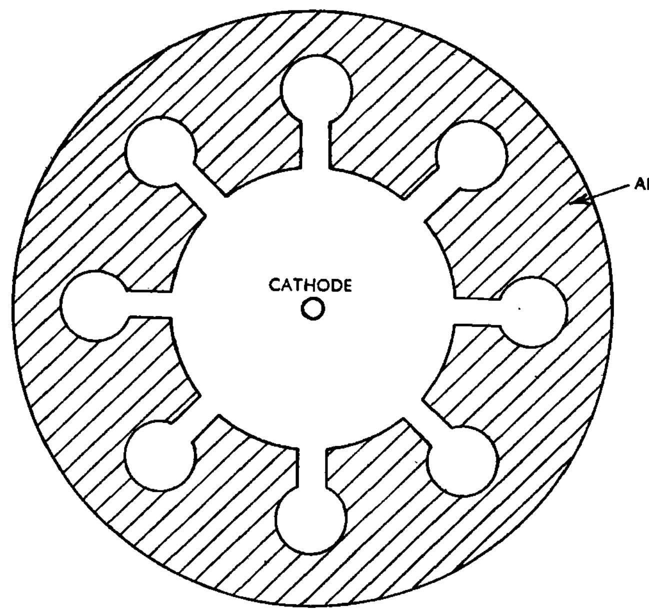
I naturally select radar as the next war-time scientific development of importance after the atomic bomb. The outstanding features of this technique, although kept secret for so many years, are now becoming so well known that it is unnecessary for me to recapitulate them. But there are one or two aspects of the subject on which I think more may be said. The application to aircraft detection of the ionospheric method of finding the range of reflecting surfaces took place independently and practically simultaneously in America, Britain, France, and Germany. But it was Great Britain which first had a chain of operational radar stations round its coast. Secondly, it was British workers who brought about the wavelength revolution in radar, when metre wavelengths were replaced by wavelengths of a few centimetres. This wavelength revolution, the importance of which cannot be stressed too highly, brought with it the possibility of producing narrow and concentrated radio beams and consequently the possibility of radar-television.

By arrangement between the three Defence Services it was the Director of Scientific Research, Admiralty, who was responsible for the development of thermionic valves; and it was as a result of work, sponsored by the Admiralty, in universities and industrial laboratories, that high-power centimetre-wave sending and receiving valves became available and opened up entirely new possibilities in the radar field. My own view is that the whole subject was transformed by the introduction of centimetre-waves. (Incidentally it is worth recalling that the valves used in the early experiments on radar at Orfordness in 1935 were those with silica envelopes made by the Admiralty. At the time they were the most suitable types available for producing conveniently the high power required to increase the range of aircraft detection.)

The invention that transformed radar, by the introduction of centimetre waves, was the cavity-magnetron, invented by




*a* **Cylindrical anode magnetron.**




*b* Multi-segment anode magnetron.

Fig. 6. Section of Electrode System of Old and New Types of Magnetron

The magnetic field is at right-angles to the paper.

J. T. Randall and H. A. H. Boot, who were members of the Birmingham University Valve Research Unit working under the direction of Professor M. L. Oliphant and developed by the Research Laboratories of the General Electric Company. The magnetron in its simple form was, of course, well known before 1940 as a generator of short radio waves, but the powers available rarely amounted to more than a few watts, especially at wavelengths as short as 10 cm. The old type of magnetron consisted of a thermionic tube, with a cylindrical anode surrounding an axial cathode filament heated to generate electrons thermionically. The whole assembly was situated in a uniform magnetic field the direction of which was along the axis. In some examples the anode was split into two equal parts.

In the cavity-magnetron of Randall and Boot the new feature

* Unfortunately, however, the heat is low-grade since, with present installations, the temperature must not be allowed to exceed 100 deg. C. This arises from the fact that it is necessary to prevent the corrosion of the aluminium which is used as a protective coating to the easily oxidizable uranium metal. The problems of attaining a higher, and thus useful, temperature of operation are thus largely metallurgical.

is that the closed, non-radiating, oscillatory circuit is part of the solid anode, inside the tube. As shown in Fig. 6, the solid anode has eight slot openings cut out of it, each leading into a cylindrical cavity. As a rough approximation, we can think of the slot as the condenser of the oscillatory circuit and the cavity as its single-turn inductance; and, as the electron clouds are rotated, due to the influence of the magnetic field, in the space between anode and cathode, energy is given to each small oscillatory circuit so that it is kept in electrical vibration. It is, of course, necessary for the frequency of rotation of the electron clouds, which depend on the strengths of the anode voltage and the longitudinal magnetic field, to be related to the oscillation frequency of the cavities so that the impulses tend to build up the oscillations in them.

Actually the dimensions of the anode structure are such that there is appreciable electrostatic coupling between adjacent slots and also magnetic coupling between adjacent cavities, so that alternate oscillatory circuits oscillate just 180 deg. out of phase.

Radio-frequency energy is extracted from the anode by means of a probe inserted in one of the eight cavities.

*The Application of Centimetre Waves.* The availability of centimetre waves brought with it two important advantages. First, it was possible to concentrate them, as in the case of light waves, with a parabolic mirror. Second, it was possible to floodlight the lowest layer of the atmosphere and so detect low targets. Appropriately enough, the first operational use of centimetre waves was made by the Admiralty in 1941 in the form of the now historic No. 271 set. This set prompted a revolution in surface detection of small craft; and increased U-boat sinkings followed as a result. Even a submarine's periscope could be detected. Ships' life-boats and rafts were also located at night, enabling survivors to be picked up. Even gannets and other large sea fowl produce echoes on occasion.

An example of the Army's employment of centimetre waves was the GL. Mark III, which is a species of radio searchlight in which an aircraft target is illuminated by a concentrated beam of radio energy. Actually the beam is not made to point directly at the target, but is switched rapidly over a very small angle from side to side of it. The echoes received in the two positions are displayed, side by side, on the cathode-ray tube. When the two echoes are exactly equal, the direction of the target lies exactly between the two beam directions. By switching the beam up and down, elevation, as well as azimuth, can similarly be obtained; and in fact the beam takes up the successive positions up, right, down and left, several thousand times each minute. Accuracies of one-sixth of a degree are obtainable in both bearing and elevation, and these quantities, together with the range measurement, completely specify the position of the target.

To this "GL" equipment, which was developed by the staff of the Radar Research and Development Establishment (R.R.D.E.) of the Ministry of Supply at Malvern, there has now been added "automatic following", so that once the equipment has, so to speak, been shown the target by its operatives, it will follow it in elevation and azimuth without any further human assistance. It does this indeed slightly more accurately than a human being can. An important application of the GL Mark III set, of use in peace as well as in war, is in connexion with the determination of wind speeds in the upper air for meteorological purposes. An ordinary meteorological balloon is used, to which is attached a special reflector so that, although the target is small, a considerable radio echo is obtained. The life-history of the position of the balloon can then be followed by the GL set in both range and direction.

The same station (R.R.D.E. of the Ministry of Supply) has also developed a whole range of radar sets for coast defence and, using the transient radio echo given by a shell splash in water, has provided the coast gunners with an entirely new method of "ranging" on a surface target. Using this equipment the Dover defences, on the last night of the German evacuation of Boulogne, sank eleven ships out of the eighteen in the two convoys that tried to run the Straits, at a range of nearly 20 miles. All the ships were, of course, quite invisible to the eye.

The most striking development of centimetre-wave technique for Royal Air Force use is the "$H_2S$" apparatus which is due to the Telecommunications Research Establishment of the Ministry of Aircraft Production. This is a most elegant set which actually gives rather crude radar-television in that it provides a rough indication of the type of country over which the aircraft is flying. On the cathode-ray tube in front of the operator are depicted the position of coastlines, large man-made structures, and built up areas, relative to the position of the aircraft. As the apparatus is likely to be developed still further, using still shorter wavelengths and thus giving greater resolution of ground detail, it may be of interest if I outline the main principles underlying its operation.

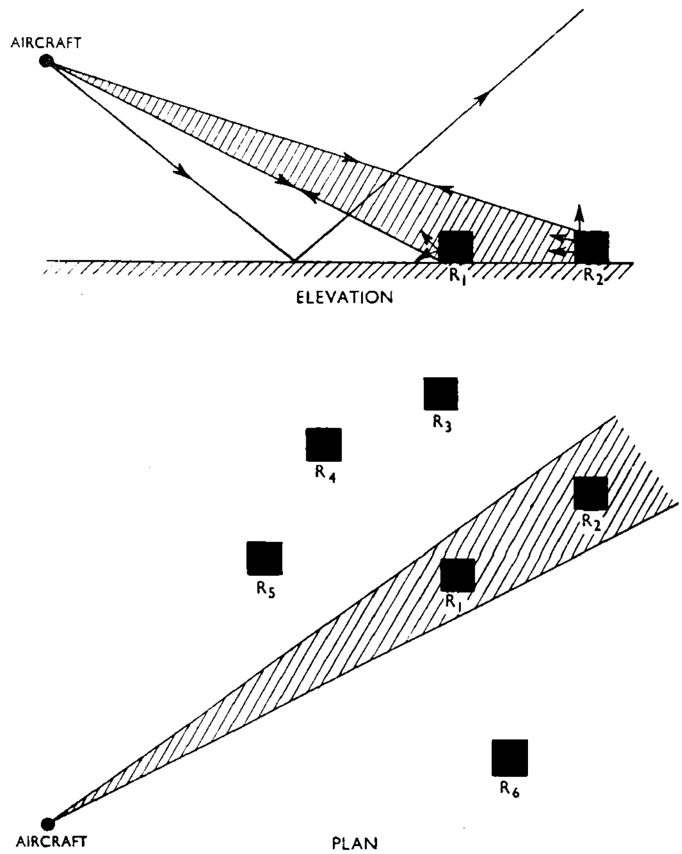



Fig. 7. Principles of "$H_2S$" Radar

A centimetre-wave beam of radio pulses, which is very narrow in azimuth, but broad in elevation, is employed and is directed downwards from the aircraft, thereby "illuminating" a radial wedge of country beneath. Now, since towns reflect more energy than open country areas, and open country areas more than stretches of water, the actual amount of energy reflected back to the aircraft depends whether the illuminated ground is town, country or water. The radio beam is made to rotate through 360 deg. in, say, 1 second, so that, in that period, the radio beam covers all azimuths in turn.

