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OR FORUM

BRITISH OPERATIONAL RESEARCH IN WORLD WAR II

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This article offers an overview of British operational research activities during World War II, and is the second in a series on the early history of operations research. The first (*Operations Research* **35**, 143–152) traced the scattered beginnings from World War I up to the activities in Britain before and during the early months of World War II.

To a modern-day OR worker, armed with a substantial body of theory, supported by a computer, and building on a large body of significant applications, some of the accomplishments of British operational research in World War II could well seem almost trivial. The approach was frequently intuitive, the models simple, and the solutions little more than what appears in hindsight to be common sense.

But such an appraisal overlooks the fact that scientists, usually civilians or civilians in uniform, moved into the precincts of the military, won their confidence, and affected their actions. It overlooks the fact that the common sense of the operations analyst could be quite different from the common sense of the military commander and could also be quite different from the common sense of scientists and engineers working in laboratories far removed from operational realities.

It overlooks the fact that many of these individuals lived under field conditions; that they were sometimes called upon to face physical danger as well as the deprivation of the stability, comfort, and equipment of the laboratories from which many of them had come. And it overlooks the fact that the work was frequently dull and boring, highly repetitive, and under extreme pressure for results.

But because they were where they had to be, these early OR workers were in position to advise designers about technical deficiencies in equipment, advise manufacturers about reliability problems, and, above all, advise users on better, more effective, and more efficient ways of employing equipment and personnel. They could help in devising training and doctrine that helped overcome deficiencies in equipment. And they were in position to recognize, understand, and sympathize with the problems of users.

The scientists among them, especially those from the universities, had to make another significant adjustment: to accept the need for secrecy and, even within military circles, restrictions on communication of the results of their work. Thus, early in the war, when the OR staff at Royal Air Force Fighter Command Headquarters at Stanmore still belonged to the Telecommunications Research Establishment (TRE), direct communication was permitted outside the command. (The origins and development of TRE, which was one of the great research laboratories of World War II, are described in the first article in this series.) But, as the work at Stanmore broadened to include problems other than those of radar, the principle was established that the work was done for the command at interest and could be communicated outside that command only with the approval of the commander.

Because of the relatively independent origins of the several major operational research sections in the Royal Air Force, this respect for the confidentiality of work done within commands created some problems. Thus, in 1941, an Operational Research Centre was established within the Air Ministry to coordinate the

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efforts of the several OR sections; it met with only limited success. An added complication was that the Directorate of Scientific Research had been transferred to the Ministry of Aircraft Production (MAP). This meant that the OR sections were under the administrative control of MAP rather than the Air Ministry. The situation improved later in the war with the creation of the position of Scientific Adviser to the Air Ministry, in November 1944; and even later, with the creation of a Deputy Directorate of Science under C. E. Gordon, whom we will meet again.[1]

In contrast with the Royal Air Force, the problem of communication among units of the Army Operational Research Group was minimized by the fact that all of the sections operating in the United Kingdom sprang from a common source. Sections that operated in oversea commands had a different reporting relationship, but apparently maintained effective communication. In the case of the Admiralty, the problem was minimized by the fact that P. M. S. Blackett kept his organization small and centralized. (Blackett is widely regarded as "the father of operations research"; the first installment of this history describes his activities in setting up OR groups in all three branches of the British military.)

Fighter Command

The R.A.F Stanmore group and its successor, the Operational Research Section (ORS) Fighter Command, exemplifies the routine nature of much of the work of the OR sections. In 1940, during the Battle of France, this group supported Air Chief Marshal Sir Hugh Dowding's opposition to the transfer of aircraft and crews to France, but such opportunities to affect strategy were rare. Most of the effort was tactical and technological, and involved the accumulation and analysis of data on engagements between British fighters and the attacking German fighters and bombers.

During the Battle of Britain, there was little time for much more than continued development of the techniques that had come out of the R.A.F. Biggin Hill experiments of 1936–1938, whose aim was to integrate radar into early air and land warning systems and into fighter plane direction and control. Thus, most of the work was in or in connection with the control centers and the communication system, with constant attention to the radar equipment and its use. The data collected and analyzed provided the understanding of the system that made possible compensation for differences in the performance of aircraft; that could detect a change in enemy tactics; or that could identify deficiencies in performance attributable to maintenance of equipment or training of personnel. But in evaluating actual accomplishments, we must take into account the fact that the Battle of Britain lasted little more than a month and that it was a period of intense concentration on operations, with little opportunity for change.

In the Battle of Britain, the basic tactic used by Figher Command involved the scrambling—i.e., rapid emergency takeoff—of fighter units, partly to meet intruders as they crossed the coastline and partly to patrol over probable targets. The task of engaging the enemy rested with the pilots, who received little additional help from the ground once the forces were joined. With information about German plans provided by the *Ultra*[2] decoding system, with the coastal radar chain to provide early warning, and with the Observer Corps to report overland movements, the chosen tactics proved adequate, given Dowding's careful husbanding of the resources available to him and the courage and skill of the pilots involved.[3]

In the event, the Luftwaffe failed to defeat the R.A.F., and German plans for the invasion of Britain had to be scrapped. But the few night attacks that the Germans carried out showed that Britain would need much more than the home chain of radar stations, should the enemy concentrate on night raids. In an effort to meet this threat, ORS Fighter Command recommended, in August 1940, that GCI (ground control intercept) equipment and techniques be developed. AI (airborne intercept) radar with a range of 3 to 4 miles was becoming available, but a modification of the coastal radars was needed before intercepting aircraft could be brought within AI range. Unfortunately, the new equipment could not be made available in time to be of use during the critical phase of the night battle—the Blitz—of September and October 1940, but it did become available as the attacks continued through the winter and into the spring of 1941. Mounting bomber losses, exceeding seven percent in May 1941, finally forced the Germans to call off the Blitz.[4]

J. G. Crowther and R. Whiddington have summarized the work of ORS Fighter Command during this period of the war:

> During the night attacks the section undertook a detailed and comprehensive analysis of all phases of night operations and presented the Command staff with an analysis of the performance of A.I., G.C.I., various forms of night interception, including cooperation with searchlights, the effect of visibility conditions, etc., the proportion of interceptions resulting in combats and combats resulting in kills. This was used in the Secretary of State for Air's Scientific Committee and the Prime Minister's Night Air Defense Committee, and subsequently became the pattern on which other Operational

Research Sections' analyses of current operations were based.[5]

The ending of the Blitz in 1941 meant two important changes in ORS Fighter Command. First, it became a recruiting ground for other OR sections and, second, it was called upon to assist in the development of a fighter offensive against northern France that was designed to keep the Luftwaffe as busy as possible and thus to take some pressure off the Russians. One result of the OR effort in this connection was the creation of the fighter direction station, based on existing radar equipment modified by the addition of height-finding apparatus; this was, in effect, a radar-based system for offensive fighter direction and control, as opposed to the defensive system used in the Battle of Britain. Other results were the development of quite effective jamming equipment to counter the German warning system, and an improved IFF (identify friend or foe) system, need for which had been generated by increased United States Air Force participation in activities over the continent.[6]

Finally, ORS Fighter Command became involved in armament problems, from the point of view of both weapon effectiveness and the training of air crews in the use of new or improved weapons. It was this type of work that led to the employment of actuaries as operations analysts, when hitherto most analysts had been physicists, communications engineers, and others with similar backgrounds who were oriented primarily toward the equipment involved. Now the need arose for specialists who could attack the mounting accumulation of data from operations. The source for much of this work was gun-camera footage, originally from the air battles and then increasingly from the ground-strafing and rocket attacks of the latter half of the war.

Analysis of air combats included studies of a new type of fighter gunsight introduced during 1944. Gross comparisons with the old gunsight were refined to include the effect of the closing range and the angle of the attack, the effect of special training in the use of the new gunsight, and the effect of experience in its use. Study of strafing runs against enemy vehicles resulted in the conservation of the cannon ammunition being used and also showed the marked effect of experience in this type of action. Rocket projectiles presented special problems because of their curved trajectories and their sensitivity to range and the dive angle at the moment of attack; the OR analyses paid off in the attacks on radar stations and on enemy communication lines, especially bridges, in preparation for the invasion of northern France. When the pilots adhered to the range and dive angles recommended by the ORS, they achieved good results.[7]

The Fighter Command contribution to the invasion of the Continent will be considered later, but one more point must be made about the value of the work of ORS Fighter Command in the crucial days of the Battle of Britain, when OR was still in its infancy and Harold Larnder, who headed the section, and his staff were still feeling their way: Charles F. Goodeve, whom we will meet later, and who was to play a major role in promoting operations research during and after the war, has estimated that radar increased the probability of intercepting an enemy aircraft by a factor of 10 and that the work of ORS Fighter Command increased that probability by a further factor of two.[8]

Coastal Command

Because of the nature of its tasks, primarily antisubmarine operations and convoy protection, plus attacks on enemy shipping, Coastal Command offered a much wider scope for operations research than did Fighter Command. Early in the war, Fighter Command's mission was defensive and was therefore largely reactive; throughout the war, Coastal Command's mission was primarily offensive. Fighter Command's great challenge, the Battle of Britain, lasted little more than a month and so allowed little time for innovation; Coastal Command's struggle with the U-boat lasted as long as the war, was intense for about 3 years, and so allowed great opportunity for innovation.

