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The Origins and Development of Operational Research in the Royal Air Force

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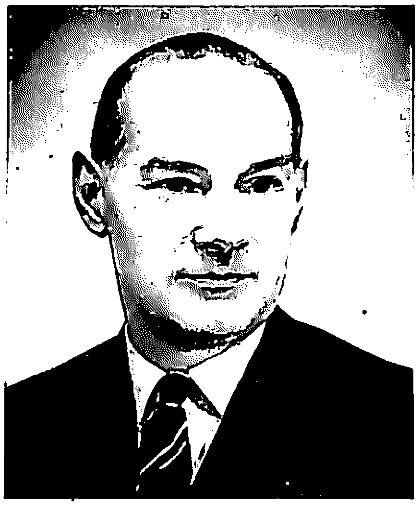

Scott Galloway

Dr. B. G. Dickins

H. Larnder

E. C. Williams

First Heads of the principal Operational Research
Sections attached to R.A.F. Commands

Frontispiece

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PREFACE

This monograph attempts to trace the origins and development of operational research in the Royal Air Force immediately before and during the last war and to illustrate the characteristic work performed by each of the operational research sections attached to Commands at home and overseas. There has been no attempt to make an exhaustive study of each section. While attention is drawn to the achievements of the scientific staff it is important for the reader to remember that the sections were integrated within Commands and worked closely with the other branches of headquarters. It happened that the results achieved were on many occasions the outcome of team work between staff officers and scientists.

The main source of information has been the accounts of individual operational research sections prepared for the Deputy Director of Science at the Air Ministry after the war. The files and folders of various branches of the Air Staff, the papers of the Operational Research Centre, later the Deputy Directorate of Science, and operations record books kept by a few of the sections were also consulted.

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May 1936.	Establishment of Bawdsey Research Station
January 1937.	Formation of Committee for the Scientific Survey of Air Offence
September 1939.	Formation of R.D.F. Research Section under H. Larnder at Headquarters Fighter Command, Stanmore, from staff of Bawdsey Research Station Staff of Bawdsey Research Station moved to Perth where they became Air Ministry Research Establishment
6 February 1940.	R.D.F. Research Section, Stanmore, redesignated Stanmore Research Section
February 1940.	Formation of Air Warfare Analysis Section under Dr. L. B. C. Cunningham
17 May 1940.	Ministry of Aircraft Production formed under Lord Beaverbrook
September 1940.	Anti-Aircraft Command Research Group formed by Professor P. M. S. Blackett at Savoy Hill House
November 1940.	Air Ministry Research Establishment, then at Worth Matravers, Dorset, became Telecommunications Research Establishment
March 1941.	Professor P. M. S. Blackett appointed Scientific Adviser to Air Officer Commanding-in-Chief Coastal Command
May 1941.	Operational Research Group formed at Air Defence and Research Establishment, Petersham
June 1941.	Stanmore Research Section redesignated Operational Research Section Fighter Command. Mr. Larnder in addition to being officer-in-charge appointed Scientific Adviser to Air Officer Commanding-in-Chief
June 1941.	Operational Research Section formed at Headquarters Coastal Command under Professor Blackett
September 1941.	Operational Research Section formed at Headquarters Bomber Command under Dr. B. G. Dickins who also became Scientific Adviser to the Air Officer Commanding-in-Chief

October 1941.	Operational Research Centre formed at Air Ministry
January 1942.	Department of Naval Operational Research set up at the Admiralty under Professor Blackett
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April 1944.	Operational Research Section Headquarters R.A.F. Middle East amalgamated with Operational Research Section Headquarters Mediterranean Allied Air Forces
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September 1944.	Bombing Analysis Unit formed in France under Professor S. Zuckerman
October 1944.	Bomber Command Bombing Research Unit began work in France
June 1945.	British Bombing Survey Unit with Bombing Analysis Unit attached began work in Germany

ABBREVIATIONS AND CODE NAMES

A.C.A.S.	Assistant Chief of Air Staff
A.D.G.B.	Air Defence of Great Britain
A.E.A.F.	Allied Expeditionary Air Force
A.I.	Air Interception
A.M.M.R.U.	Air Ministry Manpower Research Unit
A.O.R.G.	Army Operational Research Group
A.S.V.	Air to Surface Vessel
A.S.W.D.U.	Air Sea Warfare Development Unit (Coastal Command)
A.S.W.O.R.G.	Anti Submarine Warfare Operational Research Group
A.W.A.S.	Air Warfare Analysis Unit
B.A.U.	Bombing Analysis Unit
B.B.R.M.	British Bombing Research Mission
B.B.S.U.	British Bombing Survey Unit
C.H.	Chain Home (the first radio location system to be used)
C.H.L.	Chain Home Low
C.S.S.A.D.	Committee for the Scientific Survey of Air Defence
C.S.S.A.O.	Committee for the Scientific Survey of Air Offence
D.F.	Direction Finding (Method of interception control)
D.S.R.	Director of Scientific Research (M.A.P.)
Freya	German early warning equipment
G.C.I.	Ground Controlled Interception
Gee	Radar navigational aid
Gee-H	Radar bombing method used by Bomber Command
G.L.	A.A. Gun Layer (Army Radar)
H2S	Self-contained airborne radar bombing aid used by Bomber Command
I.F.F.	Identification of Friend or Foe (Radar)
IOGROPS	Indian Ocean General Reconnaissance Operations
LORAN	Long Range Aid to Navigation
M.A.A.F.	Mediterranean Allied Air Forces
M.A.P.	Ministry of Aircraft Production
M.E.W.	Microwave Early Warning (U.S. Fighter Control Device)
Naxos	German search receiver used to detect centimetric radiation, e.g. A.S.V., H2S, A.I.
N.W.A.F.	Northwest African Air Forces
O.A.S.	Operational Analysis Section (U.S.A.A.F.)
Oboe	Bombing Aid used by Bomber Command
O.R.C.	Operational Research Centre (Air Ministry)
O.R.S.	Operational Research Section

Overlord	Landings on the Continent, June 1944
P.P.I.	Plan Position Indicator
P.R.	Photographic Reconnaissance
R.C.M.	Radio Countermeasures
R.D.F.	Radio Detection and Direction Finding (From September 1943 known as Radar)
Rebecca/Eureka	Airborne navigation system (Rebecca) depending on the use of fixed ground beacons (Eureka)
Rooster	System of homing to aircraft fitted with beacon by other aircraft equipped with A.S.V.
S.A.A.M.	Scientific Adviser Air Ministry
SCR.584	Radar Director used both for A.A. fire control and fighter control (U.S.A.A.F.)
S.E.A.C.	South-east Asia Command
Serrate	System of homing on to German night fighters
S.L.C.	Searchlight Control
T.R.E.	Telecommunications Research Establishment
V.E.B.	Variable Elevation Beam
V.H.F./D.F.	Very High Frequency/Direction Finding
Window	Tinfoil strips dropped from aircraft to simulate aircraft echoes and confuse ground search radars

GLOSSARY OF NAVIGATIONAL AND BOMBING AIDS

The principal radio and radar navigational and bombing aids are briefly explained below for the benefit of the non-technical reader.

GEE (NAVIGATIONAL AID)

The basis of this system was a wireless pulse signal transmitted simultaneously by two stations, a 'master' station and a 'slave' station. By measuring the difference in time between the reception of the two signals, and by keeping this difference constant, it was possible to keep the aircraft on a pre-determined line—the line of constant difference between the two stations. Further, by means of a second pair of transmissions from the same 'master' station and a different 'slave' station, an exact point on the line could be determined. Specially prepared maps made it possible to plot this point. Gee operated over a range of about 300 miles. It was first used by R.A.F. Bomber Command on 8/9 March 1942 in an attack on Essen.

OBOE (BOMBING AID)

This was the most accurate method of bombing used in the war. The aircraft carried two sets of radar apparatus, each of which re-transmitted a signal received from a ground station of which there were two. The ground stations were thus able to measure the distance and plot the position of the aircraft. In practice one station kept the aircraft along a pre-determined track and warned the pilot when he deviated to port or starboard, while the second or 'master' station, by periodic measurements of the distance, calculated the ground-speed and announced the moment at which the bombs should be released. Like Gee, Oboe had a range of about 300 miles. Since a pair of ground stations could control only one aircraft at a time, the device was used chiefly by Pathfinder aircraft which pointed the way to the bombers behind them by dropping either coloured flares to show the release point or marker bombs to show the target. Oboe was first experimentally used in attacks on German battleships in the winter of 1941–42. It was introduced into the Pathfinder Force in December 1942 and used throughout the war. In the autumn of 1944, ground stations were set up in France and Belgium, thus bringing important targets in central and even eastern Germany within accurate bombing range.

H2S (BOMBING AND NAVIGATIONAL AID)

This was a self-contained active airborne radar apparatus. By discriminating between different reflections of radar pulses from buildings, open ground and water, a picture distinguishing these features could be produced on a cathode ray tube. Several Pathfinder squadrons were equipped with H2S by the end of 1942 and it was universal in four-engined bombers by the end of the war.

GEE-H (BOMBING AID)

An attempt was made to extend the accuracy obtained by Oboe, which could only be used by a small number of Pathfinder aircraft, to larger bomber formations of, say, 100 aircraft. It was sometimes known as 'Oboe in reverse', the main transmitter-receiver being carried in the aircraft and two ground stations acting as beacons. Theoretically Gee-H was as accurate as Oboe, but in practice its value was reduced by the additional strain imposed upon the crew instead of upon experienced operators in the ground stations. Its range was also slightly shorter than that of Oboe and therefore was little used until 1944 when mobile ground stations on the Continent enabled the one group of Bomber Command which was equipped with Gee-H to make very accurate raids deep in Germany.

INTRODUCTION

'If, instead of sending the observations of able seamen to able mathematicians on land, the land would send able mathematicians to sea, it would signify much more to the improvement of navigation and to the safety of men's lives and estates on that element.'

SIR ISAAC NEWTON.[1]

What is Operational Research? Of the many definitions offered, possibly the most concise is that it is 'numerical thinking about operations, with the aim of formulating conclusions which, applied to operations, may give a profitable return for a given expenditure of effort'. Throughout history there has been a fruitful exchange of ideas between the scientist and the fighting man. The scientist, from early times onwards, has conceived blueprints for warlike weapons. Archimedes, for example, made catapults so that the citizens of Syracuse could resist the besieging Romans, and the mind of that many-sided, prophetic genius, Leonardo da Vinci, threw out designs for all kinds of revolutionary weapons of war. Warfare, in its turn, has presented unparalleled opportunities for the development of medical science while the application of scientists' minds to military affairs has stimulated their own research. To take only one example, the foundations of dynamics were laid when Galileo set himself to solve certain problems of gunnery. But the actual study of military operations by the scientists, the intrusion of the scientist into the sphere of tactics, such as was anticipated by the foregoing remarks of Sir Isaac Newton, is new and did not occur until just before the beginning of the Second World War.

At least one student of war, however, had foreseen the need for scientific analysis in modern warfare. 'The way that decisions are reached on questions of strategy, tactics, organisation, etc., is lamentably unscientific,' wrote B. H. Liddell Hart in October 1937. 'It is due in part', he continued, 'to the difficulty of developing a truly critical habit of mind under the conditions of military subordination, and in part to the lack of any staff organ devoted to research. . . . There are no means for the comprehensive analysis of past experience, and thus no synthesis of adequately established data to serve as a guide in framing policy. . . . At present the investigation of problems is pushed on to officers who are occupied with current military business. That task ought to be given to a body of officers who can devote their whole time to exploring the data on record, collecting it from outside, and working out the conclusions in a free atmosphere. Such a body should be composed of the best intellects in the army with a good blend of practical experience, and in selecting them particular attention should be given to

[1] To Mr. Nathanael Howes, 25 May 1694. Quoted in *Correspondence from Sir Isaac Newton to Roger Cotes*, edited J. Eddleston, Cambridge 1850.

originality of thought or critical powers. It is also very desirable that they should be supplemented by a permanent nucleus consisting of some first-rate university men who have been trained in the processes of scientific inquiry; these might take Territorial commissions to give them an acquaintance with military practice.' [1]

At the beginning of the Second World War our principal form of warning against air attack was radar. At that time the Royal Air Force was superior to the German Air Force in everything but numbers. Radar offered the means to offset this disadvantage, and the evaluation of radar and the subsequent analysis of its impact on air tactics brought into existence an entirely new branch of applied science which became known as operational research. Its earliest exponents were therefore to be found at Headquarters Fighter Command, responsible for the air defence of Great Britain.

It was also realised, independently, by a few civilian scientists, some of whom had already been consulted on technical problems relating to defence, or who were shortly to become associated with operational research, that scientific methods had not yet been applied to tactical and strategic problems. In the early summer of 1940, members of this group, which included Professors P. M. S. Blackett, J. D. Bernal, S. Zuckerman and C. H. Waddington, published a manifesto in which it was said that many factors in military operations could be reduced to numerical values. 'Doing so', they wrote, 'provides problems capable of definite solution. This has, indeed, been done to a certain extent with the tactical problems of naval and air fighting, but it could be extended to many more. The scientific staffs of the Services need to play a much larger part than they seem to do in the formulation and solution of strategical and tactical problems.' [2]

These two aspects of operational research were now brought together; firstly, the evaluation of an equipment or weapon to discover how well it performed on operations and, secondly, the analysis of operations to see how the equipment or weapon fitted the tactics or, alternatively, to what extent tactics dictated the form of weapon that was chosen. Two more branches of operational research were developed in due course: one, the prediction of the outcome of future operations either in the tactical or the strategical field with the object of influencing policy, and the other, the study of the efficiency of the organisations which wielded the equipment and weapons in battle. Work along these lines had, of course, been done in the past, but it was not until the Second World War that it was done as a conscious activity.[3]

The idea of operational research was fairly slow to take root, but by the

[1] *Thoughts on War*, Chap. 6, p. 125, Faber, 1944.

[2] *Science in War*, Penguin Books Ltd., 1940.

[3] This explanation of operational research is derived from a speech made in 1952 by E. C. Williams, then Director of Operational Research at the Admiralty.

end of 1940, scientists had been attached to the principal operational commands in this country, and by the autumn of 1941 those scientists had been organised into operational research sections, each responsible to its respective Air Officer Commanding-in-Chief. Personnel were drawn from the scientific staff of the Ministry of Aircraft Production, and the Air Ministry set up a small body to co-ordinate research. Similar groups of scientists were later formed in the Army and at the Admiralty.

In October 1941, Professor Blackett, who after forming a research group in Anti-Aircraft Command had become Scientific Adviser to the Air Officer Commanding-in-Chief Coastal Command, enumerated the functions of an operational research section.[1] The first was to advise the Commander-in-Chief and his staff on matters which were not handled by the research and experimental establishments. This was done by analysing scientifically the data provided by the operational staff such as signals, track charts, combat reports, meteorological information, etc. It was essential that such scientific analysis should be done in or near operations rooms, as the data on grounds of security could not be made available to the technical establishments. The chief objection to staff officers carrying out this sort of work was, firstly, that their time was largely taken up with making executive decisions and, secondly, that scientists were often better equipped to deal with certain aspects of operations, particularly those in which probability considerations and the theory of error entered. The work of an operational research section was performed at command or group headquarters, or at stations or squadrons, as circumstances dictated. The second function of an operational research section was to act as a link between the command and the technical and research establishments. For unless the operational staff and the scientists collaborated closely, it was likely that the operational requirement desired would neither correspond to the real need nor to the technical possibilities.

As for the staff, the leading members of a section were usually scientists, either with an academic reputation, or who had served with the Service technical establishments. The remainder were also men, or women, who had been trained to think numerically, and included among others, engineers, physicists, biologists and mathematicians. The section was an integral part of the command and close touch was maintained with the operations staff. Members also spent part of their time at operational stations and studied at first hand the problems of aircrew, occasionally going with them on operational or training flights.

It was not the function of operational research sections to act in any other than an advisory capacity. The headquarters staff carried the responsibility for making decisions and could use or ignore the scientific analysis of any problem as it wished. It is important to remember this when studying the various illustrations of operational research in the following pages.

[1] 'Scientists at the Operational Level' is reproduced as Appendix No. 1.

By 1943 the operational research organisation had spread overseas to the various theatres of war in Europe, North Africa and the Far East. In overseas theatres the members of operational research sections donned uniform and were granted honorary commissions. At home, operational research extended into the field of administration and was especially useful in discovering the best means of getting the maximum amount of effort out of the available manpower and aircraft. The personal adviser to the Prime Minister, Lord Cherwell, had at his disposal a statistical analysis section which not only collated and presented statistics on both military and civil aspects of the war effort, but frequently advised on general economic policy.

Operational research sections were formed in the Dominions Air Forces, and the American Services profited by the British initial work in this field, particularly in the U.S. Navy and U.S. Army Air Forces. The former, inspired by Professor Blackett's paper, set up an analytical group in 1942 to study U-boat problems while later that year operational research, under the guidance of the research section in Bomber Command, began in the U.S. Eighth Air Force based in Great Britain.

No equivalent for operational research existed in the German armed forces, although the German scientific effort had been prominent in organising industry during the First World War and had actually stimulated British efforts in industrial research after the war. The gulf that stretched between the Nazi ideology and the intuitive thought of Hitler and the rationalistic and equalitarian attitude of scientists made collaboration impossible. Albert Speer, Reichsminister for Armaments and War Production and later Joint Chairman of the Central Planning Office, was the only adviser of Hitler with a scientific background but he was seldom permitted to take the initiative. The failure of the Germans to make use of operational research, wrote Professor Bernal after the war, 'contributed to their defeat, both in their failure to find counters to enemy weapons and in their expending disproportionate efforts on weapons which operational research would have shown to be useless'.[1]

[1] J. D. Bernal, *Science in History*, p. 581, Watts.

CHAPTER I

Origins of Operational Research, 1918 to 1939

THE INFLUENCE OF SCIENCE ON AIR WARFARE PRIOR TO 1935

There had been no scientific study of tactical and strategical problems until the opening of the Second World War, although the rudiments of operational research were present in the first struggle against Germany. A team of scientists which included Lord Rutherford was called in for consultation by the Admiralty during the anti-U-boat campaign,[1] while the Army attached officers with scientific experience to flash-spotting and sound-ranging units and to meteorological sections on the Western Front. Scientists had, of course, always been associated with the invention and improvement of military weapons and equipment, and before describing the origins of operational research in the Royal Air Force in the period immediately prior to the outbreak of war in September 1939 a brief review of its antecedents is necessary.

The nucleus of experiments with military aircraft in the early days of the Air Force was the Royal Aircraft Factory at South Farnborough, later to become the Royal Aircraft Establishment, which was concerned exclusively with the technical development of aircraft. In 1909 the Prime Minister, Mr. Asquith, appointed an advisory committee for aeronautics under the presidency of Lord Rayleigh.[2] Among its members were scientists from the National Physical Laboratory at Teddington, and this began a fruitful association with the Air Force that some twenty years later was to culminate in the invention of Radio Detection and Direction Finding (R.D.F.) or, radar, as it eventually became known.

During the years 1914 to 1918 the important role played by mechanical equipment such as submarines, wireless telephony, tanks and aircraft made the attachment of scientific advisers to the three Services essential. At the same time it was recognised that Germany had made great technical strides with the help of scientific research. Accordingly in 1918 Lord Balfour was responsible for the formation of the Department of Scientific and Industrial Research which was to deal with all kinds of scientific problems, not only in industry and agriculture, but also in the Services. Under its aegis was set

[1] J. G. Crowther and R. Whiddington, *Science at War*, H.M.S.O., 1947.

[2] Sir Walter Raleigh, *The War in the Air*, Vol. I, p. 159, Oxford, The Clarendon Press, 1922.

up the Radio Research Board which, among other things, was concerned with the development of radio-telephony in the Royal Air Force.

Directors of scientific research were appointed to the Admiralty in 1919 and to the Air Ministry in 1924 but the example of the senior and the junior Services was not followed until 1938 by the War Office. The first Director of Scientific Research at the Air Ministry was Mr. H. E. Wimperis who was later responsible for forming and encouraging the small group of scientists working on the early radar equipments. Apart from this, an aeronautical research committee was formed in 1919 to advise the Secretary of State for Air upon 'higher matters of research'. In its original form a large proportion of the committee were members of the aircraft industry, but after reorganisation in 1935 it was composed of scientists working in government departments and in the universities. The committee applied itself to such subjects as accident investigation, aerodynamics, wind tunnels, load factors, aircraft noise, engines, wing flutter, air transport, airship stressing, etc. Perhaps the most significant fact about this committee was that through its medium the Air Ministry was able to maintain contact with scientists in and outside the universities and was able at any time to draw upon the knowledge of eminent scientific men fully acquainted with current aeronautical problems whenever the need arose.[1] Prominent among the members of the committee in the first ten years after the First World War were Sir John Petavel, Director of the National Physical Laboratory, Professor Lindemann (later Lord Cherwell), Professor of Experiments and Philosophy at Oxford, Colonel Mervyn O'Gorman, vice-chairman of the Royal Aero Club and one time superintendent of the Royal Aircraft Establishment, and Mr. H. T. (later Sir Henry) Tizard, Rector of the Imperial College of Science and Technology at South Kensington.

Mr. Tizard was to become an influential figure in the Air Ministry in the years between the two world wars, and through him the Imperial College of Science became closely connected with the Directorate of Scientific Research on the Air Staff. By the early 1930's an Air Ministry Laboratory was in existence at the Imperial College with six scientific officers working under a principal scientific officer. Experiments were made with various types of engine fuel, and a highly skilled workshop staff was employed under the supervision of the scientific officers in making and modifying special types of navigational and research instruments required for use in the Royal Air Force or for the purposes of special experiments. At all times the laboratory could rely on the help of the Rector and staff at the Imperial College.

[1] It is interesting to note that in 1931 the following universities and colleges in Great Britain were engaged in aeronautical research: Oxford, Cambridge, Bristol, Manchester and Glasgow Universities, the Imperial College of Science, South Kensington, King's College, London, and Loughborough College.

SCIENTIFIC APPLICATION TO THE PROBLEM OF DEFENCE AGAINST AIR ATTACK AFTER 1935

While scientific work proceeded on a modest scale on the purely technical side of aeronautics at the Royal Aircraft Establishment, the National Physical Laboratory and the Imperial College, the world political scene combined with the economic crisis became increasingly threatening. Of particular significance to this country was the rise to power of the Nazis, German rearmament and the creation of a German Air Force. Following upon ten years of drastic retrenchment the first plans for the air defence of Great Britain against a possible German attack were made when, on 31 July 1934, the Cabinet decided to build up the home defence air force to 75 squadrons. By the following spring international tension became more acute when Hitler announced to the Foreign Secretary that Germany had achieved air parity with Great Britain and intended to have equality with France. Efforts were made to accelerate the expansion of the Royal Air Force.

Hitherto scant attention had been paid to the reporting of air raids against this country in a future war. An anti-aircraft research sub-committee of the Committee of Imperial Defence had submitted a report in 1928. It was composed of the scientific advisers to the fighting Services and its terms of reference were to report on 'the present position in regard to research for anti-aircraft purposes'. The committee was primarily concerned with the detection of aircraft by acoustic methods, believing it to be the 'only system which can be applied at present with any hope of success'. It is also of interest to note that the committee recommended that experiments should go ahead with pilotless aircraft controlled by wireless radiation. The activities of this sub-committee were suspended in November 1928.

Towards the end of 1934, on the suggestion of Mr. Wimperis, who had drawn attention to the primitive system of air raid warning then in existence, the Air Ministry set up a committee 'to consider how far recent advances in scientific and technical knowledge can be used to strengthen the present methods of defence against hostile aircraft'. It became known as the Committee for the Scientific Survey of Air Defence (C.S.S.A.D.) and had as its chairman Mr. Tizard and as members, Professors A. V. Hill, P. M. S. Blackett, Mr. Wimperis and Mr. A. P. Rowe. At the same time, but independently of the Air Ministry committee, air defence was being discussed by members of Parliament, and it was decided to set up an Air Defence Sub-Committee of the Committee of Imperial Defence under Sir Philip Cunliffe-Lister (later Lord Swinton), Secretary of State for Air, to co-ordinate all air defence development at an inter-Service and inter-departmental level. Mr. Tizard was a member of this committee, and his own committee (the C.S.S.A.D.) reported to the Committee of Imperial Defence (C.I.D.) through its Air Defence Sub-Committee, Early in 1935 Mr. Wimperis had talks with Mr. R. A. Watson-Watt, then Superintendent of the Radio Department of the National Physical Laboratory, who for some years had been engaged on investigating the properties of the ionosphere—a conducting region in the upper atmosphere which had great influence on the long-range propagation of radio waves. Mr. Watson-Watt believed that his researches might be of assistance in the problem of the detection and location of hostile aircraft by radio. In a short time the Air Ministry made provision for Mr. Watson-Watt and a small scientific staff from the National Physical Laboratory to begin work on experiments for the detection of aircraft by radio. Mr. Watson-Watt together with three scientific officers and six assistants were seconded to the Air Ministry, and in May 1935 began work on a disused airfield at Orfordness. Here were buildings in good condition that could be used as a radio laboratory and the site was within easy flying distance from the Aircraft and Armament Experimental Establishment on Martlesham Heath, thus facilitating opportunities for experimenting with aircraft. The only items needed were four 75-foot wooden masts, additional accommodation and adequate power supply. The Treasury gave permission for £12,300 to be spent on the scheme during its first year.

This is not the place to follow the development of radar. It is enough to state that on 13 May 1935 the following scientists arrived at Orfordness to install the technical apparatus and begin development of the technique of radar, Mr. L. H. Bainbridge Bell and Mr. A. F. Wilkins, Dr. E. G. Bowen (Scientific Officers), Mr. J. E. Airey (Assistant II) and Mr. G. A. Willis (Assistant III). Experimental work began at once, and in a remarkably short time satisfactory results were being obtained from the radar equipment. Demonstrations by the scientific team were given to members of the Committee for the Scientific Survey of Air Defence and of the Air Staff which by and large impressed their audiences. Such was the speed of development that by the end of July 1935 it was found possible to detect known aircraft up to a range of 39 miles while unknown aircraft had been located up to distances of 33 miles. Radar had been proved as a reliable method of longe-range detection for the guidance of interceptor fighter aircraft. It could also be used for short-range detection and location for the use of Army searchlights and anti-aircraft guns.

ACQUISITION OF BAWDSEY MANOR BY THE AIR MINISTRY

However, the performance of the existing equipment could not be improved until higher aerial towers of the order of 200 feet were available instead of the 75-foot masts employed. It was also necessary to establish a receiving station some 5 to 10 miles away to conduct experiments before planning a chain of radar stations around the coastline of Great Britain which would give warning of hostile air attack. The coast at Bawdsey about 10 miles south of Orfordness was known to be 50 feet above sea level.

Near this eminence at the mouth of the River Deben was a large Victorian mansion called Bawdsey Manor surrounded by an estate which ran for about half a mile along the cliffs. There was ample land and buildings for workshops, laboratories and living and messing facilities for the research staff.

The Air Defence Research Sub-Committee of the Committee of Imperial Defence recommended that Bawdsey Manor should be acquired as a centre for research work and headquarters for the organisation of a chain of radar stations. This was approved by the Treasury, and when the site was acquired additional accommodation and masts were constructed and Bawdsey was established as one of a chain of radar stations. Provision was made in the 1936 Air Estimates for the establishment of a scientific staff at Bawdsey comprising 10 scientific officers and some 26 assistants, and arrangements were made between the Air Ministry and the Department of Scientific and Industrial Research for certain members of the staff of the National Physical Laboratory to be transferred to Bawdsey. Among the scientific officers were Mr. A. F. Wilkins and Mr. E. G. Bowen. The establishment became known as Bawdsey Research Station. Bawdsey may also be called the birthplace of operational research.

In a short time both the Admiralty and the War Office displayed interest in the work proceeding at Bawdsey. The former decided that the staff at Bawdsey should act in an advisory capacity to H.M. Signals School at Portsmouth. Early in 1936 the Army Council agreed that a small staff of scientific officers and Dr. E. T. Paris from the Air Defence Experimental Establishment at Biggin Hill (concerned with A.A. gunnery and the interception of enemy aircraft) should be attached to Bawdsey to investigate development in the short-range location of aircraft suitable for use with aircraft and guns.

FIRST EXAMPLES OF OPERATIONAL RESEARCH

At Sir Henry Tizard's instigation a small team of R.A.F. officers with Dr. B. G. Dickins as scientific officer was set up at Biggin Hill in 1936 to study how the radar chain might be used for the interception of aircraft. A successful series of experiments took place over a period of eighteen months to two years which led to the development of an interception technique which was ultimately adopted throughout Fighter Command. The work showed the need to develop operations room equipment such as plotting tables and plaques and the techniques for using them. This work was continued by the Bawdsey Research team. The Biggin Hill experiments are important historically for two reasons. Firstly, they developed the technique that won the Battle of Britain and, secondly, they marked the beginning of an era of close collaboration between the serving officer and the scientist in the study of operational problems which achieved such great success during the war and has remained with us to this day.

Shortly before this the Air Staff came to the opinion that Mr. Watson-Watt should be transferred from the Department of Scientific and Industrial Research and be employed as the Superintendent of Bawdsey as a whole time Air Ministry official. His task would be to advise the Air Staff on radio detection and location, and in the Air Ministry hierarchy he would be placed under the Directorate of Scientific Research and Technical Development.

From 1936 to the outbreak of war Bawdsey Research Station took part in the annual air exercise held by Headquarters Air Defence of Great Britain, re-formed as Headquarters Fighter Command, Bentley Priory, Stanmore, on 14 July 1936 under Air Chief Marshal Sir Hugh Dowding. By 1938 a chain of five radar stations existed in south-east England ready to give warning of incoming hostile raids. They were used in the air exercises held that August and at the beginning of September were brought into continuous operation during the 'Munich crisis'.

Radar developed so rapidly during 1937 and early 1938 that it soon became necessary for a separate authority at a high level to deal with the growing research and expansion. Much of this work was done away from Bawdsey and Mr. Watson-Watt was absent from the station for long periods, responsibility of supervision devolving upon Dr. Paris who was himself under pressure from the War Office. Mr. A. P. Rowe, previously Co-ordinator of Air Defence at the Air Ministry, was appointed as Deputy Superintendent with the additional duty of supervising the Air Ministry radar programme. In order to solve the problem at a higher level, the Directorate of Communications Development (D.C.D.), earlier advocated by Mr. Watson-Watt, was formed in June 1938 to deal with the development of all radio equipment. Mr. Watson-Watt was appointed Director. The new directorate was also to control Bawdsey Research Station with Mr. A. P. Rowe taking the place of Mr. Watson-Watt as Superintendent. In the meantime steps had been taken to acquaint personnel of the R.A.F. in the new technique and this was done at Bawdsey, Squadron Leader R. G. Hart being responsible for the administration and operation of all radar stations.

It was at the time of the 1938 air exercises that the term 'Operational Research', which it would appear originated with Mr. Rowe, was first used in connection with the work being done at Bawdsey by a small team under Mr. E. C. Williams. They were concerned with the problem of assessing and passing on rapidly the information which came through the Chain Home (C.H.) Stations; in other words, the process of plotting, filtering and telling. They ascertained, for instance, that range-cutting[1] was the best basic method in plan position filtering on account of the erratic bearings from the C.H. plots; numerous test flights were held for them to filter, the tracks afterwards being reproduced on paper so that the direction-finding

[1] The discovery of an aircraft's position by the intersection of two accurate range measurements.

errors of the radar stations could be worked out; finally, a system of telling from the Bawdsey filter room was evolved. In the course of these analyses Mr. Williams and his team had to judge the skill of the observers operating the radar equipment and, to take one example, they discovered that the R.A.F. personnel who had been observing for some two or three hours daily for a period of six months were more competent operators than the scientists who, by comparison, lacked experience on the observer side of radar operations. All these investigations, which were in essence the development of the Filter Room system under operational conditions, must therefore rank, together with the experiments at Biggin Hill, as being the earliest applications of the science of operational research.

A second group of scientists, consisting of Mr. G. A. Roberts, Mr. I. H. Cole and Mr. J. Woodforde, went, under the instructions of Mr. Rowe, to the operations rooms of fighter groups where they observed the controllers dealing with the information provided by the radar chain. During the summer air exercises the team made a number of recommendations, most of which were at once adopted, and initiated further study. By the outbreak of war each member had begun to concentrate on a special aspect of the control of fighter aircraft. Mr. Roberts studied the procedures, relationships and working of the various stages of the reporting and aircraft control system of Fighter Command as carried out in the chain of operations rooms, in the course of which he moved away from 'the boundaries of communications engineering, equipment, electrical circuits, and all the physical paraphernalia, and . . . entered into the wider field of the executive officer responsible for the control systems as a whole'.[1] Mr. Woodforde suggested improvements to the equipment of the operations rooms so as to make them function more efficiently while Mr. Cole became involved with the extensive work on the development of new techniques for the control of aircraft during an actual interception.

FORMATION OF THE STANMORE RESEARCH SECTION, AUGUST TO SEPTEMBER 1939

In the event of war plans were made for Bawdsey Research Station to be evacuated to Dundee, but an informal arrangement was made between Mr. Rowe and Squadron Leader Hart for a small group of scientists to remain in the south and form a research section at Headquarters Fighter Command. Meanwhile the team under Mr. Williams, mentioned above, moved to Stanmore for the summer air exercises of 1939 to observe the operation of the Filter Room in its first major test in the hands of the R.A.F. This team performed such useful services to the Filter Room and Operations Staff that the Air Officer Commanding-in-Chief (Air Chief Marshal Sir Hugh Dowding) asked for a section to be permanently stationed at Stanmore. At about the same time Mr. Roberts' team was

[1] *Science at War op. cit.*, p. 92.

released from Bawdsey under pressure from Air Commodore K. R. (later Sir Keith) Park, Senior Air Staff Officer at Headquarters Fighter Command, and became the Operational System Research Section. By the outbreak of war the two sections were established at Stanmore, and Mr. H. Larnder of Bawdsey was appointed to lead the combined team. He was known as the Liaison Officer to the Directorate of Communications Development (D.C.D.L.O.). The whole section was given the name of the Radar Research Section until 6 February 1940 when it was redesignated the Stanmore Research Section. It continued to be administered by Bawdsey Research Station (later known as the Air Ministry Research Establishment).[1]

There were three good reasons why the unusual step of appointing civilians to an operational headquarters was taken. In the first place radar was not merely a new device, but a new conception of warfare, and knowledge about it was confined, with the exception of two or three R.A.F. officers, to the civilian staff at Bawdsey. Secondly, it was appreciated that the scientific analysis of operational results and evaluation of the trends of this novel type of warfare was best conducted by civilians with a scientific training, if only for the reason that technical officers of the Service were more interested in the equipment *per se* than in the wider implications of its employment. Finally, the members from Bawdsey attached to Fighter Command would provide their 'parent' establishment with information that would contribute towards the development of further radar devices. The whole operational research organisation which developed as a result of this attachment of scientific staff to Headquarters Fighter Command was based on these premises.

WORK OF THE COMMITTEE FOR THE SCIENTIFIC SURVEY OF AIR OFFENCE AND OF AIR WARFARE

In January 1937, two years after the setting up of the Committee for the Scientific Survey of Air Defence, the Secretary of State for Air convened a similar committee to deal with air operations of an offensive nature. It was composed of the members of the first committee and was also presided over by Sir Henry Tizard. Besides the civilian scientists, R.A.F. technical officers from the Air Staff and from the experimental establishments, such as the Aeroplane and Armament Experimental Establishment at Martlesham Heath, attended. The line of demarcation between defensive and offensive weapons was decided by Sir Henry Tizard, and characteristic topics discussed at these meetings were 'the scatter bombing of aircraft from above', bombs, aircraft armament and aerial gunnery.

A month after the outbreak of war the two committees were merged into one called the Committee for the Scientific Survey of Air Warfare. The subjects which came up for discussion now covered all aspects of air war-

[1] See p. 38.

fare including counter-measures against U-boats, aerial photography, camouflage, aerial mines, searchlights, the effectiveness of bombing and, of course, radio and radar. Sir Henry Tizard continued to preside over the meetings and was empowered to use his discretion to call upon other scientists to enter the discussions. The meetings which, to begin with, were held at Balliol College, Oxford, and afterwards at the Air Ministry in London, took place normally once a month until June 1940.

SUMMARY OF THE SCIENTIFIC STUDY OF AIR WARFARE PRIOR TO THE SECOND WORLD WAR

Thus, by the outbreak of war, there had been very active co-operation between the R.A.F. and scientists and experimental establishments in choosing and perfecting scientific aids. Apart from the experiments in radio-location of aircraft described above, two other scientific investigations are noteworthy. The first was the special bombing trials held in 1937–38 in which an attempt was made to discover the accuracy of bomber attacks on land and sea targets and the effect of anti-aircraft fire on low-level and dive-bombing attacks. Secondly, as already mentioned, experiments took place at Biggin Hill in 1936 in which the methods of intercepting enemy bombers in the Battle of Britain were first developed. The degree of success achieved in these experiments is evident from the superiority of the equipment of the R.A.F. at the outbreak of hostilities in spite of the belated start of active preparations for war.

Equally significant was the formation of the first operational research section in the Services. 'Operational Research', wrote Sir Robert Watson-Watt after the war, 'was, in fact, born of radar', and already there were signs that scientists were extending their activities from the examination of natural phenomena to the quantitative analysis of tactical problems. 'There was no previous work, known to me,' continued Sir Robert, 'that fits the simple criteria for classification as Operational Research, to wit that it was 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.' The attachment of Mr. Larnder and his team to Headquarters Fighter Command 'was the first of a series of such attachments and formations of civilian scientists; every command of the R.A.F. in the end had one'.[1]

[1] Sir Robert Watson-Watt, *Three Steps to Victory*, Chap. 33, p. 203, Odhams 1958.

CHAPTER II

Operational Research in Fighter Command, 1939 to 1943

COMPOSITION OF THE FIRST OPERATIONAL RESEARCH SECTION

By the end of 1940 Bawdsey Research Station had evolved into the Telecommunications Research Establishment[1] which was under the newly created Ministry of Aircraft Production (M.A.P.). The Stanmore Research Section became responsible to Mr. Watson-Watt, now Scientific Adviser (Telecommunications) at the Air Ministry.[2] The section had, in the meantime, become indispensable to the Air Staff of Headquarters Fighter Command, for in addition to working on problems relating to telecommunications it was responsible for making numerous analyses and investigations on technical and scientific problems exclusive to Fighter Command. While under nominal control of the Air Ministry, therefore, the section henceforward became responsible for the work it performed to the Air Officer Commanding-in-Chief, Air Marshal Sir Sholto Douglas, on the latter's insistence, thus setting a precedent for the sections formed later in Coastal and Bomber Command. About June 1941 the section was re-designated Operational Research Section[3] Fighter Command, and Mr. Larnder, in addition to leading the section, became Scientific Adviser to the Air Officer Commanding-in-Chief.

Besides being the first, O.R.S. Fighter Command was to become the largest of the research sections attached to R.A.F. Commands in Great Britain. By 1943 its nominal roll consisted of one principal scientific officer, four senior scientific officers and 58 scientific and junior officers, although after the creation of research sections in the Allied Expeditionary Air Force and the 2nd Tactical Air Force, it was reduced to 34 scientific officers and 25 assistants. It was also distinguished for the fact that it provided the officers-in-charge of all the O.R.S.s subsequently formed at home and overseas, with the exception of that at Headquarters Bomber Command to which, however, Mr. G. A. Roberts was attached as second-in-command.

In passing, something should be said of the varied professions of the

[1] See p. 38.

[2] In addition Mr. (later Sir Robert) Watson-Watt became Vice-Controller of Communications at the M.A.P. in 1942.

[3] Henceforward to be abbreviated to the initials O.R.S.

early members of the O.R.S. These were, on the whole, typical of the staffs of the other research sections formed later in the war. The first officer-in-charge, Mr. Larnder, had served as an engineer with the International Standard Electric Corporation and had the benefit of wide technical experience in communications work all over the world before joining the Bawdsey staff.[1] On becoming head of O.R.S. Coastal Command in 1943 he was succeeded by Mr. A. F. Wilkins, an original member of Bawdsey. Of the other permanent civil servants who formed the nucleus of the O.R.S., only one, Mr. E. C. Williams, had been engaged in academic research, the other senior officers also being technical engineers. The remainder of the staff were of varying scientific disciplines and ability. Many of them had been engaged on research work and had published scientific papers while others had only freshly graduated. Apart from engineers, there were physicists, a biologist, a mineralogist who became an expert on gun harmonisation, graduates in English and geography, a statistician and several botanists. Men with experience of the business world were rare, but there was one senior executive from an insurance company who became a useful member of a team engaged on radar work. A number of these men moved on to senior posts in newly created sections and were replaced by schoolmasters with degrees in physics or mathematics. In sections in other commands there were mathematicians, astronomers, archaeologists and economists. A small number of women graduates were also employed.

All aspects of Fighter Command's activities were covered by the O.R.S. For this purpose it was subdivided into a number of small sections, each under the leadership of an experienced scientist. One party studied operational systems (the original assignment of the O.R.S.) which, in addition to the coastal radar reporting system, included directional plotting, inland reporting of hostile aircraft and mobile operations rooms. Further, it examined automatic methods of transmitting information which would not only increase efficiency but would also economise in manpower. The members of the section dealing with night operations investigated the co-ordination of searchlights with night fighters and the use of air interception equipment. Those engaged on the study of day operations were occupied with counter-measures to the high and low level air attacks against this country and also with the Command's fighter offensive beyond the Channel. A fourth party dealt with procedures involved in operating ground radar equipment and were present at the operational trials of new equipment. Another subsection collected and examined records of enemy aircraft movement from the Royal Observer Corps, filter rooms and radar stations. A subsection was attached to No. 60 (Signals) Group not only to check the performance of equipment but the

[1] His memorandum on the compilation of O.R.S. reports is reproduced as Appendix No. 2.

capabilities of personnel operating it. The scientific appreciation of armament problems and the analysis of combat films occupied another subsection and, finally, the Statistical and Intelligence Section analysed defensive and offensive air operations by day and night, two of its tasks being the calculation of losses in future offensive operations and the distribution of manpower. The staff engaged on all this work were employed at or near Headquarters Fighter Command, but the principal operational groups also had individual scientists attached to them.

A number of the problems which confronted the O.R.S. must now be examined in detail.

THE AIRCRAFT REPORTING SYSTEM

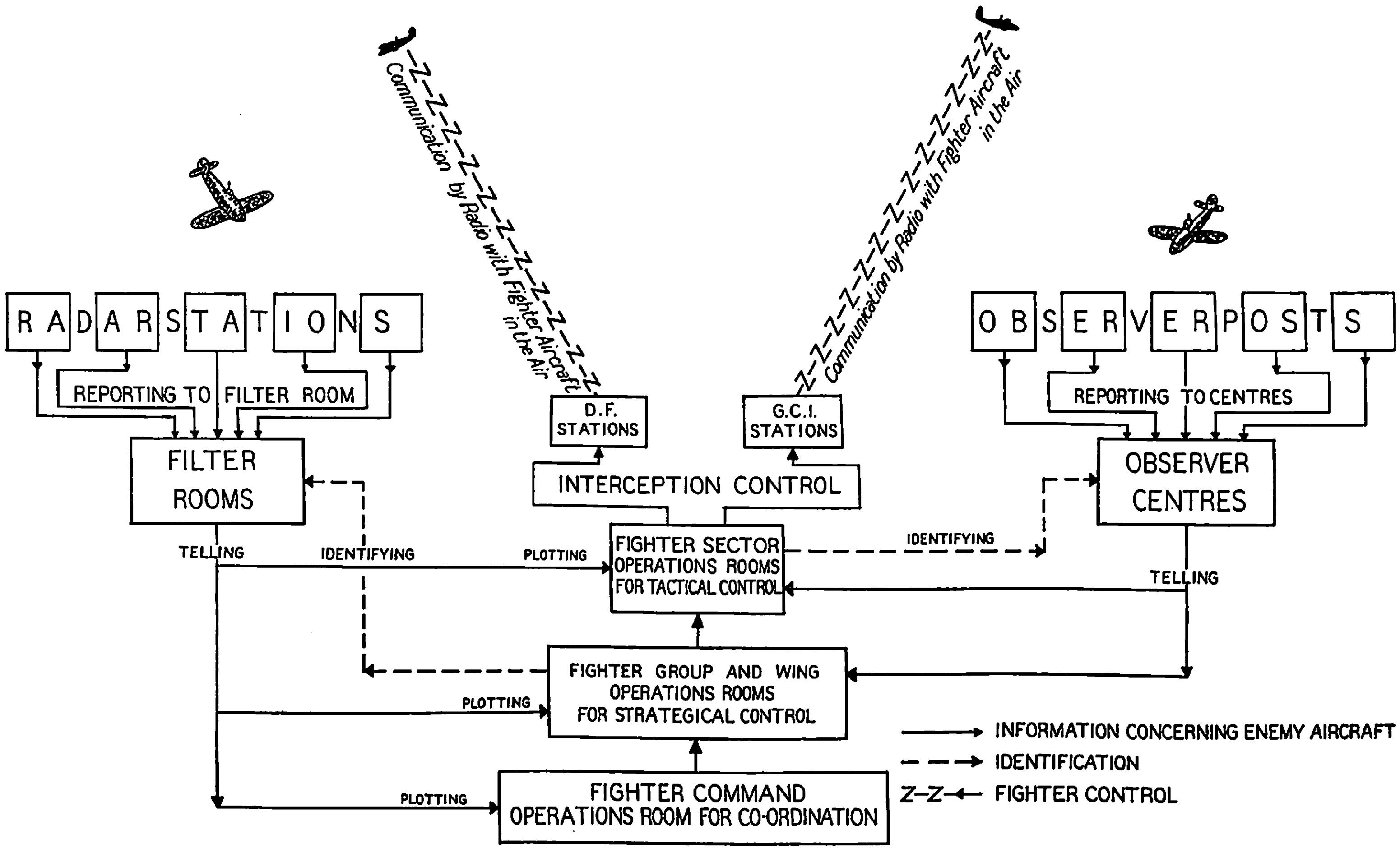
(a) *Supervision of the Filter Room*

Enemy air activity against this country during the autumn and winter of 1939 and the spring of 1940 consisted of brief penetrations over the coast by small formations, attacks on trawlers and lightships and aerial minelaying off the East Coast, principally in the Thames estuary. The high state of efficiency reached by the radar stations by the time of the Battle of Britain was to a large extent due to the fact that, from the time of the Firth of Forth raid in October 1939 onwards, the O.R.S. analysed almost every failure to intercept daylight raids. The part which the section played even at that time was instanced by appreciative notes sent to the officer-in-charge by the Senior Air Staff Officer on the occasion of any successful interception, as if the O.R.S. represented the radar chain and the research organisation behind it. Lessons were learned from most of these early investigations as, for example, attacks on lightships off the Wash and elsewhere emphasised not only that low cover was lacking, but that radar search procedure needed to be made regular.

It was on such isolated raids, again, that the scientific observers built up their experience of height filtering, and though time and again the early morning meteorological flights took enemy aircraft quite close to the English coast in the Straits of Dover without interception, others were shot down on attempting to cross the coast. Some of these successful interceptions followed team work by filterer and scientific observer, such as that of one *Dornier* 17 found at 18,000 feet by fighters as it approached the Lincolnshire coast. Evidence of its height had been peculiarly contradictory and at least one direct reading of 5,000 feet had been given, but the figure of 18,000 had eventually been allotted by the scientific observer.

In the early days of the war members of the O.R.S. were required to keep a continuous watch on the operations in the Filter Room at Stanmore, and as the orginal team from Bawdsey was too small to fulfil this commitment,

RAID REPORTING AND FIGHTER CONTROL SYSTEMS



civilians were recruited for the purpose.[1] They maintained watch at Stanmore until filter rooms were established at group headquarters, and Stanmore was responsible for tracking aircraft in the No. 11 Group area alone. Later their duties were taken over by W.A.A.F. officers.

The principal duty of these scientific observers, besides coping with the technical difficulties arising in the use of the stations, organising test flights, etc., was that of assisting in the education of the filter officers themselves, whose duty it was to supervise the entire operation of the room, but who had had comparatively little training either in the art of filtering or in understanding the process of radar itself. The section also compiled informal intelligence reports covering the main features of a day's activities round the British coast, commenting on the performance of individual radar stations, making criticisms when necessary, and in the case of enemy raids giving the results of fighter action.The reports were dictated to groups of stations at a time by the filter officer during the night watch. A copy was also sent to the Director of Communications Development at Air Ministry.

Minelaying off the Thames estuary has been noted as one of the few regular forms of air activity during the early months of the war. These aircraft invariably flew at heights under 2,000 feet and their tracks were generally fragmentary. On one of the earliest occasions the scientific observer pointed out to the Naval Liaison Officer in the adjacent operations room that the tracks gave indication, by the position at which they faded, of possible points of minelaying, and prompt action by the Admiralty produced immediate results. Although the tracks proved a far from infallible guide to the location of the mines, this assistance became a regular demand and was the first of a number of routine duties undertaken by the section, which were carried out by junior civilian staff before being handed back to the R.A.F.

(b) *Development of Filter Room Methods*

At the outbreak of war the radar chain consisted solely of Chain Home (C.H.) stations, using wave-lengths of 11 to 13 metres, the transmitting aerials floodlighting a wide area, the receiving aerials consisting of crossed dipoles which enabled elementary direction finding to be carried out. The range measurements of these stations were accurate to within one or two miles but the uncertainty in direction might easily cause an error of 10 or 20 miles in the position of an aircraft tracked by one station alone. Filtering, which was merely a process of range-cutting, was comparatively simple as long as the number of formations of aircraft present was low; errors in direction finding were then not of great consequence, but became more serious as activity increased. The observers were constantly on the

[1] The Filter Room at Stanmore at this time was responsible for the tracking of aircraft round the British coast as far as the radar chain extended.

watch for any deterioration, trying to differentiate bad operating from permanent defects of the stations. At the end of 1939 a new type of station was added to the chain, namely the Chain Home Low (C.H.L.) Station, designed to augment the low cover, and operating on a wave-length of 1½ metres. These were the first stations with rotating aerials, and though for many months they were erratic in range measurement, they were a great improvement in respect to direction finding. The technique of combining their information with that of the C.H. stations had to be developed and the filterers accordingly instructed, and it was not uncommon for members of the O.R.S. to take a part in the filtering themselves.

The determination of the heights of aircraft was for long the most serious problem confronting the filter room staff. Some attention had been given to this at Bawdsey before the war but little progress had been made in developing a systematic method of handling the information. Only the C.H. stations were fitted with facilities for height reading, and initially only aircraft at angles of elevation between about 1½° and 6° could be observed without ambiguity. The system depended on the comparison of the signals received in a pair of aerials at different heights, and it was not until later, when added facilities included the choice of a second pair of aerials lower than the first, that it became possible to resolve the ambiguities. Height calibration of the stations was very inadequate, and even when an aircraft was flying high enough for more than one radar station to make an observation of its height, there was often disagreement. Furthermore, it was quite common for a station to give a positive height reading on an aircraft which was really at an angle of elevation below the lower limit of the station, and the indication should have been, say, less than 8,000 feet; this was not entirely a matter of bad calibration, as even when this was carried out properly there would be always some finite probability of a positive reading instead of an indication of an upper limit. The O.R.S. had therefore to import elementary ideas of probability to the filterers and devise methods to assist them in rejecting obviously bad information. Members spent much time either standing by the filterers and giving them heights, or even acting systematically as height filterers.

Estimation of the numbers of aircraft in any formation presented a problem to radar operators which was never satisfactorily solved. Only long experience with every possible help in confirming their observations could do anything to improve this. Whenever opportunity arose observers and filter officers would endeavour to find out from the Observer Corps, or, in the case of formations of friendly aircraft, from the stations at which they were based, what the number and disposition really had been. Only a few simple rules could be given to the filter officers themselves for dealing with discrepancies between the estimates by different stations; for example, if one station read one aircraft and another read three, the higher number ought to be taken.

(c) *Report on the Capacity and Limitations of the Radar System*

During the late summer of 1940 the O.R.S. was asked to examine and report on the operation of the radar chain which on certain occasions reached saturation point during mass raids by enemy aircraft. A good deal of information was collected from tests of the capacity of radar operators, tellers, plotters and others playing a vital part in the transmission of radar information, in order to find out which were the weakest links in the chain. These were supplemented by observations made simultaneously in the filter room by the duty observers. A report arising from this work prepared by Mr. F. L. Sawyer, Mr. L. G. H. Huxley and Mr. E. C. Williams was a landmark in the history of operational research. It summarised past and future trends of air activity, drew attention to all deficiencies of the system as it was at that time and outlined the steps which ought to be taken to effect an improvement. For a number of years after the war there was little change in the system of reading radar displays and transmitting information by telling and plotting. This report was, therefore, circulated in Great Britain and other N.A.T.O. countries as a guide to the standards to be expected from a reporting system when fully manned and trained.

Among the most important suggestions for improvement were the decentralisation of filtering, the introduction of 'mass raid' methods of reporting heavy traffic, and the use of an 'operations console' at C.H. stations with control exercised on the out-going information by a specially trained commissioned supervisor. The idea of this console was not fully developed at the time, but it was planned that it should afford facilities for the most convenient display of all the auxiliary diagrams and graphic aids such as polar diagrams,[1] height calibration charts and coverage maps; at its focus there was to be a duplicate tube displaying the same radar picture as that in front of the radar operator but with the addition of a sheet of steadily moving paper on which the change of range of any aircraft could be recorded. Not only did the shape of the line representing the range-time graph of an aircraft indicate whether it was approaching the station radially or crossing it, and also show changes of direction, but it also made it very much easier to track each aircraft or formation continuously even after two or more tracks had to all appearances merged one into the other. In addition to this major suggestion the report also proposed that more attention should be paid by the designers of the equipment to the comfort and convenience of the user. It was, of course, familiar from industrial experience that the efficiency of an operator concentrating continuously was considerably affected by the care taken in the design of quite small details and, although the efficiency of radar operators was not studied in greater detail until some years later, it was obvious that the same considerations must apply.

[1] These were aids to height filtering used by members of radar stations based on a combination of theoretical, experimental and operational knowledge.

Action was taken on many of the proposals in the report and the first operations console with tracker was ready for trial at Dunkirk Radar Station, Kent, later in the year. In collaboration with No. 60 Group, complete operational instructions were drawn up covering the duties of each member of the crew in the operations room of the C.H. station. In addition to organising a drive to ensure that all the recommendations were implemented, bringing users and designers together in conferences, the O.R.S. planned an extensive educational programme not only for the operations officers who were to supervise the efficiency drive throughout the stations, but also for all the junior staff, and a corresponding effort was made in the filter room. Talks and lectures were arranged, together with short trips by plotters to the radar stations and later exchange tours of duty by plotters and radar operators.

Direct results followed from other recommendations in the report. Decentralisation of filtering from Fighter Command had begun before it was issued; the north of Scotland, the Orkney and Shetland Isles were equipped with radar to supplement the sole pre-war station of Nether Button, and it was logical to allow this distant growth to find its own centre of gravity under No. 14 Group, Fighter Command. The rapid extension of radar cover to the west of England after the fall of France produced a second group of stations with their own filter room, first at Plymouth in June 1940, and then after its formation at Headquarters No. 10 Group, Colerne. But without the persuasion of the O.R.S. the remainder of the chain, from Aberdeen to the Isle of Wight, might have continued to be regarded as a unit for radar information; the imposition of boundaries and the organisation of liaison between radar areas with the accompanying redistribution of telephone lines was no easy problem, as half a dozen stations might be able to plot across the frontier, but as well as convincing that this ought to be done, the O.R.S. also took their part in showing that it was practicable. Without the consequent division of Nos. 11, 12 and 13 Group areas the filter room at Fighter Command would have become congested to a degree that would undoubtedly have lowered its efficiency.

(d) *Selection and Training of Radar Personnel*

The earliest occasion of intervention by the O.R.S. in R.A.F. personnel policy arose from growing dissatisfaction with the quality of filtering. The first filterers were N.C.O. wireless operators. In many cases they were not too successful, and as N.C.O.s did not have the necessary prestige and authority when dealing with station personnel and plotters. Accordingly early in 1940 the O.R.S. recommended to the Chief Signals Officer at Fighter Command that filterers should be commissioned and after some discussion this proposal was adopted.

The O.R.S. also played a part in selecting personnel for the filter school which had been established at Bawdsey. The recruits sent to Bawdsey were picked by the Personnel Selection Centre at Uxbridge, which had only the vaguest ideas of the quality required in a filterer and believed that these could most easily be found in stockbrokers. These gave officers of high, but not the right calibre. In collaboration with the Cambridge Psychological Laboratory the O.R.S. devised suitable tests of intelligence, character and attainment which could be given to recruits as a selection test at the Selection Centre.

The Bawdsey Filter Course was itself scrutinised and overhauled in mid-1941 as it was considered that insufficient attention was being paid to theoretical radar training which had shown itself to be necessary with the increase in volume of aircraft traffic and numbers and types of stations. Fighter Command was persuaded to establish an officer who was responsible for this aspect of training. A suitable officer was supplied by No. 60 Group. For the first course, however, all of this training was given by members of the O.R.S.

The O.R.S. evolved suitable methods of training W.A.A.F. plotters who were entirely new to this sort of work. A school was set up at Leighton Buzzard and a member of the O.R.S. was entrusted with the responsibility of carrying out the training until the organisation was handed over to the Service in February 1940.

In 1941 at a time when a great increase was taking place in the number of plotters being trained, the O.R.S. re-examined the training programme at Leighton Buzzard. It was considered that the plotters should be given more information on the general working of the Fighter Command system, the part played by the Sectors, Groups and Observer Corps, and technical training on radar so that they could play a more intelligent part in the link between the radar station and the filterer. The course at Leighton Buzzard was completely overhauled and reconstructed. Intelligence tests were devised for the initial selection of entrants to the filter course and passing-out tests were also initiated.

(e) *Group Scientific Observers*

By the time the filter rooms were operating at group headquarters level instead of being centralised at Stanmore, the need for a continuous watch to be kept by the O.R.S. had largely disappeared. The filter officers knew their jobs, and the major exploratory research had been done, the main shortcomings of the radar system as a whole being already known. Much detailed work remained to be done, as new stations and new types of radar had to be incorporated into the chain, and modifications made to the old. For such purposes it was enough for the O.R.S. to maintain one observer at each group headquarters, though for training purposes a new recruit might be attached to a more experienced observer. If much of the work carried out was of an unobtrusive nature, its importance to the whole advancement of operational research can hardly be overestimated. Its value greatly exceeded even its undoubted intrinsic worth, since on it depended still much of the goodwill which enabled the O.R.S. to penetrate into new fields. Not only were many more R.A.F. officers of all ranks accustomed to the presence of scientists in their councils, but the observers themselves learnt much; most of them were marked individualists, and the experience of breaking new ground in this way stood them in good stead for later pioneering, particularly overseas.