Let us suppose that the rotating beam is stopped for a moment when it is pointing in a north-easterly direction. Let us further suppose that there are a number of regions on the ground (see Fig. 7, plan), $R_1$ to $R_7$, which substantially reflect energy, but of which only two, $R_1$ and $R_2$, are illuminated by the narrow beam. Then the pulses of radio energy emitted by the sender cause echoes to be received with delays corresponding to the respective distances of $R_1$ and $R_2$ from the aircraft. This is illustrated in Fig. 7, elevation.

Now it is possible, on what is called a plan position indicator, to portray the echoes received. These appear as bright spots on a cathode-ray tube screen. Moreover they are correctly portrayed in azimuth, and their distance from the centre of the tube is proportional to the slant distances shown in Fig. 7 (elevation). Since the cathode-ray screen has a long afterglow, the bright spots remain visible throughout a complete rotation of the exploring beam. The result is that the spots on the screen show to the eye the appreciably reflecting areas situated at all azimuths and up to all distances within the range of the set.

A further word may be said about this very elegant method of echo portrayal. The time base used with the oscillograph is arranged to start from the centre of the tube at the instant the radio pulse is sent out, and to move out to the edge of the tube, linearly. It then performs the same trace at a slightly different angle, rotating round the face of the tube in synchronism with the movement of the scanner mirror. If the radio beam is, for example, +90 deg. from the direction in which the aircraft is travelling, the time base is stroking the cathode-ray screen from the centre to the "3 o'clock" position. Echoes received from objects in the wedge of country illuminated by the radio beam appear as bright spots on the tube face, and the spots remain visible until the echoes from all the successive wedges illuminated in turn are delineated together to give the complete picture.

In Fig. 8, Plate 1, is shown an "$H_2S$ picture" of the landscape "seen" by an aircraft over the coast of South Wales, near Newport, Mon.

### RADIO COMMUNICATIONS

A great variety of telecommunications equipment has been developed for all three Services during the war, all of which have points of special technical interest. It is only possible, however, to mention one outstanding example here, namely, the Army No. 10 set, shown in Fig. 9, Plate 1, which is entirely a war product, being developed by the staff of the Signals Research and Development Establishment of the Ministry of Supply. Like much of the radar equipment, it uses centimetre waves, which, by means of a parabolic mirror, are projected forward in a beam and are received along the line of sight by means of a small receiving antenna situated at the focus of a similar parabolic mirror. Pulse modulation is employed, and eight duplex telephone channels are provided.

Originally intended for use on lines of communication, the set played an outstanding tactical role during Field-Marshal Montgomery's rapid advances in Europe. Its great merit as a substitute for telephone lines lies in the rapidity with which a circuit can be set up. Moreover in a rapid advance existing lines often suffer serious damage, and ordinary wireless communication is liable to interception by the enemy. With the No. 10 set the radiation is confined to a fairly narrow beam and security is maintained. Confidence in its security was amply justified in practice, for, despite its use in a chain of relay stations in France and Germany, the enemy had no idea we were using such equipment. It is, I think, of special interest that one of the factors that hastened the original decision to attempt the design of a set of this type was the shortage of rubber for the insulation of telephone lines! Necessity was, indeed, the mother of invention.

### IONOSPHERIC FORECASTING

During the war there has been a great intensification of the study of the ionosphere both in the Allied countries and also, as we now know, in Germany. Since radio communication over medium and long distances is usually accomplished by means of radio waves which have been reflected by the ionosphere, it is most important, especially when field sets of necessarily low power are used, that the wavelength employed should be one which is reflected by the ionosphere as copiously as possible. Indeed in such cases correct choice of frequency may often determine whether communication is established or not. This need has stimulated the attempt to predict, two or three months in advance, the optimum frequency to be used in any particular part of the world for communication at any hour of the day and over any distance of transmission. A new subject has, in fact, been founded, namely, that of "ionospheric forecasting".

The work on ionospheric forecasting conducted by the Allies may be conveniently grouped under four heads as follows:—

(i) *World-Wide Study of the Ionosphere.* This has been conducted at a number of strategically placed stations, each equipped with ionospheric pulse equipment for finding, every hour, the heights and critical frequencies of the ionized layers in the upper atmosphere. In this way it has been found possible to learn how the ionization densities vary from hour to hour, from month to month, and from year to year throughout the sunspot cycle.

(ii) *Forecasting of Future Ionospheric Conditions.* Since certain regularities and trends in the ionospheric variations can be recognized, it is possible to estimate with fair accuracy what the average heights and ionization densities will be at a time two or three months ahead. In this way the average conditions over the greater part of the world may be predicted in advance.

(iii) *Calculation of Maximum Usable Frequency for Transmission over Any Distance.* Assuming that the distribution of ionization with height in any layer is "parabolic" in shape, Dr. W. G. Beynon and I have shown how to estimate the maximum usable frequency for any distance of transmission, when the conditions in the refracting layer (i.e. half-layer thickness $y_m$; height of lower boundary $h_0$; and vertical incidence critical penetration frequency $f_c$) are known. Using the forecasts of values of $f_c$ mentioned in paragraph (ii) above, this method has been employed to predict maximum usable frequencies two or three months in advance.

(iv) *Issue of Storm Warnings.* During conditions of magnetic activity it has been found that ionospheric conditions are almost always disturbed. Usually the $F_2$ layer critical frequency is depressed and, in our latitudes, a reduction in operating frequency is required to maintain communication. The onset of such ionospheric storms can usually be recognized from ionospheric measurements in high latitudes, from reception results on circuits passing near the auroral belt, from a visual study of the sunspot activity, and from a recording magnetometer.

The work on the direct calculation of the maximum usable frequency demands a further word of explanation. Although the calculation is a little complicated, the results may be made available in a handy graphical form. It turns out that we can express the relation between the oblique incidence maximum usable frequency ($f_{max}$) as the product of the vertical incidence critical frequency and a certain factor, which we will call the M.U.F. factor. We have further

$$\text{M.U.F. Factor} = \phi(h_0, y_m, D)$$

where $D$ is the distance of transmission. The graph of the M.U.F. factor as a function of $D$ for typical values of $h_0$ and $y_m$, for both the $E$ and $F$ layers, is shown in Fig. 10. Forecasts of the type described above have been used by all three Services during the war. They have been prepared by the inter-Services Ionospheric Bureau and the Radio Research Station, Slough, working in collaboration with similar organizations in the Dominions, in the United States, and in Russia.

### THE SCIENCE OF ARMAMENTS

As I mentioned earlier, many scientific groups and individuals completely changed the subjects of their researches in war time. One of the most noteworthy examples of a change of this kind is to be found in the war work of the Road Research Laboratory (R.R.L.) of the Department of Scientific and Industrial Research. Here was a Civil Engineering organization, accustomed during peace time to work on civil engineering problems, which, during the war, became the focus of a wide variety of researches on the physics of explosions. This work proceeded under the direction of Dr. W. H. Glanville (Director of Road Research) and Dr. A. H. Davis (Assistant Director), who were largely responsible for developing investigations on a model scale, which formed such an important feature of the war work of the Laboratory.

(*a*) *Blast-Pressure Measurements.* Using the piezo-electric effect exhibited by quartz crystals, a section of the Laboratory, quite early in the war, developed a technique for the photographic registration of pressure-time curves associated with the blast waves from explosions. (Actually the piezo-electric pressure gauge was used in the 1914–18 war by the Admiralty for the same purpose, but improved electronic and oscillographic technique has more recently permitted the design of far more sensitive and accurate equipment.) The Road Research Laboratory gauges and equipment, developed by a small group working under Mr. G. Grime, have now become standard throughout all the Defence Services. With them the fluctuation in pressure from small explosive charges or from large bombs can be measured.

It was found, as a physicist would have expected, that the pressures exerted in air by model charges of explosive were the same, at scaled distances, as those arising from a full-scale charge, and they lasted for scaled times.