In addition, Coastal Command operations were inherently more complex. Each operation involved problems in navigation, search, identification, bombing accuracy, verification of results, and, not least, given Britain's weather, return to base. Whether flights were search patterns over the Bay of Biscay or convoy missions over the North Atlantic, Coastal Command planes had to know position in a way not applicable to Fighter Command; for this task they were fitted with airborne radar aids as soon as these could be made available—and the Operational Research Section Coastal Command was charged with making these aids fully effective. This was especially true of airborne ASV (anti-surface-vessel) radar.

The importance of finding solutions to the navigation and search problems is in no way diminished by the success of the British in breaking the German codes. Knowledge of the precise location of a German submarine made precise navigation to that spot even more important. The submarines' high mobility usually meant that search was necessary after an aircraft

had arrived at a given location. The same was true when an aircraft was dispatched to escort convoys: unless the navigation and any necessary search could bring the aircraft over the convoy in the shortest possible time, the effective escort time was reduced correspondingly.

On antisubmarine missions, there were several problems involved in attacking a target once it was located. For example, Blackett describes one analysis in which application of the density method showed that too few submarines were being attacked. In a meeting on this problem, an R.A.F. officer asked what color the attacking aircraft were painted. The question supplied the answer: The black night bombers that were being used for daytime raids were soon painted with light colors on their bottom and side surfaces in order to reduce their visibility.[9]

The density method used in defining this problem was the basic method of analysis used by ORS Coastal Command. It was developed in reports prepared in 1942 by E. J. Williams, and took into account the number of submarines known or believed to be in an area, the proportion likely to be on the surface at any given time, and the characteristics and performance of the aircraft patrolling the area. From this information, the probabilities of success in detecting, attacking, and killing could be inferred. Whenever results dropped below expectation, the density method facilitated analyses to ferret out probable causes and the effects that changes in methods might have. Studies might suggest deficiencies in training, or lowered equipment performance because of maintenance requirements or procedures. They might suggest a change in enemy tactics or equipment. Or, as above, they might suggest that Coastal Command aircraft be repainted.[10]

Even before 1941, the year ORS Coastal Command was formed, and certainly before the density method was developed, the lack of effectiveness of the depth charges then in use had been recognized. Williams, then at the Royal Aircraft Establishment at Farnborough, had been assigned the task of developing an influence fuze that worked in such a way that depth charges could be detonated by proximity to the submarine rather than by water pressure.

When Blackett accepted the assignment of establishing an operations research section for Coastal Command, Williams was one of the first to join him. There he went to work to improve the effectiveness of attacks on submarines. The depth charge was only one part of the problem, but Williams' study of that aspect produced the classic OR study of World War II.

The depth charges used early in the war were designed to be dropped from ships, not aircraft, and were set to detonate at about 100 feet under water. This setting was intended to allow surface vessels time to get safely away from the explosion. Furthermore, surface vessels had the advantage of asdic (sonar) in locating a submerged U-boat. Coastal Command aircraft did not need the protection of depth and they had no means of detecting a submerged U-boat.

Thus, the problem with the depth charge soon became apparent: If the submarine were caught on the surface, a depth charge dropped near it had to descend to 100 feet before exploding. If a submarine were seen to submerge, a depth charge dropped near its point of disappearance would be ineffective because of the freedom of maneuver available to the submarine. In neither case could a depth charge with a lethal radius of about 20 feet prove effective with any degree of consistency. The solution was to set the fuze at minimum depth, or about 35 feet, and to forego attacks on submarines that had been submerged for more than 15 seconds. The increase in effectiveness of depth charging was spectacular and was subsequently enhanced by the development of a fuze capable of detonating at 25 feet. There was no need to develop an influence fuze for this purpose.[11]

This understanding of the best means of using depth charges still left the problem of effectiveness in dropping them on sighted submarines. The approach to this part of the problem was to use cameras to provide data for analysis of aiming errors. These were identified by type of aircraft and direction of attack relative to the motion of the U-boat. There was also analysis of aiming methods (visual versus bombsight), of depth-charge size, and of the spacing between depth charges as they were dropped from the aircraft.

Analyses of the various problems involved in successful attacks on submarines found their principal focus in the "Bay of Biscay Campaign." In the early days of the war, Germany had relatively few submarines capable of operating in the open ocean and so its principal effort was concentrated near the ports, where the U-boats could prey on in- and outbound traffic. When asdic successfully countered this ploy, the submarines moved into the open ocean, but because of the necessity of reaching the Atlantic by way of the passage north of Scotland, they were vulnerable and also used much of their sea time in transit.

The fall of France in 1940 changed all this. Within a year of the capture of the French ports on the Bay of Biscay, the Germans had built submarine pens at Lorient and several other locations. They now had a direct route into the Atlantic and one much nearer the most-used sea lanes. Inasmuch as the submarines

could operate far beyond the range of Coastal Command aircraft, the Bay became the focus of the British effort to defeat the U-boat. And that defeat became increasingly urgent because of the increase in the number of seagoing submarines and because the North Atlantic had become Britain's remaining lifeline. Moreover, because of the development of the concept of the wolfpack, in which a submarine sighting a convoy would wait until joined by others for a simultaneous attack, that remaining lifeline was in jeopardy.

In the early days of the Bay campaign, Coastal Command had little help from either radar or operations research. The U-boats transited the Bay in daylight and could dive if they sighted an airplane. In the latter part of 1941, ASV radar became available and increased the effectiveness of Coastal Command aircraft enough that the Germans were forced to undertake the transit of the Bay at night. The ASV radar could locate the submarine and bring the aircraft close, but not close enough for an effective night attack. This problem was solved by installing powerful searchlights on aircraft that could be turned on as the planes neared their targets. This technique proved sufficiently effective that the Germans reverted to transit by day. This change involved more frequent diving, slowed submarine transit time and adversely affected German morale, but the submarines were still reaching the sea lanes.

The next move went to the Germans, who developed a device that told the submarine commander that he was under radar surveillance. The modification of the ASV radar to employ the cavity magnetron, which increased the effective range of radar and made it more difficult for a target to detect, countered the German device and marked the beginning of the end of the submarine threat. The Bay campaign ended, for all practical purposes, in mid-1943.[12] The snorkel submarine and devices to sense centrimetric radar were developed by the Germans too late to be significant in the outcome of the submarine war.

P. M. S. Blackett had come to Coastal Command in March 1941 and so was in at the beginning of the Bay campaign, but he moved to the Admiralty in December 1941. As a result, successful OR participation in the campaign was largely under the leadership of E. J. Williams. He too, however, moved to the Admiralty after about 1 year and completion of the Bay campaign became the responsibility of Harold Larnder, who came from Fighter Command, where he was replaced by A. F. Wilkins.

Before he left Coastal Command, Williams initiated what proved to be the most durable work of the Operational Research Section: the development of the concept of planned flying and planned maintenance, which, in the history of OR, is a classic example of the importance of selecting the proper measure of effectiveness.

Although much more was involved than the selection of a measure of effectiveness, including considerable study of maintenance, the heart of the problem was that the R.A.F.'s utilization of planes had been based on the availability of aircraft rather than on the missions to be flown. A squadron's effectiveness rating was based on the proportion of its aircraft that was serviceable; 70–75% was considered to be ideal.[13] The ORS studies, initiated by Williams and carried out by a rapidly expanding group under C. E. Gordon, showed that scheduled missions could be flown even if serviceability levels dropped below 50%. As a result, schedules came to be based on the missions to be flown. Service crews were reduced, more flying was achieved, and more efficient use of ground personnel resulted. This change in the basis of Coastal Command operations was to stand it in good stead during the critical days of the Bay Campaign.