(f) *Improvement of the Aircraft Reporting System and Operations Rooms*

Note has been taken of the work of the small team of observers led by Mr. Roberts which did such valuable work during the summer air exercises of 1939. His analysis revealed the great importance of maintaining the continuity of a hostile aircraft's track under a permanent reference designation and pointed out that continuity was likely to be broken when a raid passed from one division of a reporting system to another. He was also responsible for instituting the post of Raid Intelligence Officer (later termed Raid Recognition Officer) whose duty it was to relieve the Observer Corps Liaison Officer of the duties of aircraft track identification and recognition.

Mr. Roberts continued to work on the aircraft reporting system after the outbreak of war, and when, in 1940, the Fighter Command Battle orders were being revised, the portions relating to the duties of personnel in operations rooms were written almost entirely by him. Before the Battle of Britain, careful analyses were made of a number of enemy air incursions over this country with the object of discovering weak links in the aircraft reporting system.

The basic process of telling and plotting aircraft was constantly checked by the O.R.S. since, in the early days of the war, much of the information about enemy aircraft reached operations rooms in a largely unintelligible form. The O.R.S. evolved a simplified method of telling raids in which it was possible to avoid making mistakes, and which also did not waste time.

The O.R.S. also advised on the layout and display equipment of operations rooms in collaboration with the Psychological Laboratory at Cambridge which carried out experiments on the rapid reading of map grids and designed new plotting arrows, letters and numbers. It was found that a large number of operations room staff were reading display symbols under difficult conditions. A set of letters and numbers for general display use was therefore designed to give the maximum distance of safe legibility. Changes in the colour and design of plotting counters were recommended and were accepted in principle by Fighter Command but as those of the prevailing pattern existed in such quantities the change was never made.

(g) *Checking of the Early Warning System*

The O.R.S. also took a close interest in the equipment and operation of radar stations until eventually the installation, manning and maintenance of these stations became the responsibility of No. 60 Group. This was especially important in the early days of the war when the lack of experience in handling the new equipments was widespread and when little was known about their limitations and capabilities. The O.R.S. also had to impress upon Headquarters Fighter Command that a daily period of one hour's maintenance of equipment at each station was essential. This was one of the earliest interventions of the O.R.S. in staff policy. The O.R.S. argued that a controlled break in radar cover would reduce the incidence of random failures to a degree which more than compensated for the deliberate weakening of coverage.

Probably the most important contribution of the O.R.S. to the efficient performance of the early warning chain was to introduce a uniform system of calibration. The need for this became evident at the end of 1940, by which time the final C.H. stations had replaced the intermediate apparatus which had sufficed until then. The O.R.S. insisted that before any station was calibrated it must be thoroughly checked for general efficiency, for it would be a waste of time to calibrate a station which would shortly afterwards require attention to, for example, the aerial feeder lines or the phasing devices. The performance of the Chain Home Low (C.H.L.) stations was also noted by the O.R.S. and a number of modifications were suggested. The areas of responsibility of the stations were worked out by the Group Scientific Observers who recommended where additional stations were needed to strengthen the defences against low-flying aircraft.

I.F.F. (IDENTIFICATION FRIEND OR FOE)

This radar aid to the identification of ships and aircraft is generally recognised to have been the weakest link in the whole development of the reporting and interception systems. Initially there were but two radar wave-length bands covering the C.H. stations and the Army's Gunlaying (G.L.) sets, and it then appeared to be practicable to provide a small equipment in an aircraft which would receive the main pulse radiated from any station on either of these bands and retransmit a signal which augmented the ordinary response produced; this augmented signal was then observed directly on the main receiver. Even so this was only achieved by making the I.F.F. set to sweep through each band in a period of six or twelve seconds in order to respond to all stations in turn on these bands. On the introduction of the 1½-metre band for C.H.L. and Ground Controlled Interception (G.C.I.), special sets had to be developed to cover that range, and this was done at the expense of one of the two former facilities. Even then it was obvious that such an expedient was highly unsatisfactory, and as the number of types of radar equipment increased, it became more and more essential that the problem be tackled in a radically different way. With the development of electronic techniques it was possible to choose between various methods of achieving the desired aim of a universal interrogation device, so that even on purely scientific grounds the decision on a programme would have been difficult enough.

Various investigations into the I.F.F. system were made by O.R.S. Fighter Command, as, for example, in July 1941 when an attempt was made to examine the overall efficiency of the Mark II type. This was only a crude check and measured the total number of aircraft visible to each C.H. station and the number of I.F.F. responses visible. Seventy-three per cent of the aircraft gave I.F.F. responses, an answer which was almost certainly flattering. These checks were of course only taken when it was known that all the aircraft in the areas were friendly and fitted with I.F.F. which was supposedly working.

The first attempt at a universal I.F.F. system using separate interrogators as ancillary to the main radar installations was the Mark III. O.R.S. Fighter Command took a considerable part in the field trials held in South Wales in December 1941 which involved C.H., C.H.L., G.C.I., G.L. and S.L.C.[1] equipment. Although it subsequently did all it could to ensure the maximum usefulness of the system the O.R.S. was always critical of it; a number of predictions of its weaknesses were recorded in a minute to the Chief Signals Officer and proved only too true. Much preparatory work was done prior to the introduction of the Mark III system, the O.R.S. being exceptionally well-fitted to advise on the layout of the new equipment in relation to the old, and also on the operational procedure to be employed in the interrogation device.

DEVELOPMENTS IN NIGHT INTERCEPTION

The staff at Bawdsey had applied themselves to the problem of intercepting enemy bombing raids by night at an early stage in their researches, for it was certain that the enemy could not be expected for long to neglect the obvious potentialities of such attacks. An airborne interception (A.I.) radar set was evolved. Its maximum range was then only of the order of two or three miles, and although gradual improvement was expected, the production date for even the earliest patterns seemed at the time to be in the dangerously distant future. Every conceivable expedient had therefore to be seriously considered, and O.R.S. Fighter Command was deeply involved from the outbreak of war with theoretical and experimental tests of every scheme as well as helping the Command to formulate reasonable requirements and devising methods for the employment of radar facilities when the technical difficulties should be surmounted.

A number of experiments were carried out which did not involve the

[1] Searchlight Control.

participation of radar equipment, as for example, those in which balloons or aerial mines were loosed in an attempt to block the enemy raiders' approach. The difficulties of using existing radar stations for night interception were very pronounced as they were not designed for this purpose; the system of display was unsuitable and there were gaps in the vertical coverage. The stations were, in any case, in continual use for reporting the movements of aircraft to the filter rooms. In August 1940 Mr. Larnder pointed out the shortcomings of the C.H. and C.H.L. types of station for close interception and showed that if the interception of aircraft below 5,000 feet could be overcome, a C.H.L. station with a modified aerial, so that it had few gaps in the vertical coverage, could be used with advantage. The way was now open for the development of a ground-controlled interception (G.C.I.) station, and T.R.E. and the Royal Aircraft Establishment devised an equipment. Gap filling and height-finding were introduced and the newly invented plan position indicator (P.P.I.)[1] was also added to the equipment. The necessity of I.F.F. to recognise the fighter was also stressed by the O.R.S. at this time. By the end of 1940 six G.C.I. stations were operational.

The early G.C.I. stations had, however, a very limited capacity for dealing with concentrated raids. No single G.C.I. could direct more than one engagement at a time, and the maximum rate was only three or four engagements per hour. Even at the low entry rate of the early 'crocodile' night raids over Great Britain, fifteen per hour, it was only in the case of the deepest penetrations that an appreciable fraction of the enemy aircraft could be destroyed. It was essential, then, that the capacity of the G.C.I.—A.I. system should be multiplied several times.

Instead of a single controller attempting one interception at a time, it was planned that there should be two controllers each doing two interceptions at the same time. In order to do this, a third controller and assistants were brought in to do all extraneous duties including identification and allocation of targets, liaison with the sector and general co-ordination of activity within the G.C.I. In this manner the fixed G.C.I. station was introduced. The G.C.I. station took over the interception of enemy aircraft with A.I. fighters at night under the controlling authority of the sector operations room. It also took on an important function in the night interception of enemy aircraft with the aid of searchlights.

The early work on interception techniques was designed to take into account the advantages and limitations of the 1½-metre equipments. When 10-centimetre A.I. came into service with its different characteristics the G.C.I. controller had to modify his technique once again. A new technique was adopted for A.I. Marks VIII and X which was designed to give the fighter contact *before* it was turned on the target's course. In fact, when the enemy commenced using fast fighter bombers for night raiding, a 'head-

[1] Cathode ray tube with radial rotating time base, presenting an instantaneous picture of aircraft activity.

on' interception was necessary for the R.A.F. night-fighters as they had no excess speed over the enemy.

The contribution of O.R.S. Fighter Command to the successful use of A.I. in night fighting is one of the best known aspects of the section's work. It was largely the responsibility of one man, Mr. E. J. Smith, who became a properly qualified radar operator and took part not only in practice experimental flying but also in operations against the enemy. This proved an inestimable advantage. The best indication of the value of the effort put into this research was the series of instruction manuals issued by Fighter Command for the use of the successive marks of A.I., these being produced by the O.R.S.

From time to time, the enemy, by technical or tactical means, forced Fighter Command to change its methods of working. New tactics were devised to meet the changing conditions. Two examples will be given.

The A.I. Mark IV gave a maximum range not greater than the height of the fighter. This was suitable for the night raids of 1941 but involved serious difficulties when combating minelaying and other enemy aircraft which approached at low altitude. O.R.S. Fighter Command directed and took part in experiments to devise tactical means of solving the problem by increasing the effective maximum range by approaching the target from above. By this means the minimum height at which an enemy could be intercepted by A.I. Mark IV was reduced from about 5,000 feet to about 3,000 feet.

The system of A.I. fighters closely controlled by G.C.I. stations was liable to saturation by mass raids. As these were expected, a scheme was devised to use A.I. aircraft co-operating with searchlights which could not be so easily saturated. The section helped by devising tactics and working out the ideal deployment of searchlights and positioning of fighters with respect to them. It was by using this system that the record score of four aircraft destroyed in one sortie was achieved by one aircraft in 1943.

COLLECTION OF STATISTICAL INFORMATION

In addition to its radar commitments O.R.S. Fighter Command, when it had expanded sufficiently, began to collect statistical information. By degrees special statistical analyses and routine statistical investigations were performed for the Air Staff and outside establishments. Thus, for example, in late 1940, when the enemy night raids were becoming intensive a routine nightly analysis was begun of night defensive sorties, showing the number of sorties, attempts at interception, A.I. detections, visuals and combats with further divisions by type of enemy activity and moon conditions. These reports were used in the Secretary of State for Air's Scientific Committee and the Prime Minister's Night Air Defence Committee. Subsequently other O.R.S.s analysed current operations in a similar way.

Day operations were never analysed statistically for routine summaries as were the night operations, reports and figures being prepared when required for special purposes or at the request of the Command. The work of the O.R.S. in regard to fighter offensive operations in such matters as film assessments of air-to-air combats, dive-bombing and rocket projectiles will be discussed later and in Chapter 7. There was in this time, however, one hint of the wider scope of O.R.S. work on the lines of that which is now accepted as its proper function. Shortly before the final collapse of France Air Chief Marshal Sir Hugh Dowding was strongly pressed by the War Cabinet to give up squadrons for the reinforcement of the Air Force in France, and at his request the O.R.S. made a few rough calculations which he presumably used in support of his own good judgment in refusing to agree, showing how rapidly the Command would cease to be an effective fighting force if losses were sustained at the rate of the Battle of France; though the mathematics were of the simplest nature and the figures in loss and replacement very crude, this use of the O.R.S. by the Air Officer Commanding-in-Chief when considering a serious point of high-level staff policy forms a notable milestone in the progress of the idea of operational research.

THE DAY FIGHTER OFFENSIVE

By the summer of 1941 the German night raids against Great Britain had passed their peak and bombing operations in daylight were reduced to 'tip and run' raids across the Channel or the North Sea. The campaign on the Eastern Front made it necessary for Fighter Command to prevent the German Air Force from concentrating in that direction. The work of O.R.S. Fighter Command in relation to the fighter offensive over northern France was divided, firstly, into statistical work and, secondly, into planning of operations from the radar angle. The former involved mainly an analysis of effort in relation to the destruction of the German fighter force in combat and the resultant neutralisation of German fighter production; this led to the establishment of loss ratios which were utilised in planning for offensive operations and in providing basic material for planning landings on the Continent.

Early in 1942 two representatives from O.R.S. Fighter Command were attached to Headquarters No. 11 Group which was the nerve centre for cross-channel air operations. Fighter Command's offensive had only just got into its stride and at first fighter sweeps were flown and light bombers (Blenheims and Bostons) were escorted to particular targets. During the summer of 1942 American heavy bomber formations were beginning to take part and the enemy could not neglect these high-flying powerfully armed raiders. Frequently the bombers were employed more as decoys to attract fighters than to destroy important targets, the range of the current Spitfire fighter then being too small to escort bombers to the vital targets later attacked by day.

The fighter sweeps were analysed in order to assess their success as well as to determine how they might be improved. As a start modifications were recommended in No. 11 Group's raid analysis procedure to adapt it to assist offensive operations. These methods were accepted and continued to be used long after direct O.R.S. help was withdrawn.

At this time the fighters of the German Air Force in the west were more than a match for those of Fighter Command. It was of the utmost importance that all possible measures should be taken to give R.A.F. fighters tactical superiority whenever possible. Part of the solution lay in the need for Fighter Command to use superior fighters, but even markedly better aircraft would be outfought if the enemy continued to have the considerable advantage that the early warning of the approach of a fighter force brought to him by his radar system.

A study was therefore undertaken of the suitability, for offensive operations, of the type of information derived from the filter room which was found on the whole to be rather deficient. Though some recommendations for improvement were made, such as separate lines, directional plotting and better quality filterers in the No. 11 Group area, it was soon apparent that filter room information, with all its delays and inaccuracies, would never fulfil the requirements.

O.R.S. Fighter Command evolved the idea of the Fighter Direction Station which in due course No. 11 Group adopted. This was to be at first a radar set—a modified C.H.L. or G.C.I.—with a height-finding apparatus recently produced by T.R.E., the Variable Elevation Beam (V.E.B.) on a 120-foot mast, the whole on a sloping site to improve gap-filling.

In May 1942 the Air Officer Commanding-in-Chief Fighter Command, Air Marshal Sir Sholto Douglas, instructed that measures were to be taken at once to improve the aircraft reporting system in order to put the fighters in a good tactical position when the enemy was encountered. The equipment of an experimental station was now placed on the very highest priority. The basic requirements were:

(*a*) Plan position and height finding on aircraft at and above 10,000 feet at distances of at least 90 miles from the English coast, with permissible errors in plan and height of two miles and 1,000 feet respectively.

(*b*) The tracking of a maximum of six separate formations simultaneously; their alterations in plan position and height being rapidly followed.

To this end a modified G.C.I. station without the height console was to be employed, in conjunction with the V.E.B. This was later known as the Special C.H.L. or C.H.L./V.E.B. O.R.S. Fighter Command found and examined a suitable site at Appledore, Kent, and assisted T.R.E. with the work of settling the radar cover there, and of establishing the layout of the operations room on site. This was connected by landline directly to

No. 11 Group operations room where the information was displayed on a special plotting table, but a controller at Appledore carried out fighter direction on his own initiative. By June 1942 the station was working and calibration tests were made.

By the end of the year the station was beginning to control formations of fighter sweeps, and very soon settled down to controlling or assisting major operations. The success of the station led to the definite requirement by No. 11 Group of a number of Fighter Direction Stations built for the specific purpose—the C.H.L. at Appledore was not duplicated since it had several inherent faults, especially vulnerability to jamming. The new specification was briefly as follows: coverage over a sector of about 120° in azimuth, over ranges of about 40 to 120 miles with a ceiling of about 35,000 feet; early warning up to 200 miles; good comparative height measurement; high discrimination; inclusion of adequate anti-jamming measures. The T.R.E. offered two possibilities—one on 50 centimetres which could be produced fairly quickly and was in fact the Type 16 set, and the other on 10 centimetres whose development was likely to take far too long. The latter was almost identical in specification to the American Microwave Early Warning Set (M.E.W.) which was used in Britain in 1944. By May 1943 the first Type 16 set was erected at Greyfriars; others went up at Hythe, Ventnor and Beachy Head. The O.R.S. helped, and continued to do so, in the procedures, layouts and communications to be used, quite apart from constant liaison with T.R.E. during the development of the apparatus.

O.R.S. Fighter Command was also, during this period, concerned closely with the planning of a radio counter-measures (R.C.M.) programme for No. 11 Group, the chief devices being Moonshine, whereby one aircraft could simulate a large number to enemy radar, and Mandrel, a direct jamming set. The O.R.S. collaborated with T.R.E. on these requirements and attended the trials of these devices against a simulated *Freya* (German radar station). When Moonshine was ready for operation the O.R.S. advised No. 11 Group in planning its use and attempted to ensure that it was employed in such a way that its effectiveness could be assessed.

TRIALS WITH IMPROVED I.F.F. SYSTEM

The development of the fighter offensive across the Channel, the growth of U.S.A.A.F. operations and the increase in the numbers of Allied aircraft in general made an improved I.F.F. system necessary. Mention has already been made of the trials with the universal I.F.F. system in late 1941. In July 1943 after the new system had been given time to become familiar to all users O.R.S. Fighter Command organised a thorough investigation of its efficiency in operational conditions, the scientific observers at all Groups co-operating in a check of the number of aircraft recognised by its aid. These checks were on similar lines to those made previously with Mark II I.F.F. Whatever the system in use the failures could never be solely attributed to any one link. The airborne equipment was sometimes faulty but equally often the aircrew had failed to switch it on or to monitor it; it was also established that ground radar observers were quite capable of missing responses that were there.

OFFENSIVE OPERATIONS BY NIGHT

Statistical analyses of night intruder operations were produced by O.R.S. Fighter Command at the end of 1941 and again in April 1942 by which time the number of intruder sorties had increased considerably. A written summary of the operations in detail was accompanied by diagrams of total effort, flying time, etc., which emphasised the comparatively few occasions when enemy aircraft were encountered.

This document, which was not issued as an O.R.S. report since it was distributed primarily to intruder squadrons and group headquarters for information, was continued monthly (later without its diagrams) until the end of 1944, when the Operations Records Branch at Command Headquarters took over its compilation for the last few months of the war. The report changed its layout from time to time to suit the operations then taking place, such as bomber support, various types of radar patrols, patrols directed against enemy night flying training, ground and shipping attack patrols, Ranger operations (free-lance sorties by day or night) and so on. It included division of effort by duty, type of aircraft and squadron, details of casualties and combats, successes in target location and in timing and planning of operations whenever these coincided with enemy activity.

By the spring of 1943 it had been ascertained that intruders could not destroy enemy aircraft without radar during periods of low enemy activity and that catseye intruders, while continuing to harass the G.A.F. whenever possible, should be given alternative duties during such periods. A further conclusion was that the Mosquito was undoubtedly the best aircraft for intrusion.

In June 1943 Serrate operations were begun. This was a method of intercepting German night fighters by homing on to their A.I. transmissions with a specially developed radar set, combined with the use of A.I. Mark IV. A member of O.R.S. Fighter Command had organised the training and tactics of the operation. Headquarters Fighter Command then asked the O.R.S. to prepare immediate statistical narrative summaries of each night's operations from the Serrate squadrons' individual reports. This was initiated and continued until December 1943 when No. 100 Group of Bomber Command took over the operation.

DEFENSIVE OPERATIONS BY DAY

During 1942 the enemy continued to make sporadic raids against targets analysis. This work expanded when the combat analysis section became associated with the operations of 2nd Tactical Air Force and obtained an entrée into the field of armament problems.[1] From its modest start with the routine analyses of combat films the armament section of O.R.S. Fighter Command became recognised as an advisory body on every technical topic related to the lethality of the Command's aircraft, not only the accuracy of the pilots' shooting but their position in combat, not only the history of past successes but the expectation of future effectiveness with new weapons and new techniques. Gunsights as well as cameras became its concern.

From the time when the O.R.S. received combat films from Fighter Command early in 1942, and later from 2nd T.A.F., it undertook, in addition to the routine assessment of many thousands of films of air-to-air and air-to-ground engagements, an intensive programme of research into every feature capable of analytical treatment. These were on the following subjects:

(*a*) The percentages of all combats which resulted in a 'destroyed', 'probably destroyed', 'damaged' and 'no claim'.
(*b*) Comparisons between the results achieved between the different types of R.A.F. fighter against different enemy types.
(*c*) Accuracy of deflection allowance.
(*d*) Quality of range estimation.
(*e*) Accuracy with which pilots estimated the line of flight of the enemy.
(*f*) Accuracy of shooting according to range and angles of attack employed.
(*g*) Tactical approach as revealed by combat films.
(*h*) The variations in duration of fire and average length of burst, both for successful combats and otherwise.

Training films and pamphlets were produced by O.R.S. Fighter Command and when the Gyro gunsight was introduced a silent film was made which stressed and illustrated the correct methods of using the sight. This film served as a first introduction of pilots to the new gunsight and again proved most successful. Composite films of air combat were also prepared with explanatory titles illustrating the good and bad points to be noted concerning the shooting quality. These were distributed to other theatres of war and proved to be of great training value, as well as providing useful film material for showing during the pilot's periods of relaxation. Lectures were given by members of the O.R.S. armament section at fighter stations and visits were paid to various training and experimental stations. These officers, acting in an advisory capacity, helped to organise the training programme and assisted in analysing the results obtained.

The clearest evidence that the training of pilots was not allowed to lag behind the advances in aircraft and weapons is afforded by the simple

[1] See Chap. VII, pp. 140–141.

criterion of the percentage of combats resulting in the destruction of the enemy. In 1942 this average figure was 15 per cent. In 1944 it was 50 per cent. Much of the credit for this must be given to the excellent training programme planned and carried out by the Training Branch at all levels, but it is not unfair to claim that without the assistance of the O.R.S. they would have been working largely in darkness for a longer period instead of being able at every stage to measure their progress and to proceed with confidence in their methods.

When the rocket projectile began to be used by the Tactical Air Force in 1943 O.R.S. Fighter Command busied itself with collecting information on the effectiveness of these new weapons against ground targets. It helped to produce a training programme for aircrew and took part in the firing trials. It also improved the system of sight-setting by analysis of the results obtained from a number of rocket projectile shoots, each of which was measured for angle of dive, range of release, aircraft speed, point of aim and the position of shot.

MANPOWER INVESTIGATIONS

Investigation into manpower economies began in the early spring of 1942. It was a complete innovation in operational research and had been preceded only by theoretical examinations of manpower requirements in relation to flying effort carried out by O.R.S. Coastal Command. To begin with, the major difficulty was the scantiness of statistical detail relating to manpower. This continued to be a serious handicap of investigation of manpower economies. In the absence of sufficient statistical basis it was decided that the only way to tackle this job was for the O.R.S. to collect all the necessary data for itself from operational units. As the first tentative project eight operational stations were visited and there details were taken of manning by numbers and trades of ground personnel and were related to flying effort and to the average time devoted to such typical maintenance jobs as daily and minor inspections. This preliminary survey showed that manning in relation to establishment was irregular in numbers and trades as between squadrons equipped for the same function and that maintenance output per man was irregular in quantity as between squadrons.

A time recording party which observed the disposal of the working hours of each maintenance man on an operational squadron began work in July 1943 on No. 157 (Mosquito Night Fighter) Squadron at Hunsdon. The team quickly settled down to life with the squadron and was accepted as part of the station organisation while the recorders learned and noted the occupation of each man at quarter-hour intervals without being obtrusive and without getting in the way.

The report, 'Mosquito Night Fighter Maintenance Analysis', showed that the productive working hours, that is the hours spent on aircraft maintenance by maintenance men, were about two-thirds of the total working hours, in other words, that one-third of working hours was spent on parade, on guard or fatigue duties, or in waiting for work to be available. In addition to this, an average of some 10 per cent of maintenance personnel was detached daily from maintenance work for some other employment, or were permanently misemployed. An important point emerging from this investigation was that the number of men that could be economically employed on an aircraft during minor inspection was considerably greater than the number usually used, that in fact a gang of 20 was more economic in man-hours than the customary gang of 12, quite apart from the value of the quicker turn-round of the aircraft.

The findings of the report were put to the test with the result that with one dissentient out of 20 engineering officers making the trials in different parts of the country, all accepted the fact that the large gang was an economy. Investigation into economic gang size in various maintenance operations became standard practice in the R.A.F.

CHAPTER III

Direction of Operational Research and Parallel Developments in Other Services, 1940 to 1945

FORMATION OF AN OPERATIONAL RESEARCH CENTRE AT THE AIR MINISTRY

Following upon the successful collaboration of the Research Section at Stanmore with the Air Staff of Headquarters Fighter Command, radio operational research officers were attached to Bomber and Coastal Commands in the winter and spring of 1940–41. During that time the Scientific Adviser (Telecommunications), Mr. Watson-Watt, relieved the Telecommunications Research Establishment of the responsibility for administering the Stanmore Research Section. In May 1941 he proposed that operational research sections should be formed in all home commands and that the central co-ordination of these sections should be directed by a senior scientist who would be responsible to the Ministry of Aircraft Production in addition to acting as scientific adviser to the Chief of Air Staff. The attention of the new operational research sections would be extended from telecommunications to all aspects of air operations, with the object of improving both technical devices and air tactics in defence and offence.

The Air Staff acknowledged the necessity to correlate the work of the operational research sections that were subsequently formed in Bomber and Coastal Commands with the work done by the intelligence and technical staffs of the Air Ministry and the directorates of the Ministry of Aircraft Production. But they were not yet willing either to create the post of scientific adviser or to allow control of the sections to go to the M.A.P. Instead an Operational Research Centre (O.R.C.) was formed in October 1941 under Wing Commander A. C. Menzies, before the war Professor of Physics at Southampton University, who was responsible to the Assistant Chief of the Air Staff (General). Periodical meetings under the chairmanship of the Deputy Chief of the Air Staff were to be held at which matters relating to operational research would be discussed.

The staffs of the operational research sections were borne on the establishment of the Directorate of Scientific Research under Mr. (afterwards Sir Ben) Lockspeiser at the Ministry of Aircraft Production, and the Deputy Director of Scientific Research (III), Mr. R. S. Capon, dealt with administrative matters. The officer-in-charge of each section was, however, directly responsible to the Air Officer Commanding-in-Chief for the work done by his section.

As the work of the O.R.S.s increased, co-ordination between them and the Telecommunications Research Establishment and other scientific staffs in the Services fell increasingly upon the shoulders of the Director of Scientific Research at the M.A.P. The lack of a scientific adviser of eminence in the Air Ministry became apparent. The functions of the Operational Research Centre tended to be limited to distributing O.R.S. reports and ensuring liaison with outside bodies other than the departments of the M.A.P., while meetings at the Air Ministry became increasingly infrequent and after February 1943 ceased to be held.[1] A satisfactory system of central co-ordination for operational research was never evolved during the war, but an attempt was made to remedy the situation by the appointment of a scientific adviser to the Air Staff.

APPOINTMENT OF FIRST SCIENTIFIC ADVISER TO THE AIR MINISTRY

In the summer of 1943 Sir Henry Tizard pointed out to the Chief of Air Staff that the Air Ministry alone had no full time scientific adviser,[2] as the Operational Research Centre had administrative rather than scientific responsibilities and the scientific staff at the M.A.P. had no direct responsibility for advising the Air Staff on purely operational problems. (Sir Henry Tizard himself was shortly to resign from his positions as additional member to the Air Council and as member of the Council of the M.A.P.) The Air Staff were in full agreement with Sir Henry's suggestion and believed that they should have a scientist of high standing to give a good lead to the operational research organisation, both in the Air Ministry and in the commands. They were of the opinion that the future scientific adviser should not be a member of the Air Council but that he should be answerable in the first place to the Vice-Chief of the Air Staff. He would also have the benefit of the assistance of the Operational Research Centre.

One obstacle presented itself; that was the M.A.P. which had, in the first place, replaced the Department of the Air Member for Research and Development and since then had generally been accepted as the chief technical advisory body to the Air Staff. It was important that the new appointment should not clash with the M.A.P. The Air Staff emphasised that the scientific adviser would be concerned primarily with the scientific

[1] The meetings were revived by A.C.A.S.(Ops.) in January 1945 and continued until the end of that year.

[2] Professor Blackett was Director of Naval Operational Research at the Admiralty, and Professor C. D. Ellis, Scientific Adviser to the Army Council. The latter's first Scientific Adviser was Sir Charles Darwin, who was appointed in May 1942 and held this post for the following six months.

aspect of their operations, obviating any necessity for him to be the channel of communications with the M.A.P. on any question of operational requirement, development or supply.

On 8 November 1943, Sir George Thomson, Professor of Physics at the Imperial College of Science, South Kensington, who had served on the Aeronautical Research Committee during the inter-war years and on other scientific advisory bodies during the war, assumed his appointment as the first Scientific Adviser to the Air Ministry (S.A.A.M.). His terms of reference included the examination of 'air operations and the methods, weapons and equipment used, from the scientific aspect, and to advise the Air Staff and other departments of the Air Ministry thereon'. On questions relating to telecommunications he was to work in close consultation with the Scientific Adviser (Telecommunications), Sir Robert Watson-Watt. He was to be the spokesman of the Air Staff on scientific matters and was to keep in touch with the scientific advisers of the other Services.

CREATION OF A DEPUTY DIRECTORATE OF SCIENCE

For some time the need had been felt in the Air Ministry for a branch which would conduct independent scientific research in relation to operations. After his appointment as Scientific Adviser, Sir George Thomson asked for professional scientific assistance to digest technical matters and to brief him on the various problems on which he would be required to give advice. A Deputy Directorate of Science was therefore formed in January 1944 in place of the Operational Research Centre, consisting of an investigations branch containing a few high quality scientists to assist the Scientific Adviser and a co-ordinating branch to carry out the functions of the old Operational Research Centre, and in addition, to collect information for the investigations branch and to provide the administrative side both for the whole directorate and the Scientific Adviser. Wing Commander (by this time Group Captain) Menzies was appointed the first Deputy Director and he also acted as Deputy to the Scientific Adviser. The directorate remained under the jurisdiction of the Assistant Chief of the Air Staff (General).

One of the major problems besetting the Services at this stage of the war was the serious shortage of manpower and, in June 1944, a third branch of the Deputy Directorate was formed to investigate the scientific aspects of problems dealing with manpower, scales of effort, maintenance, and other problems which affected operations, but which were not directly operational in character. This arose out of the transfer of Dr. C. Gordon, the authority on planned flying and planned maintenance in O.R.S. Coastal Command, to the staff of Sir George Thomson at the beginning of 1944. As a result of his work in Coastal Command, not only had flying hours been considerably increased and the capacity of airfields enlarged, but large economies in manpower had been made without reducing total effort.[1] These schemes were to be extended throughout the Air Force. Dr. Gordon also worked on problems of the Air Member for Supply and Organisation such as the length of a technician's working week and the rationalisation of station duties. The collection of data required for the solution of these problems led to the formation, in the closing months of the war, of Air Ministry Manpower Research Units which were, in fact, administrative equivalents of the operational research sections.

DIFFERENCE OF OPINION BETWEEN THE AIR MINISTRY AND THE MINISTRY OF AIRCRAFT PRODUCTION OVER THE FUTURE OF OPERATIONAL RESEARCH

As noted already the M.A.P. had hitherto held the prerogative of giving scientific advice to the R.A.F. and it did not, therefore, look favourably upon the appointment of Sir George Thomson within the Air Ministry. The Director of Scientific Research at M.A.P. drew attention to the fact that the staff of the O.R.S. at R.A.F. commands had been recruited exclusively from M.A.P. and that Sir Robert Watson-Watt in his capacity as Scientific Adviser on Telecommunications had virtually been attached to the Air Staff from M.A.P. He felt that the duties of the new scientific adviser overlapped with his own responsibilities and went so far as to contend that the M.A.P., as it was the 'producer' responsible for the research on and the development and production of new equipment, should appoint and control all the scientists working for the Air Ministry.

The Air Staff, however, had by this time appreciated that operational research was an activity distinct from a body of scientists merely giving advice on technical matters. It recognised that there were numerous problems in the operational and logistical spheres in which the M.A.P. scientific organisation was not qualified to help and that operational research in the R.A.F. in these aspects must be maintained after the war. Furthermore, the R.A.F. system in which the O.R.S.s were responsible to the Commander-in-Chief of the Command to which they were attached was alien to the M.A.P. system of control. The Air Staff did not recognise that the M.A.P. had any right to act exclusively as an advisory body, or to control any part of the R.A.F. organisation with the exception that, for the duration of the war, scientific staff would necessarily be drawn from the M.A.P., and that, therefore, a representative of the latter would have to be attached to the Air Ministry to deal with this subject.

The problem of control of the scientists in the Air Ministry and M.A.P. was deferred until the end of the war when arrangements were made for the peacetime scientific organisation. Another matter which was postponed was the appointment of a successor to Sir George Thomson, who resigned from his post as Scientific Adviser in December 1944. It was not until 1946, after a long period of deliberation, that the Air Staff appointed

[1] See Chap. V, p. 102.

Dr. H. R. Hulme, an astronomer, as post-war successor to Sir George Thomson. Dr. Hulme had succeeded Professor Blackett as Director of Naval Operational Research at the Admiralty at the end of the war in Europe.

Meanwhile in the summer of 1945, a more logical division of responsibilities between S.A.A.M. and the Director of Scientific Research of the M.A.P. was arranged, largely at the suggestion of the Air Member for Personnel, then Air Marshal Sir John Slessor. In future S.A.A.M. was to be responsible for giving advice on the 'user' aspects of R.A.F. equipment, while scientific advice on 'producer' (i.e. research, development and production) aspects of equipment was to be the responsibility of the Director General of Scientific Research of M.A.P. The two scientific advisers were, of course, to keep in close touch, and in questions relating to telecommunications S.A.A.M. would consult the Scientific Adviser on Telecommunications. S.A.A.M., who was to be in control of all operational and administrative research sections in the Air Ministry and in R.A.F. Commands, was responsible for advising the Air Staff on 'user' aspects of operational problems and for giving scientific advice on matters of administrative research. These arrangements continued until the absorption of M.A.P. by the Ministry of Supply early in 1946.

THE JOINT TECHNICAL WARFARE COMMITTEE

Mr. Churchill, when First Lord of the Admiralty, appointed Professor Lindemann, as he then was, as his own personal scientific adviser and he held this position throughout the period when Mr. Churchill was Prime Minister. Nearly one-third of his work was concerned with the development, production and use of warlike equipment, particularly that used in air operations and in the battle against U-boats. At his disposal, for the collection of data, was a small group of economists and statisticians known as the Prime Minister's Statistical Section.[1]

By the end of 1943 the Chiefs of Staff were able to tap more specialised assistance. This was made possible by the existence of scientific advisers at each of the Service Ministries and at Headquarters Combined Operations. They were represented in a sub-committee of the War Cabinet known as the Joint Technical Warfare Committee formed that November. It included in addition to the scientists the Assistant Chief of Naval Staff (Weapons), the Assistant Chief of the Imperial General Staff (Weapons), the Assistant Chief of Air Staff (Technical Requirements) together with representatives from Headquarters Combined Operations and the Joint Planning Staff. The function of the committee was, as Sir George Thomson put it, 'not to produce detailed plans, much less to try and fight a General's battle for him. Rather (it) should produce definite pieces of data on

[1] *Lessons of the British War Economy*, edited D. N. Chester, Cambridge, 1951, pp. 58–68.

particular aspects of operations—bare bones which the staff must build into a proportioned skeleton and clothe with the flesh of a real developing situation.' It assembled reports on various problems of an inter-Service nature, of which the following are typical: the effect of interruption of lines of supply on the fighting potential of fighting formations; fire support of seaborne landings against a heavily defended coast (these two reports were specifically related to the then imminent Operation Overlord; after the landings representatives of the committee went over to the beachhead to examine evidence of the naval and air bombardment). Later reports included such subjects as 'Attacks on Japanese Trade', 'Japanese Battle Morale', 'The exchange of technical information with the Russians' and so on. The committee met periodically until the autumn of 1945, one of their final meetings being arranged to hear an eyewitness account by Group Captain Leonard Cheshire of the dropping of the atomic bomb on Nagasaki.

THE TELECOMMUNICATIONS RESEARCH ESTABLISHMENT

Before dealing with the development of operational research in the Army and Royal Navy the activities of two organisations, with which the operational research sections in the R.A.F. were closely associated, should be noted. The first and most important was the Telecommunications Research Establishment (T.R.E.) whose function it was to develop radio instruments for the R.A.F. such as aircraft interception equipment and bombing and navigational aids. It grew, with the increasing demands for radar equipment, out of Bawdsey Research Station. On the outbreak of war Bawdsey Research Station, under Mr. A. P. Rowe, was evacuated to Dundee where it became known as the Air Ministry Research Establishment. At the same time a small group of scientists who were working on the earliest form of airborne radar or aircraft interception (A.I.) moved to Perth twenty miles from Dundee. A third group consisting of scientists, who were responsible for the development and maintenance of the radar early warning system, left Bawdsey for Leighton Buzzard and formed the nucleus around which No. 60 (Signals) Group was eventually built.

Owing to the unsuitability of Dundee as a location for the Air Ministry Research Establishment, in May 1940, a move was made to Worth Matravers in Dorset. The establishment remained here for the next two years, expanding considerably and, in addition to Worth Matravers, occupying a large amount of property in Swanage. In November 1940 it was redesignated the Telecommunications Research Establishment. In May 1942 T.R.E., which was under the administration of the Ministry of Aircraft Production, moved to Malvern on account of the possibility of an enemy attack as a reprisal for the British commando raid which had recently taken place on a German radar station at Bruneval. Here it was to remain until the end of the war.

The work of the scientists at T.R.E. lies outside the province of a study of operational research although, as will be seen, the operational research sections collaborated closely with T.R.E., their task being to assess and report on the operational efficiency of equipment made by T.R.E. One of the latter's activities should, however, be mentioned as it made a valuable contribution towards the influence of scientific thought on military operations. These were the informal gatherings, known as 'Sunday Soviets', instituted by Mr. Rowe, at which scientists, senior R.A.F. officers and, on occasion, operational aircrew discussed, in an atmosphere of complete equality and outspokenness, current scientific problems in air and naval warfare.

THE AIR WARFARE ANALYSIS SECTION

The other organisation was the Air Warfare Analysis Section. This group of scientists and statisticians came into being largely at the instigation of Sir Henry Tizard who, on the outbreak of war, suggested that a committee should be formed to investigate the best methods of collecting and analysing data on aerial bombing and anti-aircraft gunfire under war conditions. Such a committee was formed in February 1940 with the Assistant Chief of the Air Staff (General) as chairman together with representatives from the three Services and Sir Henry Tizard. The Committee appointed Dr. L. B. C. Cunningham of the Royal Aircraft Establishment, who had already been working on problems of gunnery in aerial combat, to head a small staff of scientists to carry out detailed analysis work recommended by the committee and to collaborate with the Air Tactics Branch of the Air Staff.

By the end of February Dr. Cunningham and his staff, which was augmented by a small analysis section already working with No. 25 (Armament) Group, R.A.F., had begun work at Harrow. In due course they were to become part of the Deputy Directorate of Air Tactics. Their first report produced in February 1940 was 'An analysis of the performance of a fixed gun fighter armed with guns of different calibres, in single home defence combat with a twin-engined bomber.' When the German night air attacks began in earnest the section worked closely with the Research and Experiments Department of the Ministry of Home Security (of which more will be related later), making use of data collected by the latter to analyse enemy bombing technique and accuracy. The Air Warfare Analysis Section cannot be described as an O.R.S. as its work was restricted to the solution of mathematical problems relating to air warfare rather than to problems of a strategical or tactical nature, but it continued to work on analytical surveys of gunnery and bombing techniques which inevitably brought it into contact with the operational research sections of Fighter, Bomber and Coastal Commands.

PARALLEL DEVELOPMENTS IN OPERATIONAL RESEARCH IN THE ARMY AND THE ROYAL NAVY, 1940 TO 1943

Operational research in the Army started through the fact that anti-aircraft gunnery was an Army assignment, although Anti-Aircraft Command was under the operational control of Headquarters Fighter Command. Experiments with radar equipment for gun laying which determined the bearing and slant range of an attacking bomber began before the war at the Air Defence Experimental Establishment at Biggin Hill, from which, it will be recalled, a party of scientists were attached to Bawdsey Research Station. When the night raids against Great Britain started in earnest in the autumn of 1940 it became urgently necessary to make an instrument which would give the elevation of the attacking aircraft. In order to find a solution to this problem the General Officer Commanding-in-Chief, Anti-Aircraft Command, General Sir Frederick Pile, appointed the distinguished physicist, Professor P. M. S. Blackett, as his scientific adviser. Later in November 1940 an anti-aircraft wireless school was established at Petersham under Dr. J. A. Ratcliffe and some 60 scientists were trained in the use of radar equipment.

By that time Professor Blackett had formed at Savoy Hill House in London a team of physiologists, physicists, mathematicians, surveyors and other men with scientific training, but without specialist radio knowledge, to study the problems involved in controlling the fire of anti-aircraft guns at unseen aircraft. This team became known as the Anti-Aircraft Command Research Group (A.A.C.R.G.) or, more familiarly, as 'Blackett's Circus'. They spent much time on anti-aircraft gun sites during the night raids on London. One of their first investigations was the correlation of the errors in aiming of an accurately adjusted radar equipment with the slope, surface and nature of the ground, the presence of metal Nissen huts, etc., about the site. The interference discovered made it necessary for the ground around the radar receiver to be covered by mats of wire netting to give a level uniformly conducting artificial ground surface.

In May 1941 the A.A.C.R.G. and the Radio School at Petersham became the Operational Research Group of the Air Defence Research and Development Establishment under Dr. Ratcliffe, directly responsible to the Ministry of Supply. Shortly afterwards, Dr. B. F. J. (afterwards Sir Basil) Schonland, the South African physicist, became superintendent of the group. By May of the following year the Operational Research Group, which had arisen out of the application of the technique of science to the study of anti-aircraft defence, began to study military operations, concerning itself chiefly with the improvement of new weapons and equipment. In February 1943 the group, which for over a year had been jointly controlled by the Ministry of Supply and the War Office, became the Army Operational Research Group and severed its connections with the Air Defence Research and Development Establishment. It now expanded into eight sections concerned with anti-aircraft defence, new radar equipment, signals, field and anti-tank gunnery, army–air operations, infantry operations, lethality of weapons, land mines, obstacles and special weapons. In addition, during 1942 and 1943 operational research sections were set up by the War Office in Twenty-first Army Group (about which more will be related later), the Middle East, Italy and India for 'the collation and critical analysis of facts and quantitative data on military problems'.

Meanwhile Professor Blackett, who became head of the O.R.S. in Coastal Command on the strength of his experience in A.A. Command, was, in January 1942, appointed Director of Naval Operational Research at the Admiralty, although the actual Department did not form until a short time afterwards. Like the other Services, the Royal Navy had always employed a number of scientists to carry out research into new weapons and techniques such as wireless telephony and anti-submarine warfare, but with the formation of the group of scientists under Professor Blackett, advice was tendered on strategical and tactical problems. The new department was naturally preoccupied with the U-boat threat, but it also dealt with problems of gunnery, mining, radar and radio, etc. While scientific observers were sent from time to time to naval commands or units overseas, the naval operational research organisation centred on the Admiralty in London and, unlike scientists in the R.A.F. and Army, research sections were not permanently attached to operational commands. Close liaison, however, was maintained with Coastal Command O.R.S. and the relationship was particularly fruitful as Professor E. J. Williams, successor to Professor Blackett at Headquarters Coastal Command, followed him to the Admiralty in due course.[1]

THE RESEARCH AND EXPERIMENTS DEPARTMENT OF THE MINISTRY OF HOME SECURITY

The Ministry of Home Security also acquired a number of scientists for research in connection with the effect of explosions on various types of buildings and also for discovering the effect of explosions on animals to use as a guide to their effects on human beings. Later, groups were formed to deal with camouflage and smoke and fire research. This organisation became known as the Research and Experiments Department and was formed on the outbreak of war under Dr. R. E. (afterwards Sir Reginald) Stradling at Princes Risborough where it was housed in the Forestry Products Research Laboratory. In the early days of the war its main task was to analyse the effects of enemy air operations against this country and air attacks against shipping in coastal waters. Two tasks were undertaken by the department at the request of the Air Staff: first, a census of bombs

[1] *Brassey's Annual* for 1953, p. 98, 'Operational Research', by Professor P. M. S. Blackett, edited by Rear-Admiral H. G. Thursfield, William Clowes and Sons, London.

dropped over Great Britain, and secondly, quantitative studies of the total effect of air raids. All this work was done in close conjunction with the Air Warfare Analysis Section.

As the Allies turned to the offensive, one branch of this department became increasingly important. This was Research and Experiments 8 (R.E.8) which was responsible for providing the Air Ministry with assessments of the effects of Bomber Command's raids on Germany. It was staffed by leading scientists such as Professors J. D. Bernal, S. (afterwards Sir Solly) Zuckerman and W. N. Thomas; other members were Doctors D. G. Christopherson, J. Bronowski and Mr. R. B. Fisher and Mr. R. W. Bevan. Its activities were supervised by the Directorate of Bomber Operations, and in early 1944 it was transferred to Air Ministry control. By that time, with the American daylight bomber offensive well under way, R.E.8 had become a joint Anglo-American team, the American scientists and technologists including Mr. Charles Hitch, Mr. L. M. Denbitz and Mr. I. N. Pincus. In the final stages of the war R.E.8 provided the nuclei of the teams that were organised to survey the effects of Allied bombing in enemy-occupied territory, in particular the British Bombing Survey Unit which went to Germany,[1] and the British Scientific Mission sent to Japan to examine the damage caused by atomic bombs dropped over Hiroshima and Nagasaki.

The method developed by R.E.8 for assessing the results of the bomber offensive involved the study of aerial photographs of enemy targets, advice on the best type of bomb load to carry in future operations, estimates of the amount of damage done and assessment of the consequent losses in production based on the losses due to similar damage in this country. Estimates were also made of the time it would take for a factory to resume production. Finally, the department was able to say, by photographs showing structural alterations being carried out to a building, whether the alteration was likely to be for the purpose of reducing vulnerability and to what part of the building. It was because of the work of the Research and Experiments Department on the effects of raids on Great Britain that it was more appropriate for them to assess the results of Bomber Command attacks on Germany rather than O.R.S. Bomber Command which was concerned, as will be seen in the following chapter, with determining the accuracy of the operations.

[1] See Chap. VII, p. 149.

CHAPTER IV

Operational Research in Bomber Command, 1941 to 1945

FORMATION AND ORGANISATION OF O.R.S. BOMBER COMMAND

The work of each of the three principal O.R.S.s in Great Britain was characterised by the role of the command to which it was attached. O.R.S. Fighter Command, essentially defensive in character, bent its energies towards evolving an efficient early warning system against hostile bomber attacks by day and night. The task of O.R.S. Coastal Command was, first and foremost, to assist in defeating the U-boat. The problem of O.R.S. Bomber Command was to discover what happened to the bomber aircraft over enemy territory, the manner in which the enemy attempted to intercept them and the accuracy with which they attacked their allotted objectives and to suggest how the effectiveness of the attacks could be improved. Navigational and bombing aids and techniques, aircraft losses, radio counter-measures and tactics preoccupied this O.R.S. As already explained, T.R.E. was responsible for developing the various blind bombing and navigational devices; the task of the O.R.S. was to ascertain how effective they were on operations and to suggest to the Air Staff of Bomber Command the best methods of using them and how they might be improved. 'In the solution of these problems', wrote Air Chief Marshal Sir Arthur Harris after the war, 'the value of scientific research has proved inestimable. Indeed without the O.R.S. many problems would have remained insoluble, and others would have been solved only after trials and errors extravagant not only in terms of time and effort but also in lives of our aircrews.'

Operational research in Bomber Command began when, as a result of a recommendation of the Committee for the Scientific Survey of Air Warfare presided over by Sir Henry Tizard, Mr. A. E. Woodward-Nutt from the Directorate of Scientific Research at the Ministry of Aircraft Production began, in June 1940, to study bomber losses and examine phenomena reported by aircrew during operations. These investigations were continued by Dr. B. G. Dickins from the same directorate who, from August 1940, wrote monthly reports entitled 'Phenomena connected with enemy night tactics'. They dealt in particular with the action taken by enemy fighters intercepting the bombers, the type and number of aircraft making interceptions, the heights and position of interceptions, the variation of losses, interceptions and number of other aircraft seen with the phase of the moon, and balloon barrages. Conclusions as to the effectiveness of interceptions of bomber aircraft were drawn at the end of each report. Under the title 'Reports on losses and interceptions of Bomber Command aircraft' these analyses were continued by the O.R.S. until the end of the war.

In connection with bomber operations at night, Dr. Dickins, who, it will be recalled, had been associated before the war with the experiments in aircraft interception at Biggin Hill, examined the Forms 'Z' which were summaries of the Form 'Y' made out by squadrons on completion of an operational sortie. These forms provided information on the numbers of bombers intercepted and attacked by enemy night fighters. Accurate figures could not, however, be obtained entirely from the Forms 'Z' as they were immediate returns and were necessarily incomplete. Final figures were obtained only after comparison of the Forms 'Z' with the combat reports which were required to be returned by aircrew after all interceptions by enemy night fighters.

The contribution that radio aids would make towards improving the accuracy of bombing attacks had been quickly appreciated by the Scientific Adviser (Telecommunications), Mr. Watson-Watt, and in April 1941 Professor A. O. Rankine was appointed Radio Operational Research Officer at Headquarters Bomber Command. He was succeeded by Mr. G. A. Roberts from O.R.S. Fighter Command that July. At about the same time several other scientific officers arrived to analyse both radio and armament problems.

In August 1941 the Air Officer Commanding-in-Chief Bomber Command, Air Marshal Sir Richard Peirse, asked that an O.R.S. should be set up on the lines of the sections recently formed in Fighter and Coastal Commands to study operations with a view to determining how their efficiency in terms of bombs on the target per aircraft lost could be increased. On 18 September O.R.S. Bomber Command was formally established, 'for the purpose of analysing bombing operations with a view to determining weak points in the enemy defence system, to ascertain the cause of casualties so that steps can be taken to reduce them and to assess the effectiveness of bombing attacks. The section will also be investigating various radio problems relating to this Command.'

Dr. Dickins, on account of his close association with the Command, was appointed officer-in-charge and, in addition to Mr. Roberts, the original members of the staff included Dr. R. J. Smeed, Mr. G. W. H. Stevens, Mr. E. A. Lovell, Mr. H. L. Beards, Miss K. M. M. Goggin and Miss H. Lang-Brown. The section was initially divided into four groups to study the following subjects, bomber losses, success of bomber operations, vulnerability of bombers, radar and radio aids. But as the study of radar problems was so closely linked both to the success of bomber operations and to the losses suffered by the bomber force, the O.R.S. was at an early stage divided into two subsections—O.R.S.1 which dealt with research into the success of night operations and O.R.S.2 which analysed the cause of losses on night operations. A third subsection worked on problems concerning day operations until 1943 when No. 2 Group, the day bomber force, was transferred to the Tactical Air Force. When daylight operations were resumed by the Command in mid-1944 their analysis was carried out by O.R.S.1.

The formation of O.R.S. Bomber Command was apposite because for some time scepticism had been growing in certain quarters of the Air Ministry and in the War Cabinet over the effectiveness of raids by Bomber Command against targets in Germany. Photographic reconnaissance had revealed that certain oil plants claimed to have been put out of action by Bomber Command were, in fact, undamaged and working. At the instance of Lord Cherwell, Scientific Adviser to the Prime Minister, an investigation was made of photographs of night raids by Bomber Command between 2 June and 25 July. The conclusion of this report made by the Prime Minister's Statistical Section was that only about a quarter of the number of bombers which claimed to have attacked their targets actually did so.[1] The Prime Minister, in particular, was greatly concerned over the findings of the report and drew the attention of the Chief of the Air Staff to its findings. Measures were then put in train to improve the low standard of navigation in the Command.

At this time, it must be remembered, the bomber offensive was in its infancy. Only a handful of heavy bombers such as the Manchester, Stirling and Halifax had appeared. There were no precise navigational aids, and bomber crews endeavoured to reach their objectives by dead reckoning methods. The bombers therefore routed themselves independently to the target and only in moonlight and clear weather were they likely to locate their targets. At the same time the enemy installed an early warning system along the coasts of Denmark, Belgium and northern France, and a belt of G.C.I. stations was built extending through Denmark and Holland down the western frontier of Germany. The latter was backed up by a searchlight belt covering the Ruhr. Bomber Command's attacks were achieving little success and losses were on the increase. Under the energetic leadership of Air Chief Marshal Sir Arthur Harris, who was appointed Air Officer Commanding-in-Chief Bomber Command in February 1942, the situation began to improve. Gee, the navigational aid, which until March of that year had been in an experimental stage, was used operationally, and raids became more effective after attempts had been made to concentrate the bombers over the target.

The work performed by the O.R.S. proved so acceptable to Headquarters Bomber Command that by the end of 1942 the staff of the O.R.S. had expanded to 36 members. Under the Principal Scientific Officer, Dr.

[1] In fact, even fewer aircraft found the target. Of successful photographs claimed to have been taken over Stettin in three raids on the port in September 1941, about 70 per cent were plotted more than four miles from the centre of the city, several being twice or three times that distance.

Dickins, there was one senior scientific officer—Mr. Roberts, 13 scientific officers, 10 junior scientific officers and 11 assistants (Grade III). By 1944 the normal strength of the section was 48 scientific officers and 34 assistants. By that time the O.R.S. was subdivided into six groups. Apart from the two leading groups dealing with the general success of operations (under Dr. B. G. Peters) and the losses incurred in these operations (under Dr. R. J. Smeed), the third group was responsible for the analysis of statistics; the fourth group was occupied with general problems including the use of night photography, airfield control, the compilation of the Bomber Command Quarterly Review and the preparation of the Night and Day Raid Reports which provided a definitive account of each operation and included all relevant statistics together with brief statements of the weather, route, success, damage and other relevant matters. With the increasing use of radar aids to navigation and bombing and the great importance of improving the accuracy and operational use of the devices available to the Command, a fifth group was formed to specialise in research on radar aids to navigation and bombing, leaving O.R.S.1 to work on the general tactical analysis and visual bombing problems. The sixth group researched into problems of manpower economy. Members of the O.R.S. were also attached to Groups and to the Bombing Development Unit, for a time or permanently. They were known as scientific observers and acted as 'one man sections' for the immediate help of the unit to which they were attached with day-to-day problems and to facilitate the rapid collection of data for the main section.

Like the other O.R.S.s, O.R.S. Bomber Command worked in the closest collaboration with the Air Staff and had access to all information relating to past operations in order to assist in the planning of future attacks. In the Command hierarchy it was responsible to the Senior Air Staff Officer and later to the Deputy Commander-in-Chief when this post was created, but the Officer-in-Charge O.R.S. had direct access to the Air Officer Commanding-in-Chief at all times.

ESTABLISHMENT OF AN OPERATIONAL ANALYSIS SECTION WITH THE U.S. EIGHTH AIR FORCE

The American strategic bomber force, the Eighth Air Force, began operations in August 1942, and the Americans were quick to appreciate the value of an operational research section which would study the problems of the daylight bombing offensive. In May 1942 a member of the staff of General Ira Eaker, then commanding the Eighth Air Force, conferred with Dr. Dickins on the subject of an independent American Operational Analysis Section (O.A.S.) which would co-operate with O.R.S. Bomber Command. Two lawyers[1] and four scientists arrived in Great

[1] The Officer-in-Charge of the Section, Colonel J. M. Harlan, later became a Supreme Court Judge.

Britain that October and were attached to the Headquarters of the Eighth Air Force. Before taking up their appointments they were attached to O.R.S. Bomber Command and initiated into the various aspects of operational research. Mr. E. A. Lovell was given the specific task of helping the American party in these matters. Close contact was maintained by the two sections throughout the war.

PROBLEMS RELEVANT TO THE IMPROVEMENT OF NIGHT BOMBING

The most convenient method in dealing with the O.R.S.'s contribution to the improvement of night bombing is to consider very briefly, and in chronological order, the navigational and bombing aids used during the offensive. Before doing so it is necessary to see how the O.R.S. tackled a problem of this nature. It became interested in a new navigational aid during the equipment's development stage when the O.R.S. was normally consulted on such matters as presentation, coverage and facilities. The main work of the O.R.S., however, began when the device first became available to the command and usually fell into three main phases. Firstly, there were Service trials at the Bombing Development Unit, in which the O.R.S. took a leading part, to find out the accuracy and limitations of the device and to establish a training schedule. Secondly, there was the training period in which the results achieved by the average crew were obtained and analysed to ascertain whether the training programme was adequate. Finally, the performance of the equipment was tested on actual operations when the O.R.S. investigated the method of use and sought ways in which to improve its effectiveness. Work on all these phases, which often proceeded simultaneously, was carried out in close co-operation with the Operations, Radar and Navigation Branches of Headquarters Bomber Command and fell into two main classes. Firstly, the technical study of the equipment itself, and secondly, the effect of the equipment on operations as a whole.

In all the data used in reconstructing the history of a raid three main sources of information emerged. The sortie raid report[1] obtained by intelligence officers gave information about the time of events, the type and number of bombs carried and dropped, the method of bomb release and general conditions in the target area. Secondly, photographs taken at the time of bombing enabled the position of the aircraft to be fixed in space and time with considerable accuracy. As will be shown later, the plotting and interpretation of these photographs demanded much time and skill and was largely carried out by the Photo/Intelligence Branch at Headquarters Bomber Command for plottings by ground detail and by 'N' Section of the Central Interpretation Unit for more complex forms of interpretation. Thirdly, damage reports were prepared by 'K' Section of the Central Interpretation Unit on the basis of daylight photographic cover taken by

[1] A copy of the Sortie Raid Report is reproduced as Appendix No. 3.

photographic reconnaissance aircraft. Making use of all available air cover the Research and Experiments Department of the Ministry of Home Security produced more elaborate analyses of damage and also a considerable number of crater plots.

The data obtained were subjected to both qualitative and quantitative analysis. In the former the O.R.S. discovered whether the tactics employed on the raid were successful or not, gave reasons for failure and recommended improvements for future operations. The results were published in reports for restricted distribution within the Command as soon as possible. Quantitative analysis was a more detailed process, but it was of great value in that it characterised any given raid by some numerical measurement of success, or by a set of such measurements, so that a whole series of raids carried out by one bombing technique could be compared with other series carried out by other techniques. It was also possible by using these methods that seasonable and longer term changes in accuracy and the varying effects of weather could be assessed.