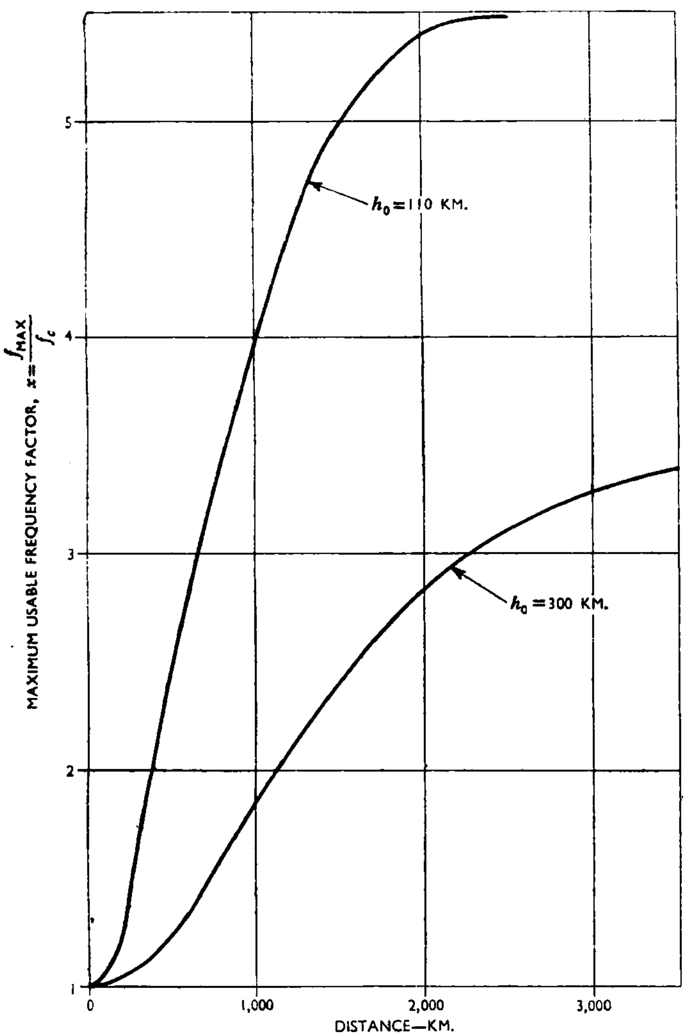



Fig. 10. Relation between M.U.F. Factor and Distance

As a consequence of this, if experiments are conducted with similar charges on various scales, and if distances are expressed in units proportional to the linear dimensions of the charge, the variation of maximum pressure, for example with distance from the charge, is the same for all sizes of charge (Fig. 11). This relationship enables one to draw a standard graph representing the performance to be expected from a given type of bomb irrespective of its size, and proved helpful in ascertaining whether a given new bomb was detonating properly. As a matter of fact, the blast observed at a distance from bombs of ordinary shapes is not very dependent upon that shape; and the Static Detonation Committee of the Ministry of Supply, under the chairmanship of Dr. H. L. Guy, standardizing a procedure which had been in use at the R.R.L., adopted a single "standard" curve for giving a first assessment of the desirable behaviour of any proposed new Service bomb. Through measurements and studies of this kind it was revealed that some of the early 8,000 lb. "block-busters" were not giving the performance to be expected from a well-detonated bomb of this weight, and experiments were conducted with modified arrangements until the standard performance was attained. The story is a complicated one, but the necessary improvements were achieved. Mr. H. Sheard was in charge of the team of workers who made the measurements.

In the latter half of 1944 and early 1945 several members of the Road Research Laboratory staff, experienced in the measurements of blast pressures from explosions and the recording of their visual characteristics, were flown to America to take part in the researches on the atomic bomb, and in the assessment of

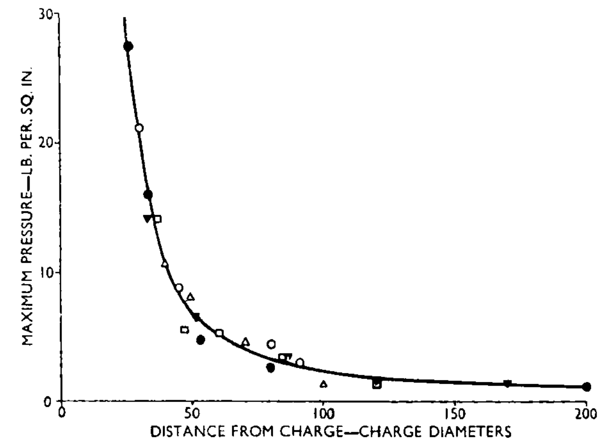



Fig. 11. Relation between Maximum Pressure and Distance from the Charge

(Road Research Laboratory, Department of Scientific and Industrial Research.)

Explosive, T.N.T.—C.E. One curve suffices for similar charges of different sizes if distances are measured in terms of the diameter of the charge.

| | | | |
|---|---|---|---|
| ○ | 4 inches diameter; | 2·8 lb. | |
| ▼ | 7 | „ | 15 „ |
| ● | 9 | „ | 32 „ |
| □ | 10 | „ | 45 „ |
| △ | 12 | „ | 76 „ |

its blast performances. They took with them a considerable proportion of the special apparatus developed at the laboratory for studying explosions, and made appropriate measurements at the trial of the first atomic bomb detonated statically in America.

(*b*) *Scale Relationships and the Use of Models.* In explosives research, especially as regards the use of explosives against particular targets, full-scale work is often impossible; but careful studies, mainly at the Road Research Laboratory, have made it possible to carry out many investigations on a small scale with the assurance that it will be possible to translate appropriate aspects of small-scale experiments into the effect on full-scale targets. A simple example of a scale relationship of this kind is illustrated in Fig. 12 which is based on work by Dr. H. J. H. Starks, and shows how, when similar explosives were buried at similar depths in homogeneous soil, the diameters of the craters formed were proportional to the diameters of the charges used; in other words, the phenomenon "scaled". This fact was used in many experiments in which study was made of the performance of underground shelters, of methods of attacking buried fortifications and works, and of the performance of "earthquake" bombs.

As a consequence of the scaling of explosive forces, it is possible to study the damage effects of explosives upon materials and objects on a model scale. It must be realized that in making a model the specific strength of the material used must be the same on the model scale as on the full scale, and the sizes of all the parts must be reduced appropriately in scale, as they would be reduced if one viewed the full-scale charge and the full-scale target through a diminishing glass. For example, in composite materials such as reinforced concrete, the larger aggregate must be scaled down, the reinforcing bars must be scaled down, and strictly the sand and cement should be scaled down also. In practice, however, it appeared that the size of the sand was not important, and while it was usual to scale the aggregate as far as possible, it was not always necessary to scale it to the full extent. It is, of course, essential to use the same explosive both on the model and full scales.

Some difficulties arise with the initiation of the explosive, particularly as it is not feasible to scale detonators and initiating systems, but excellent inferences from model experiments have been obtained when care has been taken to ensure full detonation of the model charge as well as of the full-scale charge. It is also necessary of course, to tamp or encase the charge in the scaled manner, but this condition is automatically covered if all details of the experiment are scaled. Since, as required by scale relationships, the pressures exerted by the explosive are more transient on the small scale than on the large scale, it is important that the properties of the target materials shall have no special dependence upon the rate of strain. It is not essential that the strength of the material under dynamic conditions be the same as its strength under "static" conditions, only that the dynamic strengths under the full-scale and model rates of strain should be the same. Although only experiments can decide, for a particular material, whether this condition is fulfilled, experience has shown that valuable model experiments, as regards explosions and impacts, can be conducted with concrete, "earth", steel, and other materials.

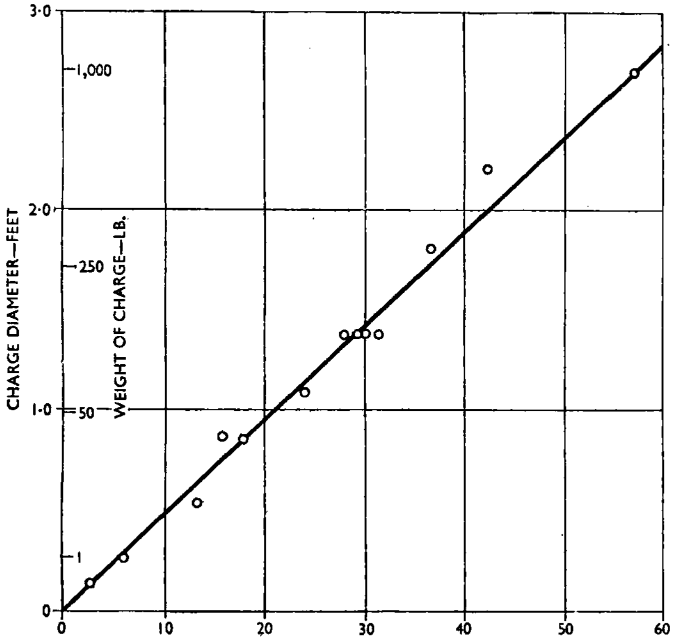



Fig. 12. Relation between Diameter of Charge and Diameter of Crater, with Explosive Charges fired in Clay Soil

Road Research Laboratory, Department of Scientific and Industrial Research.)

Charge depth in feet = 7·4 × charge diameter in feet.

With model targets exposed to scaled explosive charges at scaled distances, the pressures and stresses at corresponding points are the same (at time intervals which are proportional to the scale of the model) as the pressures and stresses on the full scale, and velocities are the same on the model scale as on the full scale. Consequently strains and failures will occur in the same manner on the various scales, and the velocity of any missiles thrown off by the shattered target will be the same on all scales.

All this, however, assumes that the pressures accompanying explosions are so high that gravitational forces are negligible in comparison with the stresses set up by the explosions. This is undoubtedly true up to the moment at which the missiles begin to move, but the distances to which missiles are thrown do not scale—they are the same on the model scale as on the full scale. For example, in the case of buried charges, the heights and distances to which fragments would be thrown would not scale, although the region of damaged earth would scale. Again, in the case of a certain dam which was studied as a target for explosive attack, the shattering of the dam was expected to scale, but it was realized that the distance which any shattered parts would be thrown or carried by water would not scale. Consequently in this experiment, and in other experiments with bridges, canal banks, etc., where gravity was involved, discrimination was necessary in interpreting the later stages of model experiments, and often a fairly large-scale check of selected expectations was desirable.

Fig. 13, Plate 2, shows the damage caused to a small-scale dam by a certain charge which only cracked the dam. The cracking would be expected to scale, whereas the displacement of parts against gravity, and the flow of water under gravity, would not scale. It is clear, however, from the model experiment, that the attack studied would be unlikely to cause great damage to the dam. Fig. 14, Plate 2, shows the close correspondence obtained on a much larger scale.