This work at Coastal Command gained quick recognition and Gordon was later transferred to the Scientific Directorate of the Air Ministry so that the benefits of planned flying and planned mintenance could be made available to the entire R.A.F.[14]

Coastal Command and its ORS played a different role in connection with the invasion of the Continent. At this point, it is interesting to speculate or, perhaps more accurately, conclude that the relations between those in charge of operations and those charged with studying operations were particularly close in Coastal Command. This may have been due to the open-mindedness of the several Air Officers commanding Coastal Command or to the caliber of the series of officers in charge of the Operational Research Section: Blackett, Williams, Larnder, and C. H. Waddington, one of Britain's foremost animal geneticists and author of a history of OR in Coastal Command.[15] With them, in a small group that averaged about 16 members and seldom got to 25, were scientists of the caliber of E. C. Baughan and J. W. Abrams. The latter was a U.S-born Canadian, a navigator turned analyst, and one of the outstanding wartime operations research workers who continued in the field after the war.

Bomber Command

While Fighter Command and Coastal Command bore the brunt of the effort against Germany well into 1942,

Bomber Command was being built up as rapidly as possible and had begun raids against German cities early in the war. The Germans claimed that the Blitz was in retaliation for these raids which, in turn, gave Britain grounds for retaliation. Such psychological or political factors were bound to affect the work of the Operational Research Section of Bomber Command.

The 1940 bomber-loss studies by A. E. Woodward-Nutt and his successors were contemporary with the Blitz and continued until they were incorporated into the work of ORS Bomber Command. More important to the formation of the Operational Research Section were the studies of bombing effectiveness initiated by Lord Cherwell, Churchill's Scientific Adviser, during the summer of 1941. Those findings were in marked contrast to the increasingly effective job that Coastal Command was doing and served to raise questions about priorities in the assignment of heavy bombers to the two Commands. The decision to continue bombing Germany was not reversed, however, and, as a matter of fact, E. J. Williams spent much of his time during 1942 defending the record of Coastal Command because the demand for heavy bombers for the strategic compaign over Germany threatened the supply of aircraft for the Bay Campaign.[16]

One of the principal factors in the increasing demand for bombers for the German raids during 1942 was a memorandum prepared by Cherwell. In it he advocated the "dehousing" of the German working population as a means of lowering morale, reducing production, and taking some pressure off the Russians. Both Henry T. Tizard and Blackett took exception to the claims that Cherwell made for such a campaign even though the former supported the concept of bombing German cities. The program went forward nevertheless, even though it was to prove even more costly and less effective than Tizard and Blackett had predicted.[17]

In this politically charged atmosphere, ORS Bomber Command enjoyed little freedom in analysis of strategic factors, but B. G. Dickins, G. A. Roberts, and company proved very helpful to Bomber Command on the tactical and technical levels.

Bomber Command did not have the advantage of experiments like those at Biggin Hill to assist it in integrating its operations with the latest technical advances. A Committee for the Scientific Study of Air Offence, under Tizard's leadership, had been formed in 1936, but it was as unsuccessful as its counterpart on air defense was successful. This disparity was due in part to a difference in reporting relationships and in part to an unwillingness to admit civilians to the councils of those responsible for bomber operations.

One result of this unwillingness was difficulty in laying on experiments. As Tizard put it, Britain started the war "with the most inadequate bombs, with rudimentary ideas of accurate bombing under conditions of war, with little, if any experience of the problem of flying in a 'blackout,' which might have been acquired at many places in the Empire, and with a fixed idea that Bomber Command would have to rely on sextant navigation over Germany, because any form of radio navigation would be dangerous."[18]

ORS Bomber Command did much to help overcome these deficiencies. Basically, the staff gathered data on bombing and bomber losses and made fundamental contributions as the war progressed. For example, the lack of fighters capable of escorting bombers had early led to a decision in favor of night bombing. The OR Section then recommended that the principle of concentration be applied to night bombing: this led to the first thousand-plane raid, on Cologne in May 1942. One concern with such concentration was the danger of collision involving friendly aircraft. "The Operational Research Section estimate was one collision, and one collision it turned out to be—a figure which gave inspiring value to the prognostications of the new science."[19]

ORS Bomber Command made significant contributions in evaluating radar equipment as it became available. The first of these, Gee (for grid), was not a radar system at all. It involved three ground stations and a special receiver in the aircraft and afforded accurate navigation out to about 300 miles.

Its successor, Oboe, was not a true radar system in that it depended upon a signal from the aircraft. In this case, two ground stations were used, with one handling navigation and the other signaling the point of bomb release. This system had the same range limitations and had the additional problem of being able to handle only one aircraft at a time.

The bombing accuracy promised by Oboe was such, however, that a way to use it had to be found. A. P. Rowe, Superintendent of the Telecommunications Research Establishment throughout the war, describes the events leading to the decision about the best means of employing Oboe. His account is an excellent example of the role played by his Sunday Soviets—weekly open meetings in Rowe's office—at TRE and of the way in which TRE supported operations research during the war:

> . . . a decision on how to use Oboe, if at all, could no longer be delayed and the subject was discussed at a Sunday Soviet during the summer of 1942. I recall clearly that all who attended that meeting were agreed that Oboe ought to be used in a Pathfinder Force; more particularly, that Mosquito

aircraft carrying Oboe should drop flares on the chosen target, after which the heavy bombers should bomb the now illuminated target or, if the target were still invisible, should use the flares as aiming points. I do not recall clearly who made the suggestion but I think it likely that credit belongs to members of the Bomber Command Operational Research Section who attended the meeting. Neither do I know whether a Pathfinder Force was in any case in process of formation at this time. We heard, however, that there were powerful voices raised against the formation of a special force to direct the main attack, and there is little doubt that Oboe came as a powerful support to those who thought otherwise.

At any rate, the views expressed at that Sunday Soviet were ventilated in all interested quarters and a decision was made to use Oboe in a special Pathfinder Force of Mosquito aircraft.[20]

The Pathfinder idea was indeed Dickins' idea and the details were worked out by Roberts. Rowe comments on the result of this example of close cooperation and communication involving a technical establishment, operating personnel and operations research:

> Rarely in war is the first use of a device attended with the brilliant success achieved by Oboe on 21 December 1942. Hitherto all the efforts of the aircraft firms to produce heavy bombers, all the brilliant organization of Bomber Command and all the courage of the bomber crews had failed to damage Krupp's Works near Essen. But on the night of 21 December it was estimated that 50 per cent of the bombs fell on the target.[21]

The third of the important bombing and navigation systems to be developed was called H_2S and was a self-contained airborne radar system. It was not as accurate as Oboe, but it had the great virtue of unlimited range and thus facilitated deep penetrations into Germany. The problem was that it incorporated the cavity magnetron and there was no evidence that German radar development had produced a comparable device. Accordingly, use of H_2S was delayed until late 1942 because of fear that a bomber carrying it would be shot down and its secret revealed to the Germans.

A bomber carrying the device was, in fact, soon shot down, but, for whatever reasons, the Germans failed to capitalize on the opportunity thus presented. They did, however, soon learn to track bomber formations by "listening in" to H_2S signals, literally from the moment of takeoff from Britain. It was not until late 1944 that crews were instructed to turn on H_2S only when within radar range of their target.[22] This apparent failure by both scientific intelligence and the Operational Research Section, Bomber Command, is especially intriguing in light of the reluctance of U.S. pilots to turn on their airborne radar for fear of detection by the enemy.

There were cases where ORS Bomber Command identified problems that could not be resolved during the war. For example, OR studies traced bomber losses due to fire to the aircrafts' fuel tanks, and proposed a nitrogen inerting system to minimize the chance of explosion or fire as the tanks emptied. Installing such a system proved to be a difficult problem that was not solved by war's end.[23] The same was true of a proposed modification of the escape hatch of the Lancaster bomber; OR studies showed that a lower percentage of crewmen survived the loss of a Lancaster than was true of other bombers, and attributed this lower percentage to the small size of the escape hatch.[24]

Delay of another kind was encountered with "Window," the name given to strips of aluminum foil of precise length dropped from aircraft to confuse enemy ground radar. The concept of Window was so simple that there was general agreement that, once Britain used it, the Germans would probably follow suit and employ it against Britain—in an attack on Malta or Gibraltar, or in renewed attacks on the Home Islands. Then the concern shifted to the invasion of Sicily, where the Germans might also have used the device to good effect. Furthermore, during 1942 and into 1943, bomber losses had remained relatively constant, so that the protection claimed for Window was discounted to some extent. Finally, intelligence advised that the Germans had thought of the idea but had held off using it for fear the British might start to use it! In July 1943, with bomber losses mounting rapidly, Churchill himself made the decision to "open the Window."