(a) *The Introduction of Gee*

Navigation by the bomber crews was, until the introduction of Gee in March 1942, based to a large extent on dead reckoning. There were only three means of fixing available, visual pinpointing, loop bearings and astro. Drift-taking also provided further assistance to the navigator. Target identification and bombing were entirely visual. An O.R.S. analysis of navigators' logs of 1941 indicated that about 60 per cent of the navigators operating at that time made use of loop bearings, but few could have converted these bearings into fixes, for the number of sorties on which a fix of some kind was recorded amounted to only 39 per cent of the total. Such W/T fixes as were obtained had an average error of 20·8 miles. Astro was the most widely advocated aid to navigation, if not so widely used. On 33 per cent of the sorties astro sights were taken, although the majority of these sights must have been used as single position lines. A note on astro navigation in 1941 stated that 68 per cent of fixes had errors less than 10 miles. The analysis indicated that of the 178 sorties considered (samples from about 30 raids) 61 per cent were completed without the navigator finding a single fix; on 23·5 per cent of the sorties the navigator found only one fix, on 9 per cent two fixes were obtained and on only 6·5 per cent of the sorties did the navigator find three or more fixes.

In this early phase of the bomber offensive, navigational efficiency was such that only a fraction of the aircraft despatched could have found themselves within 20 miles of the target on their navigators' estimated time of arrival. Of the aircraft whose photographs proved them to have reached the target area, those relying on dead reckoning alone averaged 19 minutes searching for the target after their estimated time of arrival, those obtaining one or two fixes averaged 13 minutes, and those obtaining three or four fixes averaged eight minutes' search. The need for a quick and accurate fixing device was obvious.

In the absence of any navigational aid for the bomber crews, the O.R.S. made a study of night vision and special maps were made showing, for example, the features most readily visible at night, but they had little success. Prior to the advent of Gee the O.R.S. had been considering how best it might be used to improve the accuracy of bombing. The O.R.S. envisaged the dropping of flares by a number of aircraft simultaneously over the target on the reading given by the instrument. This was necessary because the error in the reading could be several miles and it was hoped by dropping an adequate number the target would be found at the centre of the pattern. A series of trials, known by the code name Crackers, were carried out under the supervision of Mr. Roberts in which the best crews from No. 3 Group, operating over the Isle of Man, were used for dropping the flares. These trials enabled suggestions to be made for using Gee operationally. It is of interest to note this first idea of pathfinding.

A comparison of efficiency of bombing[1] for the seven months prior to the introduction of Gee and the first five months in which Gee was in operation was made by O.R.S. Bomber Command. In the first period there was a 42 per cent improvement in attacks on France and the Low Countries and in the second period it had increased to 63 per cent. There was improvement under all conditions of weather and moon brightness, but it was most marked in moderate and poor weather conditions in the latter period. The efficiency of these attacks was 11 per cent whereas in the period prior to the introduction of Gee it was only 6 per cent. In attacks on German coastal towns the efficiency rose from 33 per cent in the first period to 44 per cent in the second period, and on German inland targets (excluding the Ruhr) from 23 per cent to 29 per cent. The latter two sets of targets were mainly beyond the range of Gee and the results for the second period, therefore, did not include the effects of the using of Gee as an aid to target location but purely as a navigational aid. There was an undoubted improvement, but it was not so marked as in the case of targets in closer range. This fact illustrated the need for an efficient means of target location.

(b) *The Introduction of Oboe*

While Gee showed some improvement in the success of operations, the O.R.S. was watching carefully the development of H2S, Gee-H and Oboe at T.R.E.[2] Oboe was being developed as a precision bombing aid, but in

[1] The term 'efficiency' in this context is taken to mean the ratio of the number of aircraft despatched to the number which attacked the target area, a ratio which was estimated from the evidence of photographs taken at the time of bombing.

[2] An explanation of these navigational and bombing aids will be found in the Glossary at the beginning of the volume.

view of the complicated ground organisation and low handling capacity it could never prove to be a main force bombing aid, although it was considered to be useful for attacking such small targets as the battleships *Scharnhorst* or *Gneisenau*. O.R.S. Bomber Command, however, conceived the idea of using Oboe for marking a target. In this way the whole bomber force could be led to the target by relatively few Oboe aircraft which the system could provide. The proposal was immediately put to the Air Staff of Headquarters Bomber Command who gave it its strongest support and the development of Oboe became a matter of the highest priority.

Oboe marking became one of the most accurate forms of attack used in the war, the raids being performed exactly as forecast by the O.R.S. During March 1943 a very successful attack was made on Essen with Oboe, and subsequently this same technique was used to effect in the Battle of the Ruhr. In a few raids the damage inflicted amounted to many times that caused over the numerous raids previously carried out. In 1944, as will be seen, Oboe was of inestimable value in preparatory operations for the landings on the Continent, when small targets such as coastal batteries, railway centres and bridges were attacked with its aid.

The original idea for the operational use of Oboe for target marking was put forward by Dr. Dickins. Mr. Roberts worked out the details and organised the calibration of the system. He contributed much to the high precision achieved in operations by this invaluable aid. It is of interest to note that the accuracy of Oboe was such that during the calibration trials, in which bombs were dropped on virgin targets in France, discrepancies in the geodetic grid were revealed.

(c) *Analysis of Pathfinder Force Operations and Effectiveness of Blind Bombing Instruments*

Following the introduction of the Pathfinder Force in August 1942, the O.R.S. carried out analyses to determine whether the bombing had improved in comparison to the pre-Pathfinder Force period. It was found that there had been an improvement but the absence of satisfactory target markers hampered the accuracy of the Pathfinder Force. An analysis covering the period August 1942 to January 1943 was made in which 26 attacks were led by the Pathfinder Force. Six raids took place in bad weather when the target was not found. Eleven operations were executed in moderate weather and on six of these occasions the target was found. In good weather nine attacks were made. The O.R.S. considered that on nine of the 26 operations over Germany there was an improvement on the results that could have been expected from the results obtained in the pre-Pathfinder Force period. Over these nine 'improved' raids the expected efficiency was 25 per cent and the achieved 41 per cent. These figures indicated how efficient the Pathfinder Force might be when it would be able to offset the effect of bad weather by blind bombing devices and when satisfactory target indicators became available.

The O.R.S. also studied the relative effectiveness of raids led by H2S and Oboe and proved that very much more devastation was being achieved by raids led by Oboe markers; it estimated that during the first six months of 1943 the raids in which Oboe was used were at least three times more effective than raids led by the Pathfinder Force before the introduction of this aid.

(d) *The Development of H2S*

H2S did not enjoy the same immediate success as Oboe for it presented difficulties which only experience in its use and tactical developments could overcome. But during the period June 1943 to February 1944 the targets of Bomber Command were for the most part beyond the range of Oboe. By the end of February 1944, 23 squadrons of the main force were equipped with or converting to H2S, and approximately one-third of all sorties sent out were H2S aircraft.

The O.R.S. was closely concerned with the early trials of H2S, the subsequent training of crews in its use and, finally, its behaviour on operations. On the completion of the instrument's trials a member of the O.R.S. was transferred to the Pathfinder Force to assist in the training of the first squadrons to be equipped with H2S, the results being analysed by the main section at Headquarters Bomber Command. Observations during the trials and training period led the O.R.S. to conclude that the average operator, over a series of runs, would be able to drop 50 per cent of his bombs within the mean radius of the main built-up area of the town selected as the target.

Some difficulty was experienced, however, in identifying the target, as the response on the plan position indicator was not always clear. The O.R.S. therefore applied itself, in association with T.R.E. and the Air Staff at Headquarters Bomber Command, to improving bombing accuracy and widening the application of the equipment by a study of technique rather than by technical improvements. The basis of most techniques proposed was that while a response at close range was distorted, broken up or generally difficult to interpret, the same response was usually clear and well defined at about ten miles range, so that if a feature at this range was used as an offset aiming point there was every hope that it would at least be easier, if not more accurate, than the direct method. Besides providing an alternative to the direct method these techniques allowed H2S to be used for bombing targets where the response from the aiming point was indistinguishable from the surrounding area, for example, where the aiming point was in the centre of a very large town such as Berlin, or in open country, or, in the case of high level mining by H2S, at some point in open water. From their nature these techniques became known as reference point methods.

A number of experiments were conducted by the Bombing Development Unit, several of which involved the combination of H2S with the ground position indicator. The method adopted was to home the aircraft by H2S to a given range and bearing from some suitable reference point, and with the graticule set up to the corresponding position on the chart, to start the ground position indicator when the position was reached. From then on the aircraft was guided to the release point by the ground position indicator alone. One of these techniques was used by the Pathfinder Force with considerable success. Another method which did not require the ground position indicator was used for high level minelaying guided by H2S. In the summer of 1944 the O.R.S. made a further analysis of the efficiency of H2S bombing and found that with the exception of attacks on small towns, bombing with H2S and the ground position indicator was as accurate and sometimes more accurate than direct bombing. The O.R.S. recommended that T.R.E. should consider incorporating a bearing marker in future marks and that, in the meantime, greater attention should be paid to accurate setting up of the equipment by maintenance personnel. In the latter stages of the war the combination of H2S and Gee-H was considered for the attack of targets beyond normal Gee-H range, experiments showing that the degree of accuracy attained was not far short of that achieved by Gee-H alone.

Instructions for the training of aircrew in the use of H2S and Gee-H were prepared by the O.R.S., as they had been in the case of Gee. The instructions each described a series of exercises which were to be carried out, giving details of the methods to be used in their planning and execution. Particular attention was also given to the methods to be used in assessing and recording the results, and to any special observations required for analysis purposes. The object of the instructions was twofold: by specifying all the relevant conditions of the exercise in this way, the squadron instructor was able more readily to assess the individual in relation to the other pupils on a basis of results achieved, and secondly, the O.R.S. was able to collect a large mass of homogeneous data in the form most convenient for analysis.

Intensive study of the behaviour of H2S on operations continued to be made by the O.R.S. It was anxious that use of this equipment should not be restricted to the Pathfinder Force but that it should be fitted to aircraft of the main force since it was apparent that pathfinding technique would probably never be satisfactory in bad weather conditions. The shortage of sets made the latter proposition impracticable at first, while the bombing of short range tactical targets on the Continent in the spring and early summer of 1944 did not permit an extensive trial in blind bombing by the main force until August of that year. Brunswick was the target but the operation was a failure—a failure as an experiment rather than a failure as an idea—mainly through inexperience of the bomber crews who had had little opportunity to practise with the equipment as they had for some time recently been engaged on short range attacks in daylight, and it was not found possible to repeat the experiment before the end of the war. Thus the question of whether pathfinding or individual blind bombing was the more accurate, which the O.R.S. was striving to resolve, was never answered.

Four main reports were prepared by O.R.S. Bomber Command on the effectiveness of H2S when used by the Pathfinder Force as a blind bombing and marking device. Its value was also assessed when applied to the high level laying of mines in the sea.

Finally, the O.R.S. attempted to determine more closely the relation between the features on the ground and the responses on the plan position indicator, for it was obvious that if H2S was to be applied successfully to both bombing and navigation it was necessary to discover more than the fact that a built-up area gave a stronger response than open country which in turn gave a stronger response than areas of water. The failure to identify such prominent targets as Wilhelmshaven and Hamburg during raids made in the spring of 1943 was an additional spur to this requirement. One solution was for photographs to be taken of the plan position indicator while over enemy territory to ascertain the responses of various German targets, but this was forbidden for reasons of security until the end of 1943. In due course a valuable collection of pictures of the responses of a large number of German towns was collected. It included a series taken over Berlin during the winter attacks of 1943-44, and to assist in planning and briefing for subsequent operations on this target, the photographs were assembled, together with maps and notes on their interpretation, and issued by the O.R.S. as an 'intelligence folder'.

(e) *The Development of Gee-H*

Gee-H, a more precise aid for blind bombing than H2S in which the initial transmissions were made by the aircraft and were re-radiated by two ground beacons, came into full operational use in October 1944. As Gee-H was based on the known position of ground stations it could be used irrespective of visibility conditions over any target within range by day or night. Its tactical advantages over other bombing aids were therefore considerable, since its accuracy was far greater than that of Gee and, at the same time, it was free from the serious limitation in the number of aircraft which could be controlled by a single ground station, which was a feature of the Oboe system.

For a year after October 1943 Gee-H was employed by Bomber Command on only a small scale; it was used for laying mines in the sea and for attacks on flying bomb sites. Its performance was closely studied by the O.R.S., and as this was found to be highly satisfactory in August 1944 a large number of Lancasters in No. 3 Group were equipped with Gee-H. In the middle of October this group began a series of relatively large scale Gee-H attacks directed against synthetic oil plants, towns, marshalling yards and other targets in north-west Germany. With the onset of winter No. 3 Group was frequently called on to provide support to the ground forces when weather conditions prevented the use of Oboe marking. A notable occasion was during the Battle of the Ardennes when communication centres were attacked. The total number of aircraft despatched on these raids was usually between 100 and 200 aircraft and the attacks were continued at the average rate of three to four per week until the end of the war. The vast majority of the raids were formation attacks made in daylight, but on a few occasions Gee-H aircraft were used as ground or sky markers, and sometimes forces consisting entirely of Gee-H aircraft were despatched to bomb blindly without markers or followers.

On Gee-H formation attacks between a quarter and a third of the total force were equipped with Gee-H. The aircraft were detailed to fly in vics of three or five, or in boxes of four, each vic or box being led by a Gee-H aircraft. Surplus non-Gee-H aircraft, if any, were instructed to fly in a gaggle behind a normal vic. In addition the Gee-H aircraft usually dropped target indicator markers, sky-marking flares or coloured smoke puffs for the benefit of stragglers who lost formation and had to bomb independently. The Gee-H leaders would release their bombs blindly on their special equipment and the other aircraft released immediately on seeing the leader's bombs fall.

O.R.S. Bomber Command spent a good deal of time during the winter of 1944–45 analysing this new technique of bombing. In comparison with other bombing aids, the concentration at this time was about the same as that achieved during H2S attacks on German cities. The Gee-H raids, however, had a considerable advantage in that the concentration of bombing was far more accurately centred, the average systematic error being only 375 yards, as compared with 1,000 yards for H2S attacks. In addition the Gee-H raids were virtually independent of weather conditions provided that the cloud tops were not higher than 17,000 feet, whereas H2S (Newhaven marking) attacks, being dependent on visual marking of the aiming point, could only be carried out in reasonably clear conditions.

It was estimated that, using the Gee-H formation bombing technique, a force of 80 to 90 aircraft could achieve a density of 180 tons of mixed high explosive and incendiaries per square mile which on a German city would correspond to about 75 per cent devastation in the area where the attack fell. On most of the Gee-H attacks on German towns almost double this number of aircraft were sent and it is therefore not surprising that almost all these attacks were outstandingly successful. In particular Bonn, Solingen, Witten and Wesel all suffered extremely heavy damage as a result of attacks of this type.

Various improvements were suggested by the O.R.S. including the elimination of gross errors and the need for better formation flying, and an analysis made in the closing months of the war showed that a considerable improvement had taken place. These improvements were due principally to better handling of the equipment and to the improvement in formation flying which had occurred from continued practice.

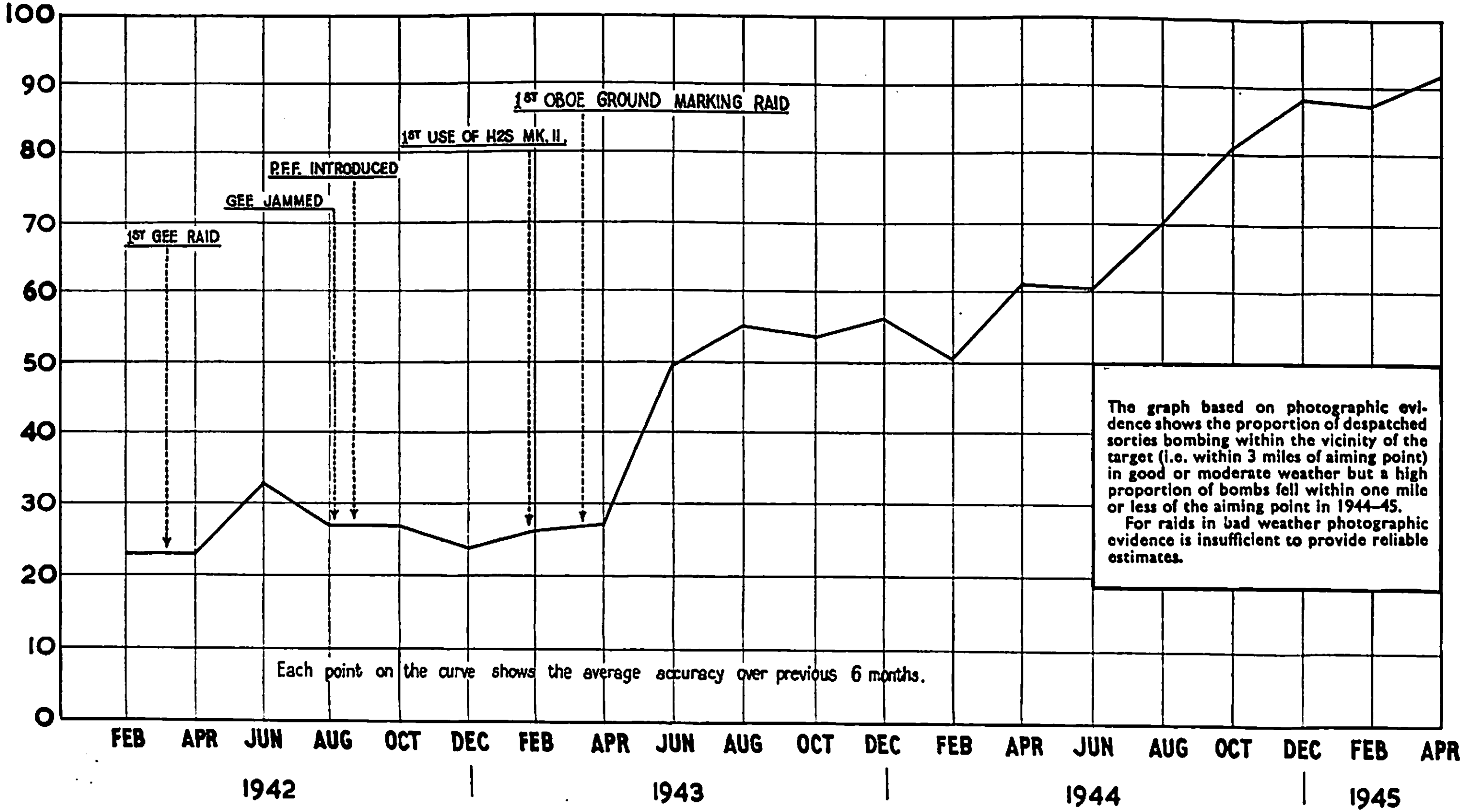
(f) *The Final Stage of the Bombing Offensive*

H2S, Gee and Gee-H were, in the final stages of the war, the chief radar-fixing devices at the disposal of the navigator by means of which he could keep a continuous and accurate record of his course and bomb with a high degree of precision. Oboe was also used as the primary method of marking in the preparatory operations for the landings in France in which Bomber Command was given the unaccustomed role of making precise attacks on small targets (marshalling yards in France and Belgium) and it was also used in the close bombing which assisted the Army to break out of the Normandy beach-head. This was the major Allied enterprise for 1944, and the operations by Bomber Command in preparing the way for and in support of the landings were vital to its success. The O.R.S. was able to supply the necessary advice on the best way to attack these precise targets.

It was not until the beginning of 1944 that detailed information on which to base any estimate of the size of the force which would be required to destroy any particular target was available. For the operations mentioned above, however, the O.R.S. developed methods of forward planning which enabled them to provide information on the effort required to achieve the level of damage desired by the military authorities. These methods were first applied with considerable success, to the attacks on the French marshalling yards, and were also made use of in the operations against coastal batteries, German marshalling yards, synthetic oil plants, U-boat assembly yards and other targets. Towards the end of 1944 the technique of forward planning was further developed to enable estimates to be given for attacks on large targets such as towns. These estimates proved of great value during the summer of 1944 when, owing to the very large number of targets which had to be put out of action within a strictly limited period of time, it was of the utmost importance that the forces at the disposal of Bomber Command should be employed in the most economical manner possible.

The attacks on transportation were the subject of a series of reports by the O.R.S. which showed that while there was a high percentage of gross errors the accuracy of the Oboe marking was approximately 330 yards. This was of the order expected when the O.R.S. had planned the requirements for these raids. A number of gross errors were eliminated by revising procedures at the ground stations and in the aircraft, while the

ACCURACY OF NIGHT BOMBING OF GERMAN CITIES (EXCLUDING BERLIN)



introduction of an Oboe Computing Section[1] enabled controllers to spend more time in checking the equipment itself.

By the end of 1944 Bomber Command had undoubtedly reached a very high standard of accuracy. This was due to a number of factors, in particular, the successful use of H2S and Oboe against precision targets in enemy-occupied countries and the Ruhr. Not only were the attacks against French and Belgian transportation targets in the preparatory operations for Overlord highly successful but in the attacks on the Ruhr oil refineries 50 per cent of bombs carried fell not more than 500 yards from the centre of the target. When Gee chains were eventually set up on the Continent even long range German area targets were attacked with far greater effectiveness, 50 per cent of bombing arriving within an area just over a mile from the aiming point, or taking the original bombing criterion devised in the early days of the bomber offensive (the number of bombs dropped within three miles of the aiming point), an overall bombing efficiency of 95 per cent was achieved. While the credit for the development of these blind bombing and navigation aids belongs, of course, to T.R.E., O.R.S. Bomber Command contributed greatly to the success of their use in the field.

(g) *Navigational Problems*

So far the development of the various radar aids to bombing and route-finding have been described. The contribution of the O.R.S. to navigation performance and techniques must now be considered briefly. This began when the O.R.S. first analysed navigators' logs in the autumn of 1942 with the object of discovering the relation between the degree of concentration of aircraft on a raid and the risk of interception by enemy fighters. After analysis of certain raids, in conjunction with the examination of logs and photographic evidence, it was found that the lower the concentration, the greater the risk of interception. Analysis of navigators' logs for different purposes continued thereafter throughout the war. One, for example, held in No. 5 Group led to a new and improved system of lighting for the navigator's cabin.

Astro sights and the frequency with which they were used on operations were also investigated. As the information could not be extracted from the navigators' logs special returns were devised. In the initial analysis the O.R.S. discovered that about 40 per cent of the bomber crews took astro sights and that the average number of sights taken by navigators who made use of astro navigation was about four per sortie. Tests were made also to discover the efficiency of several types of sextant.

[1] The Oboe Computing Section, originally suggested by O.R.S. Bomber Command, consisted of W.A.A.F. personnel under a mathematician from A.W.A.S. Their task was to take over from the Oboe controllers the calculation of target settings as the number of targets attacked per night had become so great during 1944. The section was trained by that autumn and considerably reduced the number of computational errors.

The introduction of the air position indicator into Pathfinder Force aircraft was the occasion for an analysis by the O.R.S. of its operational performance. Throughout its period of use a number of faults were indicated and improvements recommended. In early 1944, for example, the air position indicator installed in the Lancaster bomber was subject to serious over reading. A comparison was made with dead reckoning positions based on the use of the air speed indicator. The reason for inaccuracy was due largely to the over-heating of the equipment in the Lancaster, and the O.R.S. was able to prove that when modified the probable random errors of the air position indicator were less than three per cent of the air distance flown and conclusively demonstrated the usefulness and accuracy of the instrument.

For some time a large part of the main force had to rely on dead reckoning while H2S was still in short supply and when targets were situated beyond the range of Gee. Winds forecast by the meteorological officers often differed from those actually encountered *en route*, while it was obviously desirable to help navigators to make a choice of winds. A wind broadcast scheme was evolved for this purpose by the Navigation Branch at Headquarters Bomber Command in conjunction with the O.R.S. The idea was that the best navigators in aircraft equipped with H2S and the air position indicator should find winds for pre-determined sections and height zones of the route, and should transmit these winds to the group headquarters where the group navigation officer and staff were to work out a mean wind (from the values submitted) which was to be broadcast to the main force.

After introduction in one of the groups, the scheme was adopted for the whole command early in 1944 and the procedure of the wind finders and the use made of it by the other bomber crews became the subject for several enquiries by the O.R.S. One of these dealt with the raid on Berlin on 24/25 March in which severe losses were incurred. The findings of the O.R.S. report indicated lack of belief on the part of the wind finders in the unusually strong wind prevailing that night and a time delay between transmissions by wind finder aircraft and the reception of these values at Headquarters Bomber Command.

ASPECTS OF ASSESSING THE EFFICIENCY OF BOMBING ATTACKS

The O.R.S., in addition to examining the effectiveness of bombing and navigational aids, applied itself to the study of individual raids and the reasons for their success or failure in conjunction with certain sections of the Central Interpretation Unit at Medmenham. 'N' Section, under Squadron Leader B. Babington Smith which dealt with night photographs, became closely associated with the Intelligence (Photographs) Branch of Headquarters Bomber Command and with the O.R.S., as it was possible from examination of these photographs to discover the number of aircraft which reached the target, the strength and location of enemy defences and even to plot the positions of the aircraft themselves.

A system was developed whereby it was possible to plot aircraft by means of the fire patterns recorded on the films. Mosaics were constructed showing the position of fires and incendiaries in relation to the target, and these not only gave an indication of the main area under attack (which might or might not be the target for the night) but were a means of determining the position at bombing of a number of aircraft which had failed to secure pictures of ground detail, but had recorded recognisable fire tracks. In this way use was made of many films which previously would have been discarded as unsuccessful photographically, and it could be shown that crews had reached the target, even though they photographed only a mass of fires. Night photographs were also used to reconstruct the flight of aircraft before, during and after bombing. By using an open shutter camera, rigidly mounted in the aircraft, the shape of the fire tracks across the film reflected the movement of the aircraft in the sky. It thus became possible to record the different types of evasive action taken by aircraft.

Extensive use of all these diagrams and reports was made by O.R.S. Bomber Command as they were of great assistance in determining the causes of the success or otherwise of a raid and in planning future raids. The marking of targets by the Pathfinder Force was also plotted, and photographs provided evidence on the relative efficiency of different navigational aids employed by the aircraft dropping the markers. As the bomber offensive developed, not only were far larger numbers of aircraft (each carrying a camera) employed in a single raid, but the number of target condition failures (i.e. films with fire tracks but no ground detail) increased more than proportionately. Consequently a very large number of aircraft had to be 'plotted by fires' rising in some instances to as many as 500 in a single raid. Again the photographs provided the O.R.S. with a measure of the degree of concentration attained over the target. By combining this information with the evidence on markers and enemy defences, supplemented by reports of individual crews who explained how an attack developed around markers dropped by particular aircraft, together with the known plan of attack, they were able to work out changes in incidence of the main weight of attack and in many cases to explain them. In the latter stages of the war photographic interpretation was aided by the use of colour films,[1] and when Bomber Command began to operate extensively in daylight, day films were analysed by the O.R.S. along the same lines as the night photographs. Photographs were also used in the study of decoys and camouflage used by the enemy to divert attacks by Bomber Command.

The effectiveness of weapons formed another subject for research by

[1] The value of colour film lay primarily in the identification of the colour of the markers. It provided valuable evidence for O.R.S. Bomber Command in distinguishing between types of incendiaries and in detecting decoy target indicators.

the O.R.S. It worked out the most efficient bomb loads and advised on the most suitable employment of different types of bombs. An example of the latter concerned the final attack on the battleship *Tirpitz* by No. 5 Group. The O.R.S. recommended that not more than 30 aircraft should form the attacking force and forecast that three direct hits would be achieved. Three direct hits were, in fact, obtained.

The assessment of the effectiveness of bombing attacks on the German economy was the responsibility of the Research and Experiments Department of the Ministry of Home Security. O.R.S. Bomber Command did not attempt studies concerned with the policy of attacking particular target systems but applied itself to the study of the accuracy of bombing attacks, the value of alternative navigational and bombing aids with a view to suggesting ways of improving bombing efficiency.

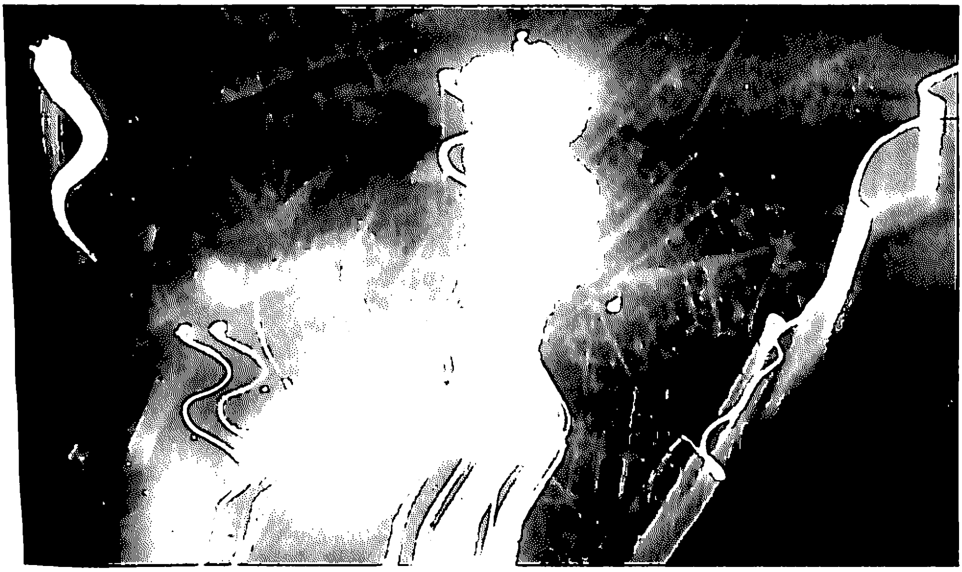
At the first opportunity, however, Headquarters Bomber Command sent members of the O.R.S. to France to study the results of bombing. Shortly after the conclusion of the war, this team, known as the Bomber Command Bombing Research Unit, which was led by Mr. H. L. Beards, visited ten towns in the Ruhr, Rhineland and central Germany which had been subjected to raids by Bomber Command with the object of making a quick survey of the effects of bombing and the causes and extent of the loss of production in certain industries. The reports which emerged from the tour dealt with the effects of bombing in a single town and therefore did not take into account the total amount of dislocation in any one industry. Assessments of this nature were left to the British and American bombing survey units whose formation will be discussed in a later chapter.[1]

PROBLEMS AFFECTING THE COST OF NIGHT BOMBING

A continuous and substantial part of the work of O.R.S. Bomber Command was to discover the causes of, and propose methods for reducing, bomber casualties. The subject was an extremely complicated one since bomber losses varied considerably with the defences encountered *en route* to and at the target, with the weather, with the flying characteristics of the aircraft, and the experience and ability of the crew, with the special radar and other protective devices carried and with the radio counter-measures used. The enemy defence system was continually changing and improving, making the problem very difficult and necessitating continuous study. As with other subjects, the O.R.S. maintained a close liaison with the appropriate Air Staff branches of Headquarters Bomber Command, in particular with the Signals, Intelligence and Operations Branches, with other O.R.S.s, especially O.R.S. Fighter Command, the Army Operational Research Group at Petersham and with the various technical establishments.

The data for research came from many sources, the chief of these being from reports by intelligence officers following the interrogation of bomber

[1] See Chap. VII, pp. 148 et seq.



Two night photographs taken by Mosquitos of Bomber Command which show target indicators scattering and bursting in the air during an attack on Berlin. Flares illuminate ground detail and the broad beams of light are searchlights

crews. Intelligence reports gave, for each sortie, particulars as to the time and height of bombing, enemy aircraft seen and the place and time at which aircraft were seen to be destroyed, together with details of intercepted wireless traffic. In order to obtain concentration in space, numbers of navigators' logs had to be back-plotted. Special equipments were placed in the bomber aircraft in order to record the evasive action undertaken. A knowledge of the accuracy of German flak was obtained from experiments made in this country on the penetrating power of hostile anti-aircraft shells combined with a knowledge of the number of flak holes in returning aircraft. Special experiments were made in order to be able to forecast the range of visibility of aircraft at different times during the period of twilight. This, together with the knowledge of the methods used by Fighter and Anti-Aircraft Commands, formed the background for the investigations which were made either on the initiative of the O.R.S. or at the request of the Air Staff of Headquarters Bomber Command.

(a) *Concentration of Aircraft over the Target Area*

Shortly after the institution of O.R.S. Bomber Command in September 1941, when losses were rising as a consequence of the enemy's controlled night fighters, the Air Staff of Headquarters Bomber Command asked the O.R.S. to examine the value of concentration. A study was made of the losses sustained by comparable raids on comparable targets in similar weather conditions and these gave strong indications of the advantage of concentration. The theory of the situation was developed and the O.R.S. recommended that the rate of arrival at the target should never be less than 50 bombers per hour when the moon was down or less than 80 bombers when the moon was high. The figure seemed large at the time and raids of this concentration were ordered by Headquarters Bomber Command with some trepidation, but it should be noted that by the end of the war densities ten times greater than this were being achieved.

The improvement in navigation brought about by the introduction of Gee made concentration more feasible, while the success of the three 1,000 bomber raids in May and June 1942 lent support to the O.R.S.'s conclusion, since in each case the actual loss rate suffered was smaller than would have been expected from previous experience on the same target and under otherwise similar conditions. The O.R.S. shortly afterwards proved conclusively that losses decreased as concentration in space and time increased, and that this was particularly marked when the moon was down. Until September 1943 the policy was for all available forces to attack one target. A concentration of ten aircraft per minute was the aim. From time to time the principle of concentration was viewed by various authorities with some misgivings but throughout the war the O.R.S. sturdily defended its correctness in night bomber raids.

The introduction of Window in July 1943 caused the enemy to despatch his night fighters to the target area rather than to feed them into the bomber stream. After recommendation by the O.R.S. the planned concentration of bombing was stepped up to 30 aircraft per minute. Raids were to be kept as short as possible, as analysis showed that for raids lasting longer than 35 minutes the missing rate was greater than for shorter raids, and aircraft in the rear of the stream were more vulnerable to attack than those in the van. Moreover, short duration raids were of advantage in preventing the mean point of impact of the raids from drifting off the target.

By early 1944 bomber casualties were increasing on account of the numbers of free-lance fighters operating in the bomber stream. There were doubts in many quarters as to whether the principle of concentration was sound. The O.R.S. maintained however that a policy of dispersion would make the bombers easy prey to the G.C.I.-controlled fighters as in the period before Window.[1] But taking a similar number of bombers, the controlled fighters shot down approximately the same number of aircraft that were then being shot down by the free-lance fighters: the only answer was to make the bomber streams as compact as possible. New tactics, in which a number of small forces were despatched against several targets in place of the long, unwieldy bomber streams directed at a single objective, were therefore recommended in the spring of 1944.

Henceforward the size of the individual bomber forces was drastically reduced, the small force in turn tending to become more and more compact. The planned concentration at bombing rarely exceeded 30 aircraft per minute but, in practice, continued improvement in navigational methods gradually led to a much closer adherence to planned routes and bombing times, with the result that the actual concentrations achieved, both *en route* and at the targets, also slowly improved. After the liberation of France, the continental Gee Chain was established, and this caused a great improvement in navigation with a marked reduction in the width of the bomber streams.

(b) *Collisions and Accidental Dropping of Bombs on Aircraft*

Up to May 1942 there had been only one recorded case of damage from a bomb dropped accidentally by one aircraft on another, and there had not been any recorded case of damage or loss by collision. When planning the thousand bomber raid on Cologne, the O.R.S. was asked by the Air Officer Commanding-in-Chief to give an estimate on the number of collisions and amount of damage caused by air-to-air bombing likely to be incurred during a concentration of 1,000 aircraft per hour over the target area. The answer (which was required immediately) was that the frequency of collisions would be not more than one per hour and the frequency of

[1] Strips of tinfoil dropped from the air which simulated numbers of aircraft on the enemy's radar screens.

air-to-air bomb strikes about five per hour. These two figures were arrived at by two different methods which were the foundation of all subsequent work on the problem. The first method, which was used to derive the figure for collisions, was to argue from the fact that a known number of raids had been carried out in the past without (as far as was known) any loss or damage by collision, and the fact that the frequency of occurrence of collisions increased only as the square of the concentration of the bombers in time. From these two facts a rough upper limit was found for the collision risk under the proposed conditions of extremely high concentration. The second method, which was used to derive the figure for falling bomb damage, was to make a direct calculation of the chance of an aircraft being hit by a bomb in space and time over the target. There was not time to make allowance in the calculation for several factors of practical importance, such as the degree of separation of the bombs falling from a single aircraft, but nevertheless the formula arrived at did not greatly differ from the more elaborate ones used later. A subsequent study of the raid revealed that only one aircraft was lost as the result of a collision.

In March 1943 the subject of air-to-air bombing and collisions was revived as there were an increasing number of accidents over enemy territory. This was due to an increase in the concentration of aircraft over the target area made possible by the introduction of Oboe ground marking. The O.R.S. made an analysis from three sets of figures: first, the numbers of aircraft of various types which returned damaged by bombs; second, the total number of aircraft which would theoretically be expected to be hit by bombs, and thirdly, the proportion of bomb strikes on aircraft which would be expected from structural considerations to cause lethal damage to some vulnerable area. The figures led to the conclusion that falling bombs were quite capable of causing the loss of aircraft, but would not destroy more than 0·1 per cent of sorties even in large scale and highly concentrated attacks. The report which was circulated down to groups allayed the fear of the danger of the falling bomb among aircrew and made it easier for the Air Staff of Headquarters Bomber Command to insist on a greater concentration of aircraft in the bomber stream.

Evidence of aircraft colliding with one another on operations was equally, if not more, difficult to obtain. As reports by aircrew were usually unreliable or incomplete owing to difficulty of observation, the following statistical sources were used: first, the statistics of bombers which had returned to England damaged in collisions; second, the total frequency of collisions in the bomber stream as calculated by theoretical methods; thirdly, the estimated chance of survival of a bomber involved in a collision. The principal reason why the collision problem proved so intractable was the lack of precision of the second and third of these sources of evidence. The theoretical formula for the number of collisions to be expected in a bomber stream depended to a critical extent on the small deviations of the bombers from their prescribed course and the magnitude of these deviations could only be guessed at. It was also impossible to ascertain the causes of collision from examining damaged aircraft. Furthermore, no help could be gained from examining the figures of aircraft damaged and destroyed in collisions over Great Britain. These figures were few in number and the conditions in which the accident took place were totally dissimilar to the conditions experienced on operations.

A number of reports were compiled by the O.R.S. on this subject, but their conclusions were cautious in tone. The evidence pointed to a loss rate of not more than 0·2 per cent of the sorties flown. This result led the Commander-in-Chief Bomber Command to issue orders to close up the bomber streams on the grounds that losses due to collisions would remain of little importance compared with losses due to enemy action.

The problem of collisions came to the fore again during the planning of precision bombing attacks and airborne operations in support of the landings in Normandy in June 1944. The estimate for the precision bombing operation was required by Headquarters Bomber Command and that for the glider operation by O.R.S. A.E.A.F. In each case the collision risk could be calculated without difficulty from theoretical considerations, given the dimensions and movements of the forces involved, although it was questionable whether the given dimensions could be adhered to in practice. The general conclusions reached were that in the case of the bombing operation the risk of collision would be a negligible factor, while in the case of the glider operation the risks might be very severe. During the following months small losses were experienced during the attack of French and Belgian transportation targets while the tug aircraft on the night of 5/6 June flew to the landing zones with navigation lights switched on so as to avoid collisions.

The advance of the Allied armies to the German frontier made the task of analysing collisions between bombers much easier. During the autumn and winter of 1944 large streams of bombers frequently flew over occupied territory under conditions not greatly different from those experienced over Germany. A number of collisions occurred and it was discovered that of those aircraft which were involved in collisions over enemy territory 64 per cent became missing. This figure gave good confirmation to earlier estimates. A report on bomber collisions during the period April 1944 to January 1945 concluded that the losses due to collisions had at no time exceeded 0·25 per cent of the sorties. The O.R.S. recommended that concentrations should not be reduced in order to reduce the risk of collision as the threat from the night fighter was still more dangerous. The recommendation became the basis of Bomber Command's tactical policy until the end of the war.

(c) *Evasive Action from Heavy Flak*

From its inception O.R.S. Bomber Command was interested in the problems arising from the evasive action (height variations up to 1,000 feet accompanied by changes in course) taken by bombers from heavy flak. Experiments carried out by the Army Operational Research Group in October 1942 attended by members of O.R.S. Bomber Command showed that the chances of an aircraft being hit whether it was taking evasive action or not were roughly even. The O.R.S. was therefore prepared when Air Chief Marshal Harris, concerned at the low standard of bomb aiming and doubting the value of evasive action, called for an enquiry.

The conclusions drawn from the O.R.S. investigation caused the Air Officer Commanding-in-Chief, on 5 May 1943, to inform all groups that evasive action over a hotly defended target was meaningless especially when a high concentration of aircraft was achieved. Furthermore, the risk of collision was increased and accurate bombing was made impossible, making a repeat attack necessary. This entailed in the long run a higher number of casualties. Later the O.R.S. report was published as a Bomber Command Tactical Memorandum in which the arguments put forward for the abolition of evasive action in target areas, except when held in searchlights, were to be communicated to aircrews.

(d) *Policy of Opening Fire First*

It became generally acknowledged among groups that enemy night fighters tended to shy at bombers if fired on first. No. 5 Group, in particular, advocated these tactics. The new enemy night fighter tactics adopted after Bomber Command began to use Window, in which freelance fighters patrolled the target area, brought about a noticeable increase in the number of combats by bombers with night fighters, especially in No. 5 Group. A comparison was made by the O.R.S. between the records of Nos. 5 and 1 Groups for two four-monthly periods immediately preceding and succeeding the date on which No. 5 Group adopted its more aggressive policy. The O.R.S. concluded that too great a readiness to open fire, as in the case of No. 5 Group, had increased the risk of attack by fighters and that a small, but growing, proportion of bombers were being attacked and damaged by fire from other bombers. While some of these incidents were due to premature firing on unidentified aircraft, the majority resulted from mistaken identification. It was considered that the results warranted a warning to crews not to fire on unidentified aircraft, and it was recommended that every effort should be made to provide means to distinguish friend from foe.

(e) *Aircrew Casualties*

There was a widespread feeling in Bomber Command that personnel casualties were high and an investigation into casualties among operational crew was made in February 1943. From the data available (drawn from casualty and medical officers' returns) it was possible to establish the circumstances of almost every incident. It was found that the number of casualties in returning bombers was low and that there were, on the average, 1,013 man sorties per casualty in returning bombers due to flak, and 1,150 man sorties per casualty due to fighter. The number of casualties per aircraft damaged due to flak was 0·07 and 0·05 per aircraft damaged by fighter. These figures did not vary greatly between various types of aircraft. Analysis showed that the number of aircraft lost primarily due to death or severe injury to the pilot must be very small. Only 20 per cent of all casualties were fatal or dangerous.

The use of special armoured clothing by American bomber crews raised the question whether protection should be issued to British crews or not. The investigation, made early in 1944, showed that the use of the American type of flak jacket would only be effective in preventing one moderate or slight casualty per thousand man sorties and that in view of its weight, with the fatigue it would produce, would be likely to do more harm than good. The adoption of the flak helmet was condemned for similar reasons. As a result of the investigation body armour was not manufactured for aircrew.

The O.R.S. also investigated the available information regarding the number of prisoners of war and the number of crews that were successful in returning to Great Britain after being forced to land over enemy territory. This report revealed that the proportion of missing aircrew that survived to become prisoners of war was 11 per cent for Lancasters, 17 per cent for Stirlings and 29 per cent for Halifaxes. The low rate for Lancasters was thought to be due to the fact that it was more difficult to move about in this narrow aircraft to the small forward compartment and to the poor rear escape hatch. It was also thought possible that the Lancaster was more liable to break up in the air and that the higher flight conditions might increase the difficulties of escape after the removal of the oxygen masks. The O.R.S. suggested that consideration should be given to the possibility of fitting a rear floor escape hatch to the Lancaster and that all the escape hatches should be re-examined with a view to re-designing to prevent jamming. More training and practice in emergency drill were also considered to be necessary.

Another survey dealt with the effect of pilots' operational experience on the loss rate of particular types of aircraft. This took place after a large number of Halifaxes became casualties in the autumn of 1942. It was found that the number of sorties which pilots made before failing to return was dependent upon the number of second pilot or 'fresher' trips they had made before becoming a captain or going on to main targets. Of the pilots who had become missing, those who had done under three second pilot or 'fresher' trips had an average life of about two operations on main targets, but those who had done six second pilot or 'fresher' trips had an average life of about eight operations. The result of this investigation was that all

Halifax pilots were sent on a series of cross-country training flights, on two or three sorties as second pilots and on two mining operations before being promoted to captains of aircraft involved in raids on main targets.

Further reports were requested by Nos. 4 and 5 Groups, and the O.R.S. again confirmed that inexperience was the major contributing factor to losses. The O.R.S. advised that efforts should be made to increase the verisimilitude of operational training and that long practice flights with fighter affiliation should be made.

(f) *Tactics on Very Light Nights*

Bomber Command was compelled to operate at night because of the high losses sustained on daylight operations. The hours of darkness over or near enemy territory were determined from the Nautical Almanac and it was assumed that it was sufficiently dark to fly over enemy territory at Nautical Twilight, i.e. when the sun is 12 degrees below the horizon. The corrections for height—in order to obtain any given degree of darkness—were given in the Almanac and these were used. But both the loss rate and the percentage of bomber sorties intercepted rose during the summer months and aircrews complained about the lightness of the northern sky at this time.

The O.R.S. was called upon to make an investigation. Among other things the method used for calculating the onset of darkness in the Nautical Almanac was found to be erroneous and a more accurate method was devised. The O.R.S. also discovered that the silhouette visibility of aircraft at twilight in the direction of the sun is greatly increased while the visibility in the opposite direction is not much greater than on normal nights. Hence although fighters—which always chose the direction of attack in which the visibility was greatest—would always have the maximum advantage, the bomber would only have a slightly greater than normal visibility range on a fighter. Therefore the bomber force in order to keep down its casualties on midsummer nights must fly low, keep as far south as possible and reduce the amount of time spent over enemy territory.

On 24 June 1944 the following conditions for attacks on the Ruhr by 300 aircraft were postulated by the O.R.S. Firstly, an attack by six successive waves of 50 aircraft each proceeding and leaving the target by different routes; the routes were to be spread over a front of about 300 miles. Secondly, an attack by six waves of 50 aircraft each proceeding to and leaving the target by different routes but all waves attacking simultaneously over a period of 12 minutes. The Commander-in-Chief gave his assent to these proposals.

(g) *New Bomber Tactics in Early 1944*

The depredations made by the enemy free-lance night fighters in the bomber streams at the beginning of 1944 provided the O.R.S. with an opportunity to make a fresh analysis of the tactics employed. It had been its practice for some time to investigate the tactical plan and results of each night's operations and to prepare reports detailing the plan employed, weather conditions, enemy defences encountered and causes of the losses sustained. Each report included a map showing outward and homeward routes for main and diversionary attacks, positions at which route markers were dropped, positions and time of night fighter interceptions and the positions, times and causes of all observed losses. In the new analysis the maps were first completed by adding to them the positions of the enemy night fighter beacons used, and the movements of the various night fighter *Gruppen*, with their approximate timing, as revealed by the intercepted wireless traffic. The latter had always been studied in preparing the nightly reports but until now the fighter movements had not been shown graphically in relation to the operational plan. It is probable that but for this omission the cause of the rising bomber losses would have been appreciated more quickly.

The O.R.S. had, however, for a long time been worried about the stereotyped attacks being mounted and had given consideration to alternative tactics and had put forward a memorandum about it. This recommended that the bombers be split up into small forces in order to avoid the attentions of night fighters or, alternatively, should be sent to the target on two widely separated routes. The use of markers *en route* should be discontinued as it was thought they were of more asistance to the enemy than to the bombers. More attention should be paid to diversions and more extensive radio counter-measures.

Headquarters Bomber Command appreciated the value of the new tactics but did not want to make a change until it was satisfied that the old tactics were outworn. Only when several bad losses had been sustained did the Commander-in-Chief order a change early in 1944. Apart from the two attacks against Berlin and Nuremberg in March (when the new tactics were not followed) the loss rate steadily declined. The tactical principles summarised briefly above, which were intended to divide and confuse the enemy night fighter defences, continued to form the basis of raid planning until the end of the war, though it was not until after D Day, when the large scale use of radio counter-measures became practicable, that the fullest value was obtained from them.

(h) *Vulnerability of Aircraft*

Until the formation of O.R.S. Bomber Command no attempt had been made to analyse precisely the cause of an aircraft's loss in action. No casualty returns were kept of damaged aircraft during the First World War. These would have been invaluable and would have shortened the time lag that occurred between the first sign that a modification was required and its incorporation in an operational aircraft. The delays were, in certain cases, responsible for grievous losses of aircraft in Bomber Command. Both before and during the first two years of the war, the main causes of loss were generally attributed to loss of petrol from a holed tank, stoppage of an engine, killing of the pilot, or damage to the controls.

A section of the O.R.S. under Mr. E. A. Lovell was established to investigate the nature and severity of damage to returning aircraft in an attempt to determine causes of loss and the general vulnerability of the various components of the aircraft. As a beginning a study was made of all existing forms rendered to Headquarters Bomber Command, including casualty signals, circumstantial reports on casualties to personnel, Forms 'Z', flight engineers' logs, etc. This information was found to be completely inadequate and a special enemy action damage form, including diagrams on which to mark the damage, was instituted. A handbook to assist in assessing the cause of damage was prepared and issued at the time since it was found that aircrew and ground staff often incorrectly diagnosed this. It is of interest to note that this system of damage reporting was copied by all other operational commands of the R.A.F. in Great Britain and throughout the bomber forces of the United States Army Air Forces. After a time it became apparent that valuable information was being missed by inadequate completion of the forms, particularly in the case of very severely damaged aircraft, and, in February 1943, it was decided to appoint Damage Inspectors (trained engineers) to each group who assisted in examining the damage on aircraft and in compiling the report.

Although in the early days of the O.R.S. there were insufficient data from which to draw firm conclusions, even in January 1942 attempts were made to provide guidance on problems of vulnerability. The first problem was to discover the comparative vulnerability of air- and liquid-cooled engines, but all that could be done in those days was to supply details of the missing rates of the various types of aircraft then in operation. It was shown that liquid-cooled engines were the more vulnerable, largely because (it was confirmed later) of damage inflicted on the radiator. The next problem concerned the comparative vulnerability of hydraulic and electro-hydraulic turrets. The data available were very scanty, but the vulnerability of the hydraulic system in, for example, the Lancaster, appeared much higher than the electric-hydraulic system of the Halifax. The number of cases of damage to the electrical part of the turret system among returning aircraft was surprisingly small, being only one case in 450 sorties.

An examination was made in collaboration with the Army Operational Research Group on the damage caused to aircraft by anti-aircraft fire. The first report showed that the great majority of aircraft damaged by heavy flak received only two or three strikes. There were few cases of aircraft having more than 20 strikes. The report also indicated that strikes from below were twice as numerous as those from above—a result which was of value not only in assessing the type of engagement by which flak damage was caused but also in calculating the expected number of strikes on various parts of the airframes.

A close watch was kept on all fragments of enemy munitions found lodged in damaged aircraft to ascertain whether they presented new or unusual features. The discovery that the enemy was using controlled fragmentation of his heavy anti-aircraft shells was made in March 1943 when a rectangular shaped fragment, showing longitudinal cuts on the outside face, struck and lodged in a bomber flying over Essen. Other fragments with similar characteristics were recovered from aircraft flying over the same area in the course of the following weeks and were sent to the Ordnance Board with the suggestion they might be the result of controlled fragmentation. Some months elapsed, however, before the experts were convinced of the correctness of this view.

The greatest single hazard to aircraft was undoubtedly the possibility of catching fire in mid-air, and the O.R.S. was deeply concerned in ascertaining the causes of fire and suggesting various remedial measures. In September 1942 an analysis of enemy aircraft casualties over Great Britain revealed that about 25 per cent of the raiders fell in flames, and it was suggested that a similar proportion of British aircraft was lost in the same manner when becoming casualties over enemy territory. Evidence showed that fire frequently derived from explosions in a fuel tank, usually one which was partially empty. One way of preventing this was to produce an inert atmosphere in tanks by injecting nitrogen supplied from high pressure bottles. The effects of a night fighter's armament on a bomber were investigated and tests in which incendiary bullets were fired against fuel tanks were made. The O.R.S. also believed that inert fragments from anti-aircraft shells caused fires in fuel tanks. There was no direct evidence as to whether fires started on the inside or on the outside of a tank, but the O.R.S. believed that the most likely origin of tank fires was the ignition of an explosive fuel vapour-air mixture inside the tank by a single shot and insisted that measures to prevent explosions inside the tanks should have priority over those designed to deal with fires starting externally.

To prove this the Royal Aircraft Establishment carried out an experiment in which two self-sealing fibre tanks of 40 gallons capacity, each containing 10 gallons of petrol, were cooled to 20 degrees centigrade and one round of incendiary ammunition was fired at each, through the space above the petrol. Both tanks at once exploded and burst into flames. In spite of this apparently conclusive evidence, trials and discussions went on interminably until at last, in April 1943, Bomber Command demanded that all four-engined aircraft should be equipped with a system for the introduction of nitrogen into fuel tanks sufficient for a seven-hour flight as soon as possible. Although the work was placed on the highest priority the first aircraft equipped with the nitrogen system did not operate until April 1944, and even then several defects were discovered, necessitating the aircraft to be withdrawn, so that by the end of the war little advance with this modification had been made.

RESEARCH INTO EXPENDITURE OF AMMUNITION BY AIR GUNNERS

The requirements for stocking aircraft with ammunition were investigated by the O.R.S. with the object of striking a proper balance between equipment, fuel, oil, etc., and the offensive load such as bombs and ammunition. There was stowage capacity for a considerable quantity of ·303 machine gun ammunition amounting to 18,000 rounds (over 1,000 pounds weight) in heavy bombers. An analysis made in June showed that 1,000 rounds for the mid-upper turret were sufficient for 99 per cent of combats (the average was 235 rounds) and in the case of the rear turret 2,000 rounds were adequate for 99 per cent of combats, 1,100 for 90 per cent and 550 for 75 per cent. The O.R.S. pointed out that a useful saving in weight could be obtained by restricting the amount of ammunition carried for use by the rear turrets of all heavy bombers engaged on night operations to 3,000 rounds (the stowage capacity was 10,000 rounds). This would allow a reasonable margin above that required for combat for gun warming and testing. At the same time it was recommended that stowage of larger capacities should be retained in case aircraft should later meet with changed conditions.

THE EFFECT OF ICING ON BOMBER OPERATIONS

A subject which caused Headquarters Bomber Command some concern was the possibility that an undue proportion of aircraft might become lost while flying in icing conditions. An early report of the O.R.S. concluded that the engine of the Wellington Ic was peculiarly susceptible to icing but that otherwise the proportion of sorties missing on operations was roughly the same whether icing conditions appertained or not. The introduction of alcoholised fuel greatly improved the performance of the Wellington when there was ice about. Later *Kilfrost* de-icing paste was spread on the edges of the wings and control surfaces, the object being that any icing forming on the paste would break away with some of the paste before any great weight of ice had been built up. Experiments were made in which half the operational force used *Kilfrost* on the leading edges of all wings and control surfaces while the other half used it only on the leading edges of control surfaces. As the two methods of application made no difference to the number of aircraft casualties it was decided in view of the amount of time required to spread on the paste, together with the extra weight upon the aircraft, *Kilfrost* paste would only be spread on the leading edges of control surfaces.

The O.R.S. continued to try to find out the proportion of aircraft lost due to icing but very little direct evidence emerged and, in the spring of

1944, it was concluded that the effect of icing on bomber operations was, on the whole, negligible. The policy of Bomber Command was then to avoid flying in icing cloud conditions, but the O.R.S. warned that if it became necessary for bombers to fly in all weathers, the icing losses would be bound to increase.

FUNCTION OF THE O.R.S. IN RELATION TO RADIO COUNTER-MEASURES

The object of radio counter-measures in Bomber Command was to reduce losses. In brief, the principle of the radio counter-measures was to deny to the enemy radar installations the information that they sought and to prevent the passing of information by wireless means. Later in the course of the bomber offensive radar search apparatus was fitted into bombers in order to provide aircrews with warning of imminent hostile action against them, and into fighters used for bomber support. Radio aids provided specifically as aids to navigation also had an effect on the defence of bombers as they assisted in maintaining a high concentration of bombers in space and time, which was proved to be a powerful tactical counter-measure against the enemy defences.

The role of the O.R.S. in this field was to study operations, suggest radio counter-measures and assess the effects. A section under Dr. S. C. Britton was established for this work. The O.R.S., of course, worked closely with the Signals Branch at Bomber Command and with T.R.E. Assessment usually took two forms, first to compare operations before and after a new counter-measure had been introduced and, secondly, to investigate to what extent the enemy had been forced to adopt new tactics and to modify his weapons. Thus an index of the effectiveness of anti-aircraft gunfire could be provided by the extent of damage on the bombers by flak while fighter activity could be gauged by the proportion of bombers reported as attacked or damaged by fighters. The statistics of each damaged aircraft were obtained from the special returns made to the O.R.S. after every sortie. Apart from attempts to estimate the quantitative effects of counter-measures, the O.R.S. found it possible to learn something of the effects by observing the enemy's reaction to their application; sometimes the reaction could be deduced from the reports of aircrews and could be detected by O.R.S. methods. Thus the position along the bomber's route at which fighter activity was experienced might be indicative of changes in the enemy defence system, in which case the normal reports of crews would suffice, or some specific effect like the behaviour and effectiveness of searchlights might be sought by having the crews make a special report on a *pro forma* prepared to extract the expected information. Other effects could only be perceived by intelligence methods, e.g. changes in frequency of enemy radar could be detected by listening equipment.

Another way by which the O.R.S. was able to assist the development of radio counter-measures was by making an analysis of the enemy's system of defence. The collection of information was, of course, the responsibility of Intelligence but frequently the value of their papers was enhanced by a more analytical scrutiny. An important example of this work which had a strong bearing on the determination of which radio aids offered the highest returns was the assessment of the relative contributions of the various causes of loss of bombers to the total wastage.

In decisions of policy, concerning either general lines or the scale and mode of application of a particular measure, the O.R.S. almost invariably had a part to play. Most of these decisions had to be based on an incomplete knowledge and frequently had to take into consideration that a device designed to confer a benefit might also have harmful effects. For example, the introduction of an electrical airborne jammer for a type of enemy radar set had a benefit incalculable because of uncertain knowledge of the enemy's reliance on that particular set and would introduce an unknown risk that the enemy would use the jamming signal as a means of detecting and destroying its source. Decisions therefore had to be based on judgments arrived at after full discussion.

The O.R.S. was represented on various committees concerned with radio counter-measures both at Headquarters Bomber Command and at the Air Ministry. Its special role in these discussions, in addition to putting ideas into the common pool and presenting assessments of the results of measures already in operation, was to present the facts gathered from all sources in a clear and balanced form either verbally or in the form of a written appreciation so that the issues to be judged could be readily appreciated. When in December 1943 No. 100 Group became responsible for the operation of radio counter-measures an O.R.S. representative was attached to the group. He was able to pay special attention to the day-to-day problems of the group while maintaining close liaison with the general investigations carried on at command headquarters.