Further experiments with larger charges and new dams resulted in the shattering of the dam and the scattering of its fragments under gravitational forces. In this case an attempt was made to assess whether the full-scale scatter would be catastrophic. As the scale of the model was one-tenth of that of the larger experiment, the shattered parts of the model (which had been thrown off with the same velocity as was expected by the scattered parts of the large model) were collected and reassembled at one-tenth of the distance from the dam to which they were in fact thrown. Fig. 15, Plate 2, shows the model after the necessary adjustment for the scattering of the parts of the dam; it was obvious that much of the dam would be thrown clear of the foundations. Fig. 16, Plate 2, shows the close correspondence to this result which was in fact obtained on the large scale.

These experiments, conducted for a special committee formed by the Ministry of Aircraft Production, were preliminary to the attacks on the Moehne and Ider Dams, and Figs. 17 and 18, Plate 3, show the damage which occurred on that even greater scale, when a charge of appropriate magnitude was used. This investigation was conducted by Dr. A. R. Collins, of the Concrete Section of the Laboratory. Other matters of interest studied on the model scale by the Concrete Section, led by Mr. F. N. Sparkes, included the attacks on the Dortmund-Ems Canal and Bielefeld Viaduct, methods of attacking anti-tank walls and the Atlantic wall, the neutralization of enemy-held "pill-boxes", and the demolition of bridges and other structures. A large part in this work was taken by Mr. J. Hayes. Laws governing the penetration of bombs and of shot and shell into concrete and other materials were also derived by a special "penetration" section led initially by Mr. A. H. D. Markwick and, since 1941, by Mr. A. C. Whiffin. The work of this section led to many developments in bomb and shell design.

(c) *High-Speed Photography.* Much use was made by the Laboratory of high-speed photography for examining the development of the detonation of high-explosive charges. A number of very useful devices were developed by the photographic section under Dr. Lonsdale but it is only possible to mention here the high-speed camera developed by Mr. W. G. Marley. This camera, which has only one high-speed moving part, namely a rotating slotted disk, takes a number of photographs at a rate of 100,000 per second.

The principle of the instrument is simple. If a house with 4 windows (two upstairs and two downstairs) faced an explosion, and if a camera lens were placed in each window, each of the lenses would give a photograph of the occurrence. If a large slotted disk were placed in front of the house and arranged so that the slot would pass in front of the windows in turn, the disk—as it rotated—would ensure that the photographs obtained by the cameras would form a succession. In one revolution of the disk, all four cameras would take a photograph. If the disk contained three slots equally spaced instead of one, the arrangement would be something like a circular vernier. As the disk rotated, one slot would soon expose one of the cameras momentarily, shortly afterwards another slot would expose a second and so on. In fact, all four cameras would be exposed in the time during which any one slotted disk moved through one-third of a revolution: for in that time the three slots, between them, would have made a complete circle of exposures. If the house had fifty-nine windows arranged round a circle facing the explosion, and if the disk had fifty-eight slots, fifty-nine photographs would be obtained whilst the disk rotated through about 6 deg.

The high-speed camera has been constructed on this principle. It contains fifty-nine stationary lenses corresponding to the windows; it has only one high-speed moving part, namely, a slotted disk. Even with a disk of only 16 slots (Figs. 19 and 20, Plate 3) at only a moderately high speed, it is possible to obtain fifty-nine photographs at a rate so high as 100,000 per second.

Fig. 21, Plate 4, shows a series of photographs of a length of high explosive detonating, and the progress of the detonation along the stick can be observed. With cameras of this type the progress of detonation in a large bomb could be observed, and any defects of the bomb should be visually revealed. With this and other photographic devices the initiation of detonation in explosives is being studied, transparent explosives being used so that the progress of detonation in the explosive itself can be noted.

Photographic equipment working on an entirely different principle has also been developed by the Armament Research Department of the Ministry of Supply under the general direction of Professor J. E. Lennard-Jones (Chief Superintendent). The principle underlying this equipment, which is called the "Arditron", is that photography is accomplished during an exceedingly brief time of illumination. A condenser is charged to a high voltage, and is discharged through a specially designed tube. The flash produced has a light intensity of 100,000,000 candle-power, and lasts only one-millionth of a second.

The essential advance responsible for the successful performance of the Arditron lies in the activation of the surfaces of the electrode system and the use of copper electrodes saturated with potassium as electrode material. The discharge tube is filled with argon at a pressure which is at least atmospheric. The result is uniform performance, while the luminous discharge, which can be rapidly repeated where desirable, is confined to a narrow axial channel. The tube is "triggered" by means of an internal electrode. Arditron tubes have been employed in the study of the behaviour of ballistic and armour-piercing caps on shell after penetrating plates, and in the study of yaw. Projectiles moving at over 4,000 ft. per sec. have, for example, been successfully photographed, while, by adapting the tube as a point source, shock waves and particles moving with velocities up to 6,000 ft. per sec. have been "shadowgraphed".

(*d*) *X-ray Examination.* The Armament Research Department (A.R.D.) has also been largely responsible for the rapid extension of the use of radiographic methods. About forty powerful X-ray sets, working in pairs as twenty twin units, have been installed in Royal Ordnance Factories for almost continuous use in the routine inspection of many millions of shell fuzes, to check their filling and assembly for safety and freedom from defects. Information has been obtained, unobscured by flash or smoke, of the behaviour of detonating explosives and flying fragments and bullets, by means of "flash" radiographs, each made in one-millionth of a second. Radiography, as the first stage of examination of enemy ammunition, has reduced the danger and hastened results. It has been applied to unexploded mines and bombs where they fell, and so has detected "booby-traps" and identified new fuzes.

Countless other radiographic applications range from the filling of a tiny detonator or small arms cartridge to the high explosive inside a 4,000 lb. bomb or 16-inch shell; from a small die-casting to cast steel gun cradles, turbine casings, ships' rudders, and propeller brackets; from the welding of thin aircraft parts to that of thick steel in high-pressure boilers, fabricated parts of ships' machinery, hulls of warships of all classes and of merchant ships, and the armour of tanks. All this has necessitated the continuous development of new apparatus and techniques, as well as the training of staff to apply the methods *in situ.*

(*e*) *The Use of Electrodeposition for Gun Barrels.* Another important development, again due to the Armament Research Department, is the employment of electrodeposition as a means of repair for worn gun barrels or as a cure for over-machining. With the expansion in the production of armaments due to the war, the proportion of work spoilt by over-machining was rising. Firms and departments were advised on A.R.D. methods with the result that production schedules were maintained and labour saved by the salvage of over-machined components by electrodeposition. Coating of any desired thickness up to $\frac{1}{10}$ inch or $\frac{1}{8}$ inch is possible in this process. The repaired surface is usually at least as serviceable as the original, and it may indeed be superior as regards resistance and protection from rust.

Forty worn 4-inch guns, required for use on merchant ships at a critical period of the war, were made serviceable by the A.R.D. electrodeposition method, while as many as 5,000 guns spoiled in manufacture by over-machining were salvaged by it. Another application of electrodeposition is the chromium-plating of 0·5-inch Browning gun barrels. In this case a method was developed which increased the life from three to five times.

### COUNTERING THE ENEMY'S ACTIVITIES

Speaking generally, we may say that the scientist is called on to satisfy two kinds of requirements. One of these is dictated by what our own armed forces wish to do. The other is dictated by what the enemy himself does. Counter-measures of all kinds are in the latter class, and require specially well-informed and prompt action. Indeed, I would say that, in general, counter-measures require comprehensive knowledge of the most fundamental kind. A good example of this arises in the problem of countering the enemy's mines at sea. Here it is readily appreciated that, to be prepared for counter-measures, it is necessary to have the most detailed knowledge of a ship's physical characteristics and of the influence it exerts on the sea around it.

Fortunately, some thought had been given before the war to the enemy's possible use of the magnetic mine, and some information about the magnetic properties of ships had been obtained. Analysis of the magnetic surveys shows that a ship has both permanent magnetism and induced magnetism. The vertical induced magnetism will evidently depend on magnetic latitude, and the horizontal component of the induced magnetism will vary with the ship's heading. It was shown, in these pre-war experiments, that the magnetic field due to the induced vertical magnetization of a ship could probably be reduced to a small value at a distance from the ship by means of a horizontal coil wound round the ship. But since it was considered likely that any non-contact mine the enemy might use would be designed to fire at a short distance from the hull, it was considered that even this residuum of uncompensated magnetic force might be dangerous. Consideration was therefore given to the possibility of enhancing, rather than neutralizing, the ship's magnetic effect so that such a mine might be exploded at a safe distance, and in 1938 a full-scale experiment was carried out in which H.M.S. *Curacoa* was heavily magnetized longitudinally by vertical coils wound round the ship. A considerable measure of success was obtained, but the protection afforded was not sufficiently certain to justify adopting a method which has many obvious practical difficulties.

The experiment did, however, suggest that the method or a modification of it might be valuable for sweeping magnetic mines; and in March 1939 a specification was worked out for a large electromagnet containing about 500 tons of iron to be fitted in the hold of a merchant ship. This sweep was actually constructed at the beginning of the war and was used with success against the German magnetic mine in January 1940. Although this sweep has been superseded by more efficient types, notably the "double-L" sweep (in which the magnetic force due to an electric circuit, which is, in part, along cables and, in part, through the sea, is employed) it is of interest to note that the enemy has made extensive use of it against our own mines throughout the war.