ORS Bomber Command was at first lukewarm toward the use of Window, which had been developed by TRE and was ready for use early in 1942. This attitude may have reflected the tension that existed between ORS Bomber Command and TRE. In any event, experiments carried out during 1942 changed Dickins' mind and he became an advocate, especially when his Section's studies showed that bomber casualties could be reduced by about one-third if Window were used. The attack on Hamburg in July 1943 more than confirmed the prediction of the efficacy of Window.[25]

The foregoing is not meant to imply that ORS Bomber Command was the only one of the OR sections to meet with disappointment, frustration or outright failure. It is more a reflection of the fact that the unquestioned success of Fighter Command and Coastal Command, and the contributions of OR to that success, have left those commands relatively im-

mune to postwar criticism. On the other hand, numerous questions have been raised in many quarters about the validity, largely in terms of cost-effectiveness, of the all-out bombing of Germany and its wartime satellites. Doubts thus raised have rubbed off on both Bomber Command and its ORS. Ronald Clark has summarized the work of ORS Bomber Command and, in doing so, has succeeded in placing that work in a favorable perspective:

> [Dickins' brief] had a deceptively simple air, but it did in fact cover virtually every aspect of Bomber Command operations, from the tactical methods of marking and attack of targets, through the methods [of] reaching them with minimum losses, to the use of new navigational and other aids and new weapons that were constantly being introduced. In this ubiquitous role of the Operational Research Section there probably lies one reason for the fact that its work has not been more frequently mentioned. It was in fact regarded as an integral part of the Command and the results of its analysis were available to the Air Staff and were frequently of great assistance in enabling them to make operational decisions.[26]

Other Royal Air Force OR Sections

As operations research continued to prove itself in the combat commands of the Royal Air Force, its value to training and transport units also came to be recognized.

In May 1944, a section was formed at Transport Command under J. J. Vincent, who had worked with C. E. Gordon at Coastal Command. This group made good use of Vincent's background in planned flying and planned maintenance and also did valuable work in the areas of navigation and accidents.

About the same time, W. E. Egner, one of the original members of ORS Fighter Command, was given the responsibility of forming an ORS for Flying Training Command. Here again, the principles of planned flying and planned maintenance were applied. Additionally, considerable effort went into bringing about uniformity in all aspects of the Command's mission. The section was about to study accidents when the war ended.[27]

Royal Air Force OR Sections Overseas

The first R.A.F. operations research section to be formed outside the Home Islands was that serving the Middle East Command, based in Egypt. The groundwork for this group was laid late in 1941 by John C. Kendrew from Coastal Command. He had been sent to Malta to instruct R.A.F. personnel in the use of ASV radar and in December 1941 moved on to Cairo to arrange for the new OR section. J. C. Bower was transferred from ORS Fighter Command to head the group, with Kendrew and I. G. deTessier, also from Fighter Command, as his principal assistants.

ORS Middle East Command contributed significantly to the anti-shipping and antisubmarine activities of the Command, facilitated air-to-ground cooperation in the Western Desert, and analyzed bomber operations. In this, as in all areas, innovation in the use of radar and associated equipment constituted an important part of the work.

The second oversea ORS was established at the headquarters of the Northwest African Air Force. The original plan, to have the unit accompany the invasion forces in November 1942, could not be realized and it was not until February 1943 that E. C. Williams was transferred from Fighter Command to establish the unit.

Simultaneously, J. D. Bernal and Solly Zuckerman, whose OR work in civil defense will be discussed later in this article, arrived in North Africa to study both allied and enemy bomb damage at Tripoli. Inasmuch as Williams was conducting similar surveys at Sousse and Tunis, an arrangement was worked out for Zuckerman to be in charge of all damage assessment, with assistance from the OR staff. This was the beginning of work that was to have far-reaching effects on the course of the war.

The main work of the Operational Research Section, at least initially, was concerned with radar, but, as the Allied Forces moved from North Africa into Sicily and on into Italy, the mission developed along much the same lines as that of other groups, to include bombing accuracy, fighter defense of ports, supply routes and convoys, and antisubmarine and anti-shipping analyses.

Operations research activity and organization in the Western Mediterranean was complicated by more than the cooperation between the Zuckerman and Williams groups. A separate Operational Research Section was established in June 1943 under J. G. Tedd from ORS Fighter Command. It was to serve the Northwest African Coastal Air Force, which included both British and U.S. units. This section was disbanded in September 1944, but during its lifetime it worked in cooperation with personnel of the Operations Analysis Section (OAS) of the U.S. Twelfth Air Force, which consisted primarily of fighter units that had participated in the North African landings. The OAS, under I. H. Crowne, worked with the British in the Northwest African Air Force as well as with the Coastal Air Force.

Most of these organizational complications were

cleared up with the formation of the Mediterranean Allied Air Forces in December 1943. The cooperation between Tedd's and Crowne's units continued, Zuckerman's work was carried on by Williams, and the Operational Research Section in the Middle East Command was broken up when that Command became part of the Mediterranean Allied Air Forces.

Meanwhile, the entry of Japan into the war in December 1941 had led to the establishment of another oversea OR Section, this time in India. The formation of this unit had been requested as early as February 1942, but staff could not be made available until October. Then the task of forming the unit fell to Kendrew, from Middle East Command. He was joined by H. M. Barkla from ORS Fighter Command and, in February 1943, was replaced as head of the group by I. H. Cole, also from ORS Fighter Command. Later, when the ORS was transferred from Air Headquarters in India to the newly formed Air Command Southeast Asia, Kendrew again took over the section. Cole returned to England to head up the ORS of Air Defense of Great Britain (successor to Fighter Command) and A. F. Wilkins, who had conducted the earliest radar experiments for the Tizard Committee in 1935, came out to Southeast Asia.

In March 1945, Kendrew returned to England and was replaced by G. A. Roberts from ORS Bomber Command. Roberts spent considerable time in England on matters affecting Air Command Southeast Asia; during his absence, the OR Section was led by Wilkins. At the end of the war in the Pacific, F. J. Prewitt took over the section, which remained active until late 1946.

Kendrew performed one more service in connection with wartime operations research. He spent some time with the ORS Royal Australian Air Force. This section had been formed in February 1944 with J. C. Bower from ORS Middle East Command in charge. It worked closely with the Operations Analysis Section of the U.S. Thirteenth Air Force in the Southwest Pacific.[28]

One more OR section completes the oversea picture. In August 1942, the Royal Canadian Air Force formed an ORS under J. O. Wilhelm. Strictly speaking, the mission of the section, like that of the R.C.A.F., was limited to Canada and surrounding waters. Thus, it had a role to play in antisubmarine warfare, but was not otherwise involved in combat. Individual members of the section served tours of duty with the Operational Research Section of the R.A.F. Coastal Command, and R.A.F. Bomber Command's OR Section reciprocated by assisting OR personnel at R.C.A.F. Bomber Command.[29]

Operations Research and the Invasion of Northwest Europe

Vital as the work of the operations research sections outside Britain was, the primary focus of attention, particularly as 1944 approached, was the continent of Europe.

Both the British and U.S. bomber commands continued to pound continental targets and, in the process, succeeded in inflicting such damage on the Luftwaffe that it was a far less significant factor in the invasion than it might otherwise have been.[30] Coastal Command, even after the victory over the U-boat in the North Atlantic, still had the task of keeping the submarine menace under control, but was now able to devote more attention to attacks on enemy shipping. The fighter commands, both British and U.S., were another story, inasmuch as their mission underwent fundamental changes in preparation for the movement across the Channel and across Europe.

R.A.F. Fighter Command, retitled Air Defense of Great Britain, still had the responsibility for defending against the occasional intruder and for harrassing the Luftwaffe in Northern France. The need for tactical support of ground operations during and after the invasion led to the formation of the Army Cooperation Command. It was subsequently called the Tactical Air Force and, as part of the Allied Expeditionary Air Force, it became the Second Tactical Air Force.

Before these changes were made, Harold Larnder undertook a study of the problems that an Operational Research Section for the Army Cooperation Command would be required to consider. As a result, M. Graham and D. H. Preist, the latter from TRE, were designated to head up an ORS for the Command. Most of the remainder of the small staff came from ORS Fighter Command. This built-in close relationship with ORS Fighter Command was supplemented by the establishment of close contact with the Army Operational Research Group.

By the end of 1943, a decision, again based on a study by Larnder, was taken to establish an Operational Research Section at Headquarters, Allied Expeditionary Air Force. This time, Larnder was transferred from ORS Coastal Command to head the new ORS. He was also designated as Scientific Adviser for OR to the Air Officer Commanding Officer.