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It is, of course, impossible to describe the whole sphere of activities of O.R.S. Bomber Command which covered practically every aspect of the Command's operations and logistics, but enough has been said to demonstrate the contribution which the O.R.S. made to the bombing offensive against Germany by reason of its recommendations in regard to bombing techniques and tactics and by virtue of the data it was able to present to the Air Staff of Headquarters Bomber Command to enable them to take sound decisions.

CHAPTER V

Operational Research in Coastal, Transport and Flying Training Commands, 1941 to 1945

FORMATION AND ORGANISATION OF O.R.S. COASTAL COMMAND

As in Fighter Command, the need for an operational research section in Coastal Command arose in connection with the development of radar equipment, in this case A.S.V. or Air Detection of Surface Vessel, which was designed to assist in the detection of ships, convoys and submarines at ranges beyond that of the naked eye and in darkness and conditions of poor visibility. The Signals Branch of Coastal Command being strange to the new equipment, Mr. J. C. Kendrew, an officer of T.R.E., was seconded in the autumn of 1940 to study the operation of A.S.V., but primarily to pay educational visits to squadrons which were being fitted with the equipment and to act as a liaison officer between Coastal Command, the Ministry of Aircraft Production, and T.R.E. He was not, therefore, at that time conducting operational research in the proper sense of the term. However, by the middle of 1941 the time was ripe for an analysis which would give the operational performance of the equipment in greater detail.

In March of that year Professor P. M. S. Blackett was appointed personal scientific adviser to the Air Officer Commanding-in-Chief Coastal Command. Professor Blackett was no newcomer to the problems of air and sea warfare for it has been seen that he had already organised an operational research section at Anti-Aircraft Command and prior to that had worked on problems of submarine detection at the Royal Aircraft Establishment. By the summer of 1941 O.R.S. Fighter Command had thoroughly proved its value and the Air Staff favoured the idea of setting up further sections. Mr. Larnder therefore visited Headquarters Coastal Command to advise on the constitution of an O.R.S. and it was agreed that it should be formed under the direction of Professor Blackett. Professor E. J. Williams, the physicist, who had also been working at the Royal Aircraft Establishment and who subsequently joined the new O.R.S., succeeded Professor Blackett when the latter became Director of Naval Operational Research in January 1942.[1]

The three principal tasks of Coastal Command were the protection of

[1] Obituary notice of Professor E. J. Williams by Professor Blackett (*Obituary Notices of F.R.S.s.*, Vol. 5, 1945–48).

convoys, in the course of which attacks might be made on molesting U-boats or surface vessels; secondly, the general protection of shipping by cutting U-boats' or surface vessels' mobility, by harassing them or sinking them at sea; and, thirdly, offensive operations against enemy shipping at sea or in port. The O.R.S. was associated with all these activities and came to be divided into four groups, in each of which a leader was responsible for the detailed direction of the officers under him. Two of the leaders were the officer-in-charge of the section and his deputy, so that there were only four officers in all responsible for the work. The four groups dealt with the following subjects:

(a) Anti-U-boat Operations
(b) Anti-shipping Operations, Photographic Reconnaissance and Weapons
(c) Planned Flying and Maintenance
(d) Weather and Navigation

O.R.S. Coastal Command did not expand like the sections in Fighter and Bomber Commands and never at any stage in its existence during the war were there more than approximately twenty-five members. Moreover, a number of them were of a high intellectual calibre and six members of the O.R.S. were, or later became, Fellows of the Royal Society. Like O.R.S. Bomber Command it refused to become entangled in routine statistical work and a small statistical section was formed for this purpose. Following the example of the other two Home Command research sections good relations were maintained with the Air Staff of Coastal Command while the section also collaborated closely with operational researchers from the Royal Canadian Air Force[1] and with the Anti-Submarine Warfare Operational Research Group (A.S.W.O.R.G.) of the U.S. Navy.

Before describing the activities of O.R.S. Coastal Command, a reference must be made to the Air-Sea Warfare Development Unit (A.S.W.D.U.) formerly known as the Coastal Command Development Unit. This unit which operated on similar lines to a normal general reconnaissance squadron was formed late in 1940 for the purpose of investigating and handling radar equipments. The unit inevitably became concerned with the development of tactics for the operational use of Coastal Command. It acted therefore as a link between the research establishments and the operational squadrons as far as new equipment was concerned. It was natural that the O.R.S., which was preoccupied with the analysis of operations, should become closely associated with its activities. By the end of the war five members of the O.R.S. were attached to the unit for the purpose of advising its commanding officer on the scientific aspects of its work, both in the forward planning of trials and in the subsequent analysis of the results obtained.

[1] For a note on the O.R.S. R.C.A.F., see Chap. IX, p. 183.

PROBLEMS INVOLVED IN THE ATTACK OF U-BOATS, 1941

First and foremost O.R.S. Coastal Command was concerned with defeating the U-boat threat. The position in 1941 was that the U-boats were operating in 'packs' well out to sea and submerged as much as possible during daylight, surfacing at night. They concentrated on their targets by making unrestricted use of wireless which was the chief weakness of this method of attack. But for the time being it was profitable. During 1941 the overall sinkings were 2,171,754 tons for a loss of 35 U-boats or 62,000 tons per U-boat lost. The average number of U-boats at sea was 24, so that these results correspond to 7,540 tons per U-boat at sea per month.[1]

The sighting and attack of a U-boat was a sudden, fleeting affair and in a few minutes several hundred hours of operational flying and even more hours of work by maintenance staff and other ground personnel might either reap a reward or be wasted. In fact, improvements to the effectiveness of attack were possible during the war on a far larger scale than in any other sphere of Coastal Command's activities; the lethality per attack on a visible U-boat rose from two or three per cent in 1941 to about 40 per cent in 1944. O.R.S. Coastal Command, working in conjunction with the Naval Staff of Headquarters Coastal Command which included several officers with wide experience of submarine warfare, claimed a share of direct responsibility for this development. Its early analyses were often in direct conflict with accepted R.A.F. doctrine and the beliefs of operational staff. There was probably no field of the Command's activities where a greater dividend was paid by the scientist's insistence on relying on facts rather than on opinions.

Throughout the war the main weapon used by aircraft against the U-boat was the depth-charge or anti-submarine bomb, usually fused with a hydrostat or time delay so as to explode without the necessity of contact with the U-boat. The depth charges were normally dropped in sticks, each stick consisting of a number of depth charges which fell in a more or less straight line along the direction of flight of the aircraft. The bombs, after hitting the water surface, travelled forward a certain distance, sinking as they did so. After the pre-set delay, or having reached a certain depth, they exploded; and each explosion created around the bomb a spherical region within which the pressures were such that a U-boat within it was almost certainly sunk. This region was known as the 'lethal sphere' and its radius the 'lethal radius'. Somewhat larger spheres corresponded to the 'damaging radius'. Strictly speaking these spheres should be defined in terms of a specified probability that U-boats lying within them would be sunk or damaged, but the accuracy with which their dimensions are known is so low that nothing is gained by insisting on such strict logicality.

[1] These figures are derived from post-war analysis and are somewhat larger than contemporary estimates.

In the first two years of the war attacks on U-boats by aircraft were usually made with depth charges fused one second delay or set for hydrostatic initiation at 100 to 150 feet. The results of these operations up to August 1941 were analysed by O.R.S. Coastal Command in a report which can certainly be taken as one of the classics of operational research literature.[1] It transpired that only about one per cent of attack had led to assessments of 'definitely sunk' and about two and a half per cent to 'probably sunk'; a further 15 per cent had resulted in some damage. The U-boats had, in fact, little to fear from an aircraft which was more of a moral deterrent rather than a killing weapon. However, the report went on to show that the comparative failure of attacks against U-boats up to that time was caused by neglect of a few simple considerations, and that aircraft could be given a killing power which was to enable them, by the end of the war, to achieve as large a total of successes as the surface craft.

The crucial point was stated in the Summary of the above report as follows:

> In as many as about 40 per cent of all attacks the U-boat was either visible at the instant of attack or had been out of sight for less than a quarter of a minute. It is estimated from such statistics and the rate at which the uncertainty in the position of a U-boat grows with time of submersion, that the U-boat which is partly visible or just submerged is about ten times more important a target potentially, than the U-boat which has been out of sight for more than a quarter of a minute. The very small percentage of U-boats seriously damaged or sunk in past attacks is probably largely the result of too much attention having been given to the long submerged U-boat. . . . That there is a considerable percentage of U-boats on or near the surface at the instant of attack, and that comparatively small returns are to be expected from attacks on long submerged U-boats, were also pointed out and emphasised in a paper[2] in December 1939.

The Air Staff of Headquarters Coastal Command were also aware of the paramount importance of attacking the surfaced target but depth settings and time delays remained such that little damage was being inflicted on these potentially vulnerable targets. It followed that fresh consideration had to be given to determining the best depth setting against surface targets. This depended very largely on the magnitude of the lethal radius.

The most important weapon was the 250-pound depth charge. The exact value of the lethal radius depended on the nature of the filling. All experimental work available suggested a radius of only about 15 to 20 feet. However, at that time it was not possible to detonate the charge at depths less

[1] The paper was written by Professor Williams.

[2] This paper would appear to have been prepared by the analysis section attached to No. 25 (Armament) Group which shortly afterwards merged with the Air Warfare Analysis Section.

than 100 feet which was too deep to do much damage to a surfaced U-boat. It was not until July 1942 that a pistol capable of detonating at 25 feet below the surface was produced.

The lethal radius of the 250-pound depth charge was, in fact, disappointingly small. Thus great importance was attached to the measures suggested for increasing it. The probability that a U-boat would be partly within the lethal sphere would vary as the cube of the radius, so an increase of the radius by 20 per cent, for instance, would raise the lethality by some 75 per cent. The O.R.S. pressed for strong action to be taken by the Command to obtain depth charges filled with the most powerful explosives. But the responsibility for the allocation of explosives for use in maritime war lay with the Admiralty and not with the Air Staff, and in 1941, torpedoes and hedgehogs[1] had absolute priority with anti-aircraft gun shells and R.A.F. depth charges following. It was not until April 1942 that Torpex-filled depth charges became available and were the standard weapon for the greater part of the war.

O.R.S. Coastal Command was also a protagonist in the cause of the low-level bombsight. In the early days of the war all low-level attacks on U-boats were carried out visually. Like the Air Staff of Coastal Command, the O.R.S. believed it was better to continue making attacks on surfaced targets, and this policy was adopted, attacks on submerged craft being developed in the later stages of the war.

A number of unofficial low-level bombsights were available at this time in default of a standard sight which had been asked for early in the war, but only one showed any signs of becoming a success. The O.R.S. played a considerable part in pushing the development of this sight, worked out detailed instructions for its use and paid many visits to stations to help in its introduction. But the sight was not a success. The two main difficulties were that, being fixed in the aircraft, it catered only for a pre-determined aircraft altitude and it was too sensitive to errors in the height fed in. At length in mid-1943 the Mark III low-level bombsight, which operated on the angular velocity principle, came into use. When first brought to the attention of O.R.S. Coastal Command in 1941, a somewhat pessimistic view was taken, but in practice it turned out to be the only successful visual sight developed for low bombing. The O.R.S. calculated suitable stick spacings for it, assuming errors on the basis of trial results. As it happened the release of depth charges by visual estimation was extremely accurate and more U-boats were sunk this way than by the use of a bombsight.

OPERATIONS AGAINST U-BOATS IN DAYLIGHT: SIGHTING PROBLEMS

Daylight operations against U-boats were dependent to a very large extent on visual sighting of the enemy, even in the days of reliable A.S.V.

[1] Depth charges discharged from mortars.

In the early years of the war this was the mainstay of the whole campaign. The problem presented was a double one. The aircraft must spot the U-boat while itself remaining unseen until near enough to deliver an attack before the enemy submerged. The first half of the problem was thus one of improving the efficiency of look-out from the aircraft. The second half was one of defeating the enemy look-out, for example by camouflage, flying at a suitable height and so on. O.R.S. Coastal Command began to grapple with the problem of visual sighting early in its existence. All sightings of U-boats up to May 1941 were analysed with respect to the state of submergence of the U-boat at the time of sighting. It appeared that in nearly 40 per cent of the cases the U-boats were already diving when first seen, or, in other words, they had seen the aircraft first. In a further 20 per cent the U-boats had already submerged (only their periscope being visible) when seen. Thus at least 60 per cent of the U-boats saw the aircraft before being themselves spotted. It was also certain that a number of U-boats spotted the aircraft and were able to submerge without ever being detected.

The O.R.S. discovered that nearly 30 per cent of the U-boats which were still visible when attacked were found in conditions of low visibility (less than two miles). This was much higher than would be expected merely from the frequency of such conditions and indicated that the U-boats were handicapped by low visibility in detecting the aircraft and that they were relying mainly on visual detection. Besides this, some U-boats failed to dive even in periods of good visibility which proved that the U-boat look-out was by no means perfect. The O.R.S. concluded that although there was room for improvement in the average sighting distance in clear conditions, this would lead mainly to an increase in sightings and to only a slight increase in attacks unless the job of the U-boat look-out was made more difficult.

One member of O.R.S. Coastal Command devoted himself to the improvement of look-out. To begin with he concerned himself with visiting stations, lecturing on the necessity of regular scanning and what sort of things to look for. He emphasised the importance of proper crew drill and the organised rotation of duties. Pressure was also exerted on Headquarters Coastal Command to improve look-out positions, provide clear vision panels, windscreen wipers, etc. He also investigated the use made of binoculars by aircrew and invented a holding device to relieve the arms of weight during long periods of continuous scanning.

THE CAMOUFLAGE OF AIRCRAFT

Early analyses made by O.R.S. Coastal Command demonstrated the importance of making aircraft while on anti-U-boat patrol less conspicuous. The essential features of the problem were very simple. The U-boats saw the aircraft against the sky which might be either cloudy or clear. In either case, what the U-boat saw was mainly the underside, which was, except in very freakish conditions, darker than the sky. In the Western Approaches, the most usual conditions were for the aircraft to be seen against an overcast cloudy sky with no direct sunlight. Under such conditions the underside was illuminated by light reflected from the sea and which was about one-twentieth the intensity of the sky light. Thus even if the aircraft reflected 100 per cent of the light falling on it, it would still appear dark against the background.

Certain measures had been taken by Coastal Command before the advent of the O.R.S. to improve the camouflage of aircraft engaged in anti-U-boat operations, and in the spring of 1941 No. 15 Group had requested permission to paint the under surfaces of their Wellingtons and Whitleys a light blue instead of the standard R.A.F. matt black. These experiments were encouraged by the O.R.S. and by the end of 1941 aircraft were camouflaged white on the under surface and sides. A scheme of camouflage was devised which allowed for three different roles, one in which searchlights might be encountered and the aircraft were to be painted black, and two for normal sea-operations. Both the latter had white under surfaces, but aircraft operating in the Mediterranean or other regions of strong sunlight were to have the sides dark sea grey instead of matt white. This scheme was adhered to in essentials for the rest of the war.

THE SITUATION IN THE WAR AT SEA 1942 TO 1943

Collaboration between the O.R.S. and the Air Staff at Headquarters Coastal Command became closer during 1942, and by mid-1943 the work had increased to such an extent that the head of the section was in danger of being swamped by the task of directing the work of more junior officers, and of thus being hindered in directing his own attention to the matters of most urgent concern to the Air Officer Commanding-in-Chief. The head of the section, now Mr. Larnder,[1] therefore appointed a deputy to assist him in the general co-ordination of work and to act in his absence. It was at this time that the section was divided into four groups as described above.

Before relating the work of the section in this stage of the war the general situation in the war at sea must be described. During 1941 Coastal Command aircraft made regular patrols against the U-boats in the Bay of Biscay and by mid-1942 it was possible to maintain a 24-hour offensive on account of the Leigh Light—an airborne searchlight which immediately proved its worth. Meanwhile, until the American counter-measures against U-boats got under way, the enemy was able to make serious depredations against shipping in United States coastal waters. But in the summer of 1942 the battle returned to the Atlantic convoy routes. By that time the naval

[1] Mr. Larnder had been transferred from O.R.S. Fighter Command at the end of 1942 to succeed Professor E. J. Williams who went to the Admiralty. After Mr. Larnder, Dr. C. H. Waddington became officer-in-charge of the section.

escorts were better trained and better equipped (with direction-finding gear and radar). On the other hand the enemy had begun to fit his U-boats with a receiver which could detect the transmission of Coastal Command aircrafts' airborne radar. This marked the beginning of the radar counter-measures war as far as Coastal Command was concerned and the O.R.S. was to play an important role in it.

The increasing effect of air power and the parallel but smaller increase in naval escorts finally broke down the Atlantic offensive which was withdrawn in May 1943. Up to the end of 1942 the exchange rate was still eight ships and 45,000 tons per U-boat lost and the ships sunk per U-boat per month still about 4,000 tons. From January to April 1943 the results were 28,000 tons per U-boat lost and about 3,000 tons per U-boat per month; from 15 April to the end of the month the results were only 5,000 tons per U-boat lost and 2,500 tons per U-boat per month—a complete failure. The summer of 1943 saw the Bay of Biscay battle at its height and the U-boat fleet was only used in operations in various distant 'soft spots', the sinkings being only 100,000 to 200,000 tons per month. In October 1943 a second attempt was made to return to the North Atlantic but the losses were so high and the results so poor that this was soon given up. This was followed by a short period during which attempts were made to use Ju. 290's for reconnaissance in order to move lines of U-boats submerged all day; this was a complete failure due apparently to the usual air-to-ship co-operation troubles, bad navigation, communication difficulties and to the low mobility of the U-boats submerged.

OFFENSIVE OPERATIONS IN U-BOAT TRANSIT AREAS AND THE DENSITY THEORY

The German occupation of the ports on the western seaboard of France provided a great impetus to the attacks against Allied shipping. For the U-boats, it opened up an easy approach to the convoy routes in comparison with the long trip round the north of Scotland from Germany or Norway. The Bay of Biscay became an important transit area for U-boats but travel across it held snags as well as advantages. For aircraft in search of U-boats it was a well defined area; on the other hand there was no need for U-boats to surface in the Bay longer than was necessary to charge batteries. It was, however, possible for U-boats to do *all* their charging by night and therefore no serious Bay offensive could be maintained without night attack. In the first phase of this battle the only technique of attack at night was by suitable illuminants (such as the Leigh Searchlight and flares) following on radar contact. The use of radar compelled enemy U-boats in the Bay to surface by day when they were more vulnerable to attack and thus it was essential for Coastal Command to have the lead in radio counter-measures to prevent the enemy using the dark. The O.R.S. therefore became indispensable. It had two tasks in connection with this offensive. First, the assessment of the actual and probable value of the operation; this was particularly important, for while Headquarters Coastal Command was fully alive to the value of offensive operations in the Bay, there was powerful opposition elsewhere which considered them a wasteful diversion from the strategic bombing offensive. In the second place, it produced a detailed assessment of results and devised new tactics and strategy.

The results of the early air offensive operations in the Bay of Biscay were summarised in two reports written by Professor Williams in March and October 1942. This was the first occasion on which the theoretical equations for 'density' of U-boats in a transit area were set out. A digression is necessary at this point to explain the theory.

It is an obvious fact that the number of U-boat sightings must increase with the flying done and with the number of U-boats available for detection. O.R.S. Coastal Command refined this platitude into a theory in which the individual factors could be quantitatively measured and estimated. From it valuable information could be obtained on the efficiency of R.A.F. operations and of the enemy's counter-measures, on the relative value of different types of operation, including operations still in the future, and on the tactics employed by the enemy.

The theory may be formalised thus: Let u be the total number of sightings or detections of U-boats obtained. This may be written—

$$u = \text{Area 'swept out'} \times \frac{\text{Number of surfaced U-boats in total area}}{\text{Total area concerned}}$$

The ratio 'number of surfaced U-boats per unit area' was termed the U-boat 'surfaced density' (D). If A be the area swept out then $u = A.D$. A can then be written as the distance flown times the search performance. The distance flown is evidently h the total hours times a the mean aircraft speed. The search performance was a more subtle idea. In the ideal case where every U-boat coming within range R is infallibly detected, then the search performance would be $2R$ and $A = 2ahR$. But this was not the case —ranges of detection have a considerable spread, U-boats are often not seen either through inattention or through their diving first, and so it was better to consider the search performance S as a parameter defined by

$$u = A.D$$
$$A = ah.S$$

where a, h, u were facts about Coastal Command's operational effort and results and D was a fact about the enemy's habits which should, at any rate in principle, be calculable. The relation between S and $2R$ became therefore a measure of the *efficiency* of the detection of the U-boats—$S/2R$ would fall as the enemy's counter-measures improved and rise as they were defeated.

In the formula given above the quantity $S \times D$ could be obtained from the Command's operational results. It was then possible to make an independent estimate of S (e.g. from ranges and estimate of efficiency) for a given type of search, and use the value so obtained to predict and compare the results of operations in different areas, and to check whether any significant change in efficiency had occurred. Alternatively, the U-boat density might be estimated making it possible to calculate S. By comparing this with the path swept the O.R.S. could estimate Coastal Command's and the enemy's tactics in the eternal tug of war between detection and evasion. Finally, even if D and S could not be estimated precisely, comparative value might be obtained provided it was ascertained that the operations were comparable in other respects. Thus, having established the efficiency of pure visual search, the O.R.S. could estimate the value of any given A.S.V. equipment by day. Since no equipment could ever be universally and suddenly fitted to an entire force, this method could be often applied.

In the Bay offensive the density both total and surfaced was usually approximately and often fairly precisely known. The width of the channel followed was bounded on the north roughly by the latitude of 48° N, on the south by the Spanish coast. The Admiralty was able, from direction findings, observed cycles of activity and other information, to provide good approximations of the amount of traffic passing. Moreover, the enemy's tactics were often carried out unchanged for months at a time with characteristic German thoroughness, and when they changed did so with dramatic suddenness. The peculiar circumstances of offensive operations in the Bay, therefore, permitted the calculation of mean U-boat densities to be made with a precision (probably plus/minus 20 per cent at times) unattainable elsewhere.

To return to the O.R.S. reports. In the first paper it was shown that, even in 1941, every U-boat was attacked about four times a year by aircraft. A 10 per cent increase in efficiency of attack would be sufficient to stop their operations. An estimate was also made of the tonnage saved by offensive operations in the Bay, and it was pointed out that this could, at a reasonable rate of kill, finally destroy the U-boats' power. In the second paper the 'density' method was employed to discover what could be done by a 'balanced' force capable of attacking each U-boat crossing the Bay once on the average, and how large a force was required. The point stressed in this paper was the great economy of the operation if done by a force of long-range aircraft properly equipped with A.S.V. In view of the opposition to offensive operations in the Bay, which will be discussed below, such conclusions were of great value.

SUPPORT OF THE BAY OFFENSIVE BY O.R.S. COASTAL COMMAND 1942 TO 1943

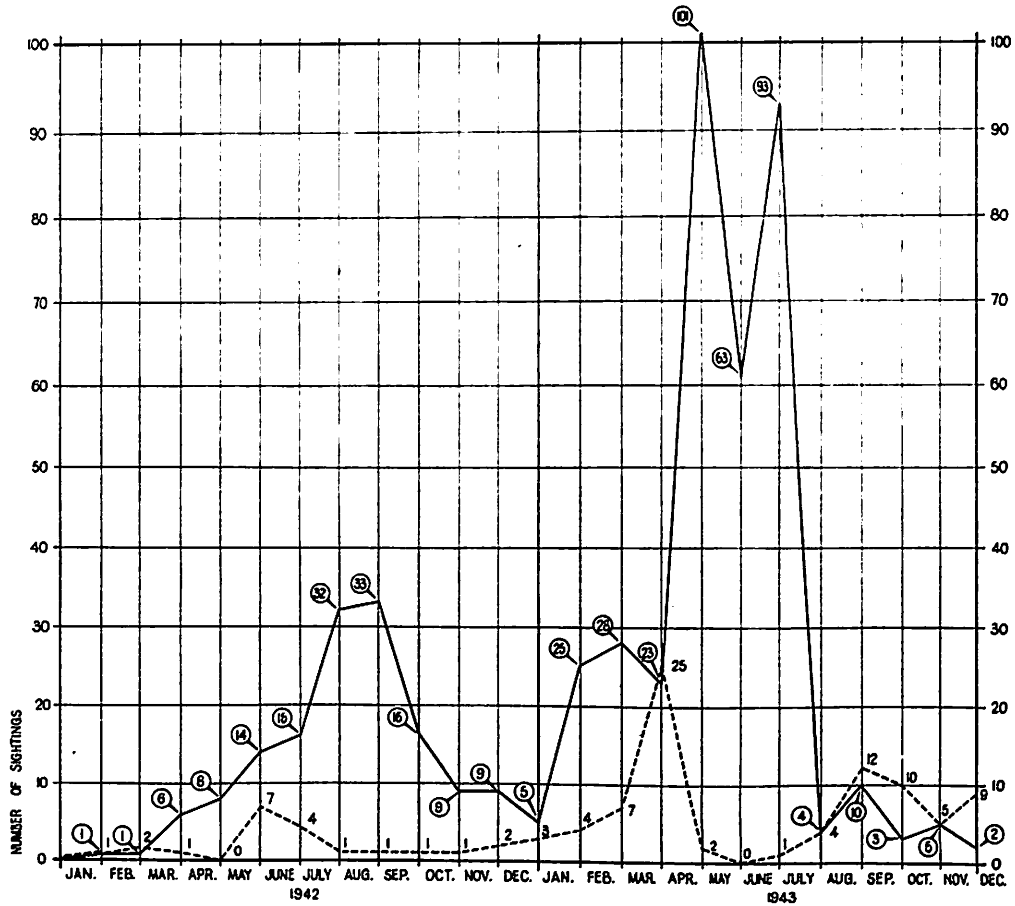
The use of the Leigh Light by Coastal Command in the summer of 1942 in operations over the Bay of Biscay compelled the U-boats to surface by day instead of by night. The enemy then resorted to using Ju. 88's to shoot down British anti-U-boat aircraft. These operations were countered by Beaufighter and Mosquito patrols in which Coastal Command was assisted by aircraft of Fighter Command. The contribution of the O.R.S. to this fighter war was to discover whether there was any enemy habit of which the Allied fighters could take advantage. In this connection sightings of enemy aircraft, their times and positions were aligned with information to obtain the best times, places and type of patrol for R.A.F. fighters; this remained a standing commitment until 1943. Probably the biggest single effect of the fighters and of the gun defence of the anti-U-boat aircraft was to force the Ju. 88's to patrol in swarms of six or eight at a time, thereby greatly reducing their chances of seeing anything. During the whole Bay offensive, including 1943, about 53 anti-U-boat aircraft were shot down by the enemy out of a total of about 9,000 daytime sorties; the Ju. 88 strength was never less than about 24 and never more than about 40 aircraft. Whether through lack of aircraft, or for what cause, the enemy never extended his air operations to cause a serious setback in the anti-U-boat offensive. O.R.S. Coastal Command in the daytime anti-U-boat offensive also assessed the value of metric and centimetric A.S.V. equipment (which will be discussed below) and worked on navigational aids and blind landings in order that maximum use might be made of the Coastal Command effort.

A search receiver to A.S.V. Mark II was introduced by the enemy in the autumn of 1942 and thus caused a setback to anti-U-boat operations by Coastal Command in the Bay during the winter of 1942–43. At the same time the value of the Bay offensive was questioned with regard to whether it was diverting too much effort, not only from air operations around threatened convoys in the Atlantic, but also from the strategic bombing of Germany. O.R.S. Coastal Command under Professor Williams stoutly supported the Bay offensive and predicted, on the basis of the 'density method', that the results in the Bay would be decisive for the U-boat campaign. The matter was thrashed out at meetings of the anti-U-boat Committee in March 1943 and it was eventually decided by the Commander-in-Chief Coastal Command, Air Marshal Sir John Slessor, that the Biscay air patrols should be strengthened, but *not* at the expense of convoy cover nor of the strategic bomber offensive.

Meanwhile the introduction of A.S.V. Mark III (modified 10-centimetre H2S) at this time compelled the enemy U-boats once more to surface by day instead of by night, and for a period of three months between May and the first week of August the anti-U-boat patrols in the Bay were highly successful. A total of 28 U-boats were sunk and 22 damaged (including those attacked by aircraft operating from French North Africa and Gibraltar).[1] The rate of kill per sighting by day increased enormously throughout the operation (from 9 per cent to about 20 per cent) although

[1] Figures based on post-war analysis. Contemporary estimates of U-boat sinkings were more optimistic.

SIGHTINGS OF U-BOATS BY AIRCRAFT IN THE BAY OF BISCAY 1942–3



Notes on Night Sightings

Indicated by -------- 25

Leigh Light and 1½ metre A.S.V. introduced on Wellingtons in June, 1942.

Introduction of 12cm. H2S (A.S.V.) April, 1943.

U-boats remain submerged at night Aug., Sept., Oct., 1942.

Notes on Day Sightings

Indicated by ———— (10)

Rise in day sightings due to night attacks from May to Sept., 1942.

U-boats fitted with anti-radar search receiver in Nov., 1942.

Climax of destruction of U-boats July, 1943.

the efficiency of night sighting never reached the level envisaged by the O.R.S. All this fully justified the contention of the O.R.S. that the Bay patrols should be maintained, and effective retaliation was made against various strategems of the enemy such as the sailing of U-boats in convoy, the employment of radar decoys and the intensifying of fighter cover over the Bay, which, it had been said, could nullify the Bay offensive.

But on 5 August the U-boats reverted to submerged passage by day and at once their loss rate declined. That month 32 U-boats crossed the Bay without loss, while in September this total rose to 60 with two sunk, and in October 70 U-boats crossed with the loss of only one of their number.[1] Nevertheless the O.R.S. maintained that the U-boats had suffered a serious setback from which, combined with the failure of their attacks on convoys, they never recovered, although the invention of the *Schnorkel* and the Type XXI boat in the closing stages of the war made the regaining of the initiative by them a strong possibility, as will be shown in a following section.

During the period of intensive operations against U-boats in the mid-summer of 1943 the O.R.S. was mainly concerned with the problem of countering flak attacks on Coastal Command aircraft (for the U-boats had been ordered to fight back on the surface). Statistical analyses were made throughout of the flak risks, but since it was not always known when an aircraft was actually shot down by a U-boat attempts were made to clear up this by group headquarters insisting on 'flash' reports being made *before* attack, and since the total number of aircraft shot down during the whole of this daytime offensive was probably not more than 25 (in three months) the statistical method had little or no basis to go on. The main help to aircrew on this subject came, therefore, from the work of an Army flak expert loaned to Headquarters Coastal Command. The only definite O.R.S. contribution was to establish the rate of loss as well as possible and to prove the odd conclusion that the team of three U-boats were no more dangerous to attack than single U-boats.

From about 15 June 1943 onwards the U-boats changed their policy into sailing in groups of three in 'vic' formation. The theory appears to have been that the flak of all three would prevent an aircraft attacking; while it was manœuvring round they could all dive, one by one, unattacked. The U-boat traffic at the time was only about 60 a month, so that the discovery of a team of three meant that practically the whole traffic for one day had been discovered and thereafter reconnaissance was no longer of much importance, the problem being how to concentrate as many aircraft as possible. This situation led to the series of reports made by the O.R.S. on the operational control of these operations and on what really took place; such investigations had always been of great importance in other commands, but this was the first time in which they became vital for Coastal Command's anti-U-boat offensive.

[1] Figures based on post-war analysis.

USE OF PHOTOGRAPHY TO DETERMINE ACCURACY OF BOMBING

O.R.S. Coastal Command was also concerned with developing a system of photographing a target, such as a U-boat, in order to discover how accurate an attack had been. It was almost impossible to obtain quantitative results with hand-held cameras and a special fitment was devised consisting of the F. 24 camera with an eight-inch lens, mounted vertically, and fitted with a mirror which threw the line of sight into the horizontal plane. But the installation was by no means ideal and the O.R.S. was given the task of setting out the factors which would have to be considered in attempting to improve it.

During the summer of 1943 photographs had been taken in about two-thirds of all attacks, but only about a quarter of the attacks yielded photographs which could be assessed with reasonable accuracy. Moreover nearly two-thirds of the photographs were taken with hand-held cameras, and, while over a half of the mirror camera photographs were assessable, only a quarter of the hand-held ones were so. The reasons why some mirror camera photographs were unassessable were investigated, and the main difficulties were found to be in the first place, that no U-boat was visible; secondly, no horizon was visible, and thirdly, the camera was switched on too late. The cure for the last of these faults was for the camera switch to be coupled to the bomb release system, so that the camera came into action automatically at the appropriate time during the attack. The underlying cause of the other two faults was mainly the small angle of view of the camera (though some of the failures to include the horizon were due to a poor installation in the Halifax which was soon remedied).

All photographs taken during attacks on U-boats were passed to O.R.S. for measurement. To start with the only method of assessment used was re-projection. By using a projection lens of the same focal length as that of the aircraft camera, and adjusting the tilt so that the horizon was projected as a horizontal, a true to scale plan view was obtained; it remained only to determine a scale. This could be done if the aircraft height were accurately known, but in practice this was not known with sufficient accuracy. A scheme for recording the radio-altimeter simultaneously with the photographs never came into operation. Scaling was therefore done by the somewhat unsatisfactory method of using some phenomenon visible in the photographs as a yardstick; this might be part of the U-boat itself, or the height of the explosion plumes, the stick spacing or preferably a combination of a number of these.

Assessment of photographs could also be done by superimposing on the photographs a perspective grid which was calibrated in terms of the height of the aircraft. This method was considerably quicker than re-projection and was in general use in the latter stages of the war. The grid was calculated for a 10 degree depression of the camera axis. Although in practice the depression varied with the altitude of the aircraft, the inaccuracy caused by using a 10 degree grid was less than the inaccuracy which inevitably arose owing to the difficulty of fixing the scale.

The information implicit in the attack photographs was of course only a part of the whole story of the attack. Information on the sortie was given on a special *pro forma* devised by the O.R.S. For its own convenience the O.R.S. extracted the information from the *pro forma* and entered it on a punched card which facilitated the sorting necessary for the answering of particular queries.

THE CONSEQUENCES OF PHOTOGRAPHIC EVIDENCE

Disagreement arose at the end of 1942 between the Air Staff at Headquarters Coastal Command and the O.R.S. over the type of bomb best suited for the sinking of U-boats, since the effectiveness of air attack on U-boats was disappointing in spite of improved depth-setting. The O.R.S. maintained that greater lethality would be obtained by a large number of small bombs thereby increasing the total number of explosions within a given length of the stick whereas the Air Staff were in favour of developing a higher calibre, and thus more destructive, bomb. In fact, the real progress was made not by changing the weapon but by study of the actual aiming accuracy obtained on operations. Photographic evidence was able to provide material, by analysis of which it was possible to provide an answer to the problem.

Early analyses bore out the contention of the O.R.S. that the immediate problem of making attacks more effective was the improvement of bomb aiming. Referred to the conning tower of the U-boat, the errors found were about 50 to 60 yards in range and somewhere near half that in line. This was even larger than the O.R.S. estimate and was of quite a different order to the 20 yards range, 10 yards line claimed by aircrew and accepted by the Air Staff as reasonable. At that time the tactical instructions and the training in low-level bombing both laid considerable stress on the need to aim-off ahead so as to allow for the forward travel of the U-boat during the time of fall of the depth charges. But it ascertained that if all the photo-assessed sticks were plotted on a single diagram the distribution of the mid-points of the sticks was not centred on the conning tower but on a point some 60 yards ahead. It was clear that this aim-off was being over-done. The estimates of bombing error were gradually made more precise as further data accumulated.

For example, it was shown that although the Command had eliminated the original systematic error ahead of the U-boat, due to making too great allowance for its forward movement, systematic errors were still present, but related to the aircraft instead of the U-boat. There was a systematic overshoot. Thus in attack from in front of the beam, the mean point of impact of the stick-centres was about 12 yards astern, while in attacks from behind the beam it was about 18 yards ahead. In attacks where the aircraft crossed from port to starboard, the mean point of impact was some 28 yards to starboard of the U-boat and it was some 18 yards to port when the aircraft was moving towards the port side.

On applying a similar analysis to the results for different types of aircraft, it appeared that the tendency to overshoot was much less in Sunderlands, and was worse in Liberators and Catalinas (bombing was generally erratic in Whitleys, most of which were being flown by Operational Training Unit crews). The Liberator and Catalina suffered from bad downward visibility from the pilot's seat; a U-boat had passed out of sight by the time the moment of release had come, and further improvement in range errors could scarcely be expected in such circumstances. The cure for the situation lay in the provision of suitable bombsights operated by some crew member other than the pilot.

The importance of the analysis of attacks lay not in any abstract theoretical interest, but in the consequences which it entailed for the practical problem of carrying out the attack in the most effective way as, for example, the demonstration of the greater destructiveness of attacks near the track direction. This, which was also strongly emphasised by the analysis made by the Senior Naval Staff Officer on the basis of crew interrogations, was actually merely a confirmation of Service belief and little more could be done about it than to encourage pilots to continue what they were already doing, namely to attack in this direction whenever it was possible, without allowing the U-boat to dive. The importance of the latter stipulation was also very emphatically brought out in all analyses; the lethality of attacks on U-boats submerged even as little as 0 to 15 seconds was very much less than on visible ones.

The most outstanding result was the incorporation by the O.R.S. of the photographic measurements of aiming errors into its statistical analyses. This led the O.R.S. to recommend an increase in the stick spacing from 36 feet to 100 feet which it calculated would lead to an increase in kills by about 35 per cent (from 19 per cent of attacks to 26 per cent). The recommendation was accepted by Coastal Command in March 1943 and the O.R.S. report on which it was based was issued as a tactical memorandum. From this time onwards the numerical evaluation of suggested stick spacings became one of the standard tasks of the O.R.S.

THE AIR DEFENCE OF CONVOYS

The pre-war conception of the air defence of sea-borne convoys was that aircraft should fly in close proximity overhead corresponding to the naval escort which provided protection on the sea. Experience soon proved that it was better to try to break up the pack of U-boats concentrating for an attack instead of merely guarding the convoy. It was also possible, by interception of enemy radio messages, to distinguish between threatened and unthreatened convoys. When O.R.S. Coastal Command first started to consider convoy actions in late 1941, it inherited a problem whose main outlines were already recognised. Its function was to suggest, from the detailed analysis of operations, how tactics could be improved within the orbit of the main strategy; and, in particular, it was able to keep a running check on the quantitative success of Coastal Command's efforts and to express the value of the operations in numerical terms. Such assessments were of great importance in considerations of general policy, where it was necessary to attempt to compare the value of air cover on convoys with the results that might be achieved by using the aircraft in some other way.

The enemy's first offensive against Allied sea-borne convoys lasted until the entry of the United States into the war, when the U-boat effort was suddenly transferred from mid-ocean to American coastal waters. The first reports of O.R.S. Coastal Command proved the validity of the distinction between threatened and unthreatened convoys and also bore out the offensive tactics employed against U-boats threatening a convoy. They also stressed the importance of very long range aircraft, the number of ships sunk beyond a radius of 300 miles being very much greater than those sunk within a radius of regular air cover.

By the opening of the second U-boat offensive against Allied convoys from August 1942 to May 1943, it had become clearly recognised policy that air cover should be used offensively, to seek out and destroy U-boats and interfere with their concentration. For this reason a high priority was placed on the provision of very long range aircraft for Coastal Command. The O.R.S. reckoned that 43 days (dawn to dawn) without air cover had led to a loss of 75 ships (the average U-boat pack consisting of 5·3 vessels) while 38 days with packs of similar size, but with air cover, had resulted in the loss of only 24 ships. Hence the air cover, which comprised only 147 sorties, had saved about 43 ships, and had reduced the U-boats' efficiency by a factor of three. Taking the average life of an aircraft at 40 sorties, and adding in the ships saved by the actual sinking of U-boats, it was estimated that each aircraft in its lifetime saved an average of 16 ships.

A further report, of which the analytical section was prepared by the O.R.S., confirmed the value of very long range aircraft to threatened convoys. From the tactical point of view the most important point was that a considerable number of sightings had been made by aircraft which failed to meet their convoys; a fact which, together with other evidence, led to the conclusion that the majority of the pack must be more than 20 miles away from the convoy, and that patrols were still being kept too close. It was suggested that one of the most profitable forms of operation would be to make sweeps some distance away from the actual convoy; though it was estimated that, owing to the navigational difficulties, it would double the value of these if they were first homed on to the convoy so that they could begin their sweep in the correct place.

This point of view was in complete disagreement with American doctrine which pinned its faith on continuous close support. In a report which appeared just after the second offensive against Allied convoys had ended, it was shown that Coastal Command patrols not only gave 40 per cent more attacks than close escort but the convoy was also quite as safe; they almost completely prevented sinkings by day, and halved the losses on the first night, and halved them again on the second. This was about as good as could be hoped for, in the absence of night cover. But the tactical problems of night escort were never satisfactorily solved. The fundamental difficulty, with the equipment available, was that of distinguishing friend from foe.

PROBLEMS RELEVANT TO THE EMPLOYMENT OF A.S.V., 1942 TO 1945

Since the introduction of A.S.V. in about mid-1941 Coastal Command had been disappointed with the infrequent contacts made with U-boats by this equipment. In order to correct this false impression the O.R.S., early in 1942, summarised the *average* pick-up ranges on selected groups of targets. At that time it was believed that their maximum range of pick-up varied as the square root of the height of the aircraft. Therefore to compare performance between squadrons and types of aircraft each quoted range was adjusted to a height of 1,000 feet.

The immediate result of analysing average ranges was to find that No. 502 (Whitley) Squadron fitted with A.S.V. Mark II had a performance considerably worse than any of the other installations. As it happened No. 502 Squadron was the one squadron properly trained for night work in the Bay of Biscay and results had been rather disappointing. As a consequence of this first analysis of average ranges No. 502 Squadron was within six weeks taken out of the line for re-equipment.

During the spring of 1943 centimetre A.S.V. was introduced in Coastal Command aircraft. An analysis of average ranges was always made by the O.R.S. on the introduction or installation of a new type of A.S.V. equipment and it was found that the American equipment, A.S.V. Mark V, was some 60 per cent better than the British A.S.V. Mark III. The latter was eventually replaced by the more powerful A.S.V. Mark VI. The experience of the O.R.S. showed that new equipments must be checked constantly. The analysis of operational ranges at irregular intervals sometimes made it extremely difficult to decide whether changes in performance were due to changes in maintenance efficiency, changes in operator efficiency, or possibly merely changes in the type of target.

An example of the way in which the O.R.S. improved the employment of A.S.V. equipment concerned the height at which aircraft should fly in order to obtain the best results. Trials by T.R.E. and the Coastal Command Development Unit with A.S.V. Marks I and II indicated that the maximum range of pick-up on submarines and other shipping targets varied approximately as the square root of the height of the aircraft (at any rate up to

10,000 feet). A paper produced by T.R.E. indicated that on theoretical grounds the range varied as the square root of the height up to a certain limit, dependent on factors such as wave-length, sensitivity of equipment and height of target. The trials tended to confirm that the theory was correct and it was concluded that the higher the aircraft flew the greater the chance of picking up U-boats. Air Staff policy consequently developed along these lines. But the squadrons did not agree with the theory, opinion being divided, some stating that at greater heights, such as 5,000 feet, the sea returns increased beyond the range at which it was considered possible to pick up U-boats.

The O.R.S. discovered that the range did not increase as the square root of the height in accordance with the theory advanced by T.R.E. but above heights of the order of 500 to 1,000 feet at a much slower rate. Analysis of the extent of the sea returns with respect to height showed that they did increase approximately as the square root of the height. It appeared therefore that the best method was not to fly as high as possible, but to fly at the height at which the difference between the average range of pick-up and the average sea returns was at a maximum. Operational results showed that with A.S.V. Mark II there was little, if any, gain in flying above 2,000 feet when searching for U-boats and that the rougher the seas the lower the optimum height. Similarly, the lower the efficiency of the set, the lower became the optimum height. These conclusions engendered much controversy between the O.R.S., T.R.E. and the Signals Branch at Headquarters Coastal Command which continued up to the autumn of 1942 when the enemy introduced counter-measures against A.S.V. Mark II. From then on, however, when other marks of A.S.V. were introduced the operational results were taken as a basis for deciding the optimum height to fly, this being the height at which the difference between range of pick-up and extent of sea returns was the greatest.

One of the factors affecting the efficiency of A.S.V. was failure by the operators to spot the 'blips' on their equipment at the earliest opportunity, or worse, failure to spot the 'blip' at all. The O.R.S. discovered that more targets were picked up by an aircraft manned by a large crew than by one manned by a small crew. Early in 1944 the O.R.S. attempted to ascertain whether the efficiency of pick-up varied significantly during the course of a watch, with the object of finding out whether watches were too long or too short. The method adopted was to analyse the numbers of contacts (aircraft and U-boat contacts were considered separately) which occurred at various periods from the beginning of the watches. If the efficiency of watch was constant, the percentage of contacts occurring after, say, 70 minutes would be proportional to the percentage of watches lasting as long as 70 minutes. It was shown that efficiency rose to a peak after about a quarter of an hour, after which it fell off rapidly and remained at a low level after about 40 minutes. Investigations were also carried out independently by the Medical Research Council Unit for Applied Psychology at Cambridge. Both the O.R.S. and the Cambridge scientists concluded that watches should never be more than half an hour in duration. Their evidence was accepted by Coastal Command which instituted a drill allowing for radar operators to be changed every 45 minutes. Prior to this the average length of watch had been well over an hour.

Analysis of disappearing contacts which had been of great value in estimating the effects of U-boat counter-measures against A.S.V. was carried out by the O.R.S. in the autumn of 1943 when the enemy began using centimetric equipment (*Naxos*). Many of the disappearing contacts could have been caused by almost anything, such as other aircraft, fish, loss of target due to bad tactics and so on. On the other hand, a few definite cases were established of disappearing contacts being caused by diving U-boats. The problem was to find out what proportion of the contacts were on U-boats and what were the causes of the non-U-boat contacts.

The statistical method adopted was as follows. If the U-boat 'blips' did not originate from U-boats it was assumed that they arose from natural causes and that they would be expected to occur in proportion to the amount of flying done. If, on the other hand, they were caused by U-boats, then they would be found in proportion to the amount of flying multiplied by the U-boat surface density. Since the periods considered (varying periods of 1943 for different types of A.S.V.) there were considerable variations in flying hours per month and average U-boat density per month, and since these did not run parallel to one another, the number of 'U-blips' to be expected on the two hypotheses differed fairly widely. It was therefore hoped to ascertain the proportion of the 'U-blips' due to U-boats.

The final formula arrived at, based on an adaptation of the density theory, was as follows—

$$K = \frac{aE}{1,000} + b$$

where K = contacts (sightings plus 'U-blips') per 1,000 hours of flying
a = search performance in square miles per hour
E = U-boat surface density in U-boats per million square miles
b = Non-U-boat 'blip' rate in contacts per 1,000 hours of flying.

By plotting K against E for each type of equipment and for night and day separately, the O.R.S. obtained estimates of a and b. As a was dependent on the efficiency of the enemy counter-measures as well as the path swept of the equipment, it was important to consider only such periods during which the counter-measures, if any, were unchanged in effectiveness. Thus for 'S' band[1] equipment only data up to September 1943 were included, as Intelligence sources had indicated that the enemy had introduced a listener to 'S' band that October. The method adopted not only gave Coastal Command a measure of the reliability of the 'U-blips', but also

[1] Centimetric A.S.V.

the actual contact search performance. Knowing from range analysis the path swept for a given equipment, the O.R.S. obtained a measure of the contact efficiency. As it also knew the actual number of sightings made, it obtained a measure of the sighting efficiency.

Having established the causes of disappearing contacts, much valuable information was gained, not only about the performance of Allied equipment, but also about the tactics of the enemy and the performance of the enemy's equipment. With regard to the former, it enabled the O.R.S. to separate the contact and sighting efficiencies which were often radically different from trial expectations. The O.R.S. held that no investigation into operational results from which absolute value of the performance of Coastal Command's or the enemy's search performance might be required could be considered complete without considering disappearing contacts.

The *Schnorkel* U-boat, which was able to recharge its batteries while remaining submerged, came into service early in 1944. The *Schnorkel* was such a small target that the average range of contacting it with A.S.V. was only about a third of the average range on surfaced U-boats. The range on *Schnorkels* was thus of the same order as the extent of the sea returns. With surfaced U-boats the more difficult task for operators and sets during operations compared to trials resulted in the average operational ranges being only some 40 per cent of the trial ranges. With *Schnorkels*, however, the lower efficiency during operations led, not so much to a reduction of range, but to many of the targets being missed altogether. Under moderate or rough sea conditions it was almost impossible to contact *Schnorkels* owing to the presence of the sea returns apart from anything else. Several types of sea return eliminators were made which were all of the filter type with different time constants. No satisfactory analysis was ever made of their operational value, mainly due to the difficulties in finding out how frequently they were used. The eliminators certainly broke up the central mass of sea returns on the tube into a series of smaller 'blips' and possibly reduced the outer extremity to a slight extent, but it was generally agreed that these smaller 'blips' were so similar to a *Schnorkel* 'blip' that the operator was unlikely to distinguish one from the other. Consequently the eliminators were probably of little value for search purposes, but were of help in homing, especially to a poor operator. The war ended before a satisfactory system of reducing sea returns was evolved. The development of weapons in order to detect and attack the *Schnorkel* is discussed below.

OPERATIONS AGAINST U-BOATS IN THE CHANNEL, 1944 TO 1945

The task for Coastal Command in the landings in Normandy (Overlord) was to 'hold the ring' by preventing the U-boats from interfering with the cross-Channel convoys. There was a divergence of opinion between the Air Staff of Coastal Command and the O.R.S. as to the best means of offering protection to the convoys. The former proposed to fly regular patrols frequently over a narrow area stretching from the southernmost corner of Eire to Brittany, and to build in this way an 'unclimbable' fence. The O.R.S. pointed out that gaps were bound to occur in the flying due to bad weather, and that U-boats could creep through the fence in such periods. It argued that a plan of 'defence in depth' would be preferable to prevent the U-boats from coming in and also to cause the maximum interference to any which did succeed in approaching their prey. These proposals were based on experience gained in operations in the Bay of Biscay. The O.R.S.'s suggestion was, in essence, adopted by the addition to the original patrol area of a further set of areas which effectively filled up the whole Bristol Channel and South-west English Channel region. Close escort to the convoys proper was also provided by land-based Swordfish of the Fleet Air Arm. A system enabling intensive cover to be provided during these operations was also worked out by the O.R.S. in which every spot in the area covered by Coastal Command could be reconnoitred at exactly half-hour intervals. This problem turned out to be one of the rather few O.R.S. investigations in which comparatively intricate mathematics were called for. A formula was eventually produced which related the length of time a U-boat could spend on the surface to the characteristics of the frequency distribution of intervals between successive aircraft.

In the first week after the landings all the U-boats sighted were of the conventional type. But from then onwards the targets of Coastal Command were almost entirely *Schnorkels*. The Germans now found that they could penetrate to inshore waters with these craft without undue risk from the air. An O.R.S. note written on 21 June 1944 pointed out that the 'search performance' against *Schnorkels* was only of the order of 0·3 miles, making it clear that the efficiency of detection was very low. Anti-U-boat tactics and strategy had to be revised drastically in the light of this invention.

The problem of dealing with the *Schnorkel* was essentially that of detecting and attacking the submerged submarine—a problem which had been under consideration for some time. Hitherto successes against U-boats had depended on their use as 'submersibles'. They were detected by eye or by radar while surfaced; they were attacked while surfaced or only just submerged, and they were driven off from convoys because they had to travel on the surface to make contact with their target. The problems involved in detection and attack of submerged submarines must therefore be summarised briefly.

It has already been explained how difficult it was to detect the *Schnorkel* by radar especially in a rough sea. The possibilities of infra-red detection were also investigated but little headway was made with this technique. There was, however, the vulnerable point in the *Schnorkel* which was that it emitted a cloud of exhaust or steam when under water which was visible to the naked eye. This cloud became more pronounced in cold weather. The O.R.S. therefore had to assess how many cases of smoke reported were really due to U-boats and, secondly, to discover the conditions during which smoke might be expected. After experiments conducted in conjunction with the Meteorological Office, it was found that if the *Schnorkel* exhausted *above* water the likelihood of smoke would be remote, but that if the *Schnorkel* exhausted *below* water the formation of a cloud was at that time probable.

While it was possible sometimes to detect the *Schnorkel* by visual means, there remained the inescapable fact that the number of 'kills' in mid-1944 fell seriously in comparison with the previous year. There were two remedies: firstly, to improve co-operation so as to bring as many aircraft and ships as possible to the scene, and secondly, to find a better weapon than the depth charge. In the first case it was found that air/ship co-operation was not profitable unless the aircraft could track the U-boat submerged. Two weapons designed for detecting and attacking submarines had, however, already been evolved—the Sonobuoy which was dropped into the water to listen for U-boat noises and transmit them through a radio link to a listener in an aircraft, and, secondly, the Mark XXIV Mine—a homing torpedo also actuated by sound. Both were the objects of lively controversy. The Sonobuoy became operational, prematurely, in 1943 after inadequate trials and with over-optimistic ideas of its performance. Its purpose was to act as an ancillary to the mine—to check on the explosion. Unfortunately the evidence transmitted by the equipment was found to be unreliable and much work was done by the O.R.S. to try to reduce 'hallucinations' experienced by the equipment.

The Mark XXIV Mine, on the other hand, was approved after a series of trials and became the primary weapon against the *Schnorkel*, being used first of all in the operations supporting Operation Overlord, by which time it had become clear that depth charges were of little use against *Schnorkels*. There were 13 direct attacks with the mine of which two were successful.

The first two known kills using the Mark XXIV Mine on Sonobuoy indication occurred late in March 1945. By then Sonobuoys had justified themselves and Headquarters Coastal Command held that this equipment together with the Mark XXIV Mine were the most promising devices to enable aircraft to regain their ascendancy over the U-boat. Evidence came in at the end of the war which bore out the conclusions of the O.R.S. that existing radar was of little value against the *Schnorkel*, but that the Sonobuoy, while ineffective against U-boats in passage, could be developed to protect convoys since a U-boat had to travel fast in order to attack a vessel and therefore moved noisily.

It is now time to consider some of the other problems which it was said were investigated by the O.R.S. at the beginning of this chapter.

NAVIGATIONAL PROBLEMS

It was of prime importance to Coastal Command aircraft that, firstly, they should patrol the assigned area and find their way to this point and home again with the greatest economy and, secondly, that aircraft on escort duties should meet the convoys under their protection as quickly as possible. It was also very necessary for aircraft to be able to operate in all weathers since U-boats which knew they were immune from attack during bad weather would be able to concentrate their attacks into such intervals.

A general study on aspects of navigation was made by O.R.S. Coastal Command at the end of 1942. This stressed the paramount importance of Dead Reckoning (D.R.) navigation, discussed the various instruments and aids which were or could be made available and made suggestions for the policy that the Command should adopt in requesting new facilities. As regards D.R., it was suggested that the main improvements to be looked for were in increasing reliance on astrofixes and the introduction of improved drift sights (including radar drift-taking by means of marker buoys), of the air position indicator and of radio altimeters. Among radar navigation aids, the emphasis was placed on Loran for the more distant areas and Gee for the nearer ones. These recommendations were, perhaps, obvious ones, but the review of the situation brought the possibilities to the fore and led to greater urgency being placed on the Command on the production of the necessary equipment. In some cases, however, it was many months before the recommendations were carried into effect, chiefly because of production difficulties and competition for priorities.

One of the most important functions of accurate navigation in Coastal Command was to ensure a rapid meeting between aircraft and convoys or independent ships to which escort was being provided. This became a subject for study by the O.R.S. In the latter part of 1941 the meeting of convoys was based on purely navigational methods. An estimated convoy position was worked out from the last datum and the aircraft was instructed to carry out a creeping line-ahead search from 20 miles in front of the convoy to 50 miles astern of it. The overall success was that 75 per cent of escorts met their convoys. But the proportion of successes was of course much higher for near-in convoys than for distant ones; the 'not-met' rate was found to be about 8½ per cent per 100 miles from shore, and at distances over 600 miles, where the threat was greatest, only 40 per cent of escorts successfully made contact. Moreover, a considerable amount of time was wasted in searching for convoys even when these were eventually met. The time actually spent on escort expressed as a percentage of the time which could be so spent if all aircraft flew straight out to their convoys without having to search, fell to 75 per cent for near convoys and to 30 per cent for distant ones. The situation was even worse than these lugubrious figures indicate, since escort to threatened convoys was less likely to meet than that to unthreatened, probably owing to the greater evasive action taken by the convoy and the resulting greater uncertainty in its position.

On further analysis of the facts, it was clear that uncertainty as to the convoy's position was a considerable factor in causing failure to meet. By comparison of Commodores' logs with the estimated positions used in briefing escorts, it was found that the average error in convoy position was about 35 miles along course and 15 miles across course, more or less independent of distance from shore. Such errors would, it was estimated, account for roughly 20 per cent failure to meet; but it could not in itself account for the 60 per cent or so failures at the more distant convoys. It was apparent, however, that the area specified for the creeping line-ahead search should be increased and the O.R.S. recommendation to this effect was acted on. In due course an exact theory relating the probability of meeting to the factors mentioned above was derived.

Attempts were also made to supplement pure navigation by homing methods of bringing about contact. The main reliance was on A.S.V. It was shown by the O.R.S. analysis that the average visibility in the not-met sorties was only about half that in those which successfully met; and the conclusion was drawn that little value was actually being obtained from the A.S.V. Mark II in use at the time. This fact was used to reinforce the Command's plea that A.S.V. beacons should be fitted on all Commodores' ships as soon as possible.

The O.R.S. believed that this would be too mild an improvement and advocated W/T homing between aircraft and ships. It calculated that if contact could be made at 100 miles, up to 90 per cent of escorts should meet even the most distant convoys. The difficulty in adopting this technique was the fear of compromising the convoy's position to the enemy by breaking W/T silence. Four procedures for such homing were laid down, but two of them required that the ships should make continuous transmissions on which the aircraft homed. In the other two procedures the continuous transmissions were to be made by the aircraft; the ships took bearings on these and transmitted them to the aircraft in short signals. W/T silence was therefore broken only for a short time and one of these procedures (known as Procedure 'B', the similar Procedure 'D' differed only in the frequencies used) was in occasional use by the end of 1941, particularly for escorts to independent ships. A preliminary analysis showed that procedure was not absolutely efficient. Of 14 attempts, five met by homing, five met without aid of homing, three failed to meet and one was doubtful.

