of the Navy, visited the place a number of times and was always much interested in it. Many other members of the Board also visited the Laboratory from time to time, particularly Baekeland, Saunders, Robins, Whitney, and Maxim.

Subsequent administrations made little or no use of the Naval Consulting Board, and finally it was abolished. It is the opinion of many of the old-timers at the Laboratory that, had it been allowed to take a more active interest in the Laboratory during its very early history and had its advice been followed, the growth of the Laboratory would have been greatly accelerated. The Laboratory definitely owes its existence to the work of the Board and particularly to its *chairman, Thomas A. Edison, who, even as early as 1910, had recognized the necessity of a research organization within the Navy.* Congress appropriated the money for its establishment in 1916.

***Science* is fortunate to have been intimately connected with two great 19th-century scientist-inventors. Edison's birth on February 11 preceded by less than a month the birth of Alexander Graham Bell on March 3, 1847.**

Alexander Graham Bell was vice-president and organizer of the Scince Company, which in 1883 published *Science*, first in Cambridge and later in New York City. Associated with Bell in this venture were his father-in-law, Gardiner G. Hubbard, of Washington, founder of the National Geographic Society; Daniel C. Gilman, president of Johns Hopkins and president of the Science Company; O. C. Marsh, of New Haven; and Samuel H. Scudder, of Cambridge, who was treasurer of the Company and served as editor of the magazine.

The Nature and Development of Operations Research

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OPERATIONS RESEARCH IS A SCIENTIFIC method for providing executive departments with a *quantitative basis for decisions*. Its object is, by the analysis of past operations, to find means of improving the execution of future operations.

The principles of operations research were developed during the war as the application of the scientific method to the broad strategical and tactical problems of warfare. Small teams of civilian scientists worked at the highest operational level in a number of major Allied commands on all aspects of military staff problems: planning, intelligence, operations, and training. Among such scientific groups were the Operations Research Group on the staff of Fleet Admiral E. J. King; the Directorate of Naval Operational Research on the Naval Staff of the British Admiralty; and the Operational Research Section of the RAF Coastal Command.

The scope and power of the operations research method has been demonstrated by five years of successful application in practice. Since the end of the war several progressive government and business activities have established operations research programs for peacetime objectives.

The specific primary purpose of operations research in the war was to discover means for making the best use of the military forces and weapons currently available. The main fields of activity have been classified as the study of weapons, the study of tactics, and the study of strategy—that is, the analysis and evaluation of the performance of existing weapons and tactics; and the determination of the cost in national resources of attaining various strategic objectives. Operations research is thus distinguished from laboratory research for military purposes, which is concerned with the continual improvement of the weapons of warfare. Furthermore, the elapsed times between the inception of a new proposal and its realization in large-scale combat are radically different for laboratory and operations research. The big "secret weapons" of the war, such as microwave radar, proximity fuses, jet propulsion, V weapons, magnetic mines, airborne rockets, and atomic bombs, were in gestation from 2 to 10 years. The big, though little publicized, successes of operations research, such as the Bay of Biscay anti-U-boat offensive, the destruction of German blockade runners in the South Atlantic, the initiation of bombing by large numbers of aircraft, and the initiation of large convoys in the Atlantic, were in action usually within one to two months after the original idea was put forward.

Origins of Operations Research

The application of quantitative reasoning to military strategy can be traced back to the brilliant British aeronautical pioneer, F. W. Lanchester, whose death occurred in 1945. Lanchester's original papers on the relationship between victory, numerical superiority, and firepower superiority in combat appeared first in 1914–15 and are collected in his book, *Aircraft in warfare* (1916).

The most important of Lanchester's results is known as the "N^2 Law." Several significant principles are exhibited by this law, which assumes that the conditions of combat are such that all units of both forces can engage simultaneously: (a) Numerical superiority may be *relatively* more important than superiority in weapon performance; and (b) it is of the highest importance to deploy available combatant units in a *single large force* and to endeavor to *split up* the enemy force (strategic principle of concentration).