One month later, in January 1944, Zuckerman was appointed as a second Scientific Adviser. His knowledge of the effects of air attack on lines of communication, resulting from his work in North Africa, Sicily, and Italy, was the basis for his appointment. And his appointment resulted in a considerable reorientation

of the plans for preinvasion bombing, which until then contemplated continued strikes at German population centers and industrial capacity. Zuckerman's studies had shown the devastating impact of disruption of the rail net on both military operations and the flow of industrial products. The result of his recommendations was that special attention was given to marshaling yards and bridges in the weeks immediately preceding D-Day.[31]

Much of the work of ORS Allied Expeditionary Air Force, for which there was no U.S. counterpart, revolved about the identification of friendly forces during the invasion and about the various plans for deception of the enemy on D-Day. These included plans for flights of aircraft to simulate both air and naval forces approaching the Pas de Calais region of France, as well as plans for jamming German radar near the actual invasion beaches. ORS Bomber Command contributed to this effort with its analysis of the use of Window for the simulation of flights of aircraft.[32]

This brief summary cannot begin to do justice to the accomplishments of the Royal Air Force during World War II or to the contributions made by the staffs of the several operational research sections. Of interest to the historian is the difficulty in separating the accomplishments of operating personnel from those of OR personnel. This difficulty arises in part from the fact that the heads of the OR sections were usually designated as scientific advisers to the commanders and as such participated in staff meetings. This meant that the OR contribution had its effect in the same way as the contributions of other staff sections. It is thus quite easy to over- or underestimate the specific contributions of the various OR sections.

Army Operational Research[33]

Generally speaking, the Royal Air Force Operational Research Sections were independent of each other and, except for the sections at Fighter and Bomber Command, each remained relatively small throughout the war. The individual sections of the Army's operations research organizations also remained small, and, while control of the groups was decentralized, the Army was more successful than the Air Force in coordinating their activities.

P. M. S. Blackett set up the first Army OR section in 1940 to assist Antiaircraft Command in carrying out its responsibilities for the defense of Britain against the Luftwaffe. Even though AA Command was under the operational control of Fighter Command, it had not had the same attention as Fighter Command and so was not as fully prepared, either in training or equipment, for the task it faced.

True, the Biggin Hill experiments of 1936 had served AA Command to the extent that the end of standing patrols for Fighter Command also meant that AA units could stand down between alerts instead of being constantly at the ready. True too, gun-laying radar sets had been developed, first at Bawdsey and then at the Army's own Air Defence Research and Development Establishment (ADRDE), but these sets could not determine altitude. This meant that, when range and bearing had been determined by radar, the measurements had to be coordinated with the altitude measurement given by sound locators—scarcely a satisfactory system. Radar equipment that could coordinate all three measurements was under development, but it was proving quite temperamental and required much the same nursing as the early coastal sets. It was this situation that led to Blackett's accepting the assignment to help AA Command.

He recommended that specialists be trained to handle the job of nursemaid. The Wireless School at Petersham, under J. A. Ratcliffe, was the result. He then set about forming his Circus—a group of scientists drawn from a wide variety of disciplines—to look into the broader problems facing the Command. The immediate problem was the Blitz, the nightly bombing of British cities, especially London. The new group was thus afforded ample opportunities for observation, both of German tactics in avoiding antiaircraft fire and of the procedures employed by the gun batteries. The days were marked by calibration and related exercises and the nights by observation of actual operations.

Basically, the scientists in Blackett's Circus studied the flow of information from the radar and sound equipment, through devices for predicting altitude, range and course, to the guns and searchlights. But they soon encountered other problems. For example, there was a period when there were only half enough radar sets for the gun batteries protecting London. This situation raised the question of the best disposition of the sets. The Command had thought that the 30 4-gun batteries at its disposal afforded full coverage of the London area. Blackett's analysis showed that this view was quite wrong; rather, the best arrangement would be to combine the units into 8-gun batteries so that all could have the benefit of radar. In the event, sufficient gun-laying radar sets became available and the consolidation of the batteries was not necessary.

Detailed analyses of this type, revealing as they did some basic misunderstanding about the effectiveness

of a weapon system, led, according to Blackett, to the practice of subjecting "as many as possible of the rules and dogmas of a fighting service or command to critical but sympathetic analysis. In nine cases out of ten the rules or dogmas were found to be soundly based; in the tenth, sometimes, chance circumstances had made the rules out of date."[34]

For example, many explanations were advanced to account for the difference in reported effectiveness between shore-based and inland antiaircraft batteries. Observation quickly revealed the reason: Inland battery claims of aircraft kills could be verified by wreckage on the ground. Shore-based battery claims could not always be verified because the wreckage frequently sank into the sea; hence, the apparent superiority of shore-based batteries.[35]

Not all solutions came so easily. Long hours, personal peril, and endless data collection at the gun sites were endured in order to gain the understanding that brought about increasingly effective use of antiaircraft artillery properly coordinated with increasingly effective radar.

Blackett transferred from Antiaircraft Command to R. A. F. Coastal Command in mid-1941. By that time, the Blitz had run its course and greater energies could be devoted to the submarine threat. L. E. Bayliss took over immediate responsibility for the Circus, but it was soon merged into an ADRDE unit designated as the Petersham Research Group, under Ratcliffe. It included some scientists from the Wireless School and others from elsewhere in AA Command as well as the remnant of the Circus.

Shortly thereafter, Rowe lured Ratcliffe back to TRE to head the Post Design Service and B. F. G. Schonland, a physicist from South Africa, took over the unit, soon to be renamed the ADRDE Operational Research Group and finally, in February 1943, the Army Operational Research Group (AORG), under control of the Ministry of Supply. AORG was made responsible for operations research for the entire Army rather than for AA Command only and its scope was broadened to include all aspects of Army operations and weapons and not just those associated with radio and radar. Bayliss and M. V. Wilkes were Schonland's principal assistants.

By 1943, eight home sections of AORG had been established. The first continued the AA tasks started by Blackett. The second continued the associated coast watching activity and later turned to protection of convoys approaching the coast (after the threat of invasion had passed). The third continued the work on Army communications. These, of course, retained the original link with radio and radar.

In June 1942, the first major break with the past occurred when two new sections were formed. The one, under R. J. Whitney, dealt with field and antitank artillery. The other, under H. A. Sargeaunt, was charged with the study of armored vehicles. For a time, Omond Solandt, the Canadian physiologist, was associated with this section as part of his work with the Medical Research Council,[36] but he soon became Schonland's deputy and succeeded him as Superintendent of AORG in 1944 when Schonland became Scientific Adviser to the 21st Army Group. Later, separate units were established for infantry and airborne operations as well as those concerned with the lethality of weapons and special weapons.

When the requirement for operations research developed in the Army commands in the Middle East, Italy, India, Southeast Asia, Australia, and in the Twenty First Army Group that was preparing for the invasion of the Continent, the decision was made that these new OR units should be under the control of the War Office rather than the Ministry of Supply. Accordingly, Charles G. Darwin was appointed Scientific Adviser to the Army Council and assumed responsibility for forming the appropriate operations research sections. In time, Darwin and his successor, C. D. Ellis, came to exercise considerable influence over AORG, with the result that there was good coordination among all units even though there were two distinct groups reporting to two different ministries.[37]

During the war, there was considerable cooperation between the sections of AORG and the operations research sections of other commands. For example, when the effect of evasive maneuvers on bombing accuracy was under study by ORS Bomber Command, AORG data showed that the chance of being hit was essentially the same whether the aircraft was maneuvering or was in straight and level flight—except when held in a searchlight beam. Given the added possibility of collision during evasive maneuvers, straight and level flight became policy.[38]

Much of AORG's work with weapons involved work study, making sure that manpower and equipment were employed effectively. Solandt has given us some examples of this work. In one case, observation of antitank gun drills showed that the work could be done by three men rather than by the six assigned to it. Those responsible for this "waste" of manpower pointed out, however, that it had taken 20 years to get enough men assigned to their units to do the cooking, bring up ammunition, and handle other chores. They recommended that the report be burned. It was. Another work study showed that one member of an

artillery crew simply stood motionless during drills. He turned out to be the horse holder—in a unit that had not had horses for 20 years.