O.R.S. Coastal Command went into this matter of homings in great detail and discovered that much the greatest cause of failure was an inability for aircraft to get into W/T contact with the ships. In most cases failure was due to administrative details such as inadequate staffing, failure of signals from shore, use of wrong codes, etc. Great improvements could in fact be looked for with a little more experience and training in the method. The importance of this was strongly urged by Headquarters Coastal Command on the grounds of the O.R.S. findings, and as a result the meetings of aircraft and convoys proceeded far more smoothly. In the period September to December 1943, the not-met rate using Procedure 'B' fell to less than one per cent; the successful use of Procedure 'B', which had originally been more or less confined to No. 15 Group, had become general throughout the Command.

WEATHER AND OPERATIONS

In Coastal Command operations, sorties were required every day and throughout the whole 24 hours and one of the main hindrances to the fulfilment of this plan was the weather. The O.R.S. was asked at the end of 1942 to study the matter and to discover whether any recommendations could be made for improving current practice. While no panacea was found to provide the Command with an infallible guard against the vagaries of the English climate data were amassed which were of great value in making clear the weather factors which had to be taken account of in planning air operations.

In early investigations the number of sorties that had been laid on but later cancelled because of reasons connected with weather was ascertained. The number of sorties which were curtailed due to the recall of aircraft on meteorological grounds was also taken into account. The first study which concerned itself with the sorties from one group indicated that the percentage of cancelled sorties over a certain period was about 16 per cent of those laid on. Of these cancellations some 20 per cent were due to petty unserviceability, but the great proportion (80 per cent) were due to reasons connected with the weather, as many as 60 per cent being cancelled owing to the weather conditions at base. On top of the cancellations, there were 10 per cent of sorties which were flown but curtailed for one reason or another. These curtailed sorties were, it was estimated, about 50 per cent as effective as completed sorties in searching the operational area. About half the curtailments were due to early recall of the aircraft because weather was closing down at the base, the other half being caused by mechanical failures, etc. Finally it was estimated that a number of sorties, which would have amounted to 5 per cent of the total, were actually desired but had never been ordered because the weather conditions were such that they could obviously not have been flown. Altogether Coastal Command was unable to fly a quarter of the sorties that were required and it was obvious that further investigations should be made. Better records were to be kept in future so that statistics could be derived in a more precise form. It was laid down that Groups should schedule all sorties which they would desire to fly, paying no attention to the meteorological conditions; records would then be kept of any cancellations or curtailment of these sorties for meteorological or other reasons, and the picture of the impediments to the performance of the Command's plan would be clear. This system of complete scheduling was introduced first into No. 19 Group and finally throughout the Command.

At first the statistics of sorties were inadequately qualified. For example when the Command was flying a steady effort over a long period the loss of a scheduled sortie was not necessarily a complete loss; a loss could be made up without undue dislocation. On the other hand in certain operations such as the Channel Stop operations before D Day, 6 June 1944, or in a convoy battle lasting only a few days, the loss of a scheduled sortie might mean a complete loss which could not be made good at a later time. It gradually became clear to the O.R.S. and then to Headquarters Coastal Command that the fundamental limiting factor on effort was the amount of maintenance effort available, and that, given adequate planning which took account of the correct number of non-flying days, there need be no reduction in the total effort put out over a long period on account of unfavourable conditions. During 1943 the scheduling of all desired sorties became general throughout Coastal Command and the statistics at the disposal of the O.R.S. therefore improved in quality. The results were summarised as they accumulated and a number of reports prepared covering successive periods and various areas. In general the results were not unlike those summarised above. The overall loss throughout the Command was about 25 per cent with, of course, variations from month to month and from place to place.

While little could be done about minimising curtailment of sorties due to weather in the operational area it was considered possible to do something for home bases. The main causes preventing take off were fog, high cross-winds and, in flying boat bases, rough seas. A number of suggestions were made for overcoming or reducing these difficulties, such as the extended use of *Fido*[1] and various forms of runway lighting. Little progress was, however, made in these directions owing to competing demands by other forces.

One of the most immediate applications of the statistics on losses of sorties was in connection with the comparison of different areas as to their suitability for major offensive effort. Thus, for example, when the enemy was sending U-boats round the Iceland–Faroes Channel in 1944, entailing an air offensive in this region, one of the most important factors was the effect of weather conditions in limiting the effort that could be maintained. It was found that on only about half the days had the Scottish bases been able to provide 50 per cent or more of the required sorties. Base conditions had been a fairly important limiting factor and it was shown that these might be considerably mitigated by suitable selection of bases, the Moray Firth area being particularly favourable. But the figures also showed that, unlike conditions in the Bay of Biscay, in northern waters the weather in the operational area was a major handicap. Out of 27 days on which Nos. 15 and 18 Groups together did less than half the required effort, base conditions were responsible for 10 and weather in the operational area responsible for the remaining 17. It appeared therefore that the weather was certain to be a very considerable handicap to any all-out offensive against the north-about traffic.

[1] Fog Intense Dispersal Of.

THE ATTACK OF ENEMY SHIPPING

Another aspect of the O.R.S.'s activities was the solution of problems arising out of the anti-shipping war. The air war against surface craft consisted of attacks against merchant vessels and in the latter stages of the war against naval craft, in particular, E-boats. The first thing to discover was the degree of efficiency attained in finding the target. Although this did not present the same problem as the location of U-boats, ability of aircraft to discover their target differed according to the area in which they operated. Thus the coastline of Norway afforded far greater protection to the enemy's coast-wise trade than did the coast of northern France, Belgium or Holland, much of which was also within radar range of this country. Secondly, the O.R.S. had to discover the extent of damage. To begin with, it had to rely on the evidence of aircrew which was often, though not intentionally, untrustworthy. Later, assessments were made easier with the assistance of the camera and analyses of films became a routine task for the O.R.S.

Unlike the U-boats, surface vessels and their escorts were able to hit back with anti-aircraft weapons and much thought had to be given to the best methods of protecting the attacking aircraft. It was found, for example, that torpedo-carrying aircraft normally required an escort of four aircraft while aircraft carrying rockets required none. This was on account of the fact that the carrying of rocket projectiles did not prevent the aircraft from using its cannon in an anti-flak role. Finally, the O.R.S. had to assess the degree of destructiveness of weapons employed on anti-shipping strikes. In this matter, it collaborated with the Department of Naval Construction of the Admiralty. Their wide experience of the effect of the enemy's weapons on Allied merchant and naval vessels was of great value in deciding which weapon or which bomb fusing to use on particular occasions. The respective efficiency of torpedoes, rocket projectiles and bombs was examined. For example, controversy arose in the early days of rocket-firing as to whether the 60-pound H.E. head or the 25-pound A.P. (Armour Piercing) head should be used against shipping. Early operations had been unsuccessful but it was impossible to say whether this was due to bad aiming or to the wrong type of head. Subsequent experience was to lead to the belief that it was both. On the basis of assumed aiming error, it was estimated by technical officers on the Air Staff that the solid head was much superior because it made a hole in the ship under water. However, even the solid head yielded few results until the operations of August 1944 made it clear that the solid head was capable of sinking quite large ships, including *Sperrbrechers*.[1] With photographic evidence to support it, the O.R.S. was able to show that the damage required to sink a vessel was in reasonable agreement with that postulated by the Air Staff. The fact that, in general, hits in two holds were necessary to sink a ship of 3,000 tons

[1] Vessels heavily armed with anti-aircraft weapons.

meant that, in general, hits from two aircraft were necessary. Thus an optimum number of aircraft was required to attack each vessel—considering efficiency in terms of ships sunk per aircraft attacking. It was shown that this optimum figure was of the order of six aircraft per ship, which was reasonably well in agreement with the operational figures.

The conclusions of the O.R.S. were found to be substantially correct after enemy documents had been examined by its representatives when they visited French ports after Allied occupation in 1944, and harbours in Norway, Denmark and northern Germany in 1945.

PLANNED FLYING AND PLANNED MAINTENANCE

The shortage of suitable aircraft for anti-U-boat operations led to investigations into the relation between flying effort and the strength of aircraft concerned. O.R.S. Coastal Command was asked to look into the problem of 'reducing maintenance' and thus to obtain more flying time from the force available. Within a short time there emerged a new field of activity known as Planned Flying and Planned Maintenance which in due course absorbed the largest single group within the section. The first reports made by the O.R.S. confirmed the truism that if Coastal Command was to fulfil an increased offensive role against U-boats, it must have an increased supply of aircraft. Simple as this conclusion was, it played a considerable part in the preparations for the Bay offensive and led to an allocation of American aircraft to the Command.

In a report dated 15 November 1942 the O.R.S. conducted a detailed analysis of the interactions of manpower, aircraft and effort.[1] In it was noted the number of hours which an aircraft spent in flight, the number of hours spent on its maintenance, the number of days spent while awaiting spare parts or tools, the number of days during which it was serviceable but did not fly and so on. It was discovered that the number both of flying and non-flying days had a profound influence on the possible number of hours that a squadron of 20 aircraft could achieve in one month and that the maximum effort could not be achieved unless the squadron attained the right, not necessarily high, level of serviceability. Also the work involved in a squadron flying 876 hours a month cannot be the same as the work involved in flying 1,752 hours a month. It can be assumed, in fact, that technical work will be directly proportional to flying hours and the manning of squadrons must be determined accordingly, not, as at the time that this report was issued, according to the number of aircraft in the squadron. To get the most out of a squadron the flying plan must be clearly outlined first and a maintenance plan worked out to fit it.

The O.R.S., having established the relationship between the state of aircraft and the intensity of flying, carried out a quantitative analysis in

[1] This work, initiated by Professor Williams in 1942, was supervised by Dr. C. Gordon, a biologist.

order to evaluate the time which an aircraft spent in being maintained and awaiting spares. No. 502 (Whitley) Squadron was selected for the trial and its flying plan was drawn up by the O.R.S. The squadron was to be flown on routine anti-U-boat patrols whenever weather was fit so that the number of days on which an aircraft was serviceable but did not fly did not come into consideration. In order to make sure that the maintenance organisation was fully employed the flying was increased gradually by one sortie per fit flying day, until there was always one aircraft awaiting manpower. When this point had been reached the state of aircraft in the squadron was noted every half-hour; this took one observer only. From these individual aircraft histories the time spent in being maintained and awaiting spares was easily calculated. As a check on the balance of establishment the histories of men were also taken to show whether any one trade was overworked and forming a bottleneck in aircraft servicing, for although the presence of one aircraft always awaiting manpower is a guarantee that the maintenance organisation as a whole is fully employed, it does not ensure that there is an adequate balance of trades within the organisation. The experiment was so successful that during three out of the five months in which the trial was conducted, the squadron exceeded its own previous maximum flying effort per aircraft by 61 per cent and exceeded the best average of any squadron over a single period by 79 per cent. This could largely be attributed to planning of the flying, since little change was made in the maintenance organisation beyond keeping it fully employed by flying the squadron to capacity.

As a result of this rather detailed investigation it was possible to calculate tasks and establishments for Whitley squadrons. It remained to evolve a system which would enable tasks and establishments to be calculated and performance with respect to task checked in all squadrons regardless of aircraft type. Since at this time O.R.S. Coastal Command were, as the inventors of the system, the only people with experience of operating the system, it naturally fell to them to play a large part in designing the staff machinery necessary for the introduction of the system into the Command as a whole.

FORMATION OF O.R.S. AT HEADQUARTERS TRANSPORT COMMAND

On a more modest scale than their counterparts in, for example, Bomber or Fighter Commands, O.R.S.s were formed at Headquarters Transport and Flying Training Commands during the spring of 1944. The O.R.S. in Transport Command originated on 8 May, its terms of reference being to advise the Air Officer Commanding-in-Chief on the scientific aspect of the activities of his Command and to conduct investigations and analyses for any branch of the staff which might require them. The Senior Scientific Officer, Mr. J. J. Vincent, who had worked with Dr. Gordon at Headquarters Coastal Command, carried the title of Scientific Adviser to the

Air Officer Commanding-in-Chief Transport Command and was assisted by nine scientific officers.

The first task of the O.R.S. was to form a statistics branch to collect information about the world-wide activity of the Command such as the state and location of aircraft, accidents, passengers carried, aircraft miles, passenger miles and ton miles flown, stage by stage, and all the data necessary for an assessment of the Command's effort and efficiency. There were four main subjects which occupied the attention of the new section. They were maintenance; radar, radio and navigation; the signals organisation, and aircraft accidents and losses. A short account of the way in which these subjects were tackled now follows.

AIRCRAFT MAINTENANCE AND ECONOMIC UTILISATION OF AIRCRAFT AND MANPOWER

The O.R.S. made a detailed survey of the way in which aircraft inspections were made at Lyneham, the main base of Transport Command in Great Britain. The maintenance problem for air line operations was very different from that experienced in normal combatant or training operations. The fundamental differences were, firstly, that flying was done to a fixed time table and, secondly, that much of the flying was done away from base. Thus, for economical working, it was essential to keep the servicing in step with the flying schedule and to minimise the servicing done away from base. Observers noted down at half-hourly intervals throughout a normal working day the employment of each airman of a gang employed on a particular aircraft. It was found that a man, when on duty at Lyneham, was able to perform seven and a half hours' work at his trade during the day. Using this figure and taking into account the amount of time necessary for leave, days off and sickness, it was possible to fix establishments on a rational basis when the flying programme was known.

The O.R.S. also discovered by suitable analysis and consideration of the working space available, the size and composition of the maximum economic gang, that is, the gang which would complete an inspection in the minimum time when the advantage of avoiding unserviceable aircraft hours was balanced against the disadvantage of lowering the productivity per man. The chief problem was that, on account of absence due to sickness or leave, a gang was never at full strength to complete a particular task. The O.R.S. recommended that a reserve should be maintained of men normally employed on low priority jobs who could fill gaps which arose in the gangs.

It transpired through studies of inspection and maintenance of the Yorks, Liberators, and Dakotas of the Command that although, apart from the inspection proper, the various tasks involved, such as preparations for air test, subsequent rectifications, compass swing and Grade I Inspection, did not absorb much manpower, a great deal of aircraft time could be lost if the sequence was not carefully organised. The O.R.S. recommended the allocation of an aircrew to the Chief Technical Officer so that air tests could be carried out without delay; the formation of a highly skilled rectification gang, prepared to work at nights, to deal with repair work that could cause undue delay if left to the normal inspection gang and, finally, standardisation of the inspection proper by working to a schedule of operations.

The reports of the O.R.S. were greatly appreciated by technical officers, both in the Command and at the Air Ministry, but were apt to be looked at askance by senior officers who feared that the O.R.S. might be overreaching itself in its capacity as an advisory body.

RADAR, RADIO AND NAVIGATION

O.R.S. Transport Command was responsible for investigating all radar and radio equipment relating to navigation, approach, landing and flying control. Its first task in this field was to make a quantitative estimate of the amount of aircraft that could be handled by any one radio-fixing system. The W/T log book of a ground station was examined during a period of activity. By estimating the time required to transmit each message, for which purpose a standard speed of operation had to be assumed, it was possible to establish an approximate relationship between the 'load' (i.e. the fraction of time for which the channel was occupied) and the 'traffic' (i.e. the number of aircraft dealt with in a given time). The results showed that the safe limit to traffic was 10 to 12 aircraft per hour, but that it was impossible to guarantee to get a fix on each one of them, or even on a majority of them. Before then, it had been generally believed that 20 aircraft per hour could be satisfactorily worked, each being given one fix at this rate of working.

The O.R.S. also drew up a plan for tracking and controlling aircraft passing through the London area in March 1945. It suggested that the zone as a whole (or 40 miles radius approximately) should be covered by three high power 10-centimetre ground radar stations similar to the American Microwave Early Warning set, and each of the five terminal airfields by some local aerodrome control radar set. Methods of identification, of height finding and the broad principles of the operation of the scheme were also outlined. Some indication, too, was given of the expected density of aircraft which could be worked and the requirements in manpower for operating the system.

THE POINT TO POINT SIGNALS ORGANISATION

During the early operations of Transport Command far too much time elapsed between the despatch and receipt of signals reporting the movement of aircraft, with the result that there were occasions when an aircraft would land some hours before the signal reporting its expected time of arrival had been received. An attempt to find out the cause of delay was made by O.R.S. Fighter Command, in the absence of an O.R.S. at Transport Command, at the instigation of the Director General of Signals at the Air Ministry. The report stimulated overseas commands into making similar investigations. Later, on the formation of an O.R.S. in Transport Command, a number of studies of air signals traffic were made. Log books, check sheets, message forms, receipt books and copies of teleprinter signals were examined. Delays were calculated arithmetically for all the signals in a sample and the results were classified. Other factors were taken into account such as the Watch System, the number of operators on duty per watch and their proficiency, the volume of traffic per hour, the number of W/T and teleprinter channels and ancillary equipment, the available space, and the relative geographical positions of the various parts of the signals section. It was found that the total delay could be conveniently sub-divided into two or three component parts: firstly, signals delay which occurred while the message was in the signals office; secondly, administrative delay which represented the time a message was held by the registries, and thirdly, cipher delay which was incurred while the signal was in the cipher office. When the various delays had been classified, the average for each group was calculated, and this, together with the maximum and minimum delays, was given in the report. The results were usually given graphically, with diagrams when they were appropriate.

A number of 'time and motion' studies were made of work in the signals traffic office, teleprinter and W/T rooms and useful suggestions were made which contributed to the smooth running of signals offices.

AIRCRAFT ACCIDENTS AND LOSSES

Transport Command combat losses were low and so losses due to accident were relatively more important than in other commands, particularly because on several occasions important passengers were involved. The O.R.S. did little more than collect statistics and arrange them in a form suitable for analysis, before the end of the war. A weakness of the reports demanded by the Air Ministry on the occurrence of an accident lay in relating the number of accidents to the number of flying hours, instead of relating separately those accidents liable to arise in taking off or landing to the number of take-offs; those arising *en route* to the number of hours flown; and those depending on the time the aircraft is on the ground through, for instance, being damaged when parked to the time the aircraft would normally be on the ground. Unless this separation was carried out a false interpretation of changes in the accident rate might be made. For example, a change in the length of sorties might lead to a reduced number of accidents per 1,000 hours although no real change in accident risk had taken place. Thus, to take a hypothetical case, assuming the accident rate for taking off and landing was one per 100 flights, for accidents *en route* one per 1,000 hours, and for ground accidents it was zero. Then with five-hour sorties for 1,000 hours flying, there would be three accidents, but with 10-hour sorties there would be only two. It is probable that the general reduction in accident rates which occurred as the war continued was, in part, due to an increase in the average length of sorties.

The O.R.S. prepared two reports on the subject of accidents to aircraft despatched by Transport Command to Gibraltar in order to discover whether there was any disparity between experienced crews and crews making the flight for the first time. It was found that during the first nine months of 1944, 6 per cent of aircraft entrusted to No. 44 Group sustained accidents up to the time of first arrival overseas and 1·8 per cent suffered irreparable damage or were missing. The accident rate for the last four months of the period was much lower than for the other five and it was concluded that this was mainly the result of efforts made to reduce accidents, for example, by improving cockpit drill, and partly the result of better weather. There was no conclusive evidence that inexperienced crews were more liable to accidents than experienced crews, nor were Beaufighters more prone to accidents than Wellingtons. The O.R.S. recommended that deliveries of aircraft should be increased in the summer months and reduced in the winter in order to avoid the bad weather. This procedure would fit in with the potentially greater time for training and preparation in the summer and the irregular flow would be supported by aircraft reserves held in the overseas theatres.

FORMATION OF O.R.S. AT HEADQUARTERS FLYING TRAINING COMMAND

Early in 1944 the Air Ministry, in view of the critical shortage of man-power in Great Britain, was keen to improve the planned flying and planned maintenance in Flying Training Command, and after a visit to its Air Officer Commanding-in-Chief on 10 March by Sir George Thomson and Dr. Gordon, who, it will be remembered, had recently been attached to the staff of the Scientific Adviser to study this problem, an O.R.S. consisting of ten scientific officers was formed. The officer-in-charge was Mr. W. E. Egner, a former member of O.R.S. Fighter Command.

The function of the O.R.S. was to advise on the best way to achieve planned flying and planned maintenance, and to bring about uniformity in the syllabus, training programmes, examinations, returns and pamphlets of the Command. To this end four reports were issued before the conclusion of the war, including studies of the training of air gunners and wireless operators and an investigation of flying activity at (Observer) Advanced Flying Units. Studies continued after May 1945 and further investigations were proposed by the O.R.S., among them being the study of the nature and frequency of accidents in training related to the standards of the pupils and type of training. Periodical checks were to be made on equipment and methods of training and advice tendered on any innovations.

CHAPTER VI

Development of Operational Research Sections Overseas, 1942 to 1943

FORMATION OF O.R.S. AT HEADQUARTERS R.A.F. MIDDLE EAST

As soon as the value of the O.R.S.s in the Home Commands had been proved plans were made for the establishment of similar sections in R.A.F. Overseas Commands. In the period under consideration the Middle East was the crucial theatre of operations and, in late 1941, the Air Officer Commanding-in-Chief, Air Marshal Sir Arthur (afterwards Lord) Tedder, agreed to the formation of an O.R.S. at his headquarters in Cairo. Mr. J. C. Kendrew who, as already noted, had done valuable work in Coastal Command was the first scientific officer to arrive in the Middle East. He paid two visits to Malta, which was already undergoing heavy air attacks, during October and December 1941, his main task being to instruct air-crew, controllers and staff officers in the operational working of A.S.V.[1] On 17 December Mr. Kendrew left for Cairo where he paved the way for the formation of the O.R.S. R.A.F. Middle East.

This O.R.S. became operational in mid-February 1942 with Dr. J. C. Bower, a physicist, as the officer-in-charge. With him as third member of the team was Mr. I. G. de Teissier, a mathematician. Both officers had served with O.R.S. Fighter Command. By the end of February a programme of work had been drawn up and Dr. Bower asked the Air Ministry to send out more scientific officers. In spite of the fact that his demands seemed to be reasonable, adequate reinforcements did not arrive until the following year. However, new members were recruited locally, both from the R.A.F. and W.A.A.F., and in a short time groups were set up to analyse ground radar, air/sea warfare, bomber operations, G.C.I./A.I., combat films, enemy radio counter-measures, the accident rate, aircraft performance and night vision, among other matters. Another important function of the O.R.S. was lecturing to R.A.F. personnel on specialised equipment such as A.S.V. and talks were given on the principles of radar to the Middle East Fighter Controllers School.

By May 1943 the section had achieved its maximum strength of 25 officers but by then the campaign in North Africa was rapidly drawing to

[1] Mr. Larnder, then Officer-in-Charge, O.R.S. Fighter Command, went to Malta for a fortnight at the end of April 1942, at the height of the battle, to advise on operational research matters. The A.O.C. Malta expressed great satisfaction at the valuable results and asked for an O.R.S. officer to be permanently based on the island. The scarcity of scientists made this impossible.

its close. The invasion of Sicily and Italy and the subsequent lengthening of communications between Cairo and the battlefield naturally reduced the O.R.S.'s responsibilities, much of its work being taken over by O.R.S. Mediterranean Allied Air Force, of which more will be related later.

There is no doubt that the most important work of the O.R.S. in the Middle East was its investigations into the anti-shipping and anti-U-boat campaign carried out by the Royal Air Force in the Mediterranean which, in all probability, more than anything else was responsible for the eviction of the enemy from the Western Desert and French North Africa. Secondly, it played an important part in facilitating air-to-ground co-operation in the Western Desert. Thirdly, it conducted an analysis of strategic bomber operations conducted from Middle East and North African bases. The extent of these activities must now be considered.

THE CAMPAIGN IN THE WESTERN DESERT

In April 1942 O.R.S. Middle East produced a report which discussed the advantages that might accrue from radio aids, in particular the Rebecca/Eureka system and mobile light warning sets in air support operations. The former was intended to be a means of identification for aircraft supporting ground operations in the desert, by which they could locate from far off, home on and recognise friendly forces on the ground, if necessary under blind conditions. Thus tactical reconnaissance aircraft could determine the position of friendly forces and plot the enemy by process of elimination. They could then home on to the Corps headquarters Eureka, drop their messages and maps and then home on to their own landing ground. Eureka sets attached to forward troops could define the bombline with much greater accuracy than before. However, the equipment did not become available in the Middle East until the campaign was over with the exception that it was used with indifferent success during the landings in Sicily. Its use did, however, have a favourable influence on the Rebecca/Eureka policy in the United Kingdom where forces were concentrating for the return to the Continent.

At the close of 1942 an O.R.S. officer visited units in the Western Desert with the object of discovering the feasibility of radio aids in offensive fighter operations. Two obvious cases for the use of radio aids were the plotting of tactical reconnaissance aircraft and the controlling of fighter bombers. Fighter bombers briefed for special targets at known positions could be vectored there, while the employment of radar plotting would simplify navigation for pilots of tactical reconnaissance aircraft in featureless country and ensure much greater accuracy in pinpointing than that obtained by dead reckoning methods. The pilot of a single-seater tactical reconnaissance aircraft would be able to concentrate on observation to a greater extent than might otherwise be possible if his position was recorded when necessary by the appropriate ground organisation. Tests were carried out with an I.F.F. beacon. At 2,500 feet a Hurricane aircraft was plotted to its turning point at 70 miles range and at 100 feet to the turning point at 33 miles.

As a result of these experiments and recommendations by the O.R.S., trials took place in the Western Desert with a tactical reconnaissance squadron (No. 40 S.A.A.F.). No. 889 Radar Station which was sited as a G.C.I. with the mean aerial height of 10 feet was used as the ground station. The Hurricane aircraft was equipped with Mark II G I.F.F. and, in addition, the pilot was equipped with a small morse key which enabled him to signal back when in positions which should be recorded. Progress was marked by trial and error but at that time the enemy was in full retreat and an understandable lack of interest in the experiments became apparent. In England, however, the Tactical Air Force preparing for operations on the Continent had ample leisure to be educated to the value of the use of radar equipment both in the air and on the ground, before being committed to active close support operations.

THE AIR WAR OVER THE MEDITERRANEAN SEA

The first contact of O.R.S. Middle East with anti-shipping operations occurred during the original visits of Mr. Kendrew to Malta. In view of the success of anti-shipping operations conducted during the latter months of 1941 his visit was significant, particularly in regard to the Rooster beacon technique. In this technique aircraft were equipped with a Rooster beacon which responded to A.S.V. signals enabling A.S.V.-equipped aircraft to home on a Rooster-equipped reconnaissance aircraft. In this way much time was saved in organising strikes against enemy shipping.

During this period a number of Wellington aircraft were converted to carry torpedoes instead of bombs. O.R.S. Middle East advised that these aircraft should be fitted with A.S.V. if their operational flying time was not to be wasted, citing in support of their argument the considerable success of A.S.V.-equipped Wellingtons operating from Malta at an earlier period.

During early 1942 the enemy used two main routes to carry supplies to North Africa—to Tripoli keeping to the west of Sicily and Pantelleria, and to Benghazi from the Gulf of Taranto passing some 100 miles west of Malta. Successes in strikes by aircraft were very limited, although air reconnaissance had revealed the location of most of the enemy shipping. The O.R.S. gave as reasons for this comparative lack of success, firstly the fact that intensive enemy air attacks on Malta limited the effort available from that island and, secondly, very few aircraft were available to No. 201 Group to operate from Western Desert bases and these aircraft were operating at extreme ranges. During the period April–May 1942 naval action, based largely on previous air reconnaissance, was responsible for inflicting heavier damage on enemy shipping. Thus improvement in the co-operation between reconnaissance aircraft, naval surface vessel and submarine was desirable in order to make the most of the available opportunities. To this end the use of Rooster by naval vessels was strongly recommended by O.R.S. A Rooster beacon fitted to a ship or submarine could be picked up by A.S.V.-equipped aircraft thus allowing the position of the ship or submarine in relation to the aircraft and therefore also its position from any convoy sighted by the aircraft to be determined. This enabled the ship or submarine to be positioned appropriately in relation to the track of the convoy. In order to avoid the use of W/T communication between aircraft and submarine, experiments on keying the A.S.V. transmissions were conducted. These experiments were successful.

By June 1942, with the cessation of enemy air raids on Malta, an upward trend was apparent in the effectiveness of air attacks on enemy merchant shipping which supplemented the operations being carried out by the Royal Navy. The greater air resources available for anti-shipping work by that date undoubtedly had a favourable influence as did also the new tactics introduced during the period—W/T homing of strike to shadower and Rooster technique as applied to air-to-air and air-to-sea co-operation. At this stage the O.R.S. discussed a further Rooster technique applicable to low flying. Low flying by the strike torpedo aircraft precluded early radar detection by the enemy. At the same time this method restricted visibility with a consequent increase in search time. By equipping a reconnaissance aircraft such as a Maryland or Baltimore with Rooster which remained in the vicinity of shipping at an altitude of between 5,000 and 10,000 feet, approaching low-flying strike aircraft (Beauforts) could converge on the reconnaissance aircraft from some 80 miles. This stratagem was used with success during the air attack on the Italian Fleet on 15 June 1942 in support of two Malta convoys and again in anti-shipping operations in July.

During the latter part of 1942 and the early part of 1943 O.R.S. Middle East analysed the operations of No. 201 Group, the air forces under A.H.Q. Malta and the Northwest African Air Forces. Both the attack of ships at sea and the effects of mining operations and of bombing attacks on harbours were examined. Both of these activities were shown to be effective in sinking and damaging shipping, although operations against ships at sea proved to be more profitable. Contrary to the situation existing in the first half of 1942, air attacks had become much more effective than naval attacks in sinking and damaging enemy shipping. The improvement in the results was obtained despite increased enemy counter-measures, particularly the jamming of A.S.V. and the extensive use of smoke-screens by convoys.

The O.R.S. was now able to analyse each phase in an anti-shipping strike. One interesting point related to the destructive power of bombs and torpedoes. It was shown that the torpedo was a more effective weapon than the bomb (as dropped by night bombers from medium altitudes), particularly when assessed according to the tonnage of shipping sunk or damaged per ton of weapon employed. Further, while location efficiency varied very considerably with different types of aircraft operating in the different areas concerned, conversion efficiency was usually very high. In regard to location efficiency it was shown that the method of W/T homing had not proved altogether successful in practice as few aircraft received the W/T transmission on which to home, although it must be said that of those aircraft which did receive the signals a high percentage located the target.

At the end of 1942 the O.R.S., on the instructions of the Air Officer Commanding-in-Chief, R.A.F. Middle East, produced a detailed report analysing the part played by the Allied Air Forces in the Mediterranean theatre in interfering with enemy supplies and making an assessment of the contribution which this effort made towards the final defeat of the enemy. The O.R.S. analysis proved that a small well-balanced Air Force can produce the most striking results under conditions where the less mobile surface forces are unable to operate. It was further demonstrated that the unified control of the Allied Air Forces throughout the theatre of operations proved to be appropriate from the point of view of organisation. Unified control led to unity of purpose.

The work of the O.R.S. in connection with A.S.V. can be divided into two phases—a first phase in which the O.R.S. was largely concerned with advocating the operational advantages to be gained by more extensive employment of A.S.V., together with the associated use of ground beacons for navigational purposes and Rooster for air-to-air and air-to-sea homing, and a second phase in which the O.R.S. analysed in considerable detail A.S.V. performance under a variety of conditions, including enemy jamming activities. Neither phase was exclusive in point of time.

The outcome of extensive examination of A.S.V. performance was the production by the O.R.S. of a manual on Mark II A.S.V. in July 1942 which covered all aspects of the equipment. It was distributed widely in the Mediterranean theatre and also in the South-east Asia and South-west Pacific areas.

Measures were also taken by the O.R.S. to prevent enemy jamming of A.S.V. equipment. Enemy radio counter-measures which began in August 1942 did not become serious until the enemy had been driven from Egypt and Libya. At this time all enemy convoys were routed along the North Sicilian coast and across the Tunisian Narrows. The enemy had the advantage of high ground on which to site his jamming transmitters. The efficiency of search aircraft was reduced, thus limiting the effectiveness of air action against enemy convoys. The obvious answer was the provision of A.S.V. of centimetric wave-length. The arrival of a number of Wellington aircraft equipped with Mark III A.S.V. was therefore welcome.

BOMBER OPERATIONS

It was not until late in 1942 that O.R.S. Middle East undertook the analysis of bomber operations, although it had referred to them incidentally in reports dealing with close support and anti-shipping operations. The O.R.S. also drew the attention of officers concerned with bomber operations to the relevant A.W.A.S. and O.R.S. Bomber Command reports which were received from the Operational Research Centre at the Air Ministry.

While the bomber forces in the Middle East at this time were small in number compared to those of Bomber Command, their judicious employment against suitable targets made them a valuable asset. Early in 1942 the O.R.S. drew attention to the necessity of concentrating raids in time with dispersal in space if losses were to be restricted to the minimum. Attention was also drawn to the performance of enemy anti-aircraft weapons with a view to indicating the desirable range of dispersion in heights of attacking aircraft to limit casualties from flak.

The light-bomber operations against targets of a tactical nature in the Western Desert were reviewed in June 1943. This report gave statistics over the seven-month period, November 1942 to May 1943, for Boston and Baltimore aircraft. Four squadrons flew some 3,000 sorties by day and 650 sorties by night in this period, some 85 per cent succeeding in bombing the primary target by day and 95 per cent by night. Failures by the light bombers to find the target were almost entirely due to weather, technical failures being rare. Casualties on the whole were light, being mainly due to enemy flak. Factors affecting navigation, target identification and bombing methods were briefly discussed. Great interest was displayed in the report which was really more in the nature of a review of tactical bomber work rather than a detailed investigation into aspects of light bombing operations.

With the help of regular statistical reports the O.R.S. was able, for example, to investigate a falling off in efficiency of target location by heavy bombers between November 1942 and the three succeeding months. They found that the more distant targets were less accurately bombed than those situated at short range. A later report investigated technical failures in detail. Engine failure was confirmed as being by far the biggest contribution to failure especially in the case of the Halifax which showed a 14·4 per cent failure due to engines. The Ministry of Aircraft Production subsequently sought greater information regarding technical details and accordingly some effort was expended in obtaining further statistics.

The O.R.S. also stressed the importance of photographing targets in conjunction with bombing, a procedure which was being profitably pursued by Bomber Command at home. The O.R.S. comments led to the Air Staff initiating a campaign to make squadrons more conscious of night photography. Some improvement in the standard of target location took place although the accumulating photographic evidence still revealed room for further improvement.

A knowledge of the bomb distribution for different types of bomber attack is necessary if rational planning of operations is to take place. As an example, data relating to the accuracy of bombing by heavy bombers was necessary when the O.R.S. was asked to recommend the type of attack and type of bombs which might be used in attacking the U-boat shelters at Scaramanga. Having regard to bomb availability in the Middle East, the employment of 2,000-pound high capacity bombs with stick spacing of 200 to 300 feet was suggested, and for coverage of the whole of this particular target area an aiming point 500 feet south-west of the centre of the pens was recommended. Other investigations requiring some knowledge of bomb distribution were tackled by O.R.S. Middle East at various times.

RADAR INVESTIGATIONS AND NIGHT AIR DEFENCE

Like its parent O.R.S. at Fighter Command, O.R.S. R.A.F. Middle East kept a check on radar station performance, and surveys of the radar system in Egypt and the Western Desert were carried out. Early in 1943, owing to the addition of a number of radar-trained officers to the O.R.S., it became possible to locate O.R.S. officers in key filter rooms, e.g. at Alexandria, Ismailia, Ramleh (Palestine), Malta, Cyprus (part-time), Mersa Matruh, Tobruk, Benghazi and Tripoli. These officers contributed to the later O.R.S. work on radar station performance. They were frequently the final arbiters in any question concerning radar system performance and they contributed materially to the general understanding of radar by Service personnel. By April 1944 radar in the Middle East was a diminishing quantity and the need for O.R.S. association with the radar organisation vanished.

Concurrently with the analysis of performance a study of operational efficiency was undertaken. An early report analysed time delays in the reporting sequence between radar stations, filter rooms and operations rooms in Nos. 250 and 252 Wing areas. The average time of transmission of intelligence via telephone links from the cathode ray tube at the radar station to its display in suitably digested form on the operations room table was 42·5 seconds. Compared to available figures from Great Britain this indicated a high degree of efficiency on the part of those concerned.

Less satisfactory was the passage of radar information by W/T. One cause of inefficiency was the complicated code which had been built up in the course of the years to provide the necessary key to the intelligence passed. The O.R.S. recommended the adoption of a single letter coding system as a substitute for the complicated 3/4 letter system in use. No appreciable loss of security was involved as the enemy undoubtedly had broken down the common elements in the existing code as readily as he would interpret the simpler code. The use of the simpler code would cut down the length of messages and being readily memorized would tend to improve accuracy in transmission. The O.R.S. recommendations were accepted and put into practice forthwith. Subsequent analysis revealed that the W/T plotting was approaching the telephone plotting in speed and accuracy.

Other improvements were made as a result of O.R.S. recommendation. A standard fighter operations grid was introduced for plotting purposes together with a uniform system for tracking raids. A comprehensive report produced in July 1942 related the efficiency of each link in the Delta fighter defence system (radar, V.H.F. D/F, communications, personnel) to the requirements essential for advance warning and interception of enemy aircraft by day. Experience of the O.R.S. in filter room layout was condensed into a memorandum and circulated to interested units. It may be remarked that this class of work was scarcely operational research, but it must be stressed that of the officers in the Command with knowledge of the relevant factors, the operational research officers had the widest practical experience backed up as it was by analytical conclusions enabling them to make authoritative comment.

A series of reports was written by O.R.S. Middle East dealing with G.C.I. cover and the night fighter defence system. These took the form, both of reviewing critically the overall cover provided by the G.C.I. stations and supplying coverage diagrams, and of dealing with individual station performance from the viewpoint of actual and possible operational and technical efficiency. Their work did not differ fundamentally from that of O.R.S. Fighter Command in a similar field and it is not intended to enlarge on it further.

The O.R.S. was also drawn into making an investigation of the enemy's radar system. Flights were made by No. 162 (Wellington) Squadron in order to obtain information, and logs of aircraft were analysed by the O.R.S. The first report covered the enemy long-range (*Freya*) stations in the Western Desert. In successive reports the O.R.S. using the logs provided by No. 162 Squadron (now prepared according to a standard *pro forma*) estimated the performance of the enemy radar system throughout the eastern Mediterranean, southern Italy, Sicily and Sardinia. It was interesting to note the rapid development of the enemy coverage coincidental with the series of defeats inflicted on his forces at El Alamein in October 1942 and subsequently. The withdrawal of the enemy from North Africa made it necessary for him to pay more attention to his defensive ground radar system.

Before leaving the subject of radar note must be taken of the part played by the O.R.S. in educating radar personnel, particularly those working in filter rooms. The extensive knowledge relating to ground radar performance and operational efficiency accumulated by various members of the O.R.S. in the Middle East and at an earlier date in Fighter Command was condensed into a manual which was distributed to filter rooms and radar stations throughout the Middle East. Education of personnel also extended to those concerned with airborne radar and another important manual was produced on A.S.V. Mark II. It was considered that the publication of these two manuals formed one of the most substantial contributions of the O.R.S. Middle East during its three years of existence.

ACCIDENT INVESTIGATION

A subject, far removed from radar, in which O.R.S. Middle East soon became involved was an investigation into the rate of flying accidents. These had risen from 188 in January 1942 to 325 in July 1942. A preliminary survey by the O.R.S. in August 1942 stressed the fact that some 60 per cent of flying accidents in the Middle East were classed as avoidable. Attention was directed to the inadequacy in the sources of information, particularly in relation to incomplete returns of casualty signals, with the result that the Air Officer Commanding-in-Chief emphasised to his subordinate commanders the necessity of the complete return of information.

In September 1942 an analysis was made of 112 accidents on which complete data were available. Of these accidents 54 per cent were avoidable accidents being due to carelessness and another 25 per cent to inexperience, errors of judgement and disobedience of orders. Even on the limited data available it proved possible to demonstrate that the accident rate diminished with the increase in operational age of the pilot. (Some 18 months before O.R.S. Coastal Command had reached the same conclusions.) Actually, for every avoidable accident made by a pilot whose flying time exceeded 500 hours, two avoidable accidents were made by pilots with 200 hours' flying experience and four avoidable accidents by pilots with 150 hours' flying experience. In October 1942 an increase in the strength of the O.R.S. enabled the allocation of one officer full-time to the analysis of accident data. This commitment was later taken over by an Accident Investigation Section.

FORMATION OF O.R.S. AT HEADQUARTERS NORTHWEST AFRICAN AIR FORCES

It had been intended that a small O.R.S. should be included in the Allied forces which landed in French North Africa in November 1942, but on account of lack of liaison by those concerned in planning the operation with the Operational Research Centre at the Air Ministry the personnel were not ready to go with the advanced air force. Not until February 1943 was the decision taken to send out an O.R.S. to the Headquarters Northwest African Air Forces which was the operational headquarters controlling both British and American air forces at that time deployed in French North Africa. Mr. E. C. Williams, one of the founder members, it will be recalled, of O.R.S. Fighter Command, was appointed as officer-in-charge that April. He quickly realised that the establishment of the section was far too small for the problems awaiting solution, particularly in the absence of an American counterpart to the O.R.S., and the Air Ministry agreed to an establishment of 15 scientific officers under the Principal Scientific Officer.

Meanwhile work began, a bomb damage assessment of Sousse and Tunis being the first task. At the same time, in February 1943, Professors J. D. Bernal and S. Zuckerman of the Research and Experiments Department of the Ministry of Home Security had been sent out to Tripoli to make a survey of Allied (and enemy) bombing on the town. Further reference will be made to this event later in the chapter. It was obviously important that duplication of the limited amount of scientific work available should be avoided; and an agreement was made between Mr. Williams and Professor Zuckerman that the O.R.S. would carry out no work on bombing survey until Professor Zuckerman had obtained all the information that he required, but that Mr. Williams would lend to Professor Zuckerman as many of his staff as possible, in order that his very important work might be done quickly.

Discussions were also held between representatives of the Operational Records Section at Headquarters R.A.F. Middle East and of the American Statistical Control Organisation, concerning the best methods of arranging for the collection and use of vital records and statistics—practically non-existent in the North African theatre. This was to provide essential material upon which the new O.R.S. could work.

In June 1943 Mr. J. G. Tedd, also a former member of O.R.S. Fighter Command, was sent at the request of Air Vice-Marshal Sir Hugh Lloyd to the Headquarters of the Northwest African Coastal Air Forces to head a permanent O.R.S. detachment to deal with the many problems peculiar to that Command.

The work of the O.R.S. in 1943 was, as will be seen, largely concerned with radar problems, but by August with the invasion of Sicily well under way it became possible to make ground surveys of bombing targets on the island. This work, according to the agreement previously made, fell under Professor Zuckerman's direction, but as Professor Zuckerman was then in England, Mr. Williams established an advance party in Palermo. At the end of August Headquarters Northwest African Air Forces which had been situated at Constantine in Algeria moved to La Marsa near Tunis, the O.R.S. accompanying it. At the same time there arrived the first representative of a projected American Operational Analysis Section (O.A.S.). He was Mr. I. H. Crowne and he was followed immediately by four American operational analysts. Very intimate liaison was immediately established with the American section which continued throughout the association of the two sections. In fact many jobs for the Command were done by the joint efforts of the O.R.S. and the O.A.S.

A period of consolidation now followed, the various members of the team settling down to work in their chosen fields of study. Reports were written on bombing accuracy, the fighter defence of ports, supply routes and convoys, the anti-U-boat and anti-shipping campaigns, radar and radio counter-measures while three members were attached to Professor Zuckerman's Bombing Survey Unit at that time established in Palermo. In December 1943 an amalgamation of the Northwest African Air Forces and the Mediterranean Air Command was made, the new Command, still integrated, becoming known as the Mediterranean Allied Air Forces. The O.R.S. Northwest African Air Forces now became O.R.S. Mediterranean Allied Air Forces without change of function.

PROBLEMS OF AIR DEFENCE

The task of the air defence system in the western and central Mediterranean was the protection of coastal convoys, in conjunction with the Allied navies, against enemy aircraft, U-boat and surface-craft attacks and the protection of essential ports, airfields, dumps and installations strung out along these supply lines, against enemy air attack. The importance of this function is apparent when it is considered that the land campaigns in North Africa and Italy were entirely dependent upon the uninterrupted working of the supply lines.

In February 1943 fighter, anti-shipping and anti-U-boat operations were combined under the Northwest African Coastal Air Forces—an integrated Anglo-American organisation formed from the Eastern Air Command and XIIth Air Force of the original November 1942 landings. The small O.R.S. detachment allotted to it, already mentioned, varied in numbers from three to six officers until its close-down in September 1944. The work of the section was organised on a separate 'fighter' and 'coastal' basis with close co-operation on problems which overlapped.

The offensive power of the enemy air force had by this time passed its peak, its principal activities being periodic raids against shipping in transit, in harbours, or lying off assault beaches. Full use was made by the enemy of radio counter-measures, evasion and special weapons such as radio-controlled bombs. In the second place, day and night reconnaissance of Allied supply routes was made in order to provide intelligence, photographic evidence and meteorological information, both for general intelligence purposes and for the planning of the air strikes. The majority of these flights were flown at low altitude. The Allied ground radar system thus had to be extremely efficient.

Although the radar system was in essence comparable to that existing in the United Kingdom the Mediterranean theatre had its own problems, in particular the difficulties of communication, the rudimentary maintenance facilities and the supply and demand of equipment and personnel which were always conflicting. The O.R.S. reorganised and rationalised the various operational and technical returns from the different types of ground radar units in conjunction with the radar and operations staff. At the same time the need for a comprehensive calibration and test-flight programme was advanced and subsequently organised.

The various returns were analysed and correlated and a series of reports on the performance of the ground radar together with operational coverage maps were produced. These reports were available to headquarters staff for planning purposes and, with the continued retreat of the enemy, for the most economical redistribution of the ground radar units available. This was most important in view of the fine balance between supply and demand and the difficulties of transporting equipment since shipping space was always at a premium. In this connection the O.R.S. was frequently asked for advice and assistance in planning future radar coverage in newly occupied territories and in thinning out radar coverage in back areas. Another function of these reports was to enable the radar staff to maintain a check on the performance of individual radar stations and thus to distribute the limited maintenance effort to the best advantage over the considerable distances involved.

The O.R.S. also stressed the need to integrate British and American units under a common operational reporting and interception procedure. The policy was not to attach O.R.S. personnel permanently to the main filter rooms but for them to pay visits to the principal fighter wings in North Africa, Italy and Corsica. Apart from advising the sector, group (or U.S. fighter wing) and command headquarters on filter room matters and on radar operations generally, the visiting O.R.S. officers frequently gave lectures to filter and operations room staff, as well as to radar operators at stations.

At the same time as the routine work on radar was being done, problems in ground radar of a more specialised or original nature arose from time to time. It was the policy to concentrate more attention on these problems as the other commitments lessened. In the course of 1943 O.R.S. North-west African Air Forces investigated the following problems: the identification of friendly aircraft which led to the installation of Mark III I.F.F. in Allied aircraft; the enemy employment of Window; the control of fighter aircraft from a ship during a seaborne assault and the anomalous propagation of radar echoes.[1] At the same time trials were made with new ground radar equipment in order to devise the best operational procedure and adapt such equipment to the existing ground radar reporting and interception system.

A detailed analysis was also made of interception returns from day and night fighter squadrons, sectors and ground radar control stations. The

[1] Anomalous propagation, or super-refraction, is the bending or refraction of radio waves in the lower atmosphere in certain conditions. It gives rise to abnormally long ranges at times that may be roughly compared to visual images in some special atmospheric conditions. The conditions seemed to vary with the wave-length of the transmission.

purpose of the reports was, firstly, to assess the operational efficiency of fighter operations as a whole and to take any necessary steps to correct weaknesses and, secondly, to keep a comparative check on the operational efficiency of squadron operations, control methods and A.I. operations.

The O.R.S. was able to make a contribution towards the countering of enemy low level air attacks against Allied convoys off the North African coast. The enemy usually selected eastbound convoys since he had good general intelligence of convoys passing through the Straits of Gibraltar. Reconnaissance aircraft shadowed the convoy, the last of these aircraft being used as a homer for the strike force. From 30 to 60 aircraft were employed, consisting of two waves, one containing aircraft carrying torpedoes and the other carrying orthodox or radio-controlled bombs. The attacks were timed for dusk and the whole operation was planned to limit radar detection to a minimum, the reconnaissance aircraft as well as the striking force approaching their target at sea level. These attacks met with increasing success for the enemy over the period mid-August 1943 to mid-November 1943, the loss rate rising to three ships sunk and two damaged per attack.

After analysis of all available information, the O.R.S. in conjunction with the Air Staff, Headquarters Northwest African Air Forces recognised that the success of these operations from the point of view of the enemy depended upon a careful navigational plan both in timing and routeing and that the best chance of combating these operations lay not in close aircraft defence of the target under conditions of semi-darkness but in daylight interception by patrols placed across the approach lanes leaving a limited number of aircraft as close defence. The introduction of these countermeasures had an immediate success, with enemy strike formations broken up as much as 50 miles away from the target; and for three attacks in January and February 1944, only one ship was sunk and one damaged for 25 enemy aircraft destroyed or probably destroyed as opposed to nine ships sunk and six damaged for 17 enemy aircraft destroyed or probably destroyed during four attacks in October and November 1943.

Like its counterpart in Cairo, the O.R.S. Northwest African Air Forces was required to co-ordinate and analyse the information being received from all sources about the enemy's air and surface warning network in the Mediterranean. The signals branch of Headquarters Northwest African Air Forces also requested that the O.R.S. should act in a consultative capacity on enemy radar and radio counter-measure matters. As already noted the main sources of information on enemy radar locations were investigational flights, results of radio listening watches, photographic reconnaissance, prisoner of war interrogations and aircrew reports. The essential need in preparing these reports and maps was for speed. Throughout most of the period, up-to-date information was required either for actual offensive operations or for the detailed planning of them. By the spring of 1944 the work had become largely routine and the O.R.S.

handed over this part of their activities to the Intelligence Branch of Headquarters Mediterranean Allied Air Forces.

EFFECTIVENESS OF BOMBING BY ALLIED AIRCRAFT

On 19 April 1943 Mr. J. G. Angles of O.R.S. Northwest African Air Forces entered Sousse in order to investigate the effectiveness of air attacks against shipping, port facilities, and, in a more general sense, the town. The object of such a ground survey was to examine a sufficient number of examples of bomb strikes to be able to state positively the usual damage caused to a given target by a bomb of particular size, type and fusing. In conjunction with calculations made on the aiming accuracy of the participating aircraft, endeavour was then made to determine the optimum size and fusing of bombs. The problem involved several variables—bomb weight and charge/weight ratio; fuse timing; type of attack; distance of bomb from target and so on. It was an essential feature of ground survey to be able to establish the size, type and fusing of the bombs employed. This work was made difficult because of the practice of attacking targets with bombs of varying specifications.

On this occasion, as also in the case of nearly every subsequent investigation, it was found that insufficient positive data existed to enable definite conclusions to be drawn. On the other hand, although not statistically significant, the evidence indicated that armaments varied in their effectiveness sufficiently for certain recommendations to be put forward. Search for additional material was made subsequently, when they fell, in the ports of Bizerta, Tunis and La Goulette, the results being in no way conflicting with those derived from Sousse. In June 1943 there followed six months of collaboration with Professor Zuckerman about which more will be related in the following section.

VISITS TO MEDITERRANEAN THEATRE BY PROFESSOR S. ZUCKERMAN IN 1943

The advances by the Eighth Army in the Western Desert after the Battle of El Alamein laid open a rich field for operational research. It had not been possible before to examine the effect of the Allied weapons on enemy equipment and installations found in captured territory. Sir Henry Tizard was probably the first to appreciate that here was an opportunity to conduct investigations which might not recur quickly, when he wrote to the Chief of Air Staff on 25 November 1942. 'It seems difficult', he said, 'to get reliable information about the material, as opposed to the moral, effect of bombing of troops, vehicles, ports, supply dumps, etc. If the information could be obtained, we should have a much clearer policy of development of bombs, sights, fuses, etc., and, I suggest also, a much better guide to tactics. Now is our chance to get it, before the mess is cleared away, and while the experience is fresh in everyone's mind. . . . What we want to know is the percentage of bombs that do the damage; and we don't want to know this to satisfy academic curiosity, but to get technical improvements. For instance, what percentage of bombs was near enough to do any real harm. . . . Then what proportion of enemy vehicles were actually knocked out? Would better results have been obtained if more fighters had been used instead of bombers?'

This idea was acceptable to the Air Staff, and Professors J. D. Bernal and S. Zuckerman of the Research and Experiments Department of the Ministry of Home Security, who had already conducted experiments on the effects of bombs on buildings, structures and living organisms in England, were temporarily loaned to the Air Ministry for the purpose of making a survey of bomb damage in the Middle East. (They were at that time attached to Combined Operations Headquarters.)[1] After some delay due to administrative matters, they arrived in Cairo on 30 January 1943 and shortly afterwards flew to Tripoli which had just fallen to the Eighth Army. Here Professor Zuckerman stayed for three weeks (Professor Bernal had been recalled to England) studying the effect of Allied bombing on the town and port and making observations on the bombing of road convoys. He then returned to Cairo where he spent a fortnight enquiring into records of sorties and other operational data with the assistance of members of O.R.S. Middle East. He flew to Tobruk and afterwards returned to Tripoli where he spent a further week before moving on to Algiers. He returned to England towards the end of March to compile his report.

Professor Zuckerman's work during his brief stay in the Middle East greatly impressed the Air Commander-in-Chief, Sir Arthur Tedder, and the following month Air Ministry received a signal from Headquarters Mediterranean Air Command asking that Professor Zuckerman should return to continue his investigations of bomb damage in recently conquered enemy territory. Permission was obtained from the Ministry of Home Security for Professor Zuckerman and a colleague, Dr. B. Delisle Burns, to go out to North Africa for a two-month tour as soon as his report on Tripoli was completed.

By this time the campaign in North Africa was over and plans were being made to invade Italy via Pantelleria and Sicily. The occupation of Pantelleria was a valuable experiment in the employment of air power in support of ground forces. It was the first time that a heavily defended objective was to be completely overwhelmed by an air force—in this case after twenty days' continuous bombing. Conditions for the attack were perfect, the Allies had overwhelming air superiority, and the target was limited; such conditions were unlikely to recur. Professor Zuckerman arrived in time to make a thorough analysis before operations began, for

[1] Under the Director of Experiments and Staff Requirements who dealt with 'novel forms of warfare'.

example, of the nature and construction of the defences, the types of bombs and fusing required and the standard and accuracy of the various types of squadrons, based on recent operational records. On the basis of this analysis the bombing programme was organised. A daily analysis of bombing results based on photographs was made (principally of attacks on batteries) and after the occupation of the island Professor Zuckerman examined the results of the bombing on the spot.

By the time Professor Zuckerman had completed his initial survey Lieutenant Colonel M. T. O'Dwyer of the Army Operational Research Group arrived in the Middle East at the express demand of the Prime Minister to examine the effects of air bombardment on defensive positions in Pantelleria. Army officers planning future operations on the Continent were anxious to discover how much damage could be inflicted by an air force on prepared positions. Evidently the War Office was unaware of the research work being carried out in Mediterranean Air Command and the Prime Minister was informed accordingly.

Professor Zuckerman returned to England at the end of August to collect personnel with technical and scientific qualifications who would return with him to conduct a survey of targets in Sicily. In addition his party was reinforced by members of O.R.S. Northwest African Air Force, as it was clear that in order to arrive at anything conclusive a very detailed and extensive investigation would have to be made. Altogether some 30 officers were assembled which, it was hoped, would enable the work to be completed in two months. All the new members were given honorary ranks including several of Wing Commander and three of Squadron Leader status. Zuckerman himself was made an Honorary Group Captain. The party was first known as the Special Air Mission, later being termed the Bombing Survey Unit. Professor Zuckerman was in complete control. However, as already observed, Mr. Williams took over the initial party to Sicily and established it in Palermo, staying there until Professor Zuckerman's arrival in September.

Professor Zuckerman's primary purpose was to determine the results of the bombing of Sicilian and later southern Italian rail communications; he was also to assess the damage caused to airfields by air attack. His party visited railway and airfield installations in Sicily and Italy as far north as Naples. A mass of evidence was obtained from a variety of sources, including those resulting from ground survey and documents taken from the Italian railway administration. By means of ground survey, assessment of bomb plots and physical damage, reports were prepared for targets such as marshalling yards and bridges. These, together with the detailed report and traffic flow records compiled by the Italian railway officials, formed the basic material from which both qualitative and quantitative analyses were made. Valuable deductions were arrived at, and both the evidence and conclusions drawn therefrom were assembled into a voluminous report. This report was to have a decisive influence on the planning of preparatory air operations for the landings in Normandy the following June as will be seen in the next chapter.

FORMATION OF O.R.S. AT AIR HEADQUARTERS INDIA

The extension of the war to the Far East and the rapid advance of the Japanese through Malaya and Burma suddenly exposed the eastern frontiers of India to air attack, while the Indian Ocean became a potential hunting ground for enemy submarines. On 9 February 1942 the Signals Staff at Air Headquarters India asked the Air Ministry for three operational research officers with filter room experience to be sent out as soon as possible. Interminable delays attended the despatch of the scientific officers, the first of whom arrived nine months later, on 29 October. This was due largely to the higher priority of the Home Commands and the Mediterranean theatre for the reception of men and equipment and also to a shortage of scientists and changes in the operational research organisation at home.

On 29 March 1942 the Operational Research Centre agreed to recruit officers for an O.R.S. in India. They were to be administered by the M.A.P. As no scientists had arrived by the early summer Air Headquarters India asked for permission to recruit scientists who were serving in the forces in that theatre or from the Indian universities. This was granted, and several officers and N.C.O.s with a scientific background were transferred from the R.A.F. to the O.R.S., but no Indian recruits were obtained. Meanwhile further urgent signals were sent to the Air Ministry asking for experienced O.R.S. officers with knowledge of ground radar. Early in August the Air Ministry agreed to form an O.R.S. on the lines of those already functioning at home and in the Middle East, and Mr. Kendrew, then in charge of O.R.S. Middle East, was to be sent out to form it. Eventually Mr. H. M. Barkla (an Honorary Squadron Leader), who had specialised in ground radar in O.R.S. Fighter Command, arrived in New Delhi at the end of October. It was not until 2 February 1943 that Mr. (Honorary Wing Commander) I. H. Cole, another radar expert from O.R.S. Fighter Command, took over command of the new section, instead of Mr. Kendrew as had been intended. By that time, in addition to Mr. Barkla, two other scientific officers had arrived from the O.R.S.s of Fighter and Coastal Commands, Mr. R. W. Piper and Mr. A. J. Brook.

