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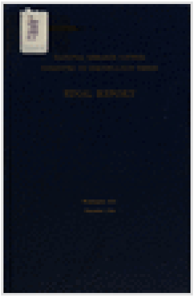

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NATIONAL RESEARCH COUNCIL

COMMITTEE ON FORTIFICATION DESIGN

FINAL REPORT

Washington, D.C.

December 1944

FOREWORD

The accompanying report of its Executive Officer has been accepted by the Committee on Fortification Design and is hereby transmitted as the Final Report on the program of research conducted by the Committee for the Corps of Engineers, U. S. Army.

It is the purpose of the report to summarize the work of the Committee on Fortification Design and of its predecessor, the Committee on Passive Protection Against Bombing, since the time of the first contract between the National Academy of Sciences and the United States of America.

Such a summary will make it possible for any future research worker to take up the problem where we left it, making use of all the many reports which the Committee has submitted, as listed in the Bibliography of this report. A field operator, facing problems of the design or defeat of fortifications during the present war, will not find it necessary to study in detail all of the reports of the Committee. For his purposes, the Appendix to the Final Report of the Committee on Passive Protection Against Bombing for the year ending 30 June 1943, Terminal Ballistics and Explosive Effects, *supplemented by the later reports of the Committee (Interim Reports numbers 26, 27, 28, 29, and 30, and Interim Memoranda numbers 10, 11, 12, and 13) will be adequate.*

In accepting this final report of Professor John E. Burchard, as Executive Officer of the Committee on Fortification Design, the members of the Committee wish to go on record as expressing their appreciation of the great services which Professor Burchard has rendered. It is due to his insight, wisdom and planning that the work of the Committee has been such an outstanding contribution to the principles of military science.

K. T. Compton
L. P. Eisenhart
F. R. Moulton
R. C. Tolman, *Chairman*

INTRODUCTION

THE Committee on Fortification Design (first known as the Committee on Passive Protection Against Bombing) was appointed by Frank B. Jewett, President of the National Academy of Sciences, on 24 June 1940, to supervise the execution of a one-year contract entered into 1 July 1940 by the United States of America and the National Academy of Sciences. This contract called for the National Academy of Sciences to make reports to the Chief of Engineers, U. S. Army, covering "the basis of design of structures to provide protection to personnel and installations, both military and civil, against bombing by aircraft." It was specifically suggested in the contract that the reports should include but not be restricted to the following:

"a. A determination of the effects of the impact and explosion of an aerial bomb and the most suitable basis of design to afford protection against such effects.

"b. A determination of the most suitable material for such construction at minimum cost, giving consideration to availability in time of war.

"c. Recommendations of the Contractor as to general procedure in designing structures which can be made the basis of information to engineers familiar with ordinary structural design, who may be called upon to design shelters for protection against bombing by aircraft."

The Committee originally appointed consisted of Dr. Karl T. Compton, Dean Luther P. Eisenhart, Dr. F. R. Moulton, and Dr. Richard C. Tolman, Chairman. In July 1940, Professor John E. Burchard became Executive Officer of this Committee. The contract was subsequently renewed by the Corps of Engineers with increased funds in July 1941, July 1942 and July 1943, the latter contract terminating 31 October 1944. Throughout the continuation of the work, the original Committee on Passive Protection