In the early days, studies of this type were handled by the scientists in the various sections, but they soon learned that work study was a specialty and that specialists could be recruited to do it; in fact, a separate Army Operational Research Section (AORS 9) was established for this purpose, thus freeing the operations research scientists for other types of study.[39]

One such study involved the 25-pounder field gun. The investigation of the effectiveness of the weapon had to begin with a definition of its function or purpose. Some regarded it as an antimateriel weapon; others saw it as antipersonnel. The latter group could not agree, however, on whether the gun should have a lethal or morale effect. Given a decision that the gun was antipersonnel and should have both lethal and morale effects, the next step was to measure its effectiveness. Observations in drill and in battle showed that the gun was far less effective than it should have been.

This conclusion led to the development of realistic means of measuring effectiveness and then to identifying factors that were degrading effectiveness. These included problems with the gun itself, with the ammunition being used, and with the effect of irregularities in the earth's surface. Overall, the analysis resulted in a significant improvement in the effectiveness of the 25-pounder.

Solandt also provides us with an example of avoiding unnecessary development because of reports from the field. Early in the war, British tanks enjoyed considerable success against German tanks in Libya. The situation suddenly reversed and tank personnel became convinced that the Germans had introduced a new gunsight. Tests of the British gunsight against a captured German one showed that the two were about equal. Some operations research and some technical people went out to Libya to investigate further and found that the Germans had hardened the armor on the front of their tanks and that the British shot was breaking up instead of penetrating this new armor. Thus, the problem was to provide a penetrating shell rather than a new gunsight.[40]

Two particularly noteworthy studies by AORG involved cooperation with the ORS of Air Defence of Great Britain; the studies were of Germany's two terror weapons, the V1 (flying bomb or buzz bomb) and V2 (rocket bomb).

When the V1 bombs were sent against Britain in June 1944, the weapons used against them were fighter aircraft, antiaircraft guns and barrage balloons. The fighters were to pick up the bombs over the Channel and were to pursue them to within about ten miles of London. At that point, the AA guns were to take up the attack and anything that they missed would hopefully run afoul of the balloons. There were problems with this plan. The fighters could not be given sufficient warning and could not be deployed efficiently to handle multiple firings of the V1s. The effectiveness of the antiaircraft guns was limited because proximity fuzes—which used a small radar unit to sense the proximity of a target and were much more effective than fuzes depending upon impact or timing for detonation—could not be used over land. When the guns without proximity fuzes did score a hit, there was a good chance that the V1 would still hit an important target, whereas it might well have overflown London if it had not been hit. AA Command and AORG and Air Defence of Great Britain and its ORS studied this problem and concluded that the guns should be redeployed to the coastal areas across the Channel from the launching sites. Then fighters would be able to patrol the Channel to within 10,000 yards of the coast, at which point the guns, now equipped with proximity fuzes, and firing out over the Channel, would take over. Other fighters could then take up the chase to the immediate vicinity of London and would now have the advantage of early warning from the gunfire along the coast. As a result of this change, the AA guns accounted for approximately 82% of the V1 bombs shot down, whereas their percentage before the change had been about half that. Churchill has written that the "new deployment was a vast undertaking, and it was executed with the most praiseworthy speed. Nearly four hundred heavy and six hundred Bofors guns had to be moved and resited. Three thousand miles of telephone cable were laid. Twenty-three thousand men and women were moved, and the vehicles of Anti-Aircraft Command travelled two and three-quarter million miles in a week. In four days the move to the coast was completed."[41]

The V1 threat to southern England was finally removed by September 1944 when the launching sites in France were overrun, but the respite was short lived. On September 8, the Germans launched the first of the V2 rocket bombs. This time, the same organizations were involved in detecting and countering the threat, with Air Defence of Great Britain and its ORS concentrating on radar detection of the missiles and AA Command and AORG using sound locators to carry out their part of the task—locating the launch sites. Solandt speaks with great pride of the

fact that the very first rocket was detected and its launch site located, so that the site could be subjected to bombing.[42]

Meanwhile, the operational research sections under the War Office were enjoying mixed success. The unit in the Middle East was given little direction or recognition and was disbanded after little more than a year, but it did produce a number of self-generated studies. The units in Italy, India, Southeast Asia and Australia fared better and did good work on a wide variety of problems. And the work of 2 ORS with 21st Army Group was outstanding.

This unit was made up of a group of scientists who, for the most part, had been together since the early days at Antiaircraft Command: M. M. Swann, P. Johnson, David Bayly-Pike and H. A. Sargeaunt. They were joined by J. G. Wallace, who had served in AORG and in 1 ORS in Italy and was a specialist in tank gunnery, and by J. F. Fairlie, a Canadian, who was a specialist in self-propelled weapons.

This group of scientists, in effect, "wrote the book" on battle analysis, developing techniques for assessing air support, artillery support—including performance of towed versus self-propelled guns—physical damage, and morale effects, gleaned from personal examination of the battlefield and interviews with prisoners of war and local civilians. Their procedures were embodied in their "Notes on the Examination of a Battlefield" and an untitled note on interviews with prisoners of war and civilians.[43]

Operational Research for the Royal Navy

In contrast to the high level of activity that marked operations research in the various commands of the Royal Air Force and Army, and for reasons that are difficult to pin down, there was no great explosion of OR activity in the Navy when P. M. S. Blackett moved there from Coastal Command in December 1941. This may have been because the Naval Operational Research unit remained small and centralized throughout the remainder of the war. And naval OR accomplishments may have been masked to some extent by the fact that Coastal Command was under operational control of the Admiralty, with the result that Blackett and his staff were deeply involved in the air offensive against the submarine.

For example, Blackett had been at the Admiralty a very short time when the controversy over Frederick A. Lindemann (Lord Cherwell)'s proposal to "dehouse" the German working population erupted. As we have seen (in the first installment of this history), Lindemann's plan could have stripped Coastal Command of the heavy bombers it needed to carry out its mission. Opposing the Lindemann plan took up much of the time and energy of both Blackett and his successor at Coastal Command, E. J. Williams. In the event, sufficient squadrons of heavy bombers, plus one squadron of American-made B-24 Liberators (at the insistence of President Roosevelt), were made available to Coastal Command so that the campaign against the U-boat could be waged successfully, if by an uncomfortably narrow margin. The official historian of the Royal Navy in World War II concluded that an opposite decision could well have cost the war.[44]

The paucity of reports on and references to specific studies by Blackett and his staff is, nevertheless, puzzling. There was, of course, plenty of room for study of shipboard radar and radar countermeasures, for analysis of naval communications, and for the application of the principles of the density method to surface vessel operations. Studies in these areas, although very important, are not likely to generate dazzling breakthroughs.

Morse and Kimball, in *Methods of Operations Research*, cite several examples of British naval operations research. They describe the analysis that led to the conclusion that cruisers should have additional below-water protection even at the sacrifice of above-water protection. This conclusion came despite the higher frequency of damaging attacks by aircraft. The data showed that bomb damage kept a cruiser out of action for about 6 months, whereas torpedo damage kept a cruiser out of action for about 19 months (counting 36 months out of action in the case of a sinking). They also cite the analysis of the effectiveness of antiaircraft guns on merchant ships. In terms of planes shot down, the guns were not very effective. But the correct measure of effectiveness was not planes damaged, but merchantmen damaged. On that basis, the analysis showed that the percentage of sinkings was significantly lower for merchantmen that carried *and fired* antiaircraft guns.[45]

The major achievement of naval operations research was slow in coming, a fact for which Blackett criticized himself and his staff. An analysis of convoys crossing the Atlantic during 1941 and 1942 showed that losses were, for all practical purposes, independent of the size of the convoy. The study, conducted primarily by H. R. Hulme and J. H. C. Whitehead, set the dividing line between large and small convoys at 40 (60 being the largest convoy that the Admiralty

would permit). Those involved in the analysis had difficulty in accepting the results and were reluctant to recommend so fundamental a change as a great increase in permissible convoy size, even in face of the staggering losses being incurred by convoys during the early months of 1943. The evidence continued to pile up, however, and the change to larger convoys was recommended and made. And the change in policy was sustained even though the first large convoy to cross the Atlantic under the new policy suffered severe losses.[46]

Operational Research in Civil Defense

Along with the emphasis placed on military operations research by the British during World War II, there were parallel efforts in the area of home defense, some of which were to prove significant to related military studies. The lead in this work on the home front was taken by John F. Baker, J. D. Bernal and Solly Zuckerman. The first two, along with E. V. Appleton, Charles G. Darwin and several others, were members of a Civil Defence Research Committee that had been formed in May 1939 to assist the Home Office Research and Experiments Branch, under Reginald Stradling, in its studies of the effects of high explosive attacks.