The work of the O.R.S. during 1943 lay largely in the field of radar. Analyses were made of the air reporting system on the eastern frontier of India, and routine inspections were made of filter rooms in the Bengal and Chittagong areas by a team of observers under the direction of the O.R.S. Reports were prepared on G.C.I. stations in which the effect of mountains on radar impulses was considered and the limitations imposed on the operations of radar equipment in mobile and amphibious warfare. Another report dealt with the preparation of vertical polar diagrams. Work was also begun on anti-submarine warfare, and a study was made of methods of patrolling and of hunting enemy submarines. While most of the staff of the O.R.S. spent much of their time in visiting groups or stations, close contact was maintained with Air Headquarters India. In November 1943 the O.R.S. was absorbed into the newly created Air Command South-east Asia. Its further activities will be described in Chapter VIII.

CHAPTER VII

Operational Research and the Allied Return to the Continent, 1943 to 1945

PREPARATIONS FOR RETURNING TO THE CONTINENT

By the end of the summer of 1943 preparations for landing on the Continent were well under way; the Chief of Staff to the (as yet unappointed) Supreme Allied Commander and a staff of planners from the three Services had designed an operation (Overlord), in which landings were to be made west of the River Seine assisted by the Royal Navy and under cover of the Allied strategic and tactical air forces. The R.A.F. in the United Kingdom was reorganised for this amphibious operation. A mobile tactical air force was created out of Army Co-operation Command, itself forming part of an Allied Expeditionary Air Force (A.E.A.F.), established in November under the former Commander-in-Chief Fighter Command, Air Marshal Sir Trafford Leigh-Mallory. An American counterpart to the British tactical air force, the IXth U.S. Air Force, was contained in the new Command together with Fighter Command, now redesignated The Air Defence of Great Britain (A.D.G.B.). Additional weight was provided by British and U.S. light and medium bomber units and troop-carrier aircraft. The operation was to take place in the spring of 1944.

Scientists had applied themselves to the radio and radar aspects of air support to the ground forces as soon as the Army in Great Britain began preparing for a return to the Continent, and before going into the scientific organisation of A.E.A.F., their early work must be described.

FORMATION OF O.R.S. AT HEADQUARTERS ARMY CO-OPERATION COMMAND (LATER TACTICAL AIR FORCE)

Discussions took place in July 1942 over the creation of an O.R.S. for Army Co-operation Command which at that time was the only formation responsible for practising the various weapons and techniques used in close support to the ground forces in Great Britain. Mr. Larnder of O.R.S. Fighter Command made a survey of the problems which an O.R.S. would be required to investigate and made his report early that September. He considered that it would be unwise to rely on the results of operational research in the Mediterranean theatre as operations similar to those carried out in close support of an army were being undertaken, although on a limited scale, by Army Co-operation Command and by squadrons of Fighter Command in certain low flying attacks over enemy occupied territory.

The Assistant Chief of Air Staff (Operations) approved the formation of the new section, and Mr. M. Graham, a physicist of broad outlook and one whose personality proved to be agreeable to senior officers, was appointed officer-in-charge with Mr. D. H. Preist, who had been working at T.R.E. on radar problems in air-to-ground operations, as his second-in-command. It was not possible on account of the great shortage of scientists to provide all the staff recommended by Mr. Larnder, but for the time being the O.R.S. would consist of two scientific officers and six junior scientific officers. They were recruited almost entirely from O.R.S. Fighter Command. The head of O.R.S. Fighter Command was to act as adviser to the new O.R.S. for its first two months. Close contact was to be maintained with the Army Operational Research Group, in particular, with those concerned with army–air co-operation problems.

But it was not until June 1943, when Army Co-operation Command was redesignated the Tactical Air Force, that intensive training in close support began. Two mobile composite groups were formed; No 2 (Light Bomber) Group was brought in and an airborne wing attached. In the meantime the new O.R.S. worked hand-in-hand with O.R.S. Fighter Command. The formation of an O.R.S. within A.E.A.F. at the end of that year absorbed the members of O.R.S. T.A.F. or 2nd Tactical Air Force, as it was now known, and additional members were recruited from O.R.S. A.D.G.B. Matters were further complicated when Air Marshal Sir Arthur Coningham took over command of 2nd T.A.F. in February 1944 when the section, as will be explained below, became absorbed into O.R.S. A.E.A.F. However, these administrative changes did not upset the scientific work of the section.

A scientific officer was attached to each composite group in 2nd T.A.F. in addition to Main Headquarters and No. 34 P.R. Wing. They examined in the months before D Day a large number of subjects ranging from suggested modifications to petrol cookers to assessing the accuracy of attacks by Typhoon fighter bombers. An idea of their variety may be gained by quoting at random from a list; this included the preparation of a map showing areas where damage to aircraft might be expected from birds during the breeding season; the morale effects of various weapons; drawing up a training syllabus for a navigational aid; the ballistics of new bombs; the best use of Oboe; aids to aerial photographic interpretation; the elimination of signals delay; the usefulness of a Type 11 radio set; the best use of the Mark XIV bombsight, etc. In addition to these activities, discussions and exchanges of view took place between Mr. Graham and Professor J. D. (afterwards Sir John) Cockcroft, Superintendent of the Air Defence Research and Development Establishment, T.R.E., and the Army Operational Research Group, while close liaison continued to be maintained with O.R.S. A.D.G.B. which was then, as has been seen, under the charge of Mr. A. F. Wilkins.

FORMATION OF O.R.S. AND APPOINTMENT OF TWO SCIENTIFIC ADVISERS AT HEADQUARTERS A.E.A.F.

The history of the scientific organisation in A.E.A.F. is complicated by the multiplicity of authorities involved in the preparations for the assault and by the apparently complicated O.R.S. organisation that grew up with them. In fact, paper differences and responsibilities were ignored by the officers involved in the work, and members of the three sections involved, i.e. 2nd T.A.F., A.D.G.B. and A.E.A.F., worked together on problems as the occasion demanded.

The formation of an O.R.S. for A.E.A.F. was discussed at the end of November 1943 by Air Marshal R. M. Hill (Air Marshal Commanding A.D.G.B.), the Senior Air Staff Officer of A.E.A.F. and Mr. Larnder, the latter still at that time Scientific Adviser to the Commander-in-Chief Coastal Command. Mr. Larnder expressed his views at some length in a paper addressed to the Air Commander-in-Chief about the new organisation and his ideas were to a large extent adopted when the new unit was formed on 24 December and Mr. Larnder was appointed to take charge.

The O.R.S. was a self-contained branch of the Air Staff at Headquarters A.E.A.F. with two main functions: firstly, to advise the Air Commander-in-Chief on the scientific aspects of matters affecting operations and, secondly, to conduct investigations and analyses for the various branches of the headquarters. Mr. Larnder himself was known as the Scientific Adviser (Operational Research) or S.A.(O.R.) and in that capacity supervised in a broad sense the work of the other British O.R.S.s in addition to being responsible for the work of his own Section. Under him was a principal scientific officer and five scientific officers. As noted above additional staff were drawn from the O.R.S.s of T.A.F. and A.D.G.B.

In addition to Mr. Larnder, a Scientific Adviser was appointed to the Air Commander-in-Chief because, to quote Mr. Larnder, 'there is no single scientist who could of his own knowledge and ability tender the best scientific advice on all points which might arise and there (is) a case for other scientists attached temporarily or permanently also claiming the title of Scientific Adviser.' On account of his study of the effects of air attacks on communications, which were to be the keystone of the preparatory air operations for Overlord, Professor Zuckerman was appointed to the post in January 1944.

Mr. Larnder had emphasised in his note to Air Marshal Leigh-Mallory that in order to discharge his duties effectively he must be taken into confidence during the planning stage of the operation. He undertook not to transmit any information to other members of his staff but to use it to enable him to ensure that the correct problems were being tackled and the available effort apportioned correctly. Headquarters, A.E.A.F., went some way to complying with his request.

Unlike O.R.S. A.D.G.B., which was primarily concerned with defence against air attack and hence became preoccupied with defensive equipment such as radar,[1] operational research for 2nd T.A.F. and Nos. 38 and 85 (Base Defence) Groups (these two formations were placed under command of A.D.G.B. until there was room for them in the beach-head) would be of a much more offensive character, being directly related to the conduct of land operations. It was important that the available scientific knowledge at the disposal of A.E.A.F. should be applied to those problems. However, Sir Arthur Coningham refused to have scientists attached to his headquarters staff, and consequently the scientists working at Headquarters 2nd T.A.F. and its lower formations were held on the establishment of O.R.S., A.E.A.F., and their work was controlled by the Scientific Adviser (Operational Research).

Mr. Larnder was anxious to preserve the identity of a T.A.F. O.R.S. in the event either of Air Marshal Coningham changing his views or of A.E.A.F. ceasing to function at a later stage in the campaign. He therefore formed a section known as O.R.S. 2nd T.A.F. within A.E.A.F. which continued to be led by Mr. Graham and was composed of the original members of O.R.S. T.A.F. Its members at composite groups (there were two attached to each composite group and to No. 2 Group) and with No. 34 (P.R.) Wing continued to function at those formations and Mr. Graham with one assistant continued to spend a large proportion of his time at Headquarters 2nd T.A.F. Air Marshal Coningham eventually agreed that when his headquarters moved to the Continent the two scientists might go with it although not as members of his staff.

While the headquarters of A.E.A.F. was essentially a joint Anglo-American concern, O.R.S. A.E.A.F. remained entirely British. Liaison was, however, maintained with the O.A.S. of the IXth U.S. Air Force.

Honorary commissions were granted to scientists attached to A.E.A.F./T.A.F. Mr. Larnder, as officer-in-charge, was made a Group Captain, and Mr. Graham, a Wing Commander. R.A.F. uniforms were to be worn by personnel serving overseas.

PART PLAYED BY O.R.S. FIGHTER COMMAND IN THE PREPARATIONS FOR OPERATION OVERLORD

Although Fighter Command, or A.D.G.B., as it was to be known, was primarily concerned with defence against air attack, it was responsible, before the advent of T.A.F., for assisting with the training of pilots for close support duties. The O.R.S. likewise became involved in various aspects of this subject extending from research into radar equipment to the solution of manpower problems. In September 1942 a working com-

[1] It was also to remain in the United Kingdom unlike O.R.S. 2nd T.A.F.

mittee was formed in Fighter Command charged with the development of units for mobile air reporting and control. The O.R.S. was represented and one member was wholly occupied with the development of operational organisation and procedure. On Exercise Spartan, the first large scale test of the army–air organisation for the landings on the Continent held in March 1943, the O.R.S. observed and reported on the operation of the Mobile Air Reporting Unit. At the request of the Command they also observed and reported on the first operation of the original reporting and control units: this was during the invasion of Sicily in July 1943. The formation and training of further units for 2nd T.A.F. was watched, and in August 1943 the O.R.S. started a detailed investigation of the mobile air reporting system in No. 83 Group, comparing the results achieved over a short period with those obtained by the static system in No. 11 Group. In January 1944 this type of work was taken over by officers of O.R.S. 2nd T.A.F. allotted to the composite groups, except for the development of the base defence organisation.

The radar section of O.R.S. Fighter Command did nearly all the basic operational research on ground radar equipments for the assault, together with much basic work on siting which was used and developed later by the A.E.A.F. siting team. Operational performance trials were also carried out on Light Warning Sets.

In August 1943 Mr. Graham asked O.R.S. Fighter Command to show the sort of coverage that might be expected from the best and worst ground radar sites on the north coast of France. The results were used by 2nd T.A.F., but the Chief Signals Officer at Headquarters A.E.A.F. later requested that the work be extended into a general survey of possible sites along the whole of the coastline between Brest and Ostend. Sites were to be found at about 20-mile intervals, firstly, very near the coast and, secondly, within 20 miles of the coast. The amount of work involved was very large, but the form of the request had been dictated by the necessity for maintaining the security of the assault area. However, the unavoidable congestion of forces and equipment that would take place in the bridgehead area made planned siting essential and, in January 1944, an officer was attached to the Command from the Ministry of Aircraft Production to organise detailed site planning. With the clarification of the planning he was joined by a representative of O.R.S. 2nd T.A.F. and an officer of the U.S. Signal Corps, representing the IXth U.S. Air Force interests. This team was formed in February 1944 and immediately began detailed siting of both radar and signals equipments from maps, photographs and special material collected by the engineers in their airfield survey. Numerous planning conferences were held and the results achieved, involving planned sites up to D Day plus 30, with a general survey of further areas in the path of Twenty-first Army Group, were incorporated in the 2nd T.A.F. signals plan.

The O.R.S. was responsible for planning the use of I.F.F. in the landings. The original plan devised by SHAEF was found to be completely unworkable as it had left out of account the known major deficiencies of I.F.F. An entirely new plan was produced with the help of the O.R.S. An examination was made of the requirements of each Service and a decision taken as to which branches were most in need of assistance. These proved to be the Royal Navy and the R.A.F. night fighters. The restrictions imposed caused some alarm when promulgated but, in the event, they proved to have been extremely well planned and were retained with but minor relaxations to the end of the war in Europe.

Research was also carried out on signals traffic and Fighter Direction Ships, in the latter case concluding with a visit by a member of the O.R.S. shortly after D Day to Fighter Direction Ship T.217 lying off the beach-head in the British sector. One other investigation should be noted as a matter of interest. In October 1943, at the request of Fighter Command, a member of the Section became involved in some short tests to try the feasibility of floating landing strips for aircraft. The idea is believed to have originated with President Roosevelt, and the experiment was certainly carried out on the instructions of the Prime Minister, who himself attended the final trials. Observations were made of the speed with which the take-off and landing of squadrons could be handled from a small area marked off on an existing airfield. A report by the O.R.S. on the preliminary trials was prepared in great haste for the Air Ministry, and was afterwards submitted to the Prime Minister. The effort required for the design and construction of such landing strips might have been considered to be justified had their operational advantages been beyond question. The trials having demonstrated that this was not the case, the proposal was rejected.

Investigations that might assist in the most efficient manning of the assault formations covering the landings were made by the manpower section. A study was made of the No. 2 Group Repair and Salvage Units which resulted in emphasis being placed on aircraft modification rather than on repair. Further work by the same team on Category 'A'[1] damage to Spitfires and Typhoons during the period of the assault, with a view to finding out whether the numbers and distribution of trades were adequate for the quickest and most efficient repair, revealed a high proportion of flak damage. As a result of recommendation the number of riggers was considerably increased in the units concerned.

Following this work, research was made into the suitability of the provisional establishments of Nos. 83 and 84 Group Support Units.[2] The

[1] Category 'A'—Repairable on site by R.A.F.
Category 'AC'—Repairable on site by contractors.

[2] Group Support Units held a reserve of three pilots and three aircraft for each squadron of the Group they served. They were responsible for the preparation of reserve aircraft to full operational standards, and also included a pilots' training squadron where pilots from operational training units were given a final polish prior to proceeding on an operational tour.

study revealed the general suitability of the establishment, but recommended an increase in the number of supervisory personnel by reason of the dispersed nature of the work.

PLANNING OF OFFENSIVE OPERATIONS

In Operation Overlord air-to-ground attack by fighter aircraft was designed to play its part on a scale eclipsing all previous operations. Thus it was necessary to determine the damaging power of all the weapons at a fighter's command on the targets of major importance, and also the best tactical uses of these weapons.

Trials with tanks, 18-pounder guns, various types of vehicle and a stretch of railway line were made at the A.E.A.F. school for training fighter pilots in close support at Millfield, in February 1944. The accuracy of all attacks was measured, where possible, for rocket projectiles and bombs and the variation of effectiveness under different tactical conditions. When direct hits or near misses occurred a study of the damage inflicted was made. It was proved conclusively that strafing was outstandingly successful for damaging or destroying vehicles. Bomb hits near enough to damage vehicles were hardly ever obtained. Opinion had previously been strongly divided, and these trials were decisive in ensuring the employment of a form of support to the Allied offensive which proved almost sensationally effective. The strafing of vehicles not only aggravated the enemy's supply difficulties, but often disorganised his retreats to the point of becoming routs.

In July 1943 O.R.S. Fighter Command was asked to investigate the problem of the best method of attacking enemy radar stations. The object was to put the enemy early warning system out of action for a period sufficient to enable the initial landings to be made with tactical surprise. Some considerable time was spent in collecting information on the German radar apparatus although the electrical details had already been discovered. Firing trials were carried out to assess the value of sensitive fused 20-mm. and 40-mm. shells for attacking *Freyas* and coast watchers. The trials showed that the ammunition used would not give the required results. The O.R.S. issued its report in January 1944 with a circulation of only four copies owing to the high secrecy content. Other types of enemy radar were later investigated in the same way.

The most difficult part of the work was in assessing the accuracy of the various weapons available under operational conditions. There was practically no data in existence on operational accuracy, and very little even for practice accuracy. Likely operational accuracies for 40-mm. cannon, rocket projectiles and fighter bombing had to be judged from the meagre practice results. For 20-mm. cannon a method was devised for estimating the number of hits obtained on different sized targets from actual operational attacks, as recorded on cine films. The estimated effectiveness (accuracy, damaging power and effort required combined) of the different weapons varied considerably, so that the choice of the most suitable weapon for a particular target was not likely to be invalidated in the estimated accuracy of that weapon.

The main recommendations of the report were that radar apparatus unprotected by emplacements should be attacked with 20-mm. cannon. It was effective in causing damage, and only required a small effort. When sandbag emplacements were present, the wall was to be breached with low level rocket projectile attacks, and the radar apparatus attacked with cannon fire as before. For heavier emplacements low level bombing was recommended, one direct hit being sufficient to breach the protective wall and do the necessary damage inside. When the apparatus was wholly or partly underground dive-bombing was recommended. It was not regarded as a satisfactory method, on account of the large effort required, but it was the only method of attack available to fighters which gave sufficient penetration to damage strongly protected targets.

THE TRANSPORTATION PLAN

One of the chief problems confronting the planners of the assault on the Normandy beaches was to discover the best way of preventing the enemy from bringing up his reinforcements swiftly and throwing the Allied armies back into the sea in the early, vulnerable stages of the operation. From the start there was considerable disagreement about the ability of the Air Forces to intervene effectively in the ground battle, particularly in the case of holding up the arrival of fresh enemy divisions. Professor Zuckerman, however, had been convinced by his investigations of air attacks upon the Sicilian and Italian railways that the Air Forces, if used against the correct targets, could be a decisive factor.

Professor Zuckerman's thesis, briefly, was that the best method of destroying the enemy's rail communications was a strategical rather than a tactical one, which was to destroy his repair and maintenance facilities rather than to bomb bridges, signal boxes, embankments and other small targets; it was better to bomb a few large railway centres over an extended period of time than to destroy a large number of small ones shortly before the assault was due to take place. Professor Zuckerman compared the continental railway system to a human nervous system, damage to any one part of which would affect the whole, in the manner of a creeping paralysis.

Between seventy and eighty railway centres, containing repair facilities and concentrations of rolling stock and locomotives, were chosen in northern France, Belgium and north-west Germany for attack, these targets being approved by Professor Zuckerman and the Railway Research Service, the latter composed of a number of well known railway experts. They reckoned that, as a result of the disorganisation caused by air attacks, the passage to the front of some nine German divisions would be delayed by at least a week. But there was formidable opposition to the Transportation Plan, as it was known. Firstly, from the British and American Strategic Air Forces which were preoccupied with bombing industrial targets in Germany; secondly, from certain quarters of the British Air Staff and from the War Office; both were unconvinced that sufficient damage would be done by the Air Forces to prevent the enemy from continuing to supply and reinforce his forward troops. Finally, there were the members of the War Cabinet, including the Prime Minister, who feared that heavy attacks on railway centres located in populated areas would cause such heavy casualties to the civilian population that an irreparable breach would be provoked in the relations between Great Britain and France.

The controversy over the Transportation Plan has been dealt with at length elsewhere. Suffice it to say that after prolonged and heated argument lasting from January until early May 1944, a month before D Day, the policy of attacking railway targets in enemy occupied territory was approved, after it had been shown that targets in urban areas could be bombed with great accuracy, thereby reducing casualties to the minimum and after reports had been received of the spreading chaos on the French and Belgian railway system.

The reason for going into these operations is that it is a striking case where scientific advice had a profound influence on the conduct of military operations. Professor Zuckerman took part in the discussions from the early meetings of the A.E.A.F. Bombing Committee up to the deliberations of the Defence Committee of the War Cabinet. Air Chief Marshal Tedder, who had been appointed Deputy to the Supreme Allied Commander, General Eisenhower, was already convinced of the rightness of Professor Zuckerman's views from his experience in the Mediterranean theatre of war, and together with Air Chief Marshal Leigh-Mallory stood unwaveringly in favour of the plan. As he saw it, every available aircraft must be employed to give maximum support to Operation Overlord. Primarily air superiority must be gained and maintained; this achieved, the air forces must be employed in attacking a common target. Oil plants and aircraft factories could only be attacked by the Strategic Air Forces, thereby contributing but indirectly to operations designed to weaken enemy resistance in and around the projected battle area. Railway centres appeared to be the most profitable target, the aim being to impede rather than to halt traffic, causing diversions and blockages of which full advantage would be taken by a roving Tactical Air Force.

Sufficient evidence has been gathered from enemy sources of the delayed arrival of certain enemy divisions in the battle area to justify both Professor Zuckerman's and the railway experts' contentions.

OPERATIONAL RESEARCH DURING THE OPERATIONS IN NORMANDY

O.R.S. A.E.A.F. did not, like the O.R.S. of 2nd T.A.F., move to the Continent, but individual members crossed the Channel to perform special tasks in the beach-head. The first members to do so arrived seven days after D Day; one observing fighter control operations from a fighter direction ship (T. 217) and the other noting the operations of No. 21 Base Defence Sector which was responsible for the air defence of the U.S. Sector including the port of Cherbourg. The subsequent report, produced by Mr. L. P. Cox, described the activities of the G.C.I. and C.O.L. (Chain Overseas Low) stations, the siting of radar units according to a pre-arranged plan and the general working of radar equipment.

On 19 July Messrs. Larnder and Graham visited the Headquarters of No. 83 Group, then situated near Creully. In the course of the next two days they visited the Group Control Centre, No. 24 Base Defence Sector (responsible for the British Sector) and two Typhoon wings which were then actively engaged in providing close support to the Army, while before returning to England, Mr. Larnder made a report to Air Marshal H. (afterwards Sir Harry) Broadhurst, Air Officer Commanding No. 83 Group, and his Senior Air Staff Officer.

The principal object of the visit was to investigate the possibilities of reducing the danger from flak to fighter bombers and the rocket-carrying Typhoons engaged in dive attack. After discussions with wing leaders the possibility arose of fitting a device to inform the pilot immediately the cooling system or radiator of his aircraft was not working, thus enabling him to use his engine for its brief remaining period of life to the best advantage. A request for a modification was made to the Ministry of Aircraft Production.

Several casualties had occurred to aircraft when about to release their bombs and it was thought that the high speed of diving produced a pressure change of some five inches of mercury in a matter of seconds which could produce a very explosive mixture in the tanks. The aircraft would inevitably be more prone to explosion when hit near the bottom of a dive. On the other hand, assuming petrol vapour to have been a contributing factor, an explosion might have been due to too full or overflowing tanks. Precautionary action over the latter was taken.

Another problem dealt with by Mr. Larnder was a complaint that Window dropped from friendly aircraft was interfering with the working of radar stations in the beachhead. On account of this, care was taken to route bomber forces so as to produce a minimum of interference with the Allied radar system in Normandy. A complaint that certain friendly aircraft were not using their I.F.F. over the battle area, thereby inviting anti-aircraft gun fire, was also dealt with.

The arrival of members of O.R.S. 2nd T.A.F. at that formation's main headquarters at Le Tronquay on 4 August occurred when the Allied armies had broken out from the beach-head. On the 7th the enemy attempted to cut the line of communication of the American forces which were executing a flanking movement south of the Cherbourg peninsula at Mortain. The attack was repulsed, due in no small measure to the intervention of R.A.F. Typhoons. In conjunction with the IXth Air Force O.A.S. and No. 2 O.R.S. Twenty-first Army Group, members of O.R.S. 2nd T.A.F. made an immediate investigation while American units were still in the vicinity. Among them there was a unanimous feeling, in spite of the fact that the R.A.F. had inflicted a few casualties on friendly troops on account of the interlocked nature of the battle, that although the number of armoured fighting vehicles claimed as destroyed was overestimated, there was no doubt that the rocket-carrying Typhoons had won the day. The reckoning of claims for the Typhoons was not made easier on account of the difficulty in distinguishing between damage inflicted by ground and by air weapons, while the efficient recovery service of the enemy towed away many vehicles capable of running again.

These problems recurred, on a larger scale, towards the end of the month when the enemy was harried by formations of Allied fighter and fighter bombers in the Falaise 'Gap'. An extensive investigation was made by No. 2 O.R.S. Twenty-first Army Group under Lieutenant Colonel P. Johnson, its object being to ascertain what losses were suffered by the enemy from air attack and, secondly, to assess the capabilities of the various air weapons employed. The subsequent report led to a denigration of the air effort particularly in regard to the efficacy of the rocket projectile. Here it must be said on behalf of the Typhoon pilots that it was impossible to use air photographs to show evidence of strikes by these weapons as it was in the case of damage inflicted by cannon or machine gun fire. The Army scientists found it difficult to recognise that the air forces were not so much concerned with destroying individual tanks or vehicles as with causing the maximum amount of confusion and terror among the enemy forces. There is no doubt that they achieved these objects.[1]

The tide of battle had covered the Falaise area by the time the scientists arrived to make their investigations, and salvage parties and looters had removed evidence. This was not so on the left bank of the Seine at Rouen where aircraft of No. 2 Group and the IXth U.S. Air Force made a series of devastating attacks on enemy vehicles of all kinds waiting to cross the river in the last week of August. On 1 September Mr. Larnder and Mr. Graham visited the area. What they saw is well described by Mr. Larnder: 'On reaching the quays it was at once apparent that we were on the scene of one of the outstanding attacks of the campaign: burnt-out vehicles, exploded and unexploded ammunition, and charred remains of loot and

[1] A description of methods for examining targets in the field written by No. 2 O.R.S. Twenty-first Army Group will be found at Appendix No. 3.

small kit, lay so thick that in some places we had to clamber over them. After proceeding two hundred yards, where there was only a relatively faint smell of the dead, we came to the main area, where the stench was of a magnitude and intensity greater than I have yet experienced. At this point we met a Dr. Germains Galerant, who was supervising the burial of the dead, with a police inspector, whom we also joined. Dr. Galerant said that the Germans arrived in a disorganised drove, with few officers, if any, and asked the way to the bridges. When told that there were no bridges, they started to use the two-barge ferry. The local inhabitants watched this going on, and waited anxiously for several days for the R.A.F. attack. When it came it was on the whole accurate, and even the first attack, which fell on the north bank, destroyed many vehicles which had crossed and were hiding under the trees of a long avenue there. The result of the attack was a "night of horror" with all the petrol in the vehicles burning, and the Germans screaming, and the ammunition exploding.'

The O.R.S. party, making a comparison between an aerial photograph of the area taken after the attack and the vehicles they saw on the ground, concluded that between 1,500 and 2,000 vehicles of all kinds, including some on the north bank, were destroyed.

Meanwhile members of O.R.S. A.E.A.F. were at work at less spectacular but equally important subjects. Time recording parties stationed at a number of airfields on the English south coast obtained information on wastage and the position and direction of strikes on aircraft by enemy flak. Casualties were, however, so light that although valuable information was obtained, the quantity of data was by no means as great as that anticipated. The value of the time recording parties was so much appreciated by the technical and engineering branches of 2nd T.A.F. that they were eventually sent over to the Continent. Other members of the Section made analyses to indicate the relative effectiveness of tactical reconnaissance and armed reconnaissance. A comparison of the effect of reconnaissance by day and by night and an investigation into bombing techniques of the light bombers of No. 2 Group was also carried out.

ACTIVITIES OF O.R.S. NO. 38 GROUP

While certain squadrons of R.A.F. Bomber Command had, since the early days of the war, been responsible for dropping agents over enemy occupied territory and for other clandestine operations, these activities increased as the time for the landings in France drew near. No. 38 Group therefore became responsible both for the control of all British troop carrying aircraft taking part in the airborne operations of the North-west European campaign and for supplying weapons and equipment to the Resistance Movement in enemy occupied Europe and for the dropping of parties of the Special Air Service in advance of the main forces. A party of operational research scientists under Dr. C. A. Wingfield, a biologist, was formed to work on radar and other problems allied to these operations. This section, which was under the O.R.S. at Headquarters A.E.A.F., continued to function in its own right after the disbanding of the latter in October 1944, as No. 38 Group then came under the operational control of SHAEF (Air) and under the administrative control of Fighter Command. The establishment of the O.R.S. at that time was one senior scientific officer and three scientific officers. A brief account will be given of the work of the O.R.S. which fell into three categories: the marking of dropping and landing zones, radio and radar aids, the compilation of statistical studies of operations and the solution of various problems arising from airborne operations.

A number of experiments with devices for marking the dropping/landing zones by day and night were made by the O.R.S. in conjunction with the Airborne Forces Development Centre at Amesbury. It was then assumed that a force of Pathfinder aircraft would locate the dropping zone either visually or by Gee. These aircraft would drop an advance ground party with equipment to prepare and mark the dropping/landing zone. It was, of course, obvious that any marking system should not easily be detected by the enemy. Two illuminants, the Holophane Light and the Air/Sea Rescue Light, were developed and later were used in the airborne assault in Normandy, but the Army was dissatisfied with the former on account of its weight and bulk and stated that its visibility from the ground drew the attention of the enemy to the dropping zone. Suggestions for an improved system of marking by night did not bear fruit as there were no further major night airborne operations in the campaign.

By December 1943, Gee and Rebecca/Eureka had been selected as the radar aids for use in operations by airborne forces. Eureka beacons were used either as a routeing aid or to mark the dropping zone itself. Considerable training was necessary with these equipments, particularly as Rebecca had not yet been fitted to most aircraft. Comprehensive trials with the equipment were also carried out by Dr. Wingfield in collaboration with the Army Operational Research Group. Later, analyses were made of the performance of Gee and Eureka beacons, both in the special operations of No. 38 Group and in the major airborne landings.

In the landings on D Day the performance of Gee was considered to be satisfactory and the majority of navigators obtained fixes on the target area. The operations, however, revealed that if the troops setting up Eureka beacons were overrun by the enemy, the main force could completely go astray. Fortunately this did not happen, but the O.R.S. recommended that a system for dropping lights and beacons without having to drop troops with them should be considered.

The airborne operation at Arnhem was executed in daylight and navigators tended to rely on their maps as soon as any difficulties in manipulating Gee were encountered. Some jamming of Gee was suspected in the first two days of the operation, and it was while investigating this possibility that Dr. Wingfield was shot down in a Stirling dropping supplies over Arnhem. (He was succeeded by Mr. I. H. Cole who had recently returned from India.) Nor were radar aids used during the crossing of the Rhine, which was carried out in daylight six months later. Altogether the results obtained with Rebecca/Eureka as a method of marking the dropping zone in an airborne operation showed that the use made of the beacons by the aircrews did not justify the difficulties experienced by the ground parties in maintaining and operating them.

The O.R.S. combined with the Operational Statistics Section of No. 38 Group in compiling an analytical daily summary of operations following debriefing of aircrew which indicated whether navigation had been successful or not and what use had been made of radar aids. A similar analysis was made after each of the major airborne operations when tug and glider pilots had been debriefed. Members of the Section also examined the concentration of tug aircraft and gliders on the ground in the Normandy beach-head.

Among the problems posed for consideration by the O.R.S. was the rate of casualties to troop carrying aircraft that might be expected from the fire of artillery supporting the landings. The O.R.S. estimated that for an airborne drop lasting one hour involving 360 tug/glider combinations flying directly over 25-pounder guns firing at maximum range, the casualty percentage would be 0·64 per cent. The number of abortive sorties due to tow-rope failures was also examined and it was found that this was largely due to the glider flying into cloud and so losing sight of the tug aircraft, and, secondly, to the glider getting into the slipstream of another aircraft. Various recommendations were made including the suggestion that an automatic pilot in the glider would be the most effective means of enabling glider operations to be carried out under conditions of bad visibility.

The heavy casualties suffered by supply dropping aircraft at Arnhem led the O.R.S. to consider the possibilities of dropping supplies 'blind' with the aid either of Gee-H or Rebecca/Eureka, or alternatively by using a Mark IXA (course setting) bombsight for visual aiming. The aircraft would then be able to fly above the range of light flak (the usual height for supply dropping was between 500 and 600 feet). Trials were carried out by Nos. 299 and 570 (Stirling) Squadrons in dropping supplies from medium altitudes (i.e. from 7,000 feet) using either radar aids or the Mark IXA bombsight. But before any positive results were achieved the aircraft were recalled for the operations supporting the crossing of the Rhine, and as the Group was heavily committed to troop carrying activities immediately after the war, further trials were never carried out.

ANALYSIS OF AIR COMBAT FILMS IN 2ND T.A.F.

From the beginning of the campaign films taken in air-to-air combat were sent back to Stanmore for assessment by the Combat Film Analysis

Section of O.R.S. A.D.G.B. to which reference has been made in an earlier chapter.[1] In order to speed up the processing and assessment of films, a mobile unit, No. 6 Film Processing Unit, was formed and trained at Headquarters A.D.G.B.; it moved to the Continent at the end of November in company with a detachment of the Combat Film Analysis Section under Mr. J. Plymen. The function of the unit was to receive, process, print and assess all combat films taken within 2nd T.A.F. and return them to the appropriate wings 48 hours after receipt. From the time the unit began to operate on the Continent no delay or hold up was experienced, even during the closing stages of the campaign when films were arriving in the unit by the hundred. This O.R.S. detachment was therefore able to influence the conduct of fighter operations more closely than any other part of O.R.S. 2nd T.A.F.

Fighter aircraft were changing over from the G.M.2 reflector gunsight to the Gyro gunsight which predicted for the pilot, as he held his aircraft on the target, the correct allowance for deflection, speed, range and air density. By D Day the Spitfire squadrons of 2nd T.A.F. had been equipped with the new sight, but replacement aircraft had not yet been fitted with it. By the end of the campaign a large number of pilots had undergone a course of training in the Gyro gunsight at an armament practice camp to which a member of the O.R.S. was attached. In a series of reports the O.R.S. showed that there was little difference between the two sights at close range but that the Gyro gunsight showed its superiority when used at ranges above 200 yards. But pilots tended to fire with it at too great a range because they used the ranging ring as if it had been fitted to the old type of gunsight. Most of the air combats were fought at short range due to the feeling of superiority with which the pilots of 2nd T.A.F. were imbued, but had the enemy made greater use of jet-propelled fighters the Gyro gunsight would have been given more scope. The O.R.S. noted that the standard of accuracy of shooting in 2nd T.A.F. during the European campaign had greatly improved since 1943. Altogether the O.R.S. analysed some 1,400 combat films according to the type of aircraft and gunsight used.

From December 1944 to the end of the war the O.R.S. detachment with No. 6 Film Processing Unit assessed all the clear combat films of air-to-ground attacks. They included attacks on 1,500 locomotives and 4,900 motor vehicles. As with the air-to-air combat films they were assessed and returned with the comments of the O.R.S. to the pilots four to five days after the attack had taken place. The O.R.S. was able to point out certain faults which recurred such as the tendency of pilots to aim at the ground in front of the target at the beginning of the burst, then to correct the sight by pulling it up too high, so that subsequent shells swept across the target inflicting little damage. Pilots tended to open fire at too great a range, so wasting ammunition, while the duration of bursts of fire when within range tended to be too short.

[1] See Chap. II, pp. 29 et seq.

A more comprehensive assessment of strafing would have been possible if the G.45 cine gun camera (originally intended for training in air-to-air combats) had gone on running for a few seconds after the guns had ceased to fire. The film thus did not show fires and explosions which often developed after the shell strike. The O.R.S. made an analysis of the performance of the camera gun and found that 20 to 25 per cent of all films taken were spoilt because of mechanical failure. Frequently the films were badly defined on account of the camera lenses being incorrectly focused and many films suffered from over-exposure due to the inadequate number of exposure settings available and to the difficulty of fitting stops and filter to the camera.

ANALYSIS OF AIR SUPPORT OPERATIONS IN THE ARDENNES AND RHINELAND

On 15 October 1944 A.E.A.F. ceased to exist as an operational command and the functions of its headquarters were taken over by Air Staff (SHAEF). The way was now open for O.R.S. 2nd T.A.F. to take over the duties of O.R.S. A.E.A.F. and for Air Marshal Coningham to recognise formally the O.R.S. which during the past nine months had existed in effect, if not accepted in principle. On 22 October O.R.S. 2nd T.A.F., now situated in Brussels, was reorganised as a team of 15 scientific officers as follows: two officers were attached to headquarters, one officer each to No. 2 Group and No. 34 (P.R.) Wing, two officers each to No. 84 Group and No. 6 Film Processing Unit, four officers to No. 85 Group and one officer each to Armament Practice Camps. Two additional officers were attached to the Bombing Analysis Unit recently formed under SHAEF. O.R.S. A.E.A.F. was disbanded on 25 November, the majority of its members transferring either to O.R.S. 2nd T.A.F. or to the Bombing Analysis Unit.

During the winter of 1944–45 O.R.S. 2nd T.A.F. continued to write reports on aspects of the campaign in North-west Europe. Early in November a visit was made in company with No. 2 O.R.S. Twenty-first Army Group to Breskens and Walcheren Island, the scene of recent fighting, for the purpose of inspecting damage caused to gun positions by R.A.F. Bomber Command. Similar visits were paid to coastal batteries at Le Havre, Calais, Boulogne and Flushing. In general it was discovered that the moral effect on the gun crews was greater than the material damage to the concrete casemates (with the exception of open emplacements).

The German counter offensive in the Ardennes led to a large effort on the part of the Allied Air Force against targets in the field and the enemy's communication system west of the Rhine. No. 2 O.R.S. Twenty-first Army Group, which had been sent to the battle area to investigate the effect of anti-tank weapons, was instructed to turn its attention to the large claims for destroyed armoured fighting vehicles then being made by the Allied Air Forces. It was to collaborate with O.R.S. 2nd T.A.F. with whom, as already seen, there had been differences of opinion in the past. On 25 January 1945 Mr. Graham and a colleague, Mr. G. C. Abel, joined the Army scientists at Aywaille, south-west of Liége, and for the next five days, in wintry weather, the whole party examined enemy armoured fighting vehicles claimed to have been put out of action by the Tactical Air Force. As only a small number of attacks by Typhoons were made in the salient, evidence of their effects was inconclusive, but there seemed to be little doubt that the American fighter bombers had met with indifferent success and for every hundred claims only one tank was indubitably destroyed by air action. On the other hand, there was ample evidence of destruction by American ground weapons. This examination led to the first joint report of the two O.R.S.s.

During the course of the work, however, it became clear that valuable lessons could be learnt by widening the study to include, to some extent, the air effort as a whole, and its relation to the enemy thrust. It was evident that study of this battle could give clear guidance on the relative parts played by direct and indirect support. Mr. Graham and a member of No. 2 O.R.S. therefore went on to examine communication centres in the salient such as Houffalize and St. Vith which had been heavily bombed. Useful information was obtained by interrogating civilians as well as by examining damaged rail facilities. The results of this study were incorporated into an enlarged report entitled 'The stemming of the enemy thrust in the Ardennes, 16 to 26 December 1944' which also included the findings of the earlier joint report. 'The data considered', wrote Air Vice-Marshal V. E. (afterwards Sir Victor) Groom, Senior Air Staff Officer of Headquarters 2nd T.A.F., in an introduction to the report, 'leave no doubt of the success of the action taken by the Allied Air Forces, which were predominantly American. . . . The thrust was slowed down by the resistance of the ground forces, particularly at Bastogne, until the weather cleared sufficiently for the air forces to go into action, which stopped the flow of fuel and ammunition to the enemy's front line troops, and so rendered them vulnerable to the ground forces. On that appreciation the battle was won by each arm fulfilling its characteristic role.'

As the two O.R.S.s were to collaborate more closely than hitherto until the end of the war, it is appropriate at this point to compare their respective organisations. While the members of O.R.S. 2nd T.A.F. were dispersed among groups and wings and only the head of the section remained at Main Headquarters together with a small clerical staff, the whole of the Army O.R.S. was concentrated at Main Headquarters, Twenty-first Army Group, also at Brussels. The Army scientists considered that while their opposite numbers in the R.A.F. had the advantage of living in close contact with operational formations this made it impossible to concentrate a number of officers on a single big problem.

Other subjects occupying O.R.S. 2nd T.A.F. for the remaining three months of the war in Europe were the Mobile Radar Control Post (a means of directing medium bombers on to targets requested by the ground forces in overcast conditions; a joint report with No. 2 O.R.S. was issued on this subject); monthly analyses of night interceptions by the Mosquitoes of No. 85 Group; a report on ground radar equipment in 2nd T.A.F., and a start was made on discovering the precise amount of damage inflicted by fighter bombers on buildings believed to be occupied by enemy headquarters. After the crossing of the Rhine by Twenty-first Army Group, which included an airborne assault on the east bank of the Rhine near Wesel, the two O.R.S.s made a detailed study of the extensive attacks against flak positions in the vicinity of the dropping/landing zones which had been an important feature of the air plan. Once again they found that the moral effects were more significant than the physical damage. The withdrawal of the enemy from Holland and areas of north-west Germany, which had been the hunting ground of Nos. 83 and 84 Groups for the past seven months, made it possible for the O.R.S. to examine the effectiveness of attacks on ground targets and the accuracy of pilots' claims. This task, and others, continued to absorb the section for two months after the cessation of hostilities on 8 May. Mr. Graham left the section on 29 June and returned to England to resume his civilian occupation. After the wartime tasks had been completed, the O.R.S. was reduced to a total of four officers.

FORMATION OF THE A.E.A.F. (LATER SHAEF) BOMBING ANALYSIS UNIT

The ambitious programme of precision bombing which was necessary to make the Transportation Plan a success, and the interventions of the Allied Strategic Air Forces in support of the land battle both north and south of Caen, in the Caumont area and at St. Lô, called for an examination of the target areas. The operation of heavy bombers in close proximity to the ground forces was still in the experimental stage and encountered criticism and misunderstanding from air officers who considered any diversion from the strategic bombing offensive against German targets to be a waste of effort and from army officers who tended to think of heavy bombers as a form of long range artillery to be brought down at will regardless of the general strategic situation. On account of this, brief examinations of the effects of bombing were made by Professor Zuckerman in his capacity as Scientific Adviser to the Air Commander-in-Chief and by members of the A.E.A.F. Bombing Committee after the attack north of Caen (Operation Charnwood) by R.A.F. Bomber Command and the attempt to break through south of Caen on 18 July, known as Operation Goodwood, in which British and U.S. heavy bombers, together with the Allied Tactical Air Forces, took part. Much was learnt about the correct type of bomb to be used in operations of that nature, the necessity for a quick follow-up by the ground forces and the effect on the enemy's morale.

The break-out from the beach-head and the advance eastward of the Allied armies made a more detailed examination possible and, as Professor Zuckerman pointed out, the Scientific Adviser Twenty-first Army Group had, until then, made a more exhaustive research in the effects of air bombardment than his colleagues on the air side. Professor Zuckerman suggested that A.E.A.F. should establish 'an O.R.S. party which would study the air problems that are at present being covered by Twenty-first Army Group'.[1] He envisaged the studies taking the following form:

(*a*) The analysis of the actual distribution of the bomb fall in relation to specified target areas, with an analysis of the bomb densities in the different areas attacked.
(*b*) An analysis of bombing accuracy, with special reference to the questions of bomblines and bomb density.
(*c*) An analysis of the factors underlying target recognition.
(*d*) An analysis of the timing of air operations in relation to the development of bomb fog.
(*e*) An analysis of the extent to which craters and debris impeded the progress of the ground forces.
(*f*) A general analysis of the relative effectiveness of the air effort in relation to the progress of the total land operations.

By mid-August 1944 the idea of an A.E.A.F. Bombing Survey Unit, later known as Bombing Analysis Unit (B.A.U.), had been accepted; it was to be self-supporting, fully mobile and capable of operating, if required, in five self-contained parties on a detached basis. The directing staff consisted of a Commanding Officer, responsible for the general administration of the unit, and a Scientific Director. Group Captain E. S. D. Drury who had been Chief Armament Officer of Headquarters A.E.A.F. was chosen for the former post, while Professor Zuckerman was made responsible for the scientific direction.

Meanwhile, Air Chief Marshal Sir Arthur Harris, on his own initiative, decided to send out a small team from his O.R.S. to examine the effects of the bombing, and his example was followed by Coastal Command and 2nd T.A.F. All these small groups became integrated in the B.A.U. together with the U.S.A.A.F. Air Evaluation Board which had recently arrived in France. A new establishment was published which allowed for a total of 14 officers, including administrative officers, and 55 airmen, including draughtsmen, clerks, drivers, motor cyclists and bomb census personnel from the Air Ministry. The heads of the O.R.S.s of Bomber Command, Coastal Command and A.E.A.F., Dr. Dickins, Dr. C. H.

[1] No. 2 O.R.S. Twenty-first Army Group had made inspections of the battlefield at Caen and to the south before the arrival of O.R.S. 2nd T.A.F.

Waddington and Mr. Larnder, were included in the unit. The purpose of the unit was to study the effects of air attacks on enemy communications, harbour installations, coastal batteries, 'V' weapon targets, submarine pens, airfields, tactical bombing targets and defences generally.

WORK OF B.A.U. ON THE CONTINENT

The main party of the B.A.U. left Stanmore, Main Headquarters of A.E.A.F., on 27 September and set up headquarters at St. Germain-en-Laye north-west of Paris. Here General Fickel, head of the U.S.A.A.F. Air Evaluation Board, offered them accommodation with his staff which was gladly accepted by Group Captain Drury. In addition to the obvious advantage of working in close proximity to the American scientists, they had the benefit of being neighbours of Headquarters Advanced U.S. Strategic Air Force under General Spaatz.

On 9 October the British and Americans agreed to form joint Anglo-American field teams; they also agreed upon the following points: to make the data collected available to both sides, though each reserved its right to draw independent conclusions from the facts; to pool all possible resources, such as photographic facilities and equipment for the reproduction of reports, and finally, to set up a joint committee for the selection of targets to prevent overlapping and duplication of work.

During October and November five self-contained parties known as Field Headquarters were working at St. Malo, Le Havre, Caen, Calais and at certain target areas in Belgium. In the St. Malo area an examination was made of the effectiveness of bombing against the Ile de Cezembre (tunnels and coastal batteries), the effects of bombing in support of the assault forces and attacks on shipping. The last named was the responsibility of the Coastal Command party. In Le Havre, fortifications, buildings used as barracks, E-boat pens, coastal guns and flying bomb sites were inspected. At Caen a general study of close support and bomb performance was made as well as an examination of specific targets, one of the most outstanding being the remains of a panzer company which had been eliminated as a fighting unit by Bomber Command in General Montgomery's offensive south of the city. The damage to the vehicles dispersed in an orchard was awe-inspiring; tanks were found thrown on their sides in craters while some had incurred direct hits or were burnt out. Other targets included the coke ovens at Colombelles, petrol, oil and lubricant dumps, and châteaux used as enemy headquarters. The accuracy of photographic interpretation was also checked. Farther east a V.1 site was examined at Watten. In connection with air attacks on the enemy's lines of communication, an investigation was made into the crossings over the Seine used by the Germans after their defeat in Normandy that August. Two large diagrams were made showing the routes followed by the Germans and the attacks made on them as they crossed the Seine. Something of the effects of bombing in the 'Transportation Plan', mentioned earlier, was discovered in an exhaustive study of the railway system round Paris and at Creil by Professor Zuckerman and his assistants.

The work of the Field Headquarters was normally divided into three stages. Firstly, the assembly of all attack data, photographic material and reports, maps and any other relevant matter in relation to the area concerned which was usually completed with the aid of the main headquarters staff, before arriving at the location. Secondly, the interviewing and interrogation of officials and any local people who could provide any useful information, and the examination of records, etc., in relation to the area concerned—to find out how far-reaching the effects of the bombing may have been in disrupting the life and production of the area, paralysing communications and installations, and how far the enemy succeeded in making repairs and so on. Thirdly, the actual visual examination and survey of the area concerned, the measuring of craters caused by the bombs, the examination of fragments of bombs, the ground examination of all damaged and destroyed buildings, railway lines, trucks, wagons, roads and bridges in order to make a complete assessment of the results on the spot.

An Anson aircraft belonging to Headquarters Bomber Command was loaned to the B.A.U. for a brief period. The aircraft and crew did such valuable work in producing photographic cover on targets later to be examined by ground survey parties that in early November they were transferred to SHAEF Air Communication Squadron to work exclusively on behalf of the B.A.U. except when otherwise required by the Commander-in-Chief, Bomber Command, or his representative at SHAEF, Air Vice-Marshal Oxland.

The most important study was that on rail communications and work was begun on French railway records almost immediately on arrival in France. Preliminary contacts with the *Societé Nationale des Chemins de Fer* (S.N.C.F.) were made through G.2 SHAEF and through the French members of the Inter-Allied Military Railway Commission, who advised the various regions of the presence of an inter-Allied party investigating the effects of aerial bombing of the French railway system. Personal contact had been made with the French operational research group of scientists through Professor Joliot-Curie and Dr. Rapkine. As a result of this, a group of about seven French scientists under the immediate supervision of Dr. Ephrussi started work on the records in close contact with the British and American groups.

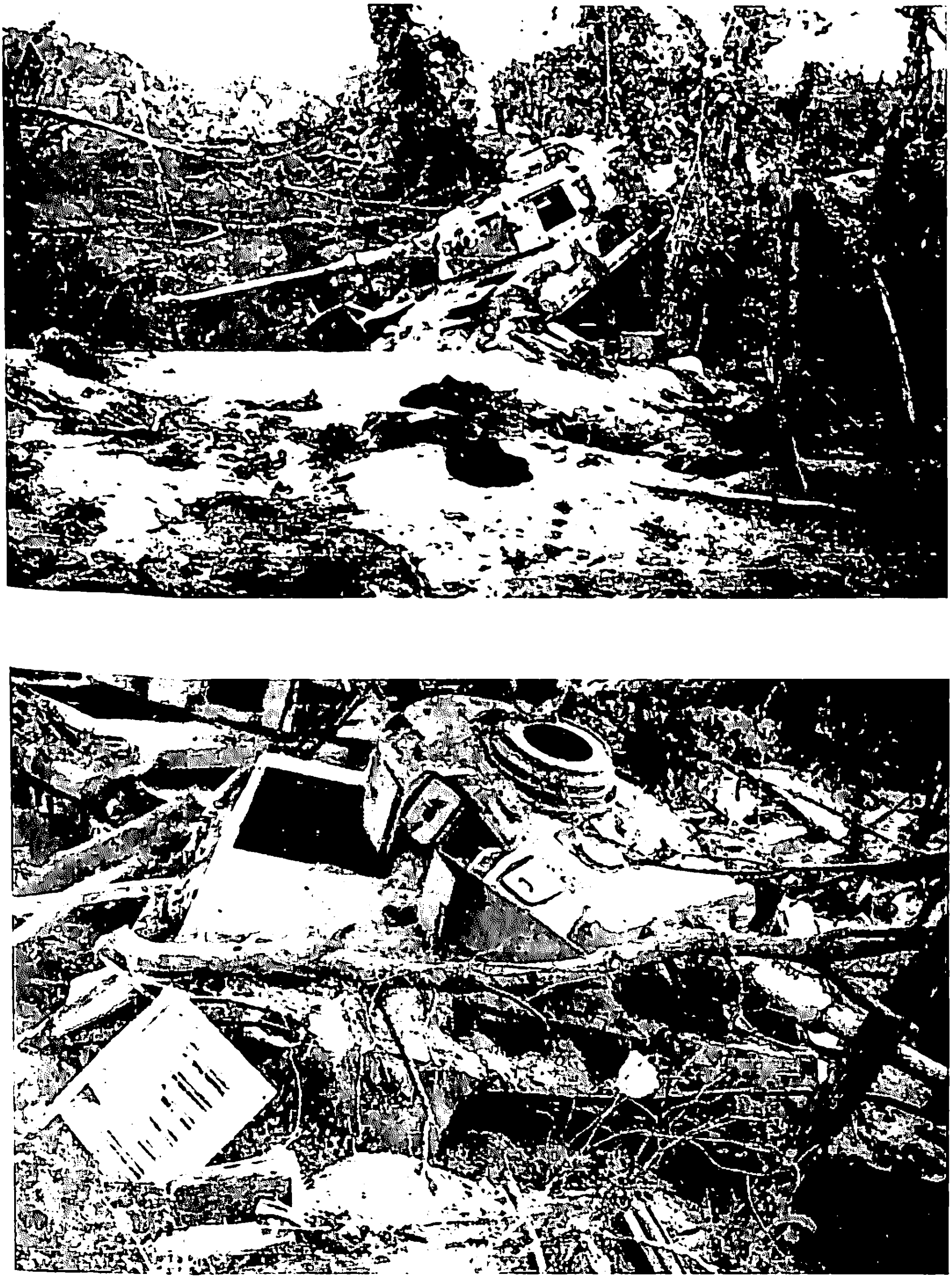
The immediate task was to estimate the effectiveness of the air attacks in the Transportation Plan. The investigation was mostly factual and involved little analysis of the figures beyond the making of graphs and tables from the original records. Afterwards the more general aspects of the air attacks on railways were examined. For such general investigations, two broad groups of records were available. In the first place there were large scale records of the flow and volume of traffic in a region; next, there were the more detailed figures on the nature of interruptions which occurred. In the Region Nord, for instance, there were figures on the duration of interruptions following line cuts, and it was possible to extract from the records figures on the time taken to repair locomotives. Further, very detailed records had been kept by the French of the effects of strafing of locomotives by fighter bombers. Research on these problems began in the Region Nord and at the same time contact was opened with other Regions to see what material was available with a view to recording the history of their traffic under Allied bombing.

By the end of November the B.A.U. had compiled ten reports. The titles of some of them indicate the extent of the work. 'Ground Survey of E-boat pens at Le Havre'; 'Damage to buildings by 500-pound general purpose bombs fused nose instantaneous'; 'Changes in the volume of French railway traffic expressed in kilometre tons, as a result of air attacks'; 'Counts of bombs on photographic cover and in the field'. It had been hoped to issue combined U.S.A.A.F. Evaluation Board/B.A.U. reports, but experience showed that this was impracticable as the method of presentation acceptable to both parties was not the same, and phraseology differed. Accordingly each side issued its own reports, although all drafts and reports were freely circulated before compilation.

With the disbanding of Headquarters A.E.A.F., the Bombing Analysis Unit came under the supervision of SHAEF, although it was not considered an integral part of Supreme Headquarters. Mr. Larnder left the B.A.U. on the dissolution of O.R.S. A.E.A.F. to return to his peacetime occupation. When the O.R.S. Coastal Command party had completed examination of attacks on shipping on the west coast of France, they withdrew from the B.A.U. and returned to England.

ATTACHMENT OF THE B.A.U. TO THE BRITISH BOMBING SURVEY UNIT

The prime purpose of the B.A.U. was to examine targets in the field; it was concerned with the close support of the ground forces and the use of air power in a tactical role. But it was also necessary to discover what the strategic bomber offensive had done to German industries, communications and cities. With the imminence of a landing on the Continent, in May 1944 proposals for the formation of a survey unit to fulfil this purpose were discussed in the Air Ministry. On 3 August the British Chiefs of Staff approved a proposal to examine the effects of Allied strategic bombing and the Air Ministry was instructed to work out details for a research body. This required close collaboration with the Ministries of Economic Warfare, Aircraft Production, Home Security and other interested government departments, and by the end of the year the British Bombing Research Mission (B.B.R.M.), as it was then known, existed only in a nebulous state



German Mark IV tank put out of action by Bomber Command during Allied break-through south of Caen, 18 July 1944 on account of differences of opinion on its eventual organisation. From the start, however, it was envisaged that the B.A.U. would become absorbed in the B.B.R.M. when the Allies occupied Germany. A large American evaluation team (later known as the U.S. Strategic Bombing Survey) was also being formed for the same purpose.

On 12 January 1945 the SHAEF B.A.U. was renamed the R.A.F. B.A.U. and shortly afterwards moved its headquarters to La Butte Rouge near Villacoublay airfield. At the end of the month Group Captain A. N. Combe took over command of the unit from Group Captain Drury. Professor Zuckerman continued to direct research. During the following weeks it was uncertain whether the B.A.U. was to continue to operate under the control of SHAEF or whether it would be placed under control of the Air Ministry, in which case it would inevitably become part and parcel of the B.B.R.M. and concentrate on problems of a strategic rather than of a tactical nature. It appeared to the Commanding Officer of the B.A.U. that its proper function was to assist the Allied Air Forces in the European theatre of war and that it should continue to examine the effects of air attacks on enemy communications, harbour installations, coastal batteries, 'V' weapon sites, airfields, tactical bombing targets, and the like. The Air Staff eventually concurred; and in any case amalgamation with the B.B.R.M. was premature, for the time being, as the latter's structure was still indeterminate.

The Allied crossing of the Rhine made it possible for the B.A.U. to examine the effects of air attack on the German railway system; the work of O.R.S. 2nd T.A.F. in the Ardennes was supplemented by studies of disrupted communications at Houffalize and St. Vith; the effects of the Napalm bomb against fortified positions and of bomb and rocket attacks against railway bridges were studied; a B.A.U. syndicate inspected the 'V' weapon sites in the Pas de Calais; after the liberation of north-east Holland a party visited the E-boat pens at Ijmuiden which had been attacked a number of times by heavy bombers. The association with the U.S.A.A.F. Air Evaluation Board continued until the end of the war when the American team left for home. By that time the B.A.U. had published 27 reports and a further 22 reports of field work were being prepared. A large number of photographs of bomb damage had been collected. The distribution of the reports had grown to such a scale that the unit became hard pressed to find reproduction facilities adequate to meet the demand.

As nothing had come of the proposal to form the B.B.R.M. and as valuable evidence of the effects of the strategic bombing offensive was being lost, the Air Ministry set up the British Bombing Survey Unit under the command of Air Commodore C. B. R. (afterwards Sir Claude) Pelly, to which it was decided to attach the B.A.U. with Professor Zuckerman as scientific adviser. By 30 June the bulk of the B.A.U. had already moved to the forward headquarters of the British Bombing Survey Unit at Hanover.

OPERATIONAL RESEARCH AND THE 'V' WEAPONS: THE FLYING BOMB

Before concluding the present chapter, a reference must be made to the part played by O.R.S. A.D.G.B. in the counter-measures against the 'V' weapons, the first of which, in the form of the flying bomb, was launched against southern England from the Pas de Calais seven days after D Day. On 15 June the flying bomb offensive started in earnest with London as the main target, continuing until 5 September. Thereafter spasmodic attacks were made both from aircraft and launching sites on the ground until 30 March 1945, when the last flying bomb fell in England.

For many months prior to the start of the attack discussions were held on counter-measures to be taken in the event of an attack, in which the O.R.S. played an important part. It was difficult to estimate the probable success of the defences against the flying bomb because of the scarcity of information concerning its construction and performance and on account of the fact that the defences had had no previous experience of a target of this nature.