The dramatic story of the speed with which the German magnetic mine (the first accessible example of which was dropped on 21st November 1939), was countered by Admiralty scientists and technical officers, has already been told. Once the enemy had shown his hand by using a ground

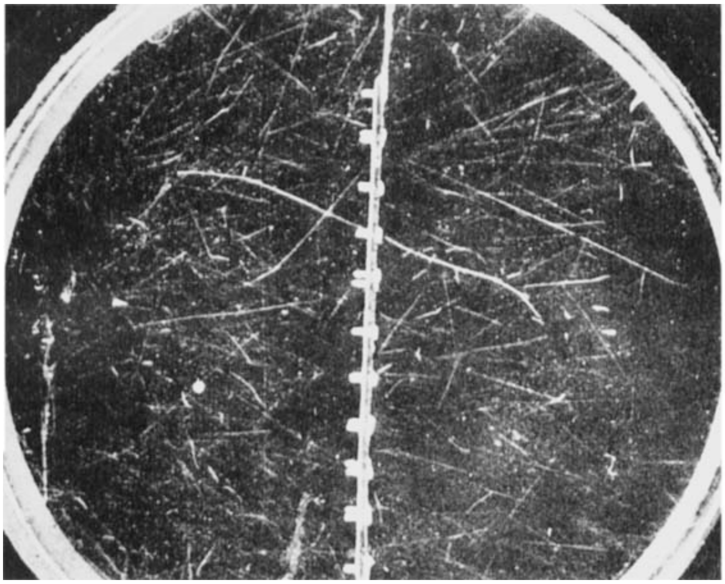


Fig. 1. The Fission of Uranium

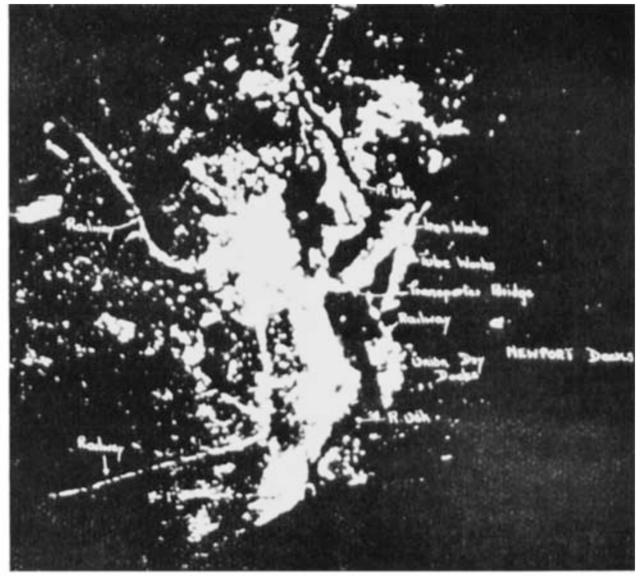



Fig. 8. "$H_2S$" Picture of River Usk near Newport, Mon.

Fig. 9. Wireless Set No. 10 in Trailer

Fig. 13. Damage to a Small-Scale Dam

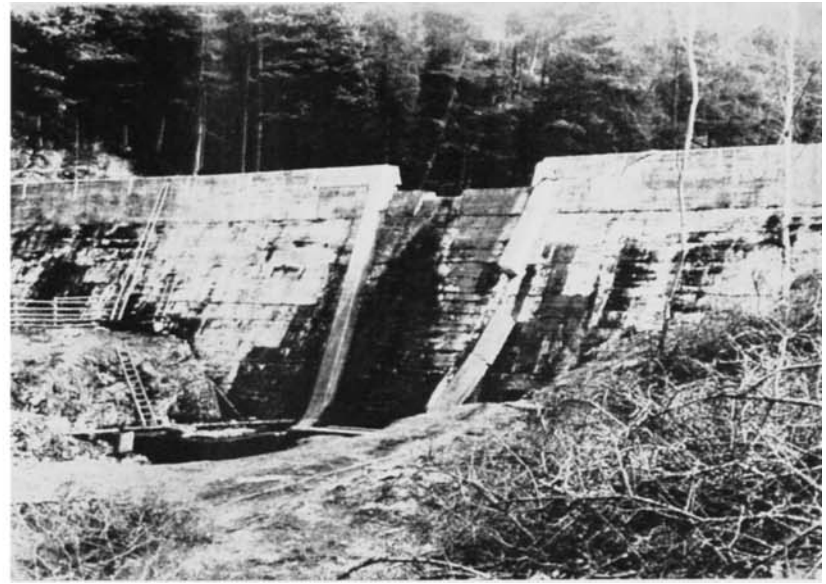


Fig. 14. Similar Damage on a Larger Scale

Fig. 15. Model Dam after Adjustment of Fragments

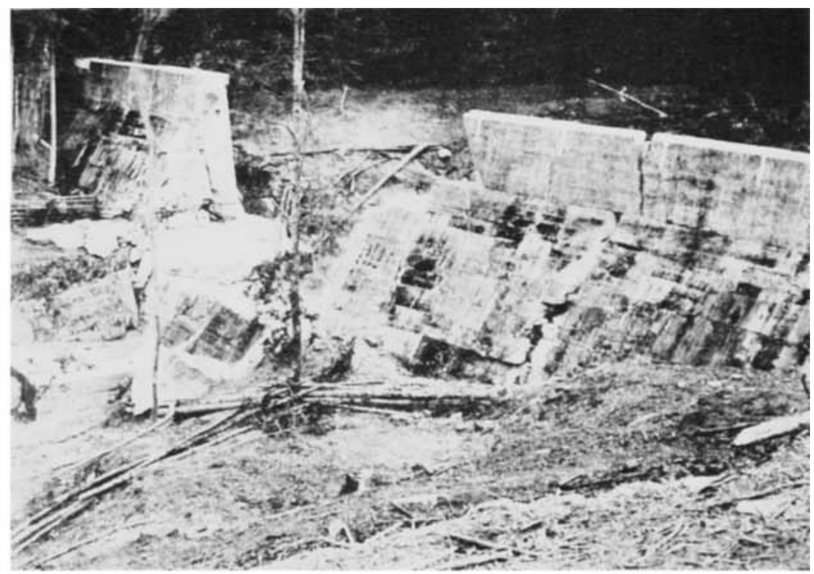


Fig. 16. Similar Damage on a Larger Scale

Fig. 17. Damage Done to Moehne Dam by Bomb Attack
(Crown copyright reserved.)