When war broke out, Bernal and Baker reported to the Forest Products Research Laboratory at Princes Risborough, which was to be the wartime home of the Research and Experiments Branch, redesignated as a Department. Baker set up a Design and Development Section with the mission of collecting reports on bomb damage from technical officers distributed throughout the country. He writes that it is "difficult to believe now [1976] but we started the war without the slightest reliable information on how structures behaved when bombed. . . ." Baker's principal interest was in the protection of industry, but his interest in the collapse of structures led to his designing what became known as the Morrison shelter, for which he obtained Churchill's approval on the last day of 1940. It was to save many British lives during the remaining days of the Blitz and during the V1 bombardment of 1944.[47]

The same information that led Baker to his designs for factory and individual protection guided the work of Bernal and his associates, who soon included Zuckerman. They undertook the task of predicting the effect of German raids on British cities. This work proved of immense value in planning for air raid protection, fire services, hospital requirements and the like. And, when the tables were turned and the weight of bombardment went against German cities, the same analytical concepts could be used both in planning and in evaluating bombing raids on Continental targets.

The most startling confirmation of the work of Bernal and his associates came on November 14, 1940, when the Germans bombed Coventry. As early as June 1940, the group had predicted the results of a raid by 500 German bombers on a typical British town. They had chosen Coventry for their example. The actual results of the 500-plane raid on Coventry tallied very closely with the forecast. "This feat gave the conception of a scientific bombing attack on Germany a new degree of reality and accuracy."[48]

Zuckerman, an anatomist and authority on primates, had first become involved in civil defense when he was asked to estimate the effect of blast on human beings. The prevailing wisdom was that the maximum overpressure that could be tolerated by a human was on the order of five pounds per square inch. Zuckerman conducted experiments with animals and concluded that humans had a 50-50 chance of surviving blast pressures of as much as 500 pounds per square inch. The effect of this conclusion on planning for personnel replacements and for hospital facilities was incalculable. This discovery revolutionized conceptions of the effects of bombing, especially as medical evidence gathered during the bombing of Britain confirmed Zuckerman's conclusions.[49]

As might be expected, the nature of the work at Princes Risborough was of great interest to the Air Ministry and, about midway through the war, the Research and Experiments Department was transferred to Air Ministry control. The work at Princes Risborough was also of interest to American authorities who were concerned with the effects of bombing. Among the American contingent that spent some time at Princes Risborough were Jacob Bronowski, LeRoy A. Brothers and Charles J. Hitch. By the time of the transfer to the Air Ministry, Baker had returned to Cambridge and Bernal and Zuckerman, after their work on bomb damage in North Africa, had become involved with Combined Operations.[50]

This brief account of operations research in Great Britain during World War II must include some mention of the work, mostly not of an operations research nature, that went on in two areas: Combined Operations under Admiral Louis Mountbatten, and the Admiralty's Directorate of Miscellaneous Weapon Development under Charles F. Goodeve.

Combined Operations

We have noted the work of Bernal and Zuckerman in evaluating the effects of aerial bombardment, particularly at Tripoli, where the damage inflicted bore little relationship to the effort involved. At about this time, both men became involved with Combined Operations, having been with Civil Defence and the Air Ministry. Bernal, who had been appointed a scientific adviser to Admiral Mountbatten, went off to Canada with Geoffrey Pyke, Mountbatten's other scientific adviser, in connection with the latter's ideas for the creation of floating airfields made of sea ice reinforced with wood pulp (to which he gave the name "Pykrete"). The concept never came to fruition, despite Churchill's interest in it.[51]

Subsequently, Bernal is credited with selling the Combined Chiefs of Staff on the idea of the floating harbors that served so well during the Normandy invasion. He is also credited with the development of the concepts of beach deduction; that is, the estimation of the gradients and stability of beaches such as those assaulted during the Normandy invasion.

After his work at Tripoli, Zuckerman returned briefly to London but was soon sent back to the Mediterranean to help plan the reduction of the fortifications of the island of Pantelleria by aerial bombing. He then assisted in planning bombing attacks in support of the invasion of Sicily and Italy and in assessing the damage caused by the bombing. It was this work that led to his assignment as scientific adviser, along with Harold Larnder, to the commander of the Allied Expeditionary Air Force, as noted previously.[52]

Directorate of Miscellaneous Weapon Development

Goodeve's Directorate of Miscellaneous Weapon Development (DMWD) overlapped in interest with Combined Operations inasmuch as it was DMWD that developed the floating harbors for the invasion of France. Most of the staff of the department, including Goodeve, who was a Canadian physical chemist, held commissions in the Royal Navy, and included, among many others, E. C. Bullard, postwar Director of the National Physical Laboratory, and Nevil Shute Norway, an aeronautical engineer better known as the novelist Nevil Shute.

In addition to the work on the floating harbors, the department was responsible for developing ideas and for testing the ideas of others. Thus, they were involved in the testing and subsequent adoption of the Oerlikon antiaircraft gun and in the development of a simple and inexpensive way of demagnetizing ships as a defense against magnetic mines, as well as a variety of shipboard bombardment devices, including the hedge hog (for throwing antisubmarine mines) and both antiaircraft and bombardment rockets.[53]

Summary

In this brief overview of wartime operations research in Britain, we have named but a handful of the perhaps 1,000 men and women who contributed to the war effort through operations research. And the few we have named tend, of course, to be the organizers and administrators rather than the subordinates who did much of the "real" work.

The background characters whom we met in the first paper in this series remained active in support of operations research throughout the war. H. T. Tizard, even though he had retired from active participation, continued in an informal role and made significant suggestions at critical times to strengthen operations research. Cherwell was most concerned with Bomber Command and, while his policies may have inhibited strategic studies by ORS Bomber Command, he appears to have made full use of tactical and technological recommendations from that unit.

Robert Watson-Watt concentrated on his telecommunications responsibilities, but he did contribute a definition of operations research that is quoted widely in the literature on OR in World War II: "An investigation carried out, by scientific method, on actual operations, current, recent or impending, at the request of those responsible for the initiation or conduct of the operations, and explicitly directed to the better, more effective and more economical conduct of similar operations in the future."[54]

A. P. Rowe and many key members of his staff at the Telecommunications Research Establishment contributed to wartime development of operations research, either indirectly through such channels as the Sunday Soviets or directly, as in the case of those who left TRE to join operations research units around the world.

New background characters in the wartime drama include Charles F. Goodeve, for the constant support he gave as a "customer" of operations research,[55] J. A. Ratcliffe, for filling the gap between Blackett's Circus and the formation of the Army Operational Research Group, and E. G. Bowen, who came to be known as the "father" of airborne radar.

Special mention must be made of the Nobel laure-

ates who found wartime operations research sufficiently important and challenging to induce them to abandon their chosen fields for the duration of the war. Considering the relatively small number of individuals involved in operations research in Britain during the war, the list of Nobel prize winners is impressive: E. A. Appleton, P. M. S. Blackett, A. H. Huxley, J. C. Kendrew, and C. H. Waddington, with A. V. Hill and J. D. Cockcroft lending their support.

The heads of the major wartime operations research sections deserve special mention for their skill in organizing their groups and maintaining lines of communication with users while at the same time contributing to the development of the role and methodology of this new activity. Among these, two names lead all the rest: P. M. S. Blackett and Harold Larnder. In the United States, the former is given great credit for his contributions to the early development of operations research, to the point of overshadowing the contributions of Larnder. Blackett did start three operations research groups in three different services, and he did write two important papers on operations research and its methods. He also wrote articles that helped to publicize operations research and its wartime accomplishments, perhaps the most difficult of these being his obituary of E. J. Williams, who died late in the war.[56]

Harold Larnder started only one operations research section, but it *was* the first. That section helped the R. A. F. through the Battle of France, the Battle of Britain, and the Blitz. When he moved to Coastal Command, the Battle of the North Atlantic was at its height. And he ended the war as Scientific Adviser to the Allied Expeditionary Air Force, after having studied that command's need for operations research in connection with the invasion of the Continent. Such assignments reflected his capacity for organization and administration, as did his paper on O. R. S. Reports.[57]

The accomplishments of wartime operations research in Britain were so significant and extensive that there is more than enough credit to go around. The point is that no less should go to Blackett and much more should go to Larnder.

When we come to the hundreds of men (and the few women) who found operations research to be a rewarding way to contribute to the war effort, we may start with Blackett's list: H. T. Tizard, Robert Watson-Watt, A. P. Rowe, and Harold Larnder from the early days and Ralph Fowler, E. J. Williams, L. E. Bayliss, Henry Whitehead, C. H. Waddington, H. R. Hulme, E. C. Bullard, Andrew Huxley and Charles Kittel as significant contributors during the war.[58] To these we may add E. C. Williams at Fighter Command, B. G. Dickins and G. A. Roberts at Bomber Command, B. F. J. Schonland and Omond Solandt at Army Operational Research Group, and John F. Baker, J. D. Bernal and Solly Zuckerman in civil defense.