After the attacks had begun, a continuous watch was kept on the performance of radar stations concerned with the tracking and interception of flying bombs. The range of pick-up, the length of track, the number of plots produced on each flying bomb, all came under careful scrutiny. A special O.R.S. group was set up at Fairlight to keep a constant watch on station performance and to carry out other functions to be mentioned below.

All suitable radar stations in the path of the flying bombs were used for controlling fighters. In addition controllers were placed in Maidstone and Horsham Royal Observer Corps centres and they controlled fighters. Two members of the O.R.S. visited some of the stations and squadrons. During their visit, they made observations in regard to the radar coverage in relation to the interception of flying bombs, tactics of ground control, tactics of fighters and other matters.

The O.R.S. armament section made a continuous analysis of combat films taken by defensive fighters. From these films, analyses were made of wander of aim and range of firing, length of burst and other relevant features of the combats with flying bombs. One report analysed successful combats by Tempests and Spitfire XIV's with the closing range of fire. The figures differed most markedly from those obtained in fighter versus fighter combat. Another report showed that the risk of damage from a flying bomb exploded in mid-air was negligible at ranges over 150 yards.

O.R.S. A.D.G.B. worked out a method of intercepting flying bombs for free-lance fighters, especially the intruder night fighters which patrolled just off the French coast. The method was essentially to fly with the bomb on the beam; an approximately cut-off interception then took place. This simple technique was accepted as sound by the Command, and a memorandum and illustrative diagrams were sent to all squadrons engaged in counter-measures against the flying bombs.

Until the attack started the expected speeds and heights of the bombs were largely a matter of speculation, and it was therefore of the utmost importance for all types of planning that these should be measured immediately. The first rapid estimates were made by a combination of results from a number of sources. Several members were in readiness at radar stations, particularly at the Microwave Early Warning set at Fairlight, and made observations directly on the apparatus. These were supplemented by the Reporting System Observation Section at Maidstone Observer Centre and a more exact analysis followed. Speeds were obtained by films from Fairlight. These films gave a timed picture of the Plan Position Indicator every 20 seconds. The flying bombs shown could be plotted accurately, and a 'least square' straight line was fitted to the space-time curve of this data. Corrections were then added for change in azimuth, and the wind, to give a final air speed. With this method a group speed accuracy of about ± 2 per cent was obtained, a maximum additional ± 5 per cent was introduced with the wind correction. Perhaps the most difficult operation was to match these tracks with those of the filter room, in order to give them designations. Heights were more difficult to obtain. The radar gave no measurements as the flying bombs were too low and the bulk of the information came from the Royal Observer Corps.

At the beginning of the flying bomb attack, the O.R.S. party at Fairlight began to analyse the tracks of flying bombs produced by the Microwave Early Warning set. The main purpose of the analysis was to determine the points of origin of the flying bomb in occupied France, by producing the tracks back. It was, of course, impossible to determine the precise firing point owing to errors in the tracks, the facility of the flying bomb to be launched in one direction and then to set course for the target a few minutes after take-off, and other factors. However, the method did provide a means for indicating an area in which one or more launching sites would probably be found. From this information, photo-reconnaissance of the area by aircraft was carried out, and if launching sites were detected, they were put on the list of targets to be attacked by the heavy bombers.

Early in 1944 a member of the O.R.S. was attached to A.E.A.F. to carry out assessments of damage after air attacks on flying bomb sites, and then to estimate the number of sites capable of action at any moment.

THE LONG RANGE ROCKET

In the summer of 1943 an inter-departmental committee under Sir Robert Watson-Watt was set up to study various means of detecting the approach of rockets and the location of the sites from which they were fired. The officer-in-charge of O.R.S. Fighter Command, Mr. A. F.

Wilkins, was a member of this committee. The O.R.S. was made responsible for the general efficiency of the warning system and for computing the firing points from the observed data, and an officer of the O.R.S. was instructed to take charge of this work.

In view of the communications required, it was decided that the necessary computations should be done in No. 11 Group Filter Room as a number of necessary lines were already available there. Accordingly, a special switchboard was installed and the necessary facilities for computations provided. It was decided to use the existing C.H. stations working on wave-lengths of about 12 metres for detecting rockets. From late 1943 onwards the C.H. stations from Dover to Ventnor and later Southbourne, Ringstead and Branscombe were fitted with the necessary equipment and cameras. These stations maintained a watch for rockets up to D Day, but with the capture of Cherbourg and the advance through France the three westerly stations were closed down, and thus were never used actively in the operations against rockets. As it was then thought that the enemy would fire from north-east France or Belgium, the C.H. stations as far north as Stoke Holy Cross (Norwich) including that at Bawdsey were converted for the special watch and Ventnor was withdrawn. This radar cover was supplemented by a system of microphones installed by the Army Sound Ranging Unit, which recorded the shock wave of the projectile on film and enabled a bearing of the firing point to be obtained, and by Army flash spotting units.

The organisation functioned exactly as planned when the first rocket fell on 8 September 1944, and the area from which the rocket had been fired was calculated to be just south of Rotterdam. With the start of rocket activity the Computing Section, which was manned by Service personnel, was expanded to operate on a 24-hour watch basis. An O.R.S. officer was responsible for the work of this Service section. The O.R.S. was responsible for checking the film interpretation and firing point assessments of the duty watch personnel, and the production of statistics of the activity.

The occupation of Belgium by the Allies made it possible to move two mobile radar stations to sites near Malines and Eindhoven. A radio link was established with the filter room and film information passed by code. A direct telephone link was later substituted.

No. 33 Wing was established as the R.A.F. component of the Forward Continental 'Crossbow' organisation located at Malines, and the Army component was the 11th Field Survey Regiment, R.A. There was a small O.R.S. detachment at No. 33 Wing in parallel with an Army Operational Research Group detachment in the 11th Field Survey Regiment. The work of the O.R.S. here followed similar lines to that in the United Kingdom but the different equipment and different geography produced a number of interesting differences. The work was, in all probability, more comprehensive and included greater liaison with the technical sections to effect improvements, especially in the timing system and the console recording; siting of radars as the war moved forward, and far greater liaison with intelligence agencies on the overall performance of the V-2s, etc.

The actual echo of a rocket rising after firing was usually visible to the C.H. station operator but passed too quickly for any immediate readings of range. Nor was the display suitable for doing this. It was, however, used as a warning that a projectile was on its way and this information was used to warn one of the Army G.L. Mark II sets deployed for the purpose around the Thames Estuary. A warning system was organised by the O.R.S. and constant efforts made to improve its efficiency. If the C.H. warning was from the echo of a rocket later picked up by a G.L. set, it was practically certain that the rocket would fall in this country and warnings were passed to the London Passenger Transport Board who closed the sluice gates under the Thames.

The methods for estimating the firing points were based almost entirely on the information taken from the C.H. station films although the bearings given by the Army Sound Ranging Unit were used until this unit was moved to Belgium in December 1944. From the films it was possible to read the range of the response to half a mile and time to half a second. The time was taken from a master clock at the filter room which transmitted a synchronising pulse to all the stations at each half-hour. Later, on the advice of the O.R.S., the Astronomer Royal gave permission for the use of a direct line from the master clock at Greenwich. After an incident, films were changed, developed and assessed at the station and the information phoned to the filter room. By range cuts the ground path of the rocket was plotted, and extrapolated back to an estimated firing point. It was, of course, necessary to allow for the horizontal distance travelled by the rocket between the firing point and the point at which it was visible to the radar stations, and various other allowances, such as for slant range and the earth's curvature, were made.

Towards the end of the activity very accurate results on firing were obtained by the Army using an SCR.584[1] radar installation which was sited at Steinbergen, only about 35 miles from the firing points in The Hague. This gave results to within about 100 yards and the C.H. information was only needed as confirmation, or when the SCR.584 failed to obtain an echo.

The last rocket fired against this country fell on 17 March 1945. During the whole time, just under 4,000 suspected incidents were examined by the computing section, and of these 1,115 were actual incidents in this country. Firing points were quoted for about 90 per cent of these.

The part of O.R.S. A.D.G.B. in offensive operations against the 'V' weapon launching sites was mainly analytical. In early 1944, the first rocket projectile dive-attacks by fighters were made chiefly against flying

[1] An American produced Radar Director used for controlling both A.A. fire and fighters.

bomb installations. At first the technique and especially the range estimation were very much at fault and analysis by the O.R.S. of the combat films taken during these attacks resulted in correction of these faults and much improved results. A study was also made of fighter bomber attacks on installations connected with rocket firing. The targets concerned were chiefly individual buildings often within towns in enemy occupied territory and it was essential not to scatter bombs among the surrounding houses; the bombing therefore called for the utmost possible precision, and the results may be said to be the optimum obtainable in this form of attack.

CHAPTER VIII

Operational Research in the Mediterranean and Far Eastern Theatres of War, 1944 to 1945

MOVEMENTS AND ORGANISATION OF O.R.S. MEDITERRANEAN ALLIED AIR FORCES (M.A.A.F.)

By the end of 1943 operations in the Mediterranean theatre were concentrated on driving the Germans out of Italy. The Mediterranean Air Command and the Northwest African Air Forces were therefore amalgamated and became the Mediterranean Allied Air Forces (M.A.A.F.) under the American air commander, General Ira Eaker. The Deputy Air Commander-in-Chief was an R.A.F. officer in the person of Air Marshal Sir John Slessor, who had arrived from R.A.F. Coastal Command where he had been an enthusiastic supporter of operational research. In accordance with the new arrangements O.R.S. Northwest African Air Forces became O.R.S. M.A.A.F. without change of function. When the advanced headquarters of M.A.A.F. moved from North Africa to Caserta in Italy, the O.R.S., at the insistence of Sir John Slessor, also moved to Italy as soon as possible, but as there was no accommodation in Caserta, the section was temporarily established at Naples where it managed to carry on its essential work. The main headquarters of M.A.A.F. moved to Caserta on 24 March 1944 and the O.R.S. moved with it from Naples.

Headquarters M.A.A.F. had assumed control of the air forces in the Middle East as well as those in North Africa and Italy, and as there was little work for O.R.S. R.A.F. Middle East to do, it was amalgamated with O.R.S. M.A.A.F. on 20 April. Mr. (Honorary Wing Commander) E. C. Williams, who continued as head of the section until the end of the war, now had under his control 23 scientific officers. He had also taken charge of the Bombing Survey Unit, formerly led by Professor Zuckerman. For the next twelve months until the end of the war, members of the section were temporarily attached to different groups in the Command and also carried out independent investigations. Thus, two officers spent some weeks with No. 205 Group, the R.A.F. night bomber force in the Mediterranean area, to discover the falling-off in the amount of flying. A detachment of the Bombing Survey Unit went to Rome after its capture to collect information from the various ministries on the effect of Allied bombing. Visits were made to the south of France after the Allied landings in August to observe the effects of bombing on port installations in Marseilles and Toulon and to Rumania to study the damage at the Ploesti oilfields. Later, a party went to Greece to note the effects of rocket projectile attacks in Athens. Much time was also spent in the analysis of air attacks on rail communications in Italy and an officer was attached to the Desert Air Force to work on problems of close support by aircraft during the Eighth Army attack on the Gothic Line. In December 1944 the research sections in R.A.F. Middle East and the Mediterranean Allied Coastal Air Force were finally closed down.

After the German surrender in Italy in April 1945, the Bombing Survey Unit began to collect material for an analysis of the air attack of communications and industry in northern Italy, believing that it would eventually be required by the British Bombing Survey Unit (B.B.S.U.). However, the sudden end of the Japanese war caused both O.R.S. M.A.A.F. and the Bombing Survey Unit to be disbanded in September 1945. The B.B.S.U. was so occupied with field work in Germany that it was decided not to examine the Italian targets.

Throughout this period valuable assistance was given by the O.R.S. to the American operational researchers, although some confusion and overlap occurred among the latter when independent operations analysis sections were started in the XVth U.S. Air Force and in the XIIth U.S. Air Force in April 1944. The operations analysis section at Headquarters M.A.A.F., referred to in an earlier chapter, broke up in October 1944 and, with one exception, the members returned to the U.S.A. The section at Headquarters XVth Air Force continued its work, but only one officer remained in the XIIth Air Force. A U.S. Air Evaluation Board, similar to the one formed in North-west Europe, to which reference has already been made, was also set up that October to carry out a large scale survey of weapon effectiveness. It was the view of O.R.S. M.A.A.F. that this board might have taken the place of the defunct Operations Analysis Section but for the fact that the members were inexperienced and lacked the necessary technical qualifications. The board was given considerable help by the O.R.S.

O.R.S. M.A.A.F. had to deal with a variety of problems as this command was a composite one and was responsible for the operation of all types of aircraft in the Mediterranean, whether fighters, bombers or reconnaissance aircraft. There were more problems than the O.R.S. was able to cope with and this compelled it to concentrate on those that were the most important. The fact that M.A.A.F. was an integrated command of British and American units did not provide any serious problems. As noted above, cordial relations were established with the Americans, and members of both sections worked together on problems of mutual interest. In the following section some of the problems which the O.R.S. attempted to solve in the last year of the war in the Mediterranean theatre will be described.

BOMBING EFFECTIVENESS

The ultimate aim in work on bombing effectiveness carried out by the O.R.S. was to be able to assess in advance the bombing effort required to achieve a given military objective. The aim was not achieved, but the investigations as they proceeded produced answers which were useful in the secondary, but still very important, aim of assessing the day-to-day effectiveness and of finding methods for improving it. The general plan of the work followed the same lines as that done by O.R.S. Bomber Command described in an earlier chapter, including assessing the effect of enemy opposition, weather and other factors on accuracy, the cost of operations, the correct bomb type and fusing for the given target and the success and operational use of radio and radar aids to bombing. As the greater part of the bombing took place in daylight, research was carried out on the pattern size for formation bombing.

A detailed study was made in June 1944 of the bombing accuracy of Nos. 42 and 57 U.S. Bomb Wings which at that time were engaged on attacking bridges in Italy. The chief sources of information were the bomb-fall plots and the mission reports published in the daily operational summary. It was found that a considerable improvement in the concentration of pattern size, and even more in aiming accuracy, had occurred since the attacks on Pantelleria in 1943. Later, when documents were captured in Rome, it became possible to determine the damage caused by medium bombers on bridges even more accurately and hence to obtain the relationship between the average air effort expended on each attack and the results achieved.

Not only had the American medium bombers improved their own accuracy after a year's operations, but this accuracy was very appreciably higher than that of similar groups in North-west Europe. A number of explanations had been offered for this difference of accuracy between similar formations: theatre differences such as weather and type of target; degree of enemy opposition; differences in the method of analysing accuracy; differences in training and experience. When one of the Bomb Wings (No. 42) was transferred to southern France to support General Eisenhower's forces, an analysis of its operations was made by the O.R.S. Although the targets were of a different type, it was revealed that since the move to France bombing accuracy had decreased, yet remained substantially higher than that of similar medium formations of the IXth U.S. Air Force. The records proved that the decrease was not due to increased opposition or worse weather or to changes in tactics. It was concluded that the high accuracy of the two medium Bomb Wings was mainly due to long experience and intensive training.

Analyses of the accuracy of fighter bomber attacks were more difficult on account of the greater variety of targets attacked. Photographic strips taken by photographic reconnaissance aircraft of stretches of railway line attacked by fighter bombers were examined and the analysis provided an average figure for accuracy over a certain period and against the average opposition encountered during the operations. It was possible to analyse attacks on small bridge targets in the same way.

In September 1944 a visit was paid to the Desert Air Force, then engaged in operations against the Gothic Line, to investigate the question of close support bombing. It became obvious that the main effect of such attacks was to destroy enemy morale, and to raise that of Allied troops during an attack. The problem arose as to whether attacks on communications behind the enemy lines, in this case bridges, were more profitable than close support operations. A comparison was therefore made between the effects of fighter bomber attacks on bridges over the River Senio and attacks against gun positions. The method adopted in the first case consisted in obtaining from each photographic reconnaissance photograph of each bridge (taken every few days) the bomb-fall plot (to determine accuracy) and damage caused. Details of each attack were available. From the accuracy figures the probability of scoring a hit on each bridge with a given weight of air effort could be deduced. From the reports of damage seen in aerial photographs, the damage caused by each type of bomb could be ascertained.

Two interesting facts emerged in regard to the bridge cutting operations. The first was that the accuracy of the fighter bombers fell as soon as the anti-aircraft defences of the bridge were strengthened. The approximate scale of effort required per bridge was provided for use in future attacks. Secondly, it was shown that the 1,000-pound bomb was much more effective against masonry bridges than the 500-pound bomb normally carried by the fighter bomber. Spitfire bombers carrying only one 500-pound bomb were therefore better employed in close support operations where morale factors were all-important.

A study of crater plots near gun positions revealed the proportion of attacks against the correct target and the accuracy attained. It was confirmed that the effect of such attacks was less in causing material damage than in restricting enemy activity and depressing their morale, and there was a considerable saving of life among Allied troops. Due to the difference in the visibility and type of target the accuracy attained in these attacks on enemy gun positions could not be expected to approximate to that achieved against bridge targets.

ANALYSIS OF OPERATIONS BY NO. 205 GROUP R.A.F.

Numerous attempts were made to assess the accuracy of night bombers of No. 205 Group. At first this Group consisted of six Wellington squadrons based in Tunisia, and later at Foggia. In 1944 a Halifax squadron and several Liberator squadrons were added to the Group, while the Wellington squadrons were decreased in number. No. 205 Group constituted the entire strategic night bomber force, and was used to attack such targets as port installations, factories, marshalling yards, bridges and other communication targets. The force was complementary to the strategic day bomber force consisting of the XVth U.S. Air Force. When occasion demanded No. 205 Group was also used in a tactical role. In the Mediterranean theatre air and ground opposition to night attacks was usually far smaller than in western Europe, so that relatively simple bomber tactics could result in high bombing accuracy without exorbitant losses. Evidence on the results of attacks was obtained from photographic reconnaissance, ground survey, information from enemy sources, photographs taken while aircraft were bombing, and plots of 4,000-pound bombs studied in conjunction with photographs taken by the aircraft dropping them.

It was popularly believed, particularly by civilians in enemy occupied territory, that the night bombers achieved greater accuracy than the heavy day bombers. Attempts were made to verify the accuracy of this belief by the O.R.S. at the end of the war; a comparison was made between a small number of attacks by day and night bombers on similar types of targets (marshalling yards) in northern Italy and central Europe. Although evidence of accuracy was difficult to obtain, a comparison of photographs combined with an examination of bomb craters showed that the concentration of aircraft, relative to the aiming point, was not significantly different from that for all No. 205 Group night bomber raids on marshalling yards in March and April 1945. It was therefore concluded that the accuracy deduced for this series of raids could be taken as reasonably typical of all such raids. This accuracy was slightly less than that of the heavy day bomber attacks on similar targets.

The greater accuracy which French and Italian civilians invariably claimed for night bombers might partly be ascribed to their desire to please R.A.F. officers and also to the small amount of damage caused in non-target areas in night attacks. The smallness of this damage was due to the relatively small forces employed, but this was not known to civilians, who would associate the drone of aircraft for long periods at night with considerable air forces.

RADIO AND RADAR AIDS TO BOMBING

During 1944 the Desert Air Force made a request for radio or radar aids for tactical bombing. O.R.S. M.A.A.F. was called upon to advise on this problem. Bombing aids such as Gee-H and Oboe were not at that time available for the Mediterranean theatre and something had to be improvised from available equipment. Experiments were made with the American SCR.584 for close control. This equipment could not at first be used for close support bombing and a technique had to be developed for using the equipment in its original (anti-aircraft) form. The method of control using the unmodified equipment involved employing two controllers, each with access to the R/T channel, one on the range indicator and the other on the azimuth indicator. The aircraft flew on a predetermined radial track from the station over the target and was directed on to this constant azimuth by the azimuth controller. The range controller gave warning of the approach of the release point and actually gave the order to release bombs.

This technique took a considerable amount of working out, and it was largely due to the O.R.S.'s assistance that the two SCR.584 sets used by the Desert Air Force in the spring offensive of 1945 had a good deal of operational success.

ASSESSMENT OF CLOSE SUPPORT OPERATIONS

The assessment of air attacks in close support of the Army was not easy. Relevant information was gathered from a variety of sources—interrogation of prisoners of war, study and analysis of intelligence reports, discussions with Army and Air Force officers, and ground surveys of battlefields after capture. Although much interesting and useful information was gathered, this was not available in sufficient detail and did not cover a sufficiently wide range of operations to form the basis for quantitative study; for which it was realised that a much larger number of observers and widespread organisation for gathering material would be required.

In general the main effect of air attack was one of morale encouragement of our own men and the destruction of the will to resist of the enemy. The method used in assessing the material damage was always to determine, from the accuracy of bombing, the density of bombing in the neighbourhood of the targets. Then taking into account the vulnerable area of the target (either as estimated by direct observation, or from the Army Operational Research Group data available from other theatres) it was possible to calculate the probability of the target being destroyed or damaged by a given weight of attack. The Army was especially keen on fighter bombers attacking enemy gun positions to subdue enemy shelling and thereby reduce the number of casualties among Allied troops. To assess the value of this form of aerial warfare, it was necessary to consider not only the effort required from the Air Force (aircrew and ground crew) and the material wastage involved, but also the reduction in air effort available for attacks on other targets—often bridges behind the enemy lines.

Several reports were prepared to demonstrate the relationship between air effort and results achieved. It was intended that these reports would help senior Army officers to determine the relative scope of two forms of activity open to fighter bombers used in close support, i.e. attacks on gun positions and front-line defences and, secondly, attacks on supplies behind the enemy lines.

In the final phase of the Italian campaign the employment of the light bombers of the Desert Air Force was considered by the O.R.S. and it was recommended that these squadrons would be more usefully employed in night bombing attacks on communications as German movement by day was sparse due to Allied air activity. A change-over to night attacks was made by the Desert Air Force during the break-through to the River Po in April 1945, and many attacks were made on bridges used by the enemy in retreating across the Po. The enemy was consequently forced to leave much fighting equipment on the south bank, and he found it impossible to re-group and put up an effective stand. Surrender was thus forced upon him.

GROUND SURVEY OF TARGETS

While nothing as ambitious as the survey of air attacks on rail communications in southern Italy and Sicily made by the B.S.U. in 1943 was again undertaken, several interesting surveys were made in the final phase of the war. The first of these was an examination of the French battleship *Strasbourg* and the St. Mandrier coastal battery, both near Toulon, made after the Allied landings in southern France.

In October two members of O.R.S. M.A.A.F. went to the Rumanian oil refineries with a small team of six observers. The terms of reference were extremely comprehensive and included the special function of investigation in detail of specific bomb incidents, which might throw light on the relative merits of various types of bombs and fuses as applied to refinery equipment. The very extensive data collected by the party were taken back by the visiting members to the Air Ministry where the analysis was carried out. In addition to all this information on damage, a study was made of the most suitable tactics to be employed in bombing operations against refineries. It was found, for instance, that it would be more profitable to cause the maximum damage to all installations in the plant rather than to attempt to destroy precise targets. Secondly, on account of the ease with which it was possible to shut down plants, more use should be made of the surprise factor, or alternatively, the plant should be kept in a constant state of alert so that work would have to go on all the time. In this way the plant would run greater risk of damage by fire. Care should be taken to attack at irregular intervals while every attempt was to be made to exhaust the smoke screen put up by the enemy over the refinery. Other recommendations included the use of incendiary and long delayed action bombs.

The next investigation involving ground survey arose in January 1945 when a detailed inspection was made of the results of the rocket projectile attacks carried out against enemy strong points in Athens. This proved successful in establishing the fact that, by using rocket projectiles against relatively undefended gun positions, opposition could be reduced sufficiently to enable the ground forces to proceed as far as the next gun position.

ATTACKS ON RAIL COMMUNICATIONS

The O.R.S. attempted to discover the effect of the bombing of railways and the policy of interdiction upon the efficiency of the German Army and hence upon the course of the battle. For the purpose of this study it was essential to obtain the most reliable available information about the physical damage caused by the bombing, the delay to traffic caused and the tonnage of military supplies or the number of military trains moving on the railways before and after the bombing. It was also necessary to have the most complete and reliable sortie data so that the type of aircraft, kind of attack, type of bombs dropped and number of sorties, could be related to the actual damage caused.

It had been found in the investigations in southern Italy and Sicily that the information obtained from the central departments of the railway organisation was usually more reliable than that obtained at lower levels. Unfortunately after the Allied landings in Italy the central control of the railways had been taken over by the Germans and information thereafter was extremely difficult to obtain as statistics and other documents had been destroyed in the usual methodical German fashion.

An attempt was made to discover the material effects of particular types of attack on railways. Examinations were made of a certain stretch of the main line to Rome from the north for which fairly complete data were available and which was considered to be important by the enemy. It was difficult, however, to relate the number of sorties flown against this line with the number of air raids reported by the Italian officials. However, a definitive list of sorties was compiled for the stretches of line that had been subjected to analysis and the attacks were related to the actual cuts on the line and the physical damage caused.

It was even more difficult to discover the effect of the damage to railways on the movement of military supplies by rail. Here again this was due to the railways being taken over by the Germans and the subsequent failure to find key documents, for example, daily train schedules with details of the composition of trains. The central line from Bologna, through Florence to Rome, provided the most comprehensive records which fortunately covered the important period of Operation Strangle (the interdiction of railways in central Italy prior to the fall of Rome) from February to June 1944. Three problems were studied: the relative success of medium and fighter bomber attacks; the effect on the flow of traffic of attacks on marshalling yards as against bridge attacks; and, finally, the methods used to reduce the capacity of the line, for instance by one half, and those that reduced the flow to an absolute zero.

Lack of statistical data made it very difficult for the O.R.S. to obtain a comprehensive view of the enemy's supply situation in order to discover the effect upon his fighting efficiency on account of reduction in supply. These problems were approached from an historical point of view aided by common sense. The problem was seen as one which involved research into what had happened, a sorting and an appraisal of documents, an attempt to discover causal relationships between the bombing effort, the different methods and aircraft used and the damage, delay and reduction of capacity caused. The second problem was the presentation of the material so that the relationships were clear to the reader. Most of the material was incorporated in tables and figures which showed graphically the results in relation to the effort and often these results and their relationship to other similar results on other parts of the railway system. Very detailed statistical analyses were not attempted.

The whole of this study of the lines of communication ran frequently into socio-political and economic problems: such variables as the effect of the Germans having to use Italian labour, the morale of Italian workmen under air raids, the necessity or otherwise of the Germans supplying the Italian population with food, fuel and clothing, the supply of raw materials for clothing and maintenance from Italian sources, were all encountered.

ENEMY SHIPPING LOSSES IN THE MEDITERRANEAN

Several important lists of Italian shipping losses were obtained by the O.R.S. from the Italian Government and it was hoped to determine the relative amounts of Italian shipping sunk and damaged by various causes. In the case of air attack the O.R.S. intended to assess effort against results for various forms of attack and weapons, and the wastage of Italian shipping was to be assessed and related to the scale of the attack. Here again lack of details of sorties, failure of captured documents to give cause of loss and damage and lack of accurate geographical location were not conducive to quantitative analysis. In November 1944 the Italian Ministry of Marine compiled more comprehensive lists of Italian and German merchant shipping lost through war causes. All this information went to London and analysis was carried out jointly by the Air Ministry and the Admiralty.

RESEARCH INTO MAINTENANCE AND SERVICEABILITY

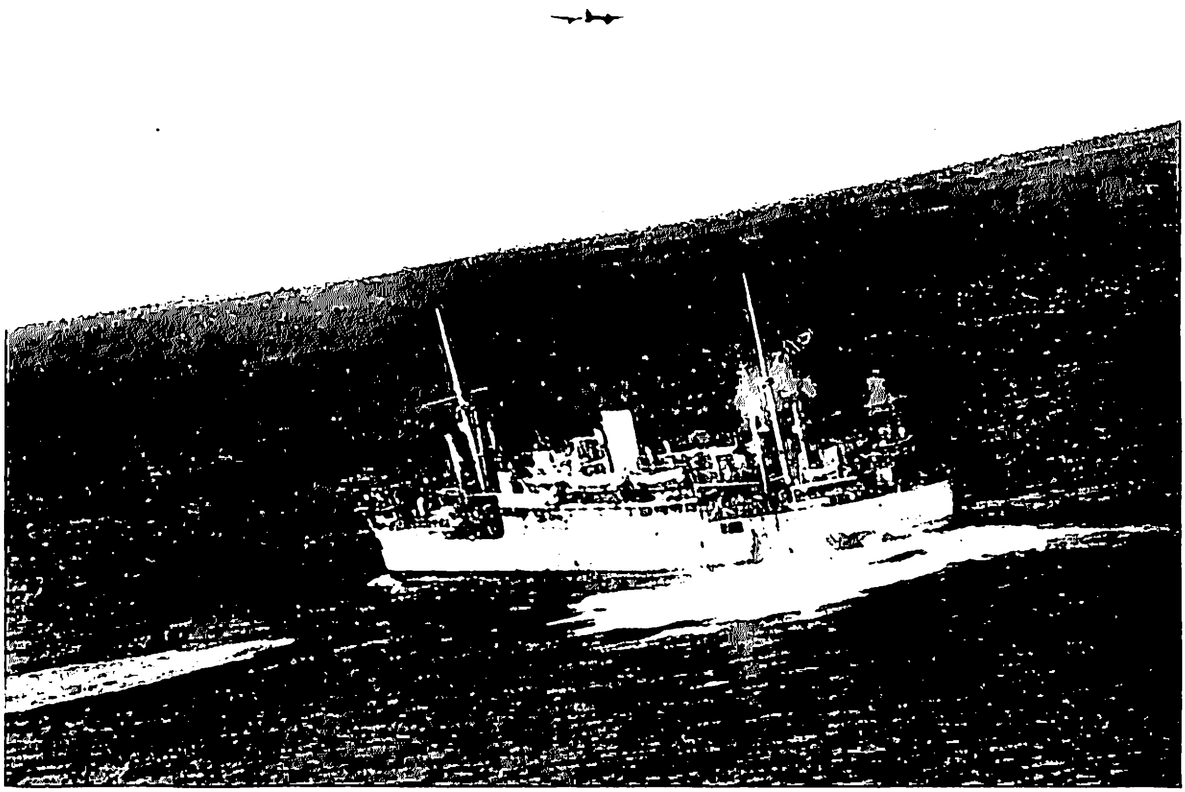
Like the O.R.S.s in the Home Commands, O.R.S. M.A.A.F. was called upon to solve a number of problems of a logistical nature. An example of how it dealt with a problem of planned flying and planned maintenance occurred in the spring of 1944 when it attempted to discover the causes for a decline in the effort of No. 205 Group. This group, the heavy night bomber force in the Command, then consisted of six Wellington squadrons and one Liberator-Halifax squadron. It was being employed every night when weather permitted. Headquarters M.A.A.F. believed that the nightly effort, amounting to less than 60 sorties per night, was smaller than might be expected for the established strength of 120 aircraft. A thorough investigation was made, extending from Group headquarters down to squadrons, repair and salvage units, and maintenance units. Data were selected to determine such matters as the manpower requirements in maintenance and repair for a given amount of flying, the input and output of repair and salvage units and maintenance units of aircraft requiring repair and maintenance, and the average actual, as distinct from established strength of squadrons.

The conclusion from all available data was that the prevailing conditions arose mainly from a lack of balance between the various maintenance organisations—squadron, wing, repair and salvage unit and maintenance unit. As a result squadrons were under strength, and a large amount of manpower was used uneconomically in efforts to obtain the maximum amount of flying out of a reduced number of available aircraft. In addition shortages of certain vital items—tyres and tools—were also partly to blame. Aircraft were piling up in maintenance units which were unable to carry out the maintenance required for the amount of flying undertaken. A number of proposals to restore the balance in the capacity of the maintenance organisation and to permit a more economic use of manpower were made in the O.R.S. report summarising these investigations.

Another subject for research was the strength and balance of aircraft in the Desert Air Force in early 1945. The O.R.S. had to discover the actual number of aircraft available and the use that was made of them, together with likely changes in future commitments and the corresponding changes in the air effort that would be required. Finally, a survey was made of changes in existing activities (either by increase or decrease of the effort allocated to various types of aircraft). This led the O.R.S. into the field of tactics and it found itself propounding on the most suitable role for the various types of aircraft in the Desert Air Force. Thus it discovered that the daylight operations by light bombers had outlived their value, while the long range fighter bomber such as the Mustang had taken the place of the Spitfire bomber with its inadequate range and bomb load. Medium bombers could be replaced with advantage by further fighter bomber squadrons. Medium and heavy bombers were, in any case, unsuitable for attachment to a tactical air force for long periods, and the ideal was for the latter to call upon the strategic air force for close support when required.

THE COST OF AIR OPERATIONS

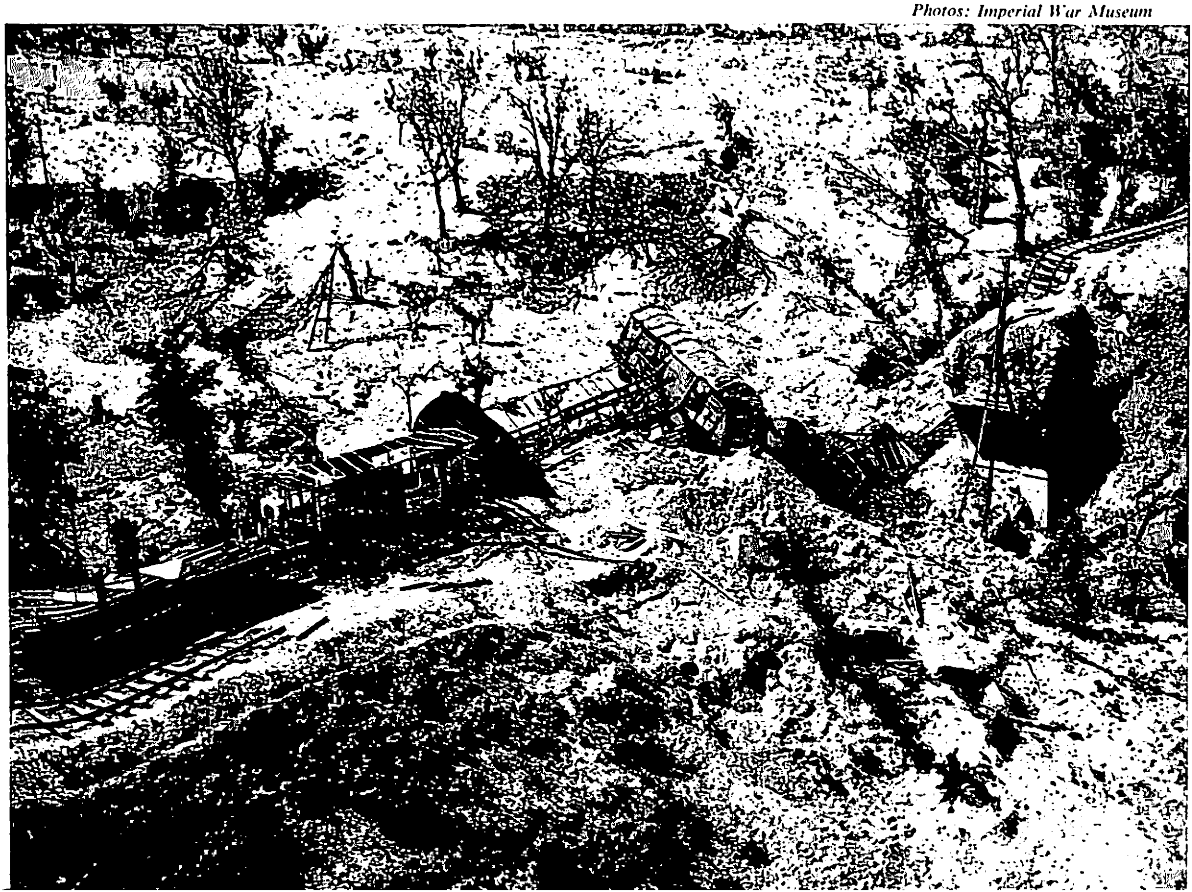
Losses to aircraft in the Mediterranean theatre were less severe than in North-west Europe and consequently more attention was paid to achieving the maximum effort from the bombing than to evolving measures to reduce the number of casualties. The bulk of the bomber force in this command was American and it was naturally the responsibility of their operations analysis section to inquire into the loss rate of bombers. Preliminary investigations, however, were made by the British scientists in



Above: Attack on shipping in the Mediterranean by Beaufighters, November 1943

Below: Wrecked bridge and rail transport at Arezzo, July 1944

Photos: Imperial War Museum



August 1943 into losses to anti-aircraft fire of Flying Fortress formations before the arrival of the American scientists. It emerged that when two formations followed each other over the target losses tended to be higher in the second formation, and especially so if that formation flew at a lower altitude. The O.R.S. recommended that a stepped-up formation be adopted. At a much later date reports from a German prisoner of war, previously an anti-aircraft gunner, stated that German anti-aircraft fire tended to lag behind and below the target; thus if the target were the first formation, considerable damage might be caused to the second formation if it chose to bomb from lower altitudes.

A more fundamental approach to the whole problem of aircraft losses to anti-aircraft fire was made in October 1944. The aim was to set up a quantitative standard of anti-aircraft opposition and effectiveness so that figures could be compared of losses due to anti-aircraft fire in different theatres, using different tactics, or of different aircraft when subject to the same degree of opposition.

For this purpose a number of simplifying assumptions were made. For medium bombers operating between 7,000 and 12,000 feet only those heavy anti-aircraft guns located within seven miles of the target were assumed capable of inflicting damage. The effectiveness of anti-aircraft fire was defined as the percentage of the attacking force hit (damaged or destroyed) divided by the number of heavy anti-aircraft guns plotted within a seven-mile radius circle centred on the target. This ratio was defined as the *susceptibility* of the aircraft to anti-aircraft damage when flying under given conditions. A further ratio, the *vulnerability* of an aircraft, was the proportion of aircraft hit by anti-aircraft fire which were thereby unable to return. This second ratio was a characteristic of the aircraft rather than of the defences. The product of susceptibility and vulnerability gave the percentage of aircraft over the target which were lost to anti-aircraft fire, for every gun on the target area (i.e. within seven miles of the target).

There were two reasons for measuring susceptibility in terms of aircraft hit rather than of aircraft destroyed. First, the number of aircraft involved in a given number of sorties was greater—leading to a more reliable figure for the susceptibility. In the second place, the chance of a hit on an aircraft resulting in its loss depended less on the anti-aircraft fire characteristics than on the structure of the aircraft. The separation of the ratios, susceptibility and vulnerability, was a first step in distinguishing between differential loss rates due to differences in aircraft and to differences in anti-aircraft fire. Investigations into the susceptibility and vulnerability of Marauders and Mitchells of the XIIth U.S. Air Force and of fighter bombers were rendered abortive on account of changes in tactics, slackening of enemy anti-aircraft fire due to shortage of ammunition, and lack of adequate and reliable data.

A final example of the work of the O.R.S. in assessing the cost of air operations will be taken from its study of the capacity of emergency landing strips used by the Desert Air Force in Italy. In December 1944 the advanced fighter bomber airfields were grossly overcrowded; there were often nine fighter bomber squadrons operating from a single runway (consisting of pierced steel planking). As many as three sorties could be carried out by a single aircraft daily, and the airfield was unable to deal with this scale of effort. Aircraft were frequently kept flying over the field for periods of up to three-quarters of an hour, awaiting permission to land, thereby increasing engine wear, and reducing the number of sorties of which the squadron was capable. Airfields could not be extended owing to shortage of pierced steel planking, nor could new airfields be built.

The O.R.S. was requested to investigate the position and discover the amount of waste incurred and, if necessary, to determine the effect of reducing the number of squadrons, thereby enabling them to operate more efficiently. Should such a reduction be necessary, it was to ascertain the maximum number of squadrons that could operate without impairing efficiency. Finally, the O.R.S. was to discover the effect of airfield congestion on the accident rate.

An examination both of the airfields and flying control records was made, the latter revealing that aircraft did not leave at intervals of less than one minute on the average, whereas the actual time required to take off in an aircraft was approximately half a minute. By observing the movements of aircraft prior to take-off and after landing, it was clear that delays occurred at the entrance and exit to the runway, rather than on it. A modified airfield layout was suggested which met with general approval. This provided for separate entrances to, and exits from, the runway. In previous airfield design the necessity of these had been overlooked for traditional reasons. The airfield layout which had once been suitable had been retained in spite of a different form of traffic, itself caused by different aircraft types being adopted. The modified airfield layout was adopted very successfully by the Desert Air Force and reduced congestion.

The subsidiary part of this investigation, which was to discover how many accidents were caused by congestion, was carried out jointly by the O.R.S. and the Accidents Branch of Headquarters M.A.A.F. The O.R.S. dealt with the possibility of accidents occurring on account of psychological factors due to airfield congestion (e.g. a pilot making a faulty landing because of the need for speed in avoiding congestion). The accident rate per hundred landings and take-offs was obtained for a number of days corresponding to very slight, medium, and intense activity. It was found that the accident rates thus computed were substantially similar, except for days of very slight activity when it was higher. This was to be expected since such days generally arose in bad weather conditions. The O.R.S. concluded that high-intensity operation of an airfield did not lead to an undue psychological pressure on pilots' minds resulting in a rise in the incidence of accidents.

OPERATIONAL RESEARCH IN SOUTH-EAST ASIA COMMAND

The creation of a Supreme Allied Commander, South-east Asia, Admiral Lord Louis Mountbatten, on 15 November 1943, and the subsequent divergence of the R.A.F. from the control of the Commander-in-Chief India forecast a more aggressive phase in the war against Japan. A more efficient system of control followed a month later when the British and U.S. Air Forces were integrated in one command under an Air Commander-in-Chief, Air Chief Marshal Sir Richard Peirce. South-east Asia Command, however, still ranked on a low priority both for men and equipment, particularly as the attention of those responsible for the conduct of the war was fixed upon imminent operations in North-west Europe. The low status in priority was nowhere more apparent than in the sphere of operational research.

Little more than a month had elapsed since his arrival at New Delhi when Admiral Mountbatten began to demand scientists from the British Chiefs of Staff in order to form an O.R.S. at his headquarters which would not only co-ordinate the researches of the naval, air and army scientific sections, but would assist in the planning of amphibious operations which were to be a predominant feature of Far-Eastern strategy. Admiral Mountbatten was anxious to gain the services of Professors Zuckerman and Bernal, who, as already noted, had served on his staff at Headquarters Combined Operations. The transfer of these scientists, the former then engaged in advising on preparatory air operations for Overlord, and the latter acting as Adviser to Headquarters Combined Operations, to the Far East was strongly opposed by the Chiefs of Staff and eventually, in February 1944, Dr. T. W. J. Taylor, then Director of the British Central Scientific Office in Washington, was appointed Scientific Adviser to the Supreme Allied Commander, although he had had no previous experience of operational research. He had, however, while in America, gained a knowledge of the specialist supplies and weapons which would be of value to South-east Asia Command. This decision only partially satisfied Admiral Mountbatten and he continued to agitate for a small, permanent scientific staff representing the three Services who would deal with problems related to combined operations and naval-air matters. His views were supported by Professor A. V. Hill, then in New Delhi at the invitation of the Government of India, and who for a time interpreted for the Chiefs of Staff the requirements for scientific research in South-east Asia Command. The Chiefs of Staff were unable to approve, giving as their reason the lack of scientists with experience in that type of research, and they suggested instead that each of the Service O.R.S.s in South-east Asia Command should include two scientists of high standing, one of whom would act as adviser to the Supreme Commander. They recognised that it was unlikely that experienced scientists could be provided until the end of the German war.

Admiral Mountbatten therefore had to be content with Dr. Taylor and one scientist representing the Army at his own headquarters and the fairly strong O.R.S. at the neighbouring Headquarters Air Command South-east Asia. It was again suggested that a possible way of alleviating the acute shortage of operational research staff would be to recruit scientists from the Indian universities, but although Admiral Mountbatten had given his consent, provided these men first received initial training in Great Britain, the scheme did not materialise. It was not until January 1945 that an assistant was provided for Dr. Taylor in the person of Dr. T. F. Gaskell who until then had been attached to Combined Operations Headquarters in London.

As for the other two Services, the Army had formed an O.R.S. in India in July 1943 while a second section worked in the field in Burma in the autumn of 1944. The Research Directorate at General Headquarters New Delhi was transferred to Headquarters Eleventh Army Group where it supervised the work of the army operational researchers who were chiefly engaged in studying the reactions of men and equipment in jungle conditions. There was no comparable naval operational research team, an omission which seems all the more extraordinary considering the important role assigned to naval forces in this theatre. A scientist, Dr. Lindsay, was, however, attached to the Headquarters Eastern Fleet with whom the operational researchers in No. 222 Group maintained contact.

Parallel to the operational research organisation in the R.A.F., an operations analysis section was formed at the headquarters of the Commanding General U.S.A.A.F. India-Burma, General G. E. Stratemeyer. Its terms of reference were similar to those of the O.R.S. and included bombing accuracy, battle damage to aircraft, bomb selection and fusing, air cargo and troop movements, target and aiming point selection, etc. As General Stratemeyer also commanded the Eastern Air Command (composed of the British 3rd Tactical Air Force and the Strategic Air Force which was an Anglo-U.S. force) three members of the section were located at the headquarters of this Command at Calcutta. Shortage of staff did not permit the section to work for formations subordinate to this headquarters. It was therefore decided that any formation which required the services of operational research should send in a request to the heads both of the O.R.S. and the O.A.S. who were then to allocate the tasks as they thought fit. The other two members of the O.A.S. dealt with problems relating to the U.S.A.A.F.'s operations from China and air transport over the 'Hump' from India to China. These were commitments outside the province of Headquarters South-east Asia Command. A full integration of the British and American sections was therefore considered to be undesirable. However the closest co-operation was maintained as far as was consistent with the great distances between headquarters in this theatre.

ORGANISATION AND DEVELOPMENT OF O.R.S. AIR COMMAND SOUTH-EAST ASIA

A little more than two months after the O.R.S. had been absorbed into Air Command South-east Asia Mr. (Honorary Wing Commander) Kendrew, an early exponent of operational research at Coastal Command and in the Middle East, and who had been originally intended to lead the O.R.S. in India, took over its command from Mr. Cole. The latter was required to return home for further service with Air Defence of Great Britain. Being the farthest away from home of the operational research sections, its development was inevitably handicapped by shortage of staff and, moreover, the unfamiliarity of members of the O.R.S. with Service procedure in asking for requirements and dealing with matters of overseas allowances, etc., involved a good deal of time being wasted in unprofitable paper work. However, due to the efforts of the head of the section and to the good offices of Professor A. V. Hill, four additional scientific officers arrived from Great Britain early in 1944, in addition to Mr. Kendrew. By the middle of the year, serving under the head of the section were six senior scientific officers, two scientific officers and three junior scientific officers. Four R.A.F. officers were temporarily attached to the section together with six N.C.O.s. Mr. Kendrew also acted as Scientific Adviser to the Allied Air Commander-in-Chief which enabled him to deal with general problems such as operational requirements, liaison with outside operational research organisations and with the Air Ministry and M.A.P., while he also collaborated with the Scientific Adviser to the Supreme Commander and liaised with the planning and intelligence staffs at the latter's headquarters.

Like the sections in other theatres of war, the O.R.S. was located in the Air Staff Branch of headquarters and was responsible to the Senior Air Staff Officer. The main headquarters of Air Command South-east Asia remained at New Delhi until October when it moved to Kandy, Ceylon, the site of Admiral Mountbatten's headquarters. The headquarters of the O.R.S. moved with it. There were five major commitments of the O.R.S. in the following subjects: radar and air defence, bombing problems, tactical air force problems, sea reconnaissance and strike problems, air transport, supply dropping, and forward planning. The section was organised to deal with these problems in the following manner. The officer-in-charge of the section remained at air headquarters with two or more assistants, when he was not visiting the widely scattered subsections of the O.R.S. The remainder of the staff were attached to the various groups in the field, ranging from Manipur and Bengal in eastern India to Ceylon. Three officers were attached to the Headquarters 3rd Tactical Air Force at Comilla and two officers each to the two fighter/fighter bomber groups operating in Manipur and Arakan, Nos. 221 and 224 Groups respectively. One officer worked with No. 293 Wing (day and night fighters) which was responsible for the air defence of the Calcutta area. Two officers were attached to the Strategic Air Force, consisting of British and U.S. heavy bomber units which were engaged in attacking communications, industrial and naval targets. At Colombo, headquarters of No. 222 Group, responsible for general reconnaissance at sea over a vast area stretching from the coast of East Africa to the Persian Gulf and the Bay of Bengal, were two scientific officers, both of whom had had valuable experience of anti-submarine warfare in Coastal Command. The O.R.S. was also represented at the Headquarters of No. 229 (Transport) Group.

There were many problems in South-east Asia awaiting the attention of the O.R.S., many of them unlike anything tackled by operational researchers elsewhere. Mr. Kendrew soon realised that an efficient and responsible staff was essential since each individual would frequently have to take decisions on his own, on account of the difficulties of communication and the wide distances between headquarters and the front. Furthermore current operations in the Far East were becoming increasingly offensive and swiftly moving. For this reason competent and independent scientific advice was required rather than the routine analysis of past operations. He wanted to begin at once studies in the field of forward planning for the campaign of 1944 in order that the lessons learned might be applied to the major, and it was hoped decisive, operations of 1945.

Mr. Kendrew did not, however, stay long enough to see the concluding stages of the war against Japan. He was recalled to Great Britain early in March 1945 to act as liaison officer for South-east Asia Command on the staff of the Scientific Adviser to the Air Ministry and was replaced by Mr. (Honorary Group Captain) G. A. Roberts, another pioneer of operational research, who arrived in Kandy from Headquarters Bomber Command in February. Mr. Roberts spent much of his time representing the Air Commander-in-Chief in London and while he was absent the section was led by Mr. A. F. Wilkins, former head of O.R.S. Fighter Command, who had volunteered for service in South-east Asia.

At the beginning of the final stage of the Japanese war O.R.S. Air Command South-east Asia was composed of some 15 civilian scientists and seven Service officers. They were distributed as follows: Group Captain Roberts was assisted by one scientist and three Service officers at Headquarters Air Command South-east Asia. A scientist was attached to Headquarters No. 222 Group concerned with maritime operations. At Headquarters Eastern Air Command (formerly 3rd Tactical Air Force) were two scientists and a Service officer working on radar and allied problems while an officer each was attached to its subsidiary formations, Nos. 221 and 224 Groups and the Strategic Air Force (of which No. 231 Group was the R.A.F. component), who concerned themselves with problems connected with radar cover, fighter control, bombing accuracy and bombing effectiveness. Close support by the air forces was the responsibility of a team of four officers known as the Weapons Effectiveness Detachment under

Mr. (Honorary Squadron Leader) J. W. Vernon. Finally, three O.R.S. officers specialising in Planned Flying and Planned Maintenance were attached to Base Air Forces, South-east Asia. O.R.S. officers on occasion worked on incidental problems, for example, the scientists at Headquarters Strategic Air Force made suggestions for the reorganisation of the reception facilities for B.O.A.C. passengers at Calcutta and the motor transport section at Headquarters No. 231 Group was saved about two hours' daily clerical work by improvements in office routine.

The services of the O.R.S. were still required after the sudden end to the war in the Far East and Mr. (Honorary Wing Commander) F. J. Prewett, who succeeded Mr. A. F. Wilkins, was in charge of the section, now redesignated Research Branch Air Command South-east Asia, until shortly before it was disbanded late in 1946.

The work of the O.R.S. in the final stage of the war must now be examined in more detail.

RADAR PROBLEMS

As in 1943, radar and radio matters occupied a large proportion of the O.R.S.'s time. The extensive eastern frontier of India, the air defence of which was the responsibility of 3rd Tactical Air Force, provided a number of problems, not the least of which was the training of the personnel manning the radar posts and serving in the Mobile Wireless Observer Companies. A thorough study was made of the various processes of the reporting system; an analysis was made of plotting speeds achieved in practice at various types of radar station and also of the accuracy of radar heights while research continued on anomalous propagation. Several training manuals were produced by the O.R.S., including one describing in humorous language a new method for the rapid preparation of vertical polar diagrams under the title 'Polar Diagrams while you wait'.

In connection with anomalous propagation, or super-refraction, Mr. Barkla accompanied Dr. H. G. Booker of T.R.E., who was making a study of its effects in the lower atmosphere in India, on a tour of inspection of meteorological stations in southern India, Ceylon, and New Delhi. An investigation was also made into the Japanese early warning system with the object of locating gaps in the cover through which the American long-range ground-attack Lightnings might be routed.

Mr. E. J. Smith, who, as mentioned earlier, was a pioneer of airborne radar in Fighter Command, arrived in India for a two months' visit early in 1944 to make a general survey of aircraft interception. He spent some time with No. 1577 Flight which was then experimenting with the H2S equipment in the Far Eastern theatre and made a report on the trials. He visited a number of squadrons using aircraft interception equipment and A.S.V. (both one and a half metre and centimetric types) and in most cases gave lectures to aircrew both on existing and future equipment.

An examination was made of the incidence of corruption in signals traffic at the Signals Branch of Headquarters Air Command South-east Asia and a report was issued. The work was directed in the initial stages by Mr. I. H. Cole and was concluded under the supervision of Mr. Kendrew.

STUDY OF COASTAL OPERATIONS BY NO. 222 GROUP

Early in the summer of 1944 the Headquarters of No. 222 Group undertook the co-ordination of all general reconnaissance operations in the Indian Ocean. To this end a special staff under the Deputy to the Air Officer Commanding No. 222 Group was appointed which would be free from the internal work of the Group, and in order to avoid confusion with the Group staff, the new organisation became known as IOGROPS, an abbreviation for Indian Ocean General Reconnaissance Operations. Liaison was maintained with Headquarters Eastern Fleet, also situated at Colombo. Mr. H. D. Poole and Mr. A. J. Brooke were attached to IOGROPS. Initial work included reports on the performance of A.S.V., the value of anti-shipping sweeps south of Ceylon based on an analysis of shipping densities and sinkings in the area. Their recommendations led to appropriate operations being initiated. They also made a detailed study of shipping, U-boat and air effort in the Indian Ocean with the object of assessing the efficiency of the latter. They rewrote the Indian Ocean Tactical Instruction on the subject of U-boat hunts in collaboration with the Tactics and Navigation Branch. Studies were made of air escort to convoys and, in particular, they assessed the number of unnecessary hours flown in escorting less important convoys in unthreatened areas. Figures for day and night convoy escort patrols were produced and were accepted by the Royal Navy as standard. Finally, the two members of the O.R.S. contributed articles on topical items of operational research to the IOGROPS *Quarterly Review.*

PROBLEMS OF THE STRATEGIC AIR FORCE

Operational research began in the Strategic Air Force when two scientists from O.R.S. Air Command South-east Asia were attached to its headquarters at Calcutta in June 1944 in order to assist the Air Staff in the planning of operations. Their advice was based either on the application of scientific principles to the problems in hand or on the result of the statistical analyses of operations previously carried out by the Strategic Air Force. They also propagated the lessons derived from the findings of other O.R.S.s in different parts of the world.

This detachment was principally concerned with the operations of No. 231 Group (the other two groups in the force were American Liberators and Mitchells) composed of Wellingtons and Liberators but work was also carried out with the Americans. Early reports included studies of the fuel consumption of Liberators and the bridge bombing technique of No. 490 Mitchell Squadron U.S.A.A.F. Training programmes were prepared for the R.A.F. Liberator squadrons which had changed over from night flying to a day bombing role.

Other work performed by this subsection included a study of the ammunition requirements of Liberators operating at night; tables giving pre-set dropping angles and time delays for target marking; a report on the advantages of removing camouflage paint from the Liberators enabling them to carry a heavier bomb load and to fly farther; illustrated calculations of force requirements for a particular target; a comparison between R.A.F. and U.S.A.A.F. bomb loads which purported to show that the former carried a greater bomb load to nearby targets while the latter carried greater loads to the more distant targets; finally, a detailed analysis was made, in collaboration with the Navigation Section, of navigation logs to discover the relation between final and cumulative errors. The subsection also prepared articles on operational research for No. 231 Group Navigation Bulletin.

In July 1944 Dr. A. F. Munro arrived in India to assist in the introduction of night vision training to the Command on the same lines as the work he had done in R.A.F. Bomber Command and in the Middle East. This entailed a good deal of time being spent in making up a training syllabus at the Headquarters of the Strategic Air Force and at No. 3 Refresher Flying Training Unit at Poona. Dr. Munro also studied the subject of acclimatisation and deterioration of personnel under extreme conditions of climate. This involved measurement of basic metabolic rate and other constants for personnel who had spent varying lengths of time in the country. Studies were made at certain transit camps through which new arrivals and tour-expired personnel passed.

AIR SUPPORT TO THE FOURTEENTH ARMY

Problems relating to air support had hitherto been dealt with by the O.R.S. officers attached to No. 221 Group operating in support of the Fourteenth Army. Mr. G. W. R. Fielden was also attached to No. 10 Army Operational Research Group to cover all aspects of air support to the Army including tactical support and air supply. At the end of March 1945, as a result of the increasing volume of air support to the Fourteenth Army in Burma, the Weapon Effectiveness Detachment was formed by the O.R.S. at Headquarters No. 221 Group. The task of this team was to assess the effectiveness of R.A.F. weapons used in close support of the Army and the general usefulness of close support for the purpose of advising on the planning of future attacks. Japanese positions were examined, after capture by the ground forces, by officers of the Weapons Effectiveness Detachment operating with advanced elements of the Army.

Various close support trials such as, for instance, the dropping of bombs on bunkers and trench systems, static detonations and strafing trials were carried out at the Jungle Targets Research Unit which was established by Mr. J. W. Vernon at Gauhati in Assam late in 1944. An officer of the O.R.S. was permanently attached to this unit to act as scientific adviser to the weapons trials held there.

Another member of the Weapons Effectiveness Detachment became attached to the R.A.F. Airborne Commando (later renamed Airborne Control Unit). This was formed in June 1945 to organise and co-ordinate all the Visual Control Posts[1] working with advanced elements of the ground forces as well as with airborne troops and clandestine forces penentrating far behind the enemy lines. The officer concerned, Mr. (Honorary Flight Lieutenant) R. de P. Daubeney, underwent a course of training in parachute jumping and the control of aircraft by the V.C.P. system before joining the unit. His task was to study the efficiency of the V.C.P., in particular the rapid transmission of information, and to make out reports of individual attacks directed by the V.C.P. containing all available information on damage done and the accuracy and success of the operation. The unexpected surrender of the Japanese, however, precluded the need for the extensive airborne and clandestine operations that had been planned.

At the end of the Burma campaign which culminated in the capture of Rangoon, the Weapons Effectiveness Detachment made a study of offensive air action in support of the Fourteenth Army. The general conclusions were that air support played an important part in the campaign, possibly being felt by the enemy more when he was being attacked in rest areas or on the line of communication than when he was ensconced in a well protected bunker. The O.R.S. was careful to qualify this statement by pointing out that other factors such as the collapse of the Japanese attack on India, the imminence of the end of hostilities in Europe and the effect of other types of air operations (including strategic) were also factors in causing a collapse of morale.