Lanchester has given an interesting discussion of Nelson's victory at the Battle of Trafalgar, showing that the latter's tactics were the optimum in the light of the N^2 Law.

The original conception of teams of scientists working at the operational level in military commands goes back to P. M. S. Blackett, professor of physics at the University of Manchester. Blackett guided the emergence of "O.R." from a small trouble-shooting party attached to the British early-warning radar chain in 1940 to the point where, in 1945, operations research men were attached to nearly every large British military command including, for example, Combined Operations, South East Asia Command, Tactical Air Force, Coastal Command, Fleet Air Arm, and the British Chiefs of Staff. Related work on broad logistic problems was carried out in the Ministries of Supply, Production, and War Transport.

Operations research was introduced into the U. S. forces through the influence of the British work as communicated largely through the reports from London by Shirley Quimby, of Columbia University. The nucleus of the first U. S. group was formed in 1942 in the Naval Ordnance Laboratory under the stimulus of Ellis Johnson, then on leave from the Carnegie Institution. This group, which dealt with mine warfare problems, was later transferred to the Navy Department; from here it directed the tremendous aircraft mining blockade of the Inland Sea of Japan in 1945. Philip M. Morse, of the Massachusetts Institute of Technology, started the Anti-Submarine Warfare Operations Research Group, which reported to both the Army and the Navy. This group was later to expand into the Operations Research Group on the staff of the Commander in Chief, U. S. Fleet. As the major American group, it dealt with submarine and anti-submarine warfare, aircraft and amphibious operations, and anti-aircraft and new weapons analysis. Its work has been described by P. M. Morse (*Tech. Rev.*) and Jacinto Steinhardt (*U. S. Nav. Inst. Proc.*, 1946, **72**, 649).

In the U. S. Army there were a considerable number of separate Operations Analysis Sections whose work was divided between the statistical analysis of operations and the nursemaiding of new weapons and equipment in the transitional stage between the laboratory and the widespread use of the new gear in combat.

Personnel for Operations Research

It is often asked why scientists are required for operations research work, since the actual details involved are fairly simple and apparently might be done by any college graduate without specialized training. The answer has two parts: First, a scientist is, by profession, trained to reject unsupported statements and has an instinctive desire to rest all decisions on some quantitative basis, even if the basis is only a rough estimate. This makes scientists good at detecting the existence of problems and questions of which the regular military staff may be unaware. Second, scientists, through their research experience, are trained to get down to the fundamentals of a question—to seek out broad underlying principles through a mass of sometimes conflicting and irrelevant data. They know how to handle data and how to guard against fallacious interpretations of statistics.

The particular type of mentality which is a success in operations research appears, from wartime experience, to be found most frequently in physics and biology and their associated borderline sciences; the special outlook seems to be found somewhat less commonly in mathematics, engineering, and economics, although there are some brilliant exceptions.

The actual responsibilities of operations research groups attached to high commands are usually advisory, rather than executive, in nature. The groups must have freedom to initiate studies and must have access to any information required.

Operations Research Problems

A proposed operation frequently is such that a study of its inherent capabilities reveals the basic philosophy underlying the operation and leads to the recommendation of a *single course of action*. Two important examples of this nature are given here:

(1) *Thousand-plane raids*. Statistics of the losses of RAF Bomber Command aircraft over selected German cities indi-

cated that the percentage of aircraft lost fell off as the number of aircraft participating in the raid increased, suggesting that the German defenses were being saturated. If, then, the number of aircraft is increased over the saturation limit, the number of casualties should remain constant, and the *effectiveness ratio*,

$$\frac{\text{tons of bombs on target}}{\text{own aircraft lost}},$$

should therefore increase. On the basis of this analysis the first thousand-plane raid in history was made by the RAF in 1942; the results of this and subsequent large raids confirmed the prediction.