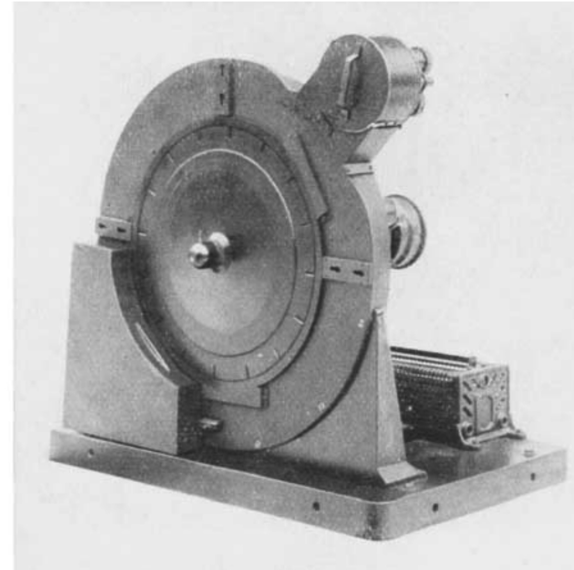


Fig. 19. The Marley High-Speed Camera

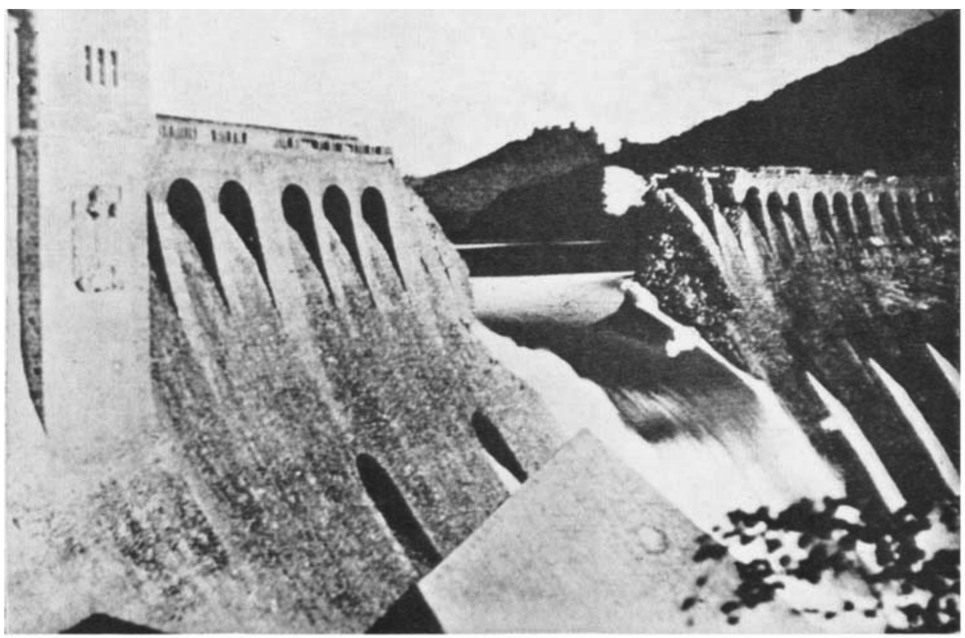


Fig. 18. Damage Done to Moehne Dam by Bomb Attack

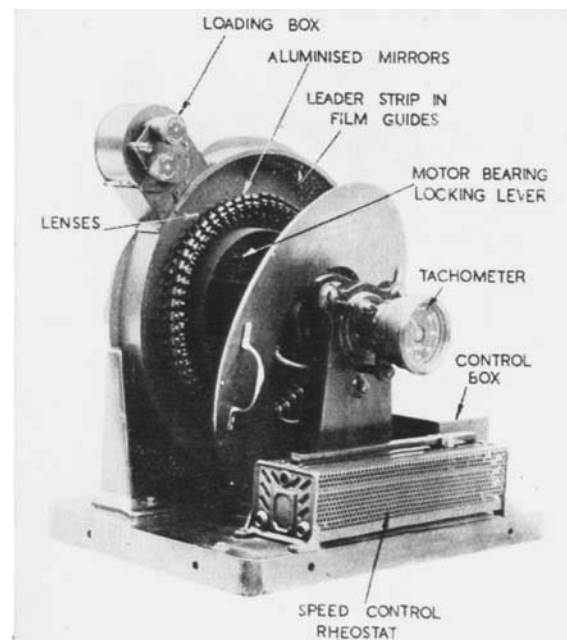



Fig. 20. Another View of the Marley High-Speed Camera

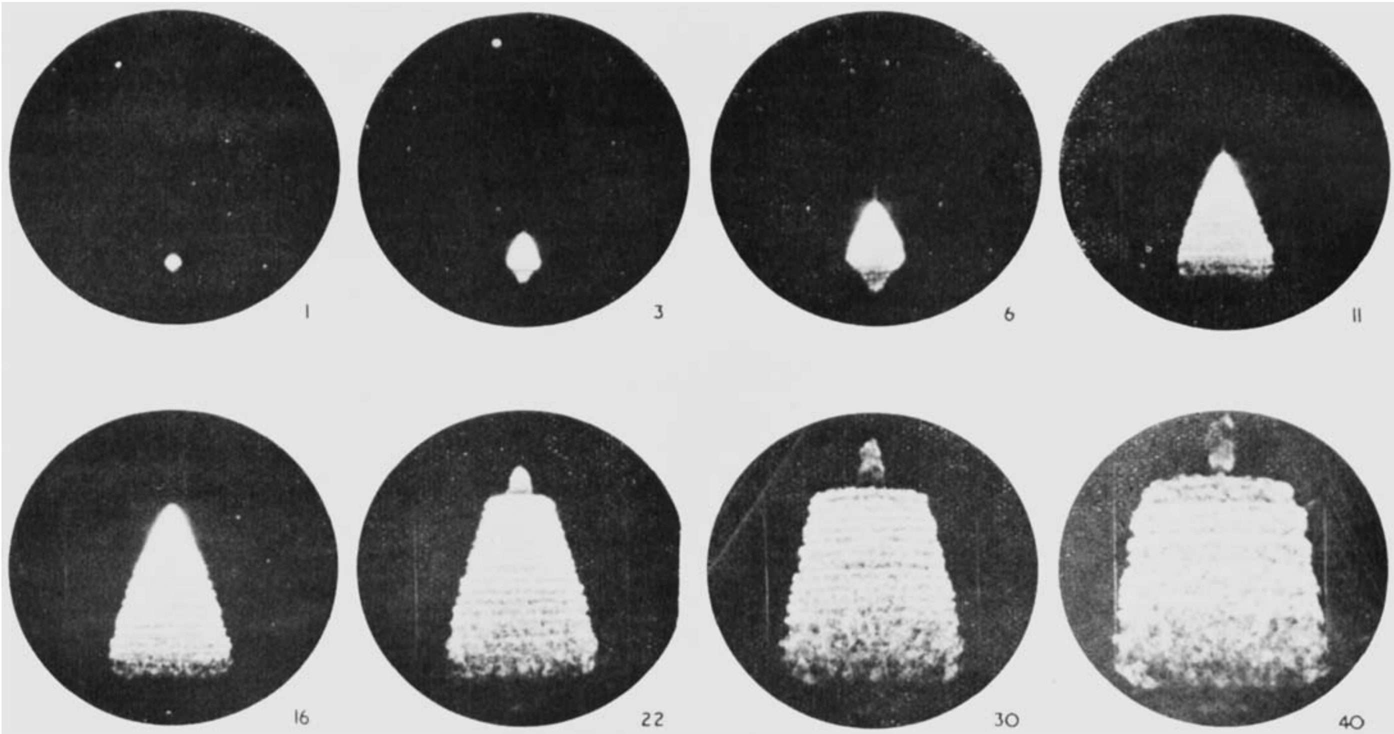



Fig. 21. Detonation of a 2 lb. Charge of Tetryl, 4 feet long × 1 inch in diameter
Frame speed, 76,000 per sec. Selected frames shown. Frame interval, 13·1 micro-seconds.

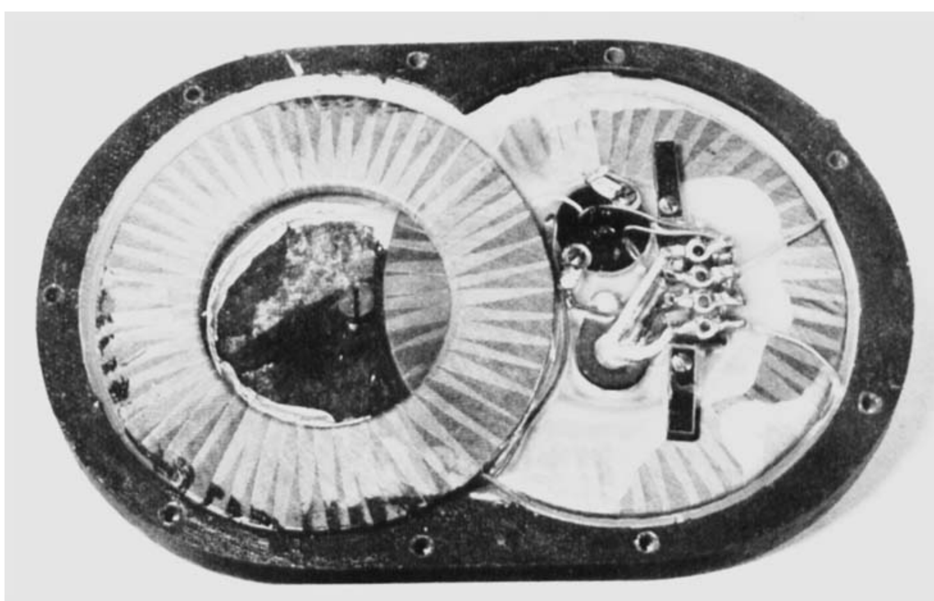


Fig. 22. Detector Unit of Mine Detector, showing Overlapping Coils

mine, it was fairly clear what kind of protection for our own ships was required. The vertical component of the ship's induced magnetism was recognized as being the chief potential danger and it was realized that horizontal coils carrying an electric current were required to neutralize it. Thus the practice of "degaussing" began. It was simply a large-scale application of the principles of electromagnetism.

Another application of simple electromagnetic principles was the attempt to find if it was possible to cause a ship to acquire permanent vertical magnetism which would be approximately equal and opposite to the magnetism induced by the vertical component of the earth's field, and so neutralize it. Considerable success was achieved, and a large number of ships were "wiped", as the term goes, in this way. Unfortunately the magnetization was found to decay, necessitating "rewiping". But in spite of this, the method was of great use in providing quickly a measure of protection for a large number of ships. A great many of the small ships used at Dunkirk were, for example, dealt with in this way.

The compensation of the permanent longitudinal magnetism of certain ships provided additional problems. But here, again, an operation involving the well-known electromagnetic principles of demagnetization was carried out on a large scale. A temporary coil, with its axis parallel to the length of the ship, was first wound round the ship. Then a current was passed through this coil. The current was repeatedly reversed and reduced in magnitude, and the ship was demagnetized. It was found particularly necessary to demagnetize one ship in this way, H.M.S. *Curacoa*, since she had retained a great deal of permanent magnetism from the experiments carried out on her before the war.

Another important example of the application of simple physical principles is embodied in the apparatus developed for detecting anti-tank and anti-personnel land mines. It is a familiar fact of electrical theory that, while the coefficient of self-induction of a coil is, by definition, always positive, the coefficient of mutual inductance between two coils can be either positive or negative, according to the sense of the magnetic linkage between the coils (when one of them is carrying a current). There must, therefore, be one particular disposition of the coils in which the mutual inductance is zero (Fig. 22, Plate 4). (For example, if two flat coils are placed one on the top of the other so that they are co-axial, the condition of zero mutual inductance may be reached by sliding one of them in its own plane so as to diminish the overlap of the coils. The zero mutual inductance position is one of partial overlap.)

The fundamental idea underlying the operation of a mine detector operating on these lines was first suggested by two Polish officers. One of the two coils is connected to an oscillator generating alternating current of an acoustic frequency. The other coil is connected to an amplifier and telephones. If now there is zero mutual coupling between the two coils, no signal will be transmitted to the amplifier and no sound will be heard in the telephones. As soon as the coil system is, however, brought near a metallic object, this condition of balance is upset and a signal is immediately heard in the telephones. Equipments of a number of varying designs, based on this principle, have been developed by the Ministry of Supply. They are suitable for detecting the presence of metallic or partially metallic mines.

Another field in which fundamental work has yielded information of the highest value is that of the detection of underwater objects. Here, as is now well known, the outstandingly successful equipment has been, and continues to be, the "Asdic", developed before the 1939–45 war, by H.M. Anti-Submarine Establishment. The operation of this system is exactly analogous to the operation of a radar set, except that sound waves are used and the waves travel, of course, in water and not in the lower atmosphere.