Recommendations by the O.R.S. included the statement that more care should be given to the planning of air attacks on enemy positions and that a distinction should be made between a harassing attack and an attack designed to destroy an enemy position. It was also better to make one concentrated attack in a certain quarter than to weaken the air effort by making a number of attacks using smaller quantities of aircraft. More use could have been made of incendiary bombs when attacks were made against positions in Burmese villages. The Army should ensure that positions intended for attack would be occupied by the enemy at the time of attack and that they should easily be distinguished from the air. Troops must be ready to follow in swiftly on the conclusion of an air attack. Finally, in view of the valuable work done by the Visual Control Posts, this

[1] Small parties of R.A.F. officers and radio operators with a jeep who controlled air attacks on targets requested by the Army.

system of inter-communication between ground and air should be developed to make attacks in support of the ground forces more deadly and records should be kept of the damage achieved on each attack.

AIR TRANSPORT

Mr. G. M. Lawrence was attached to No. 229 (Transport) Group (equipped with Dakotas) to act as general statistical adviser and compiler of analytical reports. His first report recommended a number of changes in organisation, but he was recalled to Great Britain just as his work was bearing fruit and caused operational research in that Group to come to a standstill. After a short period, however, the work was continued when a Planned Flying and Planned Maintenance Section began work at Base Air Forces, South-east Asia.

OPERATIONAL RESEARCH IN THE SOUTH-WEST PACIFIC AREA

Before leaving the war against the Japanese a brief account must be given of operational research in the South-west Pacific area. Here Royal Australian Air Force Command was engaged on offensive operations against the Japanese forward bases over an area stretching from the Solomon Islands to New Guinea and the Netherlands East Indies and, secondly, in maritime reconnaissance and protection of shipping in that area and around the Australian coast line. These tasks involved flying over vast stretches of sea and over territory which were not as accurately mapped as were the European theatres of war. They involved problems which, together with that of finding the best way to destroy the particularly tough Japanese bunkers and other defences in eastern New Guinea where the Australian Army was fighting, provided much fresh material for an operational research section to work on.

An O.R.S. was formed at R.A.A.F. Headquarters at Melbourne in February 1944, its officer-in-charge being Dr. (Honorary Wing Commander) J. C. Bower who, it will be recalled, was previously head of the O.R.S. at Headquarters R.A.F. Middle East. In addition to the small section at Melbourne which was mainly administrative in character, two subsections were formed, one at R.A.A.F. Command Headquarters at Brisbane which controlled operations by R.A.A.F. units over land and sea, to study operational problems relevant to the Command and to analyse operational records, while the second was attached to No. 9 (Operational) Group (R.A.A.F.) which had been supporting operations by the Australian Army in the Milne Bay-Goodenough Island region, to deal with problems arising out of air operations in New Guinea.

The section's first report was produced in April 1944 and was a review of bombing accuracy, collating the lessons learned in the European and Mediterranean theatres of war. Further reports were issued which dealt with the operational accuracy of astro-fixes; delays in priority signals traffic from the R.A.A.F. Command W/T station; the comparative efficiency of incendiary and high explosive bombs against targets in the South-west Pacific area which demonstrated that there were many targets against which incendiary attack could be profitably used; the effectiveness of bomber missions in which comparisons of the results achieved by different classes of aircraft showed that the effect of adverse weather was an important factor; and an analysis of times taken by priority cypher signal from R.A.A.F. Command Headquarters to various areas.

Meanwhile, at the end of October 1944, the First Tactical Air Force, R.A.A.F., composed largely of Beaufighters and Kittyhawks, had been formed under the Commanding General XIIIth U.S. Air Force and it moved to Morotai Island in preparation for operations against Japanese-occupied Borneo. A visit was paid by Dr. Bower to the Headquarters of the First Tactical Air Force in November, to which shortly afterwards a subsection of the O.R.S. was attached. The initial programme of operational research at this headquarters included investigations on planned flying and planned maintenance, the operational employment and usefulness of rocket projectiles, investigations into the causes of the high casualty rate among aircrew in particular relation to fighter aircraft (it had already been shown that the casualty rate was considerably higher during the first ten sorties of an operational tour) and efficiency in employment of I.F.F. The O.R.S. was also interested in the camouflage of aircraft. Kittyhawks engaged in low level strafing and bombing had been camouflaged with drab colours which was effective as aircraft used to approach their target against a background of treetops and often against a dark cumulus cloud formation. It had, however, been noted that the white leading edge to the wings greatly diminished the value of the camouflage.

During the first six months of 1945 when the R.A.A.F. was carrying out preparatory operations for landings at Brunei and Balikpapan in Borneo, the O.R.S. produced a number of reports. Among these was an analysis of mission failures including strikes, mining operations, searches, armed reconnaissances and photographic reconnaissances. The report showed that 49 per cent of the abortive sorties were attributed to bad weather conditions. Other reports included an analysis of failures to release bombs and mines from Liberators and Catalina aircraft; mechanical and bomb release failures in fighter bombers and bomb detonation failures; casualties received from Japanese anti-aircraft gun fire and an analysis of the expectation of error in High Frequency Direction Finding position lines. An analysis of attacks carried out by Beaufighters using rocket projectiles indicated that while these weapons could be usefully employed against anti-aircraft gun positions as diversionary tactics in support of the main bombing or strafing attack, suitable targets were limited and the O.R.S. held the opinion that rocket projectiles could only play a minor part in operations in the South-west Pacific area.

Headquarters R.A.A.F. Command was anxious to obtain information about operations in South-east Asia Command and it was arranged that Mr. Kendrew, on relinquishing his post at O.R.S. Air Command South-east Asia, should visit Australia and the South-west Pacific area on his way back to Great Britain. A useful exchange of information concerning anti-shipping operations and the effect of air weapons against Japanese defences was made.

CHAPTER IX

The Value of Operational Research in the War and its Future

SCOPE OF OPERATIONAL RESEARCH IN THE SECOND WORLD WAR

An outline of the organisation and work of the principal operational research sections in the R.A.F. at home and overseas has now been drawn. In the latter stages of the war operational research proliferated and it has not been possible to describe the work of some of the smaller offshoots of the organisation as, for example, the units devoted to research into man-power problems. Nor has any attempt been made, apart from a brief description of the O.R.S.s in the Royal Australian Air Force and the Royal Canadian Air Force,[1] to describe the setting up of operational research sections in the Dominions Air Forces. The development of operational research in the U.S.A.A.F. and U.S. Navy, it has been seen, was also inspired to a very large extent by the example of the close collaboration of British scientists and the Services.

At the beginning of the war each of the Services had its own scientific research departments and laboratories, such as the Royal Aircraft Establishment at Farnborough and the Admiralty Research Laboratory at Teddington. The procedure for obtaining technical information and equipment was for the executive military staff to state their requirements in new devices and weapons, and these were passed by the Ministry concerned to the appropriate research establishments. The formation of operational research sections at R.A.F. command headquarters enabled the scientists to see for the first time at close quarters how technical equipment such as radar worked under operational conditions and they were able to point out possibilities which the military executive was not scientifically equipped to see.

From the study of equipment it was but a short step to the study of the efficiency of the individuals operating the aircraft, equipment and weapons. This, in turn, led to the analysis by the scientists of tactics, both our own and those of the enemy. Finally, in order to gain the best results and to make the best use of our available resources, it was necessary for operational research sections to scrutinise the working and efficiency of individuals and the system into which they fitted.

Throughout the war scientists were at a premium on account of their scarcity and the operational research sections never increased in size like

[1] For a note on the O.R.S. R.C.A.F., see pp. 183-184.

many other war-time organisations.[1] The pioneers of operational research amounted to a handful of men such as Professors P. M. S. Blackett and E. J. Williams together with G. A. Roberts, E. C. Williams, H. Larnder, B. G. Dickins, J. C. Kendrew and A. F. Wilkins, who initiated operational research in the various commands at home and abroad. While some of the most outstanding men of science in the country were associated with operational research such as Sir Henry Tizard and Professors Bernal and Zuckerman (and it was at this level that much of the most original thought took place), equally valuable work in the sections was done by men such as Larnder and Dickins, who, in addition to their scientific ability, were practical men, able to work with and advise R.A.F. officers on day-to-day problems concerning current operations. As the system for gathering data became more comprehensive the operational research sections were called upon, not only for new and far-reaching ideas, but for small items of advice or information on tactics or a type of equipment. There was, as will be discussed shortly, a danger of original work being swamped by routine activities.

CHARACTERISTICS OF THE OPERATIONAL RESEARCH SCIENTIST

Many of the rank and file of operational research scientists were men who had not then achieved academic eminence. But this was not among the five essential characteristics of a good operational research worker. Some kind of scientific or numerical training was, of course, necessary, the most successful operational research scientists being engineers and physicists, but not all scientists were able to grasp the principles of operational research. In addition the following qualities were required: good inductive powers; a practical outlook; imagination and, lastly, the ability to secure the co-operation of others. Another characteristic was the versatility of many of the operational research scientists, especially in the earlier stages of the war. 'The complete disregard for frontiers between the different subjects', wrote Dr. Gordon after the war, 'and the readiness to accept any problems as within their terms of reference has been a refreshing contrast to the rigid specialisation that has developed in all other branches of science. The operational research sections have recaptured the atmosphere of the period of the foundation of the Royal Society.'

In the research sections attached to overseas commands where communications were difficult and distances between command headquarters and groups considerable, experienced men were essential as they had to take decisions on their own initiative. Moreover, on account of the composite nature of overseas commands which were responsible for air defence, long-range bomber and coastal operations alike, each scientist in a section

[1] At the end of March 1945 there were 200 scientific officers engaged on operational research in home and overseas commands.

tended to specialise and there were never enough men available to afford the presence of 'passengers'.

It was emphasised by several officers in charge of sections after the war that scientists should not be allowed to become stale by remaining for too long a time in a section. The pioneers of operational research, originating in O.R.S. Fighter Command, were constantly on the move from one theatre of war to another. On the other hand, in other home commands, scientists frequently preserved the thread of continuity at an operational headquarters as Service officers were rarely on the operations staff of one command for longer than a year. In Bomber and Coastal Commands it would have been unwise to remove scientists in key positions. So, for instance, Dr. Dickins remained Scientific Adviser to Air Chief Marshal Sir Arthur Harris throughout the period of the latter's appointment as Commander-in-Chief Bomber Command, and scientists such as Professor J. H. Orton, E. C. Baughan and J. R. Vezey remained at Headquarters Coastal Command working on problems relating to the U-boat campaign. In fact, the work of several scientists who remained in the same section throughout the war, far from becoming stale, improved as new problems arose. In respect of overseas sections the return of repatriated scientists kept home research establishments informed about conditions in the various theatres of war.

Experience of flying was not essential, but in certain cases experience of certain branches of flying was required. Several officers took the normal courses in navigation and one trained as a radar operator in a night fighter. Scientists occasionally flew on operations. Very few had previously seen service in the R.A.F. and it was a frequent cause for complaint that, in view of the scarcity of scientists, not enough effort was made to recruit tour-expired aircrew with academic qualifications. Their experience allied to scientific capabilities would have been invaluable. One officer in O.R.S. Fighter Command (Squadron Leader S. C. Davies) did, in fact, have the benefit of operational experience. He had been engaged on Government aerodynamic research in Australia before the war and had also worked at Farnborough; after serving as a pilot in Wellingtons in the Middle East, where he was awarded the D.F.C., he was transferred to operational research. He ended the war serving with O.R.S. R.A.A.F. in New Guinea.

STATUS OF THE OPERATIONAL RESEARCH SCIENTIST

It has been stressed that the impartiality of the scientist was preserved by his civilian status, but this view was not held universally. The officer-in-charge of O.R.S. Fighter Command declared that senior officers were usually prepared to listen to and even be advised by the expert who knew his job. Thus the absorption of scientists into the Service would have solved the problems of pay, allowances, use of transport, compensation for injuries received on active service, etc., which frequently provided headaches for those administering research sections. While on duty overseas operational research officers were granted honorary commissions. The consensus of opinion was that the wearing of uniform overseas facilitated movement, particularly in the battle area, while in countries like Egypt and India there was no precedent at that time for a professional officer class in civilian clothes, and there was always the eventuality of being taken prisoner of war. A dissenting view of this matter came from the officer-in-charge of O.R.S. M.A.A.F. who held that uniform did not confer any of the privileges or safeguards that were supposed to adhere to those in possession of it, while it made it more difficult for the scientist to approach other ranks on terms of equality. He concluded that it was a matter of principle that the research worker should always be a civilian and don uniform only when it was essential.

The question of rank was a vexatious one, particularly as research sections operated at command or group headquarters, and it often happened that scientific officers were junior in rank to the staff officers whom they advised. In home commands the head of a section normally held the rank of Principal Scientific Officer which was equivalent to the rank of Wing Commander.[1] He was therefore technically junior to the heads of branches of the air staff. Some compensation was gained by the fact that, in addition to being officer-in-charge of the section, he was titled Scientific Adviser to the Air Officer Commanding-in-Chief and had the privilege of direct access whenever he required it. Most scientists engaged on operational research believed that their ranks and those of their opposite numbers on the air staff should be synonymous.

Although the operational research scientist was jealous of preserving his civilian identity, his proximity to headquarters, particularly in an overseas theatre where he wore uniform, made it incumbent upon him to observe military discipline. Lack of knowledge in elementary military etiquette was likely to provoke hostility to the presence of scientists and a short course of training was deemed necessary. Discipline within the section was another matter and here it was largely self-imposed, the overriding purpose being to complete the task in hand. As far as can be ascertained civilians were rarely, if ever, recruited into operational research sections overseas.

STATUS OF AN OPERATIONAL RESEARCH SECTION

In his early paper defining the nature of operational research Professor Blackett had emphasised the importance of the section being integrated within the air staff. At home recognition came fairly easily but this was not so overseas, and it was felt that more could have been done by the Air Ministry, particularly in the Mediterranean theatre, to define the nature

[1] In the final stage of the war heads of sections were promoted to Superintendent and held the honorary rank of Group Captain.

and purpose of an operational research section and to draw up an establishment. Good relations between scientists and staff officers depended to a large extent on the attitude taken towards operational research by the Air Officer Commanding-in-Chief. O.R.S. Coastal Command, for instance, was linked more closely to the operational branches of its headquarters than several other sections as, for example, the O.R.S. at Headquarters Fighter Command. The Commander-in-Chief of Bomber Command also drew heavily upon the advice of his scientific officers. 'The attachment to the Command of scientists and technicians for short periods', he wrote, 'can never prove as satisfactory as when scientific officers share the life of the Command and have an understanding of its problems.' This was proved when the O.R.S. of Fighter Command was moved from Stanmore to Garston, near Watford, for a short period in 1943. Being separated from the operations and intelligence branches, its work soon fell below standard. The section was later reabsorbed into the Headquarters of Air Defence Great Britain.

Representation of the research section at staff meetings was most necessary and initially was sometimes overlooked. In the early days at Headquarters Coastal Command liaison between air staff and scientists was sometimes spasmodic. Thus the decision to proceed with the development of the 600-pound bomb as a substitute for the 250-pound depth charge was taken at a meeting at which the operational research section was not represented. This decision was almost certainly a mistake; if a substitute had been necessary, the 100-pound bomb would have been better. In practice neither was desirable as a replacement of the depth charge, which remained the best bomb-type weapon throughout the war.

Relations between the scientists and the R.A.F. staff officers with whom they worked were, on the whole, good. Reference will be made below to the generous tributes paid to the operational research sections by several of the leading air commanders. There were also a few officers who, like Air Vice-Marshal Bennett, took the view that scientists tended 'to have preconceived ideas and they then set out to prove these ideas regardless whether they were right or wrong. There is no doubt that when a scientist is determined to prove something, it is extremely difficult to prevent him.'[1] Although senior scientific officers were entrusted to positions where they could exercise a powerful influence on the direction of operations, they rarely, if ever, acted in any other than an advisory capacity, leaving the responsibility for taking decisions to the staff officer.

EXTERNAL RELATIONS OF OPERATIONAL RESEARCH SECTIONS

The lack of a central agency co-ordinating the efforts of the operational research sections was felt in the latter stages of the war. To quote from Sir Henry Tizard, writing in another context, 'the body (is) healthy enough.

[1] A.V.M. Donald Bennett, *Pathfinder*, p. 192, Muller 1958.

and its physiology is quite appropriate, including the many local motor centres. But it has no head to control its overall rate of activity and growth, to guide its effort in the right directions.'

Operational research was initiated at the command level, the officer-in-charge being responsible to the Commander-in-Chief. While in the early stages this situation had compensations in that it offered no danger of interfering with the above-mentioned relationship between commander and scientist, by the middle of 1943 the lack of co-ordination was beginning to be noticeable. There were certain problems, the work of planned flying and planned maintenance, to name one, where more unified direction of the work of command research sections would have been valuable. It should be mentioned here that Mr. R. S. Capon, the Deputy Director of Scientific Research (III) of the M.A.P., acted as a valuable liaison officer between the technical establishments and the research sections throughout the war. He also performed a valuable service in recruiting scientific staff.

It has been shown that close contacts were maintained between the operational research sections of the home commands and with scientists from the Dominions and the United States of America. Moreover, there were opportunities for senior scientists to exchange views when they sat on inter-Service committees such as the Prime Minister's U-boat and Night Air Defence Committees. During 1943 a few meetings of scientific advisers were held under the chairmanship of Sir Charles Darwin at the Royal Society, Burlington House, on a 'demi-official' basis, and in the last year of the war scientists met on the Joint Technical Warfare Committee.

Relations with T.R.E. were maintained satisfactorily, both on the personal level and in the invaluable T.R.E. 'Soviets'. The tendency for the research sections to act as a 'sales agency' for technical devices manufactured by T.R.E. was resisted. The research sections fulfilled admirably their function of interpreting operational requirements and occasionally took part in controversies with T.R.E. which were usually advantageous to the development of the equipment in question.

The liaison maintained with the operational research sections of other air forces noted above deserves closer examination. Through the agency of the Operational Research Centre (later Deputy Directorate of Science) contact was maintained with the Dominions Scientific Office in London. Through it, for example, arrangements were made for scientists of the operational research section of the Royal Canadian Air Force, under Professor J. O. Wilhelm, to be trained by O.R.S. Coastal Command.[1] A small number of Canadian scientists performed valuable work for this

[1] The O.R.S. in the R.C.A.F., formed in August 1942, consisted of an operational research centre under one officer at Air Force H.Q. Ottawa and small sections at Eastern and Western Air Commands based at Halifax and Vancouver. They dealt with such problems as the best methods of search for missing aircraft, methods of selecting air-crew, bombing and navigational training assessment, and the operation of coastal radar sets (History of the Defence Research Board of Canada by Captain D. J. Goodspeed, Chap. XI, p. 166).

section for periods of a year or longer, while serving at the same time as a pool for Canadian operational research. Canadian scientists were also attached to No. 6 (R.C.A.F.) Group of Bomber Command in the capacity of representatives from O.R.S. Bomber Command and as damage inspectors. Collaboration between British and U.S. scientists in all theatres of war was of the closest nature, as, for instance, the contacts between scientific officers of the U.S. Anti-Submarine Warfare Operational Research Group and O.R.S. Coastal Command, and between O.R.S. Bomber Command and the Operational Analysis Section of the American Strategic Bomber Force based in Great Britain.

DIRECTION OF WORK IN AN OPERATIONAL RESEARCH SECTION

The work of an operational research section, unless it was to be of little but academic value, had to fulfil the needs of the command to which it was attached. It had to be relevant to current problems so that action could be taken on the recommendations of its reports. Original thinking was necessary to act as a stimulus to the operations staff. One dangerous trap into which a section was prone to fall was for it to be regarded as a statistical section. A large proportion of its analytical work was based on statistics culled from *pro formas* designed in the first place by the research section. In order to keep the section on the lines of original research statistical duties had to be delegated to R.A.F. personnel or to special statistical sections as in Coastal Command. In O.R.S. Fighter Command, for example, the large amount of statistical work brought about an inflation of staff and dilution of scientific personnel so that the section tended to lose its best research characteristics. O.R.S. Bomber Command, on the other hand, set up a mechanised statistical system with Hollerith machinery which was run by a small subsection.

It should be unnecessary to add that the volume of the work of a research section must correspond to the development of the campaign with which it is concerned. A striking example of opportunities missed occurred in the Middle East where the operational research section at Headquarters R.A.F. Middle East Command was brought to its maximum strength *after* the Battle of El Alamein. It was, of course, during the preparatory period that air operations played such a critical and intensive part in the Western Desert Campaign.

One final aspect of the operational research section's work, to which perhaps insufficient attention has been paid, is that of education. Much time was given up to instructing aircrew or radar personnel in the use of new equipment and, in addition, a number of training manuals were written by research staff. This was an important, if unspectacular, activity, and again, one which could eventually be delegated to R.A.F. personnel.

COMPARISON WITH U.S. OPERATIONAL RESEARCH ORGANISATION

The organisation of operational research in the U.S. Armed Forces proceeded on lines parallel to our own, including the same desire to make use of civilians and to keep them as civilians, and to make each research section answerable to its Service chief. There were, however, a few differences between the two organisations. A minor difference was that the Americans preferred the term Operational Analysis to Operational Research. This was an advantage since O.A.S. and O.R.S. were at once distinguishable. Secondly, the two naval operational research sections, the Anti-Submarine Warfare Operational Research Group and the Mine Warfare Operational Research Group, were organised on a functional rather than on a Command basis, the anti-submarine group, for example, serving the U.S.A.A.F. as well as the U.S. Navy, and the co-operation it got from the former being at least as good as that from the latter, in spite of the fact that the group was organised under the U.S. Navy Department. Thirdly, the Americans recruited their research workers from a somewhat wider field than our own and included a number of business men and skilled lawyers. It was held that the lawyer who has in the past successfully worked with experts could master a new problem very quickly and rapidly prepare a case. Finally, there was a tendency for the operational research sections of the different Services to liaise even more closely than those attached to the British Services.

TRIBUTES FROM AIR COMMANDERS

Operational research in the R.A.F. was fortunate in that in its formative years it had the encouragement of a number of far-seeing senior air officers. Among those who paid tribute to the work of the sections were Air Chief Marshals Sir Arthur Harris, Sir Trafford Leigh-Mallory, Sir Sholto Douglas and Sir John Slessor, each of whom advocated continuance of operational research in peacetime. 'There is no doubt that the O.R.S. has been of great value during the war', wrote Sir Arthur Harris, 'and that there is a definite need for such an organisation in the peacetime air force', and elsewhere he wrote that the 'prosecution of a modern war without one would be unthinkable'. Sir John Slessor stated that he regarded operational research as 'absolutely essential in any modern air force in war or peace'. Furthermore, he wrote, 'the scientific approach, the habit of objective and analytical thought in which the scientist is brought up from the beginning of his training and which the professional warrior with his many other preoccupations cannot be expected to equal, can be as valuable in the sphere of tactics as in that of technique. In point of fact, of course, the two are inseparable these days. That does not mean, and no experienced operational research scientist would suggest, that the scientist can in any way replace the commander or staff officer. What has been called "strategy by slide rule" can never replace, though it can valuably supplement, the habit of strategic thought born of years of study and practical experience of war. Moreover, let us not forget that behind the machine stands a vital factor in any calculation, the man, whose human capacities and limitations, whose reactions to fear, fatigue and discomfort, it is the business and training of the professional officer to know. It is not, I think, a contradiction to state that the more complex and terrible become his weapons, the more important become the training and management of the man.'

PROPOSALS FOR THE DIRECTION OF SCIENTIFIC RESEARCH AND DEVELOPMENT IN THE SERVICES AND THE FUTURE OF OPERATIONAL RESEARCH

In conclusion, a brief survey must be made of the proposals drawn up for the direction of scientific effort and the future of operational research after the war. There have been frequent references throughout this monograph to the lack of co-ordination of the scientific effort in the Services, and in the latter stages of the war a good deal of thought went into devising a better system for the future. At the instance of the Lord President of the Council, at that time Sir John Anderson, a report was made by the eminent scientist, Sir Edward Appleton, which took into consideration all the research and development projects of the various Government departments. Sir Edward pointed out the lack of an agency which would adjust the priorities for research programmes according to the needs of current strategy. The Chiefs of Staff took action upon his report and instead of readapting the existing Joint Technical Warfare Committee which was more concerned with the 'user' aspect of scientific warfare rather than with the research and development side, they decided in February 1944 to appoint a Joint Committee on Research and Development Priorities on which were represented the three Services, Headquarters Combined Operations, the Ministries of Supply and Production, the Department of Scientific and Industrial Research and the Radio Board. The committee's terms of reference were threefold. It was to prepare directives for the approval of the Chiefs of Staff in the light of which research and development priorities could be assessed; secondly, it was to consider and settle questions of priority arising between projects for which different Ministries were responsible; finally, it was to resolve difficulties which arose from the allocation of scientific staff to the different Ministries.

Later that year, however, the scope of the Committee's work expanded so much, particularly in view of such developments in warfare as the flying bomb and the long range rocket, that it was decided by the Chiefs of Staff in March 1945 to reconstitute the committee by including in it the Deputy First Sea Lord, the Deputy Chief of Imperial General Staff and the Deputy Chief of Air Staff. Its new name was the Deputy Chiefs of Staff Committee.

Besides the duties mentioned above, the new committee was to proffer advice on questions submitted to it by the Chiefs of Staff regarding the organisation of science in the field of defence and, secondly, to observe scientific developments relating to warfare in foreign countries and to maintain liaison with the Dominions on scientific matters.

At the end of the war Sir Henry Tizard was invited by the Chiefs of Staff to write a paper on the direction of our scientific effort in the post-war period. In it Sir Henry stressed the increasingly technical nature of modern warfare, and while acknowledging the close link that had been forged between the scientists and the Services during the war years lamented the lack of central direction of the various research projects. He proposed that a permanent scientific adviser be appointed to the Government, served by a small planning staff, who would act as chairman to a more closely knit Deputy Chiefs of Staff Committee to guide and advise on scientific work in the Services. Having approved Sir Henry Tizard's recommendation, the Chiefs of Staff proceeded to appoint what was, in effect, a reconstituted Deputy Chiefs of Staff Committee to be known as the Committee on Defence Research Policy. Its two main functions were, firstly, to determine the objectives for defence research and the required total scale of effort in terms of men and money and to decide all questions of priority between the major projects and, secondly, to facilitate the interchange of views between the Services and the world of science. The composition of the committee was to be the same as that of the Deputy Chiefs of Staff Committee. The Scientific Adviser to the Government, who was, in addition, a member of the Scientific Advisory Committee to the Cabinet, was to preside over it.

In the meantime the Air Ministry and Ministry of Aircraft Production had been considering the future of operational research in the Royal Air Force. They also sounded the opinions of the heads of the operational research sections. There was no question of winding up the operational research organisation as its contribution to the increase of efficiency and economy in the use of air forces had been widely acknowledged. Establishments would, of course, be reduced in relation to the post-war size of the Royal Air Force. The future development of aeronautics would be increasingly rapid, bringing about a revolution in tactics. Operational research would provide a link between tactics and design enabling operational staffs to have a clear picture of the existing state of scientific and technical development. Conversely, operational research would enable design staffs to be provided with information on the behaviour and use of equipment in the Service and the development of tactics. Operational research sections would be concerned in the future, as they were during the war, with the analysis of operations and exercises which would provide commands with a means of assessing the efficiency of weapons and techniques; they would advise on the planning of operations and the tactical development of aircraft, weapons and equipment; they would assist in formulating the command's requirements for the above; they would carry out both the quantitative study of strategical problems and research into historical records in addition to studying intelligence gained from foreign powers; finally, their members would give lectures on the technique of operational research to staff officers.

The recruitment of staff was also considered and various measures were suggested to alleviate such limiting factors as secrecy and the lack of opportunity to do original research, unavoidable when working with the Services, in order to attract the best scientific minds. It was also hoped to prevent the hiatus in scientists, which was such a handicap to the growth of operational research, by creating a reserve of scientific officers who would be recalled to the operational research organisation on the outbreak of war. But the ever-increasing complexity of techniques and equipment, together with other factors, the discussion of which lie outside the scope of this monograph, made the envisaged interchange of scientists between universities and military and civil departments to a large extent impractical, and so, for some years to come, the chief exponents of operational research were those who had acquired their skill during its evolution in the Second World War.

APPENDIX 1

Scientists at the Operational Level

A note prepared by Professor P. M. S. Blackett, F.R.S., in 1941

1. The object of having scientists in close touch with operations is to enable operational staffs to obtain scientific advice on those matters which are not handled by the Service technical establishments.

Operational staffs provide the scientists with the operational outlook and data. The scientists apply scientific methods of analysis to these data, and are thus able to give useful advice.

The main field of their activity is clearly the analysis of actual operations, using as data the material to be found in an operation room, e.g., all signals, track charts, combat reports, meteorological information, etc.

It will be noted that these data are not, and on secrecy grounds, cannot, in general, be made available to the technical establishments. Thus, such scientific analysis, if done at all, must be done in or near operation rooms.

The work of an Operational Research Section should be carried out at Commands, Groups, Stations or Squadrons as circumstances dictate.

2. SCIENTIFIC ANALYSIS OF OPERATIONS

To what extent is it useful to do analysis of operations in a more scientific manner than is done normally by Service specialist officers?

Experience over many parts of our war efforts has shown that such analysis can be of the utmost value, and the lack of such analysis can be disastrous. Probably the main reason why this is so, is that very many war operations involve considerations with which scientists are specially trained to compete, and in which serving officers are in general not trained. This is especially the case with all those aspects of operations into which probability considerations and the theory of errors enter. Serving officers of the highest calibre are necessarily employed in important executive posts, and are, therefore, not available for detailed analytic work.

Schedule of Typical Operational Research

The records of some war operation (e.g. air attacks on U-boats for the previous six months) are taken as the data. This is analysed as quantitatively as possible, and the results achieved are 'explained' in the scientific sense, i.e. brought into numerical relation with the other operational facts and the known performance of the weapons used. When this has been done, consideration is given to possible modification of the tactics to improve the operational results.

The first step—that of collecting the actual data—is by itself of enormous importance, for it is not uncommon for operational staffs to be unacquainted with what is actually being achieved. An Operational Research Section is not in general concerned with 'hot news', though they should be prepared to so concern themselves if specifically requested to do so.

On the Validity of Deductions from Observations

A typical problem is as follows: a weapon A is calculated by a service technical department to be 50 per cent more efficient than a weapon B. Actual operations over a given period show, say, two successes for A and four for B. Does this prove that B is a better weapon than A?

Such points arise continually and require the highest scientific judgement to resolve. In particular a grasp of fluctuation phenomena (i.e. Poisson's Distribution) is required. If the average number of hits on some target in a given time is m, then (on certain assumptions) the chance that exactly x hits will be obtained in the same time is

$$\frac{e^{-m}m^x}{x!}$$

Value of Scientific Confidence and Numerical Thinking

The scientist in considering an operational problem very often comes to the conclusion that the common sense view is the correct one. But he can often back the view by numerical proof, and thus give added confidence in the tactics employed.

Or when two alternative qualitative views, 'A is best' 'B is best', are in dispute, he can often resolve this numerically into some such statement as that 'A is x per cent better than B in January and y per cent worse in June'.

In fact, the scientist can encourage numerical thinking on operational matters, and so can help to avoid running the war by gusts of emotion.

Operational Experiments

Since new weapons and devices are inevitably put into service relatively untested, the first few months of the use of a new device must be considered as an extension of its development trials. An Operational Research Section can function usefully here in a liaison capacity between the operational staff, the technical department which produced the device, and the development unit which tested it.

Further it is often possible, by collaboration between controllers and the staff of an Operational Research Section, to arrange operations on certain occasions so as to obtain data to clarify some doubtful point. For instance, the relative merits of different forms of anti-submarine sweeps by aircraft is a matter of (a) mathematical calculation, (b) test by actual operations, perhaps over a long period of time.

3. DISTRIBUTION OF REPORTS ON OPERATIONS

One of the functions of an Operational Research Section is clearly to write periodical reports on various aspects of operations. Except when secrecy questions prevent, these should be given a wide circulation, e.g., in the Air Force to squadrons to be read by the aircrews. In this way, the tactical education of the men on the job can be raised.

4. OPERATIONAL REQUIREMENTS

One of the most important duties of a Command is to state its requirements for new devices and weapons. Such requirements are passed, in general, through a department of a Ministry (which acts partly as a filter room, partly as a specialised department and partly as a post office) to a Service technical establishment.

The only places in this chain where the real operational facts are known is at the Command Groups and Stations. Unless the operational requirement is considered scientifically at the Command jointly by the operational staffs and scientists, it is possible that the operational requirements decided on will not correspond (a) to the real need, (b) to the technical possibilities.

In other words, an Operational Research Section can act usefully by interpreting

(a) the operational facts of life to the technical establishments, and

(b) the technical possibilities to the operational staffs.

A considerable wastage of war effort has occurred through lack of this joint discussion.

Nothing in this Section or in Section 2 should be taken as implying that an Operational Research Section should be the only channel by which a technical establishment obtains operational experience—on the contrary the direct contact between a technical establishment and operational units is generally essential.

5. ORGANISATION AND PERSONNEL

An Operational Research Section should be an integral part of a Command and should work in the closest collaboration with the various departments at the Command.

The head of the Operational Research Section should be directly responsible to the Commander-in-Chief and may with advantage be appointed as his scientific adviser.

A considerable fraction of the staff of an Operational Research Section should be of the very highest standing in science, and many of them should be drawn from those who have had experience at the Service technical establishments.

An Operational Research Section which contents itself with the routine production of statistical reports and narratives will be of very limited value. The atmosphere required is that of a first-class pure scientific research institution, and the calibre of the personnel should match this. All members of an Operational Research Section should spend part of their time at operational stations in close touch with the personnel actually on the job.

6. NEW DEVICES

'New weapons for old' is apt to become a very popular cry. The success of some new devices has led to a new form of escapism which runs somewhat thus—'Our present equipment doesn't work very well; training is bad, supply is poor, spare parts non-existent. Let's have an entirely new gadget!' Then comes the vision of the new gadget, springing like Aphrodite from the Ministry of Aircraft Production, in full production, complete with spares, and attended by a chorus of trained crews.

One of the tasks of an Operational Research Section is to make possible at least an approach to a numerical estimate of the merits of a change over from one device to another, by continual investigation of the actual performance of existing weapons, and by objective analysis of the likely performance of new ones.

The actual operational effectiveness over a period of time of any weapon can usefully (even if platitudinously) be considered as the product of three factors; the first $N(t)$ is the number in use, expressed as a function of the time; the second P is the scheduled performance of the weapon; and the third $S(t)$ is the average state of serviceability and training, i.e., the actual performance expressed as a fraction of the schedule. The probable form of $N(t)$ could be obtained from the production statistics of existing weapons. Relatively little is known of the form of $S(t)$, but probably a good first approximation would be to take $S(t) \propto (1 - e^{-tT})$ where t is of the order of two months to one year according to the type of gadget. Some operational research might usefully be directed towards elucidating this function. One could then attempt a numerical estimate of the gain or loss involved in the change over from one device to another, and so attempt to avoid the unduly heavy overhead costs of too rapid change over.

In general, one might conclude that relatively too much scientific effort has been expended hitherto in the production of new devices and too little in the proper use of what we have got. Thus, there is a strong general case for moving many of the best scientists from the technical establishments to the operational Commands, at any rate for a time. If, and when, they return to technical work, they will be often much more useful by reason of their new knowledge of real operational needs.

APPENDIX 2

O.R.S. Reports

A paper prepared by Mr. H. Larnder on 9 June 1943

1. INTRODUCTION

The purpose of this memorandum is to clarify the position regarding the preparation and distribution of reports produced by the Operational Research Section of Coastal Command. In particular the reasons for and methods of distribution of O.R.S. reports outside the Command need careful consideration.

2. PURPOSE OF THE O.R.S.

(a) The purpose of these sections is to provide Commanders-in-Chief with a trained scientific staff who can collect data and undertake research into and analysis of technical, tactical and general operational factors from which can be drawn deductions and lessons which will serve to guide Commanders-in-Chief and their staffs in the conduct of future operations. The nature and scope of the activities of these sections is primarily a matter for the decision of Commanders-in-Chief.

(b) The absolute and paramount duty of an O.R.S. is to serve the interests of the Command to which it is attached, and many of its investigations and findings will be of a parochial nature.

(c) At the same time, many lessons should be learned, the knowledge of which is beneficial to other Commands, Departments, or Research and Development Establishments. When such is the case permission should be sought to communicate these findings to those who would benefit.

3. OPERATIONAL RESEARCH CENTRE

(a) There is set up at Air Ministry under A.C.A.S. (Operations) an Operational Research Centre among whose functions are those of correlating and ensuring a satisfactory distribution of such O.R.S. reports as receive the Command's permission for outside circulation. This Operational Research Centre has no direct authority or control over the various O.R. Sections—who are solely responsible to the A.O.C.-in-C. of the Command to which they are attached—but, in addition to ensuring a wide distribution and exchange of information between the British O.R.S.s throughout the world, the O.R.C. also arranges for exchange of information with similar organisations in the United States of America.

(b) The outside distribution of O.R.S. reports should, so far as possible, be through the O.R.C., as this not only automatically makes use of the correct Air Ministry channels, but also ensures that any question of 'security' is carefully safeguarded.

(c) Unless otherwise requested, O.R.C. gives a very wide circulation to reports—always, however, keeping a careful eye on the security aspect—but if, at the request of the C.-in-C., a limited outside circulation is desired, O.R.C. are empowered to obey this request and refuse to extend information beyond those for whom specific permission has been given.

4. WHY O.R.S. REPORTS ARE PREPARED

(a) By no means all the action provoked or advice given by an O.R.S. appears in report form. Queries are answered or findings communicated by minutes on files, notes, or by word of mouth—as with any other Department or Branch of the Command. Especially is this true of certain operational statistics, which may have been provided as part of a more comprehensive paper or instruction being prepared by the Command.

(b) However, there are cases when the O.R.S. prepares reports for consideration by Air Staff or by a Branch of the Command. These reports may be prepared because:

(i) The O.R.S. has been asked to report on a subject.

(ii) The O.R.S. feels it should report on a subject.

(iii) It is considered that the results of several small and disconnected investigations on some matters, when welded together into one report, form a worthwhile and useful survey of the situation as a whole.

5. OBJECT OF AN O.R.S. REPORT

(a) All reports should be written with a definite object in view, such as:

(i) Provoking action—in this case an estimate of the return to be expected is desirable.

(ii) Confirming that measures taken by the Command are, or are not, yielding the results expected.

(iii) Establishing clearly principles which may be applied to an operation or plan, the precise outcome of which cannot be foreseen.

(iv) Establishing the use or limitations of some piece of equipment from a study of the results obtained in operational use, etc.

6. NEED FOR COLLABORATION BETWEEN SCIENTISTS AND SERVING OFFICERS

(a) Each scientist believes that, by virtue of his special training, he has something to offer which the average serving officer has not, and if this belief were not justified the possession of an O.R.S. would be of no benefit to a Command. It is very necessary, however, for the scientist (who surely cannot believe himself to be omniscient?) to have an equally firm belief that serving officers, by virtue of their training and experience, have something to offer which the scientist lacks.

(b) These convictions, which should be mutual between Scientific and Service personnel, must lead any thinking scientist to the logical conclusion that he will save much time and make a better job of any problem he is tackling by seeking the advice and collaboration of his Service colleagues, both during his early investigation and during the preparation of his draft report.

7. FORM OF AN O.R.S. REPORT

(a) When a report is necessarily lengthy and contains a wealth of detailed data and calculations, a precis or abstract should be written to accompany the report, *even in draft form.*

(b) This precis should, where applicable, be divided into four sections as under:

(i) *Introduction*
This should state clearly what the object of the investigation is, and why it has been carried out.

(ii) *Method*
Under this heading should be a brief description of the method employed, factors considered, and an assessment of the reliability of the findings. The object of this is to enable an early appreciation to be made by the reader of the validity of the findings of the report or investigation.

(iii) *Conclusions*
Here should be stated the main conclusions arising out of the investigation.

(iv) *Recommendations*
When applicable, positive recommendations should always be made—especially is this true of the report in draft form.

(c) The report proper should then follow as a separate paper. Detailed mathematical calculations or closely reasoned points of considerable length are best dealt with by making them appendices to the report.

(d) When a report is too short to justify a separate precis of abstract, the form of the report should follow that laid out above for the abstract as nearly as is practicable.

(e) The paragraphing of reports should be on the military model which has been adopted in this memorandum.

8. REPORTS INTENDED FOR CIRCULATION WITHIN THE COMMAND

(a) The wording may be forceful and the subject matter treated almost unlimited in a draft report which is meant as an honest constructive criticism or comment on the activities of the Command—providing it is for the Command's eyes only. In a manner of speaking, an O.R.S. enjoys the one supreme privilege of the court jester of old, namely that of saying things which would be *lèse majesté* from anyone else. This privilege is a very great one—it should be used on occasions, but never abused.

(b) Before submitting any report to high authority—unless instructed to the contrary—see that it goes up with comments attached by any branches of the Command concerned so that the report and these comments may be studied together. Providing the collaboration advised in para 6 has been effected, there should be very little need for comment by the Service, except to signify agreement, and it should be a point of principle for each member of O.R.S. when he writes a report to see that he has so well covered each point as to reduce comment to a bare minimum.

9. REPORTS INTENDED FOR EXTERNAL CIRCULATION

(a) No report is to have outside circulation without a covering letter from Air Staff except by special permission. This is a sound and reasonable ruling, and one which should, in the vast majority of cases, give the O.R.S. reports greater weight in both the Scientific and Service worlds than would be the case of a report issued without such a covering letter.

(b) The fact of the matter is that unless this covering letter is, in general, one which backs up the O.R.S. findings, then O.R.S. must reckon it has failed in serving its Command, since it failed to convince them on an important point—the point must have some importance or O.R.S. should not be seeking outside circulation.

(c) Many reports as written for internal circulation will be in a suitable form for outside circulation, but this will not always be the case, and then a separate report with a different method of treating the subject will have to be written.

(d) To illustrate this point—it is easy to imagine that an investigation may reveal:

(i) The best method of using some form of equipment.

(ii) That we have consistently used this equipment poorly.

(e) Obviously it is a good thing to bring conclusion (i) to the notice of other Commands, but equally it is obvious that no good will be served by bringing (ii) to the notice of any Command other than our own. So the report, for outside circulation, should be rewritten in such a manner that conclusion (ii) could not be derived from it.

10. APPLICATION FOR PERMISSION TO CIRCULATE O.R.S. REPORTS

(a) According as to the subject matter, this permission will be given by the C.-in-C., or in his absence by the Senior Air Staff Officer.

(b) Whether the application is for internal or external circulation the procedure is the same. The report in draft form is to be sent to the Branch most concerned, with a minute suggesting the distribution desired by O.R.S., and asking for a draft covering letter and further suggestions for distribution. On return, and after agreement has been reached on the covering letter and wording of the report, both the draft report and draft covering letter should be sent to the appropriate authority for final approval. This request, together with the draft report and covering letter, must be brought to the notice of the Officer-in-Charge, or Deputy C.-in-C., before despatch.

(c) When, and only when, this final approval has been given will the report be stencilled and circulated.

APPENDIX 3

The Sortie Raid Report used by Bomber Command

In respect of each returning operational sortie by Bomber Command aircraft a detailed report was obtained, from interrogation by the intelligence branch at squadron level, and submitted through groups to headquarters. The precise form of this report has varied with the changing requirements of the branches interested, in particular the O.R.S., and questions no longer required were deleted as soon as possible in order to spare both tired crews and the hard-pressed intelligence officers. Originating with a discussion at the Group Commanders' Conference of 9 August 1941, and following closely the existing Form 'C' used in No. 5 Group, the Sortie Raid Report was tried out in No. 5 Group during November and December 1941, and was adopted by all operational Groups as from 1 April 1942.

On page 201 is the *pro forma* of the Sortie Raid Report which was used from November 1943 until (with minor modifications) the end of the war. It will be seen that Section 'A' is concerned mainly with identification and with data ascertainable before take-off. Section 'B' was intended for items of immediate importance (e.g. enemy ship sightings) which were telephoned to group at once and did not, in fact, appear on the Sortie Raid Report at all. Section 'C' was used as a guide for interrogation, replies being given only where applicable. Moreover, the headings of Section 'A' were not repeated on the Sortie Raid Report itself. The completed document resembled the specimen shown on page 202.

A comparison of these two forms will, in most cases, make the Sortie Raid Report self-explanatory, but the following commentary may be helpful.

(a) The symbol, (30 + 8), after the Captain's name means that he had completed 30 operations in his first tour, and eight in his second; such data were used as evidence of experience.

(b) The target given in Section 'A' is the briefed target; that in C(1) is either the target actually attacked or, in the case of abortive sorties, the place, time, height and reason for abandoning the mission.

(c) The load dropped, C(5), was quoted by the Pathfinder Force and by the Main Force in all cases where the load was split up between two or more aiming points.

(d) Under C(6) was to be given the colour of marker bombs and, for target indicators, the time at which it was seen to cascade; the latter information was used in tracking down decoy target indicators.

(e) C(7) would be answered in place of C(6) in such cases as bombing on dead reckoning from a previously identified landmark, or bombing blindly by radar aids.

(f) The bomb-load dropped was ascertainable from the load carried (Section 'A') less any returns under 9(a) or (b).

(g) Questions C(10) and (11) were later discarded.

Different parts of the Sortie Raid Report were of importance to various branches at Groups and at Command Headquarters, and to different subsections of the O.R.S. So far as raid analysis is concerned the data of main importance were:

(a) target attacked
(b) bombs dropped on target
(c) time, height, heading, and airspeed at bomb-release
(d) what was in bombsight (or other method of bombing)
(e) bomb aimer's and pilot's reports
(f) aircraft identity (squadron number and aircraft letter).

From this information a time histogram of the raid was constructed, known from its size as the 'Table-cloth', in which each vertical column represented one minute and each unit cell one sortie. Each half-inch-square cell contained the identification (e.g. '101.G'), a coloured symbol indicating the point of aim (e.g. green target indicators), a symbol to show if that aircraft's photo had been plotted, and in some cases a special bomb-load symbol (e.g. indicating H.E. only).

Above the Main Force histogram the Pathfinder Force marker aircraft were separately shown, with an additional symbol to indicate the kind of marker dropped. In the case of (say) a green target indicator of average burning time seven minutes, a horizontal green line would be drawn extending over seven columns. An additional horizontal row of cells would show (by small dots) minute by minute reports of the cascading of (say red) target indicators.

SORTIE RAID REPORT

Section A

Group:	A/c Squadron and letter:
Date:	Station and Raid Report No:
Bomb load and fusing including special flare loads	A/c Type and Mark:
Special Equipment:	A/c Number:
Target:	Captain: No. of Ops:
Navigator's Watch Error:[1]	Function:

Section B

Immediate reports.

Section C

(1) Target attacked:
(2) Weather over target at the time of bombing:
(3) How did you identify the target:
(4) Time of attack (to nearest minute): Height (to nearest thousand): Heading (magnetic): Indicated airspeed (in m.p.h.):
(5) Load dropped on target:
(6) What was in bombsight:
(7) If bombsight not used, how did you bomb:
(8) Bomb aimer's description of target area:
(9) (a) If any bombs, flares or target indicators were jettisoned, state place, time, and height and reason:
(b) If any were brought back, give details and reason:
(10) Give place and time where route or warning markers were seen or dropped and remarks as to effectiveness:
(11) What (if any) of the special equipment mentioned above was:
(a) unserviceable:
(b) not used:
(12) If a defect affected the result of the mission, state which component or equipment failed:
(13) Was the aircraft damaged by (a) fighters, (b) flak, (c) other causes, e.g. falling bombs, collisions? If so, give brief particulars:
(14) If you knowingly deviated from the ordered route, state the route taken and give the reason for the deviation:
(15) Describe effects of any adverse weather encountered, e.g., ice, thunderstorms, electrical storms:
(16) Pilot's personal report:
(17) Initials of Interrogating Officer: Time of Origin:

[1] Pathfinder Force only.

SPECIMEN COPY OF RAID REPORT FOR MAIN FORCE

Section A

4 Group
2/3 October 1943
2 × 1,000 Medium Capacity Tail Delay ·025
24 × 30 Incendiary. 690 × 4 Incendiary
30 × 4 'x' type Incendiary
Gee, Mark XIV Bombsight,
Boozer, Monica,[1] H2S
Munich

102*G*
Pocklington 442
Halifax II 1A
LW 246
P/O Smith (30 + 8)

Section C

(1) Munich
(2) 2/10 to 3/10 strato cumulus 5,000 ft. Visibility excellent.
(3) Red and Green target indicators (T.I.) seen cascading. Checked on dead reckoning run from N. tip of Wurm See, which was identified visually.
(4) 2131: 18,000 ft: 052M: 270 m.p.h.:
(6) Mean Point of Impact of Green T.I.s. One of these seen to cascade at 2129.
(8) No Red T.I.s seen at time of bombing; Greens well concentrated with exception of one about 5 miles to east. Much smoke in target area.
(9) (a). 1 × 1000 medium capacity hung-up and was jettisoned 49 12N 09 34E 2202 hours, 19,000 ft.
(10) Ruby Spot fires seen near Wurm See on run at 2126. These were scattered over an area of several square miles.
(11) H2S Monica.
(13) Port Wing damaged by incendiaries over target. Believed flak damage to starboard inner engine 40 miles short of target, 2120, 19,000 ft.
(15) Severe icing *en route*, lost height 2,000 ft. This caused us to be several minutes late in reaching target.
(16) Fighters and searchlights very active in target area. Coned for 3 minutes after bombing. At 2135 Lancasters passed 200 ft. below.
(17) LCL. 0712 3 October.

[1] Boozer and Monica were radio counter-measures to air interception equipment carried by enemy night fighters.

APPENDIX 4

The Examination of a Battlefield

This note has been extracted from the history of No. 2 O.R.S. Twenty-first Army Group, 1944 to 1945.

Although this is an Army operational research report, it describes identical problems encountered by O.R.S. 2nd Tactical Air Force during its work in North-west Europe.

1. CRATERS

(a) Except when filled with water, craters will usually yield clues as to their origin in the form of fragments. Learning from experience one soon becomes expert in distinguishing fragments of the 60-pound Semi-armoured Piercing Rocket Projectile from those of a shell, etc. The edge of a crater is harder to determine because one is not often on the scene early enough to recognise that easily distinguished appearance of newly disturbed earth; the sight of vegetation growing in a crater is usually a good indication of age, but in damp soil and with hot weather one can be deceived in this.

(b) *Bomb Craters*

There are so many variables concerned in the determination of crater sizes that no reliable guide can be given. The very large and very small bombs make craters that can be recognised but the intermediate sizes present difficulties. However, armed with the knowledge that a target has been attacked with 500 and 1,000 pound bombs of the same type and fusing, it is usually possible to distinguish the two sets of craters by their relative size. Craters in roadways will generally be filled in by the time the ground investigators arrive, but one can make a fair estimate of the size of the crater by inspection of the disturbed surface. Bomb craters in shallow water show up quite well on aerial photographs.

(c) *Air Cannon and Machine Gun Scars*

A metalled road that has been strafed shows very definite pock marks. Where strafing occurs in grass land, holes as large as six inches in diameter can often be seen.

(d) *Rocket Craters* (60 pound Semi-Armour Piercing/H.E. Aircraft Rocket)

Although with different types of soil and different angles of dive a variety of shapes and sizes have been encountered, the most usual type of crater is oval, some 8 feet by 5 feet and about 18 inches deep. Digging in the crater will generally reveal characteristic fragments but this is often unnecessary because of the presence, in or near the crater, of the easily recognised rocket motor and/or fins. The motor resembles a three-foot length of drain pipe (three and a half inches in diameter).

2. EXAMINING VEHICLES

(a) Where a retreat has taken place one has always to be on the look-out for vehicles destroyed by the enemy to prevent them falling into our hands. This is usually indicated by the presence of the metal cases in which the German demolition charges are carried and by the fact that the centre of destruction is located in a standard part of the vehicle, under the engine hatches of a tank, for example. Vehicles that were destroyed on routes are generally pushed off by bulldozers and one has to try and estimate the position at the time of the kill and to assess what was original damage and what was done by the bulldozer.

(b) *Multiple Damage*

Cases will be found where more than one weapon has done damage to a vehicle and then one has to resort to deductive reasoning and the interrogation of local civilians or to class the damage as 'unknown causes'. This problem is aggravated by the tendency of the troops to use knocked out vehicles as practice targets. Knowledge of the course of the battle will serve to show whether a Piat or Bazooka hit was the cause of destruction, or the work of an enthusiastic marksman at a later date.

(c) *Cannon and Machine Gun Hits*

When small holes are found in a roof, bonnet or upper surface of mud guards, it is generally safe to assume that the vehicle has been strafed but, as pilots are apt to fire at 'dead' vehicles, other possible causes of damage must be sought as well. Bullet holes in the sides may be caused by the machine gun of an armoured fighting vehicle but are often the results of musketry practice.

(d) *Fragments of Shells and Bombs*

Such fragments make jagged holes in the sides of vehicles. It is generally advisable to go to the crater and see whether fragments from it could have struck the vehicle, always remembering that if it were in motion at the time of the burst, it would have moved some distance before coming to rest.

(e) *Direct Hits by Bombs and Rockets*

As neither bombs nor rockets are ever used singly, except in the case of mechanical hang-ups, one should look around for the other one of a pair; it should not be many yards away.

(f) *Fires in Vehicles*

Vehicles that have been hit by any form of projectile tend to take fire and this causes extra damage due to bursting petrol tanks and exploding ammunition. The appearance of vegetation in the immediate vicinity will usually give a good indication of when the fire took place.

(g) *Dead Bodies*

The presence of dead bodies in a knocked-out vehicle is a sure sign that it was not destroyed by the crew. An examination of their situation and attitude may yield useful information if one applies a Sherlock Holmes technique; in fact, this technique is used so often in battlefield investigation that one can say that the famous detective would have been a first-class Operational Researcher.

3. EXAMINING GUN POSITIONS

(a) All types of gun posts have been examined, ranging from the shallow pit dug for the 20 mm. light anti-aircraft gun to the reinforced concrete casemates of the heavy coastal guns. They fall into two classes, those apparently made by the troops in the field (varying enormously according to the circumstances) and those made by conscripted labour (prepared long before the battle and built to standard specifications).

(b) *Finding Gun Positions*

They are easy to find when built in the open as they are more built up than excavated. Quite large positions were, however, nearly missed when they were hidden along the edge of a wood, but the prominent barrel of the abandoned gun usually caught the eye.

(c) *Unoccupied Sites*

When a gun site is overrun or the troop is forced to retreat, some evidence of occupation is invariably left; empty cases, clothes, papers, empty tins and cigarette packets. But, when no such evidence is found, one should examine the ground for tracks before stating that the site had definitely been occupied.

(d) *Dummy Sites*

These were often so well devised that they deceived the eye until one approached quite near. Wooden poles were used to simulate gun-barrels.

(e) *Damaged Guns*

Guns still on site when the positions were investigated were either intact, suggesting surrender or rapid retreat, destroyed by the crew, indicated by standard damage (breech blocks blown, muzzles split or, in the case of A.A. guns, mountings demolished) or destroyed by some weapon of ours.

(f) *Signs of Activity*

Empty cartridge cases tell their own story. The numbers of unused rounds found on a site is often of interest as cases have occurred where positions were overrun because the ammunition was exhausted. All records, documents and personal papers such as letters and diaries are well worth scrutiny. Identification of the unit from such sources can be tied up with the P.O.W. interrogation. Graves with or without dates on them, and dead bodies all yield valuable information. Wheel-tracks through or purposely avoiding recent craters all suggest the withdrawal after shelling had begun.

The following is intended to show what results may be expected from interrogations and to give some indications as to the methods used.

1. ENEMY PRISONERS

(a) *Information obtainable*

Enemy order of battle, losses, actions, weapons, methods, reactions and opinions. Thus prisoners of war are a potential source for everything we wish to know about the enemy.

(b) *Method of obtaining Information*

Enemy P.O.W. are hostile. It therefore requires a trained interrogator to extract their knowledge from them. He should be in touch with all other intelligence sources (i.e. documents captured, summaries). This is a limitation as, while a battle is in progress, all available interrogators are required to obtain purely operational information. On the other hand P.O.W. have nothing else to do other than answer questions and the method of evacuation draws witnesses from all parts of a battlefield to one central point—the P.O.W. cage—so that a few interrogators can cover a wide field. Although for administrative reasons P.O.W. are evacuated rapidly to the rear, it is possible to follow back along the line of communication any bunch that is particularly interesting. This was done by this section in the course of enquiries following the Ardennes and Rhineland battles. Visits were made to base cages and information obtained during the battles was used to pick out P.O.W. who might have useful knowledge.

(c) *P.O.W. as a Guide to Enemy Morale*

Experience shows that only limited information can be obtained as to enemy reactions and morale. The physical appearance of prisoners as long as they have only just left the battlefield may be a guide to the effect of our attacks, but P.O.W. stories of reactions were never very satisfactory. An American team of psychologists made an attempt at Boulogne to assess scientifically the morale effects of our attacks on the fortress. They asked a large number of prisoners a number of psychological questions and analysed their answers in terms of their own psychological teaching. This method, though offering possibilities, also requires especially skilled persons for its application.

At British Base Cages other methods were used with some success in order to obtain P.O.W. opinions and reactions without the intrusion of an interrogator. These methods, useful for establishing general trends in P.O.W. thought, were too long range for the needs of a section which hoped to report on a battle within a week or so of its conclusion.

Generally speaking, the best guides as to morale effects were:

(i) The comparison of P.O.W. stories with other authentic accounts—P.O.W. from Walcheren gave the interrogator the impression that the German batteries had remained in action half the day whereas an official naval observer showed them to have fired for less than an hour.

(ii) The interrogator's own opinion based on observation of the man in question.

(iii) The ratio of enemy killed and wounded to the number of prisoners.

A final limitation to the information obtainable from prisoners is their usual complete lack of knowledge in respect of time and place of any events that they describe.

2. THE CIVILIAN POPULATION

Whereas more limited in the information that it was able to give, the civilian population had certain advantages over enemy prisoners as a source.

Time and place were usually more easy to identify. If we wanted information from a farmer, whose haystack had been burnt whilst concealing a tank or some other enemy vehicle, it was not like asking a soldier who had seen plenty of burning haystacks. The farmer nearly always knew exactly how and when he had suddenly become a much poorer man.

Whereas it was not possible to get an accurate picture of the nature of enemy traffic on a given route, it was possible to establish which actual road was used and when, two points seldom clear to P.O.W.

In dealing with civilians it was not necessary for the interrogator to be trained and in France and Belgium, as most of the section spoke adequate French, they were able to ask questions at will. Even in Germany no serious difficulties occurred on this account; the civilian population was seldom hostile.

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The suffix letter 'n' denotes a footnote

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