(2) *Large merchant-vessel convoys.* A similar analysis of the losses in North Atlantic merchant-vessel convoys showed that the average number of ships sunk in a convoy was a constant, independent of the size of the convoy. It was, in fact, found that the percentage casualties, L, were given approximately by the equation,

$$L = c/SE, \qquad (1)$$

where S is the number of ships in the convoy, E the number of escort vessels, and c is a constant. As a direct consequence of this analysis early in 1943 the time between convoys was lengthened so that each convoy was larger and protected by more escorts.

This decision resulted in greatly diminished losses.

In many operations it is desired to maximize the yield or productivity of the operation with respect to *several competing factors.* Two examples are:

(1) *Bombing of Japan.* Squadrons of B-29's based in the Marianas for the purpose of bombing Japan were able to put in a fairly definite number of flying hours per month, this time being distributed between operational missions and training. If no time is spent on training, it is found that the average proportion of the bomb load dropped on the target is low; if all the time is spent on training, obviously no bombs will be dropped on the targets in Japan. An analysis of the improvement in bombing accuracy with training indicated that the maximum bomb weight on the target was achieved if about 10 per cent of the flying time is spent on training and 90 per cent on operational missions; it was further shown that this distribution doubled the bomb weight on the target obtained with the original distribution of about 4 per cent training and 96 per cent operations. Training problems of this character are encountered in many situations in civilian as well as in military economy.

(2) *Submarine wolf packs.* A submarine which patrols a shipping lane independently is likely to attack only the contacts made by itself. If groups of submarines patrol a route together, each submarine can attack contacts made by its neighbors as well as by itself, thus tending to increase the productivity of a submarine war patrol. There is clearly an optimum size for such a wolf pack. An upper limit to the size would be given by the number sufficient to destroy totally any task force or merchant-vessel convoy encountered. Actually, such total annihilation was extremely rare and in general would require enormous forces. Another consideration determines the optimum: if the pack is too large, contacts which otherwise might have been made on other shipping routes are missed. The U. S. Navy used groups of three submarines in attacks on Japanese shipping.

Exchange Rates

Perhaps the most characteristic feature of the operations research methodology is the discussion of a problem in terms of *exchange rates.* The exchange rate is essentially the ratio of output to input for a given type of operation, as measured in suitable units. For example, in the early stages of the campaign against Japanese shipping it was desired to know which of the available means of attack—submarines, aircraft, and mining—could most profitably be expanded. By considering expenditures on construction, training, operations, and replacements it was possible to get values of the exchange rate,

$$\frac{\text{Japanese ships sunk}}{\text{Allied man-years of effort}},$$

for the three means of attack; the result demonstrated the profitability of U. S. submarine operations.

Similarly, the geographical distribution of flying effort by Allied aircraft in the anti-U-boat war was largely determined by the exchange rate,

$$\frac{\text{flying hours}}{\text{U-boat sightings}}.$$

In a "hot" area this ratio might be less than 100; in areas characterized by heavy overflying the ratio was as high as 25,000. The analysis indicated the value of transferring aircraft from the Gulf of Mexico to the Bay of Biscay, for example. A parallel study discussed the relative profitability of using anti-submarine aircraft to bomb the U-boat bases on the French coast, to escort threatened convoys, and to do routine patrol of shipping routes.

The British had laid down a program for building a certain number of escort-type vessels in 1943. These vessels could be equipped for minesweeping or for anti-submarine duty. A study of the exchange rate,

$$\frac{\text{merchant vessels saved}}{\text{new naval escorts built}},$$

indicated the importance of the anti-submarine escorts. A similar analysis was made of the value of the "armed guard" crews on merchant vessels.