Finally, there are those who learned of or participated in operations research during World War II, who appreciated its value and recognized its potential, and who were instrumental in its continued service to the military and its extension into nonmilitary areas. Here there is no question but that Charles F. Goodeve's name leads all the rest.

Notes

1. Air Ministry, *The Origins and Development of Operational Research in the Royal Air Force* (London: HMSO, 1963), pp. 33–36.
2. F. W. Winterbotham, *The Ultra Secret* (New York: Dell Publishing Company, Inc., 1975; hardcover edition, New York: Harper & Row, Publishers, Inc., 1974). The *Ultra* system unscrambled and interpreted secret German messages to and from units in the field or at sea.
3. Air Ministry, *Origins*, pp. 12–20.
4. A. P. Rowe, *One Story of Radar* (Cambridge: University Press, 1948) pp. 68–74, on the development of airborne radar.
5. J. G. Crowther and R. Whiddington, *Science at War* (New York: Philosophical Library, 1948), pp. 93–94.
6. Air Ministry, *Origins*, pp. 24–29.
7. J. Plymen, "Operational Research," *Proceedings of the Centenary Assembly of the Institute of Actuaries*, 3 (1950), pp. 313–328. The same issue includes an article by Max Lander, "War and the Actuary," pp. 291–297.
8. Charles F. Goodeve, "Operational Research," *Nature*, 161 (March 13, 1948), p. 377.
9. P. M. S. Blackett, *Studies of War, Nuclear and Conventional* (New York: Hill and Wang, 1962) pp. 216–217.
10. C. H. Waddington, *OR in World War 2* (London: Elek Science, 1973; unpublished edition, 1946), pp. 206–220; Air Ministry, *Origins*, pp. 82–83.
11. Air Ministry, *Origins*, pp. 76–78.
12. Waddington, *OR in World War 2*, pp. 226–242; Air Ministry, *Origins*, pp. 81–86.
13. In effect, the emphasis on serviceability was being pushed to an extreme (100% serviceability could be achieved if no planes were flown) that actually reduced the number of missions flown.
14. Waddington, *OR in World War 2*, pp. 40–48; Air Ministry, *Origins*, pp. 102–103.
15. See Note 10.

16. Blackett's support of Williams' position and his recommendation that 190 heavy bombers be transferred to Coastal Command led the head of that Command to characterize the recommendation as slide rule strategy of the worst kind.
17. Ronald W. Clark, *Tizard* (Cambridge, Mass.: The MIT Press, 1965) p. 163; Birkenhead, *The Professor and the Prime Minister* (Boston: Houghton Mifflin Company, 1961) pp. 257–267; C. P. Snow, *Science and Government* (New York: Mentor Books, 1962). Snow makes the disagreement on bombing policy between Cherwell, on one side, and Tizard (with Blackett) on the other, a central theme of his Godkin Lectures at Harvard in 1960. Tizard rated Cherwell's estimate of damage as being four to six times too high; Blackett rated it at six times too high, and the Strategic Bombing Survey at the end of the war rated it at ten times too high.
18. Clark, *Tizard*, p. 163.
19. Air Ministry, *Origins*, pp. 62–63; Ronald W. Clark, *The Rise of the Boffins* (London: Phoenix House, 1962) p. 221.
20. Rowe, *One Story*, p. 145.
21. Rowe, *One Story*, p. 146. See also Air Ministry, *Origins*, pp. 40–51, on radar development.
22. Alfred Price, *Instruments of Darkness* (New York: Charles Scribner's Sons, 1977; first edition, 1967), pp. 215–216.
23. Air Ministry, *Origins*, pp. 70–71.
24. Freeman J. Dyson, "Reflections, Part I," *The New Yorker*, 55 (6 Aug 79), pp. 37–46; Air Ministry, *Origins*, p. 66.
25. Birkenhead, *Professor*, pp. 251–257; Guy Hartcup, *The Challenge of War: Britain's Scientific and Engineering Contributions to World War II* (New York: Taplinger Publishing Company, 1970), p. 152.
26. Clark, *Boffins*, p. 211.
27. Air Ministry, *Origins*, pp. 103–108.
28. Air Ministry, *Origins*, pp. 109–126.
29. Air Ministry, *Origins*, pp. 183–184.
30. Churchill, *The Second World War. VI, Triumph and Tragedy*, p. 3, writes: "So great was our superiority in the air that all the enemy could put up during daylight over the invasion beaches was a mere hundred sorties." See also Clark, *Tizard*, p. 307.
31. Air Ministry, *Origins*, pp. 127–129.
32. Clark, *Boffins*, pp. 229–230.
33. I am indebted to Professor Ronald W. Shepherd, Future Systems Group, Royal Ordnance (formerly of the Royal Military College of Science), for making available working papers of historical and bibliographical significance to the history of operations research and particularly to Army operational research. In this section, I have drawn freely on his "A Short Account of the Origin and Early Development of Operational Research for the Army" (Working Paper OR/WP/March 30, 1983).
34. See Note 35.
35. Blackett, *Studies of War*, pp. 209–211.
36. There was a close relationship between the Medical Research Council and the various Army operational research sections. Early in the war, civilian scientists with medical and related backgrounds were attached to Army units in combat areas and were permitted to enter battle areas to obtain first-hand data about battle conditions and relevant physiological problems. This established precedents for the Army OR sections as they were formed. (Letter, R. W. Shephard to author, undated.)
37. Air Ministry, *Origins*, pp. 40–41, and Owen Wansbrough-Jones in "Operational Research in War and Peace," *The Advancement of Science*, IV.16 (Jan 48), pp. 320–332.
38. Air Ministry, *Origins*, p. 65.
39. Omond Solandt, "Observations, Experiment, and Measurement in Operations Research," in Joseph F. McCloskey and John M. Coppinger, eds., *Operations Research for Management* (Baltimore: The Johns Hopkins Press, 1956), pp. 267–281. Also Solandt, interview, March 26, 1976. AORS 10 was concerned with battle analysis and was headed by F. R. N. Nabarro, one of the original members of Blackett's Circus.
40. Solandt, "Observation," pp. 279–280.
41. Churchill, *The Second World War VI. Triumph and Tragedy*, pp. 47–48; Solandt, interview, May 14, 1984.
42. See Note 40; Solandt, interview, May 14, 1984.
43. R. W. Shephard, *Readings on Early Military Operational Research (with Particular Reference to Army OR)*, Working Paper OR/WP/8, (Shrivenham: The Royal Military College of Science, 1984), pp. 99–310.
44. S. W. Roskill, *The War at Sea, 1939–1945, II. The Period of Balance* (London: HMSO, 1957), p. 371.
45. Philip M. Morse and George E. Kimball, *Methods of Operations Research*, 1st edition, revised (Cambridge: The Technology Press of MIT, and New York: John Wiley & Sons, Inc., 1951), pp. 48–49 and 52–53.
46. Blackett, *Studies of War*, pp. 228–233. N. Falconer, "On the Size of Convoys: An Example of the Methodology of Wartime OR Scientists," *Opnl. Res. Quart.* **27**, 2 (1976), pp. 315–327.
47. Letter, Baker to author, October 6, 1976.
48. Crowther and Whiddington, *Science at War*, p. 99.
49. Crowther and Whiddington, *Science at War*, p. 98.
50. Air Ministry, *Origins*, p. 42.
51. Clark, *Boffins*, p. 140.
52. Bernard Fergusson, *The Watery Maze, The Story of Combined Operations* (New York: Holt, Rinehart & Winston, 1961).
53. Gerald Pawle, *The Secret War* (New York: William Sloane Associates, 1957), is the story of the Direc-

torate, Miscellaneous Weapons Development, Admiralty.
54. Widely quoted. See, for example, Air Ministry, *Origins*, p. 9. The final form of the definition is probably postwar.
55. Letter, Charles F. Goodeve to author, December 21, 1976.
56. An extract of the *Obituary Notice of the Royal Society* for March 1947 is included in Blackett, *Studies of War*, pp. 235–239.
57. Appendix 2, "O. R. S. Reports," in Air Ministry, *Origins*, pp. 194–198.
58. Of these, we shall meet Ralph Fowler and Charles Kittel in the next article in this series. Henry Whitehead worked with P. M. S. Blackett on antisubmarine warfare.