A great number of basic scientific problems arise in this connexion, such as the refraction of sound waves in a medium in which the velocity varies with depth due to gradients of temperature and salinity; and also the scattering of waves by surfaces of irregular shape. Throughout the war the enemy had to change his tactics repeatedly because of the success of Asdic detection, but, due to the fundamental knowledge amassed in the fields mentioned, the many new requirements arising from these changes were efficiently and expeditously met. Asdic detection has, in fact, been responsible for more U-boat sinkings than has any other technique and, throughout the war, this country has maintained the lead which it had previously established in this vital field of defence science.

I will conclude this section on counter-measures with one more example, this time chosen from the field of civil defence.

In November 1939, the Technical Branch of the Air Raid Precautions Department, Home Office (later called the Research and Experiments Branch, Ministry of Home Security) asked the National Physical Laboratory to devise and develop equipment for cutting a hole into, and removing the explosive contents of, unexploded enemy bombs. The use by the enemy of delayed-action bombs was expected, and it was also anticipated that special fuzes would be fitted, with "booby traps", which would operate on any attempt to remove the fuze or to move the bomb bodily. In cases where such bombs were located close to valuable buildings or important lines of communication, or amongst power leads or other vital services, cutting open the bomb case and removal of the main explosive filling provided a possible means of rendering the bomb innocuous.

After preliminary consideration of the problem Dr. S. L. Smith, of the Engineering Department, National Physical Laboratory, and his staff, decided to design a machine to perform the combined operations of trepanning a hole in the bomb case, melting the main filling with a jet of steam and ejecting the molten explosive by means of the steam-pressure developed inside the bomb. The complete cycle of operations was automatic after the attachment of the machine to the bomb case. Power for all the operations was supplied by a steam boiler placed 60 yards from the machine and connected by a single flexible steam pipe.

This machine was designed in the Engineering Department of the National Physical Laboratory and a prototype model was constructed in the Department's workshop. In April 1940, after considerable development and experimental work, this machine was ready for production. About this time the responsibility for the organization of the means for dealing with unexploded bombs was transferred from the Ministry of Home Security to the War Office. By arrangement with the War Office, the Ministry of Supply took over, as from 1st April 1940, responsibility for the necessary further research and technical development of the various methods for dealing with unexploded bombs, including the work at the National Physical Laboratory. This was placed under the general supervision and direction of the Unexploded Bomb Committee under the chairmanship of Dr. H. J. Gough. In this way began the wonderful scientific story of bomb disposal.

### OPERATIONAL RESEARCH

I now turn to one of the most striking scientific developments in the course of the war, namely the work of the Operational Research units of the three Services. This is entirely a product of war time, for even the name was unknown in 1939. It developed directly from the recognition that not merely was it necessary that the war effort should be sustained with scientific equipment, but also that it should be fought in a scientific manner. The result was a gradual extension of the field in which scientists had been accustomed to operate, an extension from the purely technical field to the tactical, to the strategical, and finally to the economic field. In this way the whole range of warlike activity was finally the subject of scientific examination and advice—a gratifying result which followed as much from the open-mindedness of the Services as from the enthusiasm of the scientists. Naturally this happy state of affairs did not develop overnight. At the beginning of the war the Services were unaccustomed to work in co-operation with scientists in operational planning, and were therefore unaware of what might accrue from such co-operation; moreover the majority of scientists had had little experience of military affairs and were in no position to tender useful advice. Thus it happened that the first steps in Operational Research were carried out with no thought of the developments which followed.

Historically, operational research was born when radiolocation was first given to the Services. Here was a new technique, more complicated by far than any the Services had had previously to operate, and more complicated not only technically but also in its tactical and strategical implications. Furthermore there were practically no serving officers with any previous experience of radar technique, which had been developed under conditions of secrecy by a small circle of scientists and technicians. To help the Services in the initial stages, a few of these radar scientists were therefore lent to Fighter Command in order to assist in the integration of the new technique with the fighter defence system of Great Britain. Similar assistance was given to the Army during the introduction of radar methods of anti-aircraft prediction. In this way operational research started to develop in these two services; in the Navy it was introduced at a later stage.

The early studies were made in a fairly narrow technical field, and the scientists employed were mostly specialists in radio physics. Soon, however, the range of problems studied became greater. This followed for two main reasons. First, it soon became obvious that technical radar problems could not be considered effectively in isolation from the general tactical picture, and that improvements in tactics and control might be as important as improvements in the technical performance of the radar gear; and second, it was realized that scientists attached to Service staffs were, by virtue of their training, capable of making useful contributions towards the solution of problems lying entirely outside the radar field.

The methods used in operational research are various, and it is not possible to reduce them all to standard form. The following remarks may give some indication of the general approach made to many problems. The first step is to evolve indices of the effectiveness of a given operation, technique or tactic, the criterion being that the index must be relevant to the objectives of the operation, and that it must be capable of evaluation in terms of known data. Past operations are then studied, either statistically or by actual observation of service personnel carrying out the operations, and the data so obtained are used to evaluate the index. The next step is to estimate the effect, on the "efficiency index", of various possible changes in the conditions of the operations. Finally recommendations may be made to the Service, on the basis of which improvements in the operations may be made; continued study makes it possible to see whether the changes introduced do in fact result in the improvements anticipated.

As an example, the percentage of bombs falling within 1,000 feet of the aiming point may be taken as an index of the efficiency of bombing operations; and this is a quantity which can be evaluated after each attack with the help of suitable photographic technique. The effect of variables on the bombing accuracy may be estimated either directly (as in the case, for example, of the effect of flying height on accuracy, by comparing the accuracies of bombing attained in operations carried out at different heights, all other conditions being the same), or indirectly by reference to trials simulating operational conditions but more susceptible to control and experiment, or by purely theoretical studies.

In practice, problems are usually at least one degree more complicated. Improvement in one direction may lead to deterioration in another; in the case of bombing accuracy, for example, a longer pre-release bombing run might improve accuracy, but would probably lead to higher aircraft losses from anti-aircraft fire. In such a case it is necessary to strike a balance; where the number of variables is great this may be a very difficult matter. In general the number of variables is ordinarily too great for explicit solution of an equation relating them with the efficiency, especially since many of the variables are likely to be inexpressible in numerical terms. In such cases the best that can be hoped for is a solution of the partial differential equation obtained by maintaining all but one or two of the variables constant. To state the matter in mathematical terms, the equation

$$E = f(A, B, C, \ldots)$$

(where $E$ is the efficiency, and $A$, $B$, $C$, etc., are the variables) may be insoluble; but it may be possible to evaluate

$$\left(\frac{\partial f}{\partial A}\right)_{B,\,C,\,D,\text{ etc.}}$$

and thus to predict with some confidence the effect of altering condition $A$, on the operation as a whole.

To give an adequate idea of the range of problems studied by Operational Research Sections would require more space than is available here. The following problems—one each from the Army and Air Force, and two from the Navy—cannot, therefore, be more than a selection from a very wide field. They are chosen because they are typical, and because in all of them the studies of operational research sections had a considerable, and in some cases a major, influence on the conduct of operations.

*Operational Research in the Army.* During 1943 the enemy sent ships through the Straits of Dover only at night. The Coast Artillery, under the command of Brigadier C. W. Raw, C.B.E., T.D., wished to fire their heavy guns only at the occasional important targets, such as large merchant-men. Fifteen-inch shells were not to be wasted on the more frequent, smaller, vessels such as trawlers and E-boats. Reconnaissance showed what vessels were waiting in enemy ports, but only centimetric radar could tell when a ship was actually passing through the Straits. Could the radar also tell which were the important targets?

Brigadier Raw consulted scientists of the Army Operational Research Group, and agreed to the use of a radar set for experiments. These tests showed that target size could be estimated if the strengths of the radar echoes were measured. Under tuition the gunners manning the radar set soon became expert in making these measurements. The strength of the echoes from selected parts of the French coast were measured also, and used as standards to record any variations in the performance of the radar set. The signal strengths of echoes from known friendly vessels at various ranges were compared with these standards. After some months of experiment a chart had been drawn which related the three variables, signal strength, range, and size of vessel. When enemy vessels were detected, their signals were plotted on this chart; and their size could thus be estimated in comparison with that of our own ships. The big guns, controlled by other radar sets, were then put on to the right target; as a result half of the important enemy ships which tried to slip through the Straits were sunk or damaged.

This research had another important outcome. Sometimes a radar set was found to be receiving signals of less than one-thousandth of the expected power, owing to unsuspected defects. Knowing, from the work at Dover, the signals to be expected from any ship, such ships could be used as test objects, and the radar mechanics at other sets could be told when to suspect the performance of the sets, and to search for trouble.

As a result, the centimetric radars which were used to protect our convoys in E-boat Alley, and elsewhere, came to give far better detection ranges than had been previously thought possible, and often could detect aircraft at ranges more than four times those formerly obtained.

*Operational Research in the Air Force.* In the Air Force, a typical study was that of the conditions under which night bombing raids might most effectively, and with the least losses, be carried out against German targets in the face of the enemy's very highly developed night defence system. It was shown that if the bombers were very highly concentrated in time and space there would be a possibility of saturating the defences, since the enemy could control only a limited number of night fighters, and fire only a given number of anti-aircraft shells, within a given space-time region; and therefore the higher the concentration of bombers in that region the lower the percentage losses. These tactics would result also in a higher time-concentration of bombs falling on the target, giving the further possibility of saturating passive defence measures (fire-fighting services, etc.). These tactics were adopted with considerable success; later studies were also made of the effectiveness and optimum employment of radio counter-measures directed against the enemy's control, warning, and interception system.

*Operational Research in the Navy.* Two examples of the results of Operational Research in the Navy may also be cited, dealing respectively with the size of convoys and with the effect of speed on the safety of ships from U-boat attacks.

(1) *Size of Convoys.* The experience of U-boat attacks on trade convoys was analysed early in 1943 with a view to determining the marginal values of escort vessels and of aircraft. In the course of the work, the apparent conclusion emerged that the number of casualties in a convoy, in an attack on a given scale, and with a given number of escorts, had on the average been roughly independent of the size of the convoy. Thus it appeared that a convoy of forty to fifty ships suffered no heavier losses, on the average, than a convoy of thirty vessels.

If this conclusion were firmly established, the action to be recommended would be a decrease in the frequency of sailing of convoys, with a consequent increase in the average size. This would be expected not merely to reduce the total casualties, but also to permit of a greater number of escort vessels per convoy, or alternatively to free some vessels from close escort duty for other anti-U-boat purposes.

The various possibilities which might have led to a spurious conclusion—such as the effect of weather, more efficient escorts, or more air-cover for large convoys—were therefore examined, and it proved possible to discard each of them. The plausibility of the result of rough independence of losses on convoy size was strengthened by an *a priori* argument. This showed that the length of the convoys' perimeter which had to be protected, increased only very slowly with the number of vessels in convoy.

Finally, it was necessary to consider the handling aspect of large convoys. A collection of Commodores' reports revealed that, while large convoys had been more unwieldy than smaller ones, they had not been unmanageably so.

(2) *Effect of Speed on Safety.* The effect of speed on the safety from U-boats of ships sailing independently was not easy to determine, owing to the lack of adequate data arising under *comparable* conditions. A long study of many individual voyages at various speeds, and the potential U-boat threat, was accordingly necessary.

The conclusions were that at low speeds a ship was extremely vulnerable to U-boat attack. Fast vessels were very safe from U-boat attack, and the degree of safety increased still further as their speed increased. In the intermediate speed range, the safety depended critically on the speed made good, a small increase in the latter making a marked increase in the former.

These general features (though not their magnitudes) were verified by both *a priori* analysis and operational studies of attacks on independent ships. These analyses verified among other results, that the critical speed was in the region of the maximum surface speed which a U-boat would be prepared to maintain for several hours.

The nature and magnitude of the "speed effect" having been reliably determined, it became possible to consider various questions, to which quantitative answers had not previously been feasible. A few of these are summarized below:—

(a) *The Optimum Speed of New Construction.* The cost, labour, and time of building of a merchant ship of given speed could be compared with the cargoes it was likely to carry during the war, allowance being made for relative safety from U-boat attack. From these it was possible to infer the optimum economic speed of new construction, on any appropriate hypothesis of the duration of the war and the scale of U-boat effort.

(b) *The Value of Defence against Torpedoes.* Various devices could provide a merchant ship with limited protection against torpedoes, but would slow down the vessel. The resultant effect of these factors, for a given speed of ship, could be estimated.

(c) *The Value of Zig-zagging.* A zig-zag makes a ship more difficult to hit, but reduces the mean speed of advance. Here again it was possible to make a quantitative assessment of each of the conflicting factors.

It cannot, of course, be claimed that every research carried out resulted in radical changes in operations. But many researches showed where improvements in the efficiency of operation could be effected and they frequently assisted in the formulation of new operational requirements. Moreover, those researches which did result in radical change often produced most startling results. Also those that did not often had the effect of preventing proposed changes which could not have been beneficial.

But enough has perhaps been said to give some indication of the way in which operational research developed *ab initio* during the War, and to show that it is, if not a new science, at least a new field for the application of science, with a technique of its own. There seems no reason to doubt that similar methods can be applied, with equally important results, to peace-time activities. It therefore seems important that those concerned with organizing various branches of our national life in the post-war years, should consider whether the methods of operational research can make useful contributions in other fields.

### THE VARIED NATURE OF WAR-TIME SCIENTIFIC RESEARCH

The above examples of research have been selected from some of the better known and more obvious sections of our war-time scientific effort. But other scientific problems of quite remarkable range and variety arose in many, not so obvious, fields. Much work has, for example, been done on packaging, the importance of which was not recognized at the beginning of the war. Losses in equipment in transit and storage, however, emphasized the need for proper protection, especially against rough handling and moisture. In the stress of the German war the peculiar and often novel problems involved in the campaign against Japan were not overlooked. Much research and development has therefore been directed towards making stores and equipment efficient and durable under severe tropical conditions. Problems arising from shortages of strategical materials, such as molybdenum, tungsten, and tin, have also prompted much metallurgical research.

Sometimes it has been necessary to make an analysis of a metal fragment, of enemy origin, the smallness of which precluded the adoption of normal methods. At the Bragg Laboratory of the Naval Ordnance Inspection Department a micro-chemical method of analysis has been worked out in which the analysis of a sample of steel for the elements silicon, cobalt, copper, titanium, and tungsten can now be made on a sample of 0·03 gram whereas the amount required for ordinary routine chemical methods is about 24 grams.

Two outstanding war-time developments in industry have been the invention and production of polythene, and the development of diamond dies employed in the production of fine tungsten wire for electric lamps and radio valves. Polythene, produced by Imperial Chemical Industries, has proved quite essential as a low-loss material for insulating radio-frequency equipment, and it is certain that, without it, many of the aircraft applications of radar would not have been possible. Before the war, diamond dies were made in Holland and Switzerland. When these sources were cut off, we had to make them for ourselves. Their construction is extremely difficult and requires great skill and scientific control. Yet this task was successfully achieved by several firms working for the Diamond Die Control of the Ministry of Supply and, by 1942, small diamond dies of excellent quality were being produced in time for the greatly increased valve production called for by our gigantic demands for radio equipment.

Even the washing of Service clothing gave rise to a variety of interesting scientific problems. The process developed by the Wool Industries Research Association for preventing the felting and shrinking of woollen goods was used for the production of underclothing and socks for the troops, while the Launderers' Research Association has advised on field laundries and the best means of washing without or with very little soap. The latter research association has also devised a method of treating blankets with oil which has done much to reduce cross-infection in hospital wards.

Mention should also be made of the application of mathematical statistics to war production and inspection under the heading of Statistical Quality Control, widely known now as "S.Q.C.". The pioneer work on this subject by Dr. B. P. Dudding and Dr. L. H. C. Tippett in this country, before the war, had not attracted the attention it deserved. In 1940, however, there were a number of urgent problems of production and inspection which turned people's ideas to the practical application of statistical methods. Quite early in the war, for example, Mr. J. R. Womersley, at Woolwich, conducted statistical surveys of accumulated records of Gun Proof, while Mr. A. R. V. Steele introduced control charts in the Filling Factories. Later the Ministry of Supply Advisory Service, under Mr. Womersley, gave lectures, demonstrations, and assistance on the subject of S.Q.C. to a great many firms.

Most remarkable results have attended these new developments in saving (*a*) scrap material, (*b*) idle machine and operator time, and (*c*) inspection staff and space. One large filling factory, for example, has estimated its savings, due to the application of S.Q.C., at £70,000 per year. Similarly an engineering firm was able to turn nearly three-quarters of its inspection staff back into production after introducing S.Q.C.

Finally I would like to draw attention to another large and important field of war-time scientific work which the engineering scientist might perhaps be inclined to overlook. We must never forget that, whatever instruments of war the engineering scientist may devise, it is, after all, the men of war on operations who use them. It has therefore become recognized as a primary need to maintain the safety, efficiency, and comfort of the fighting man in relation to his weapons and environment. This task, which has involved much experimental research, often of a hazardous nature, by physiologists and others, has been undertaken by the Medical Research Council in collaboration with each of the three Fighting Services.

## THE VITAL CONTRIBUTION OF INDUSTRIAL RESEARCH AND DEVELOPMENT UNITS

As I mentioned earlier, it was decided, at the beginning of the war, to reserve the research teams in industrial firms and research associations. The importance of this decision cannot be over-emphasized in the light of later experience. For there has been built up, during the war, the most intimate form of collaboration between Government scientific research establishments and the research organizations of industry. Very often, once the requirements in the case of a particular weapon or instrument had been roughly formulated and a line of attack selected, the further research and development was entrusted to the research laboratory of an individual firm. Moreover, since the rapidity of production is always a desideratum in war time, the desirability of early consultation with industry in any project has become fully recognized.

## CONCLUSION

I now come to the end of what has, of necessity, had to be only a few fragments of a great story. It is a story through which the word co-operation runs like a thread—co-operation between the Services, Science, and Industry. But although our scientific and technical effort in the last six years has had to be directed to warlike ends, it cannot be said to have been all wasted. Much of it has led to permanent additions to human knowledge, and their peace-time applications are, in many cases, clearly manifest.

But I would add two further comments of a general character. In pre-war days there was an impression in some quarters that, while our achievements in fundamental research were second to none, this country had been somewhat slow in applying the discoveries of science to practical ends. It must have been disconcerting to our enemies, and surprising to our friends and even to ourselves, to find how little support the experience of war has given to that impression. For there has been ample proof, for all to see, of the speed and efficiency with which our industries were able to apply and develop new ideas born in our research laboratories.

Finally, we must not forget the influence of these scientific achievements on the public mind. It is worth noting that our experience in war prompts an awakening to the benefits of scientific research. I think this comes about because, in a period of fast-moving events, the four processes of research, development, production, and use follow so swiftly on the heels of one another that even a short memory recognizes cause and effect. It seems to me, therefore, that we can claim, as one of the most welcome results of our war-time scientific experience, that there has been prompted, in the public mind, an even greater realization of the importance of scientific research as a means of ensuring the security and prosperity of our own people.

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