The profitability of the RAF Bomber Command raids on German cities was analyzed in terms of the exchange rate,

$$\frac{\text{Allied man-years in bombing effort/bomb tons dropped}}{\text{enemy man-years on defenses and indispensable repairs/bomb tons dropped}},$$

thus giving an effective man power exchange rate. The rate, when broken down for different types of aircraft, showed the surprising effectiveness of the Mosquito raids and the superiority of the Lancaster over the Halifax bomber. A parallel analysis of the situation from the enemy point of view considered the economics of bombing with the V weapons as compared with conventional bombing.

The allocation of U. S. submarines to the several submarine commands was considered in terms of the exchange rate,

$$\frac{\text{Japanese ships sunk}}{\text{submarine months at sea}}.$$

A somewhat similar analysis considered the disposition of minesweepers as between the East and West coast ports of England.

Effectiveness Ratios

The basis of the reliability of the estimated exchange rates lies in the remarkable constancy of certain effectiveness ratios involved in the operations. For example, the figure of 60 mines laid/ship sunk has been found to occur in every aircraft mining campaign—German mines in British ports, British mines on German routes, and U.S. mines on Japanese routes.

Similarly, the probability that an aircraft will attack a U-boat which has been sighted is a number which averages the same for different aircraft types and different theaters of war. In submarine operations the value of the effectiveness ratio,

$$\frac{\text{Japanese ships sunk}}{\text{torpedoes fired}},$$

was the same in Japanese coastal waters as in the South China Sea.

Blackett has pointed out that the stability of certain factors involved in operations "appears rather unexpected in view of the large number of chance events and individual personalities and abilities that are involved in even a small operation. But these differences in general average out for a large number of operations and the aggregate results are often found to remain comparatively constant. . . . It is applicable whenever operations have been in progress and tactics have been sufficiently stabilized, as they often are for months at a time, for definite experimental data on the results of past operations to be obtained. It should be remembered that the technical instruments of warfare do not change rapidly owing to the long duration of development and production. And even tactics cannot usually change very fast owing to the necessary duration of training. Thus the condition of relative stabilization of operational technique is quite often fulfilled."

The real significance of the constancy of the effectiveness ratios lies in the possibility of transplanting data from one area to another with reasonable assurance of coming out with a correct result. For example, the average number of rounds from the five-inch guns of destroyers required to break up a Japanese pillbox on Tarawa could be expected to be approximately the same as the number of five-inch rounds required to destroy a German pillbox of the same size on the Normandy coast. The value of using effectiveness ratios in the planning of force requirements and logistic support may easily be appreciated.

Peacetime Applications of Operations Research

The operations research methods and techniques have wide application to modern government and industry. Quoting Steinhardt, "These techniques are those of the competent scientist, applied to large-scale human operation as a whole, with the aim of fitting the operation to its purpose, and of measuring the effectiveness with which the operation is carried out."

The British have been thoroughly convinced of the value of this type of research and are developing a number of peacetime applications to civil life. There are plans for conducting operations research in civil aviation (British Overseas Aircraft Corporation), housing (Ministry of Works, under J. D. Bernal), steel industry (British Iron and Steel Institute, under Sir Charles Goodeve), and commerce (Board of Trade, under T. Easterfield). These enterprises, because of their national character and size, lend themselves more suitably to the application of operations research than do small local enterprises. There have also been several economic advisers in the Cabinet Offices and in the former Ministry of Production who approach broad national problems using quantitative criteria and measures of effectiveness.

The accomplishments discussed include only a few selections from a great collective effort. It is impossible to mention or to give adequate credit to all of those who shared in the work. Tribute must be paid, however, to P.M.S. Blackett, F.R.S., the dean of operations researchers everywhere; and I wish to add my personal thanks to him for the privilege of spending many months of the war with his group in the Admiralty. I wish also to express my appreciation to P.M. Morse and H.R. Hulme for many stimulating discussions of the methods of operations research.

It is hoped that the publication of this paper will serve to stimulate the establishment of operations research groups in the United States for the advancement of peaceful objectives. This powerful new tool should find a place in government and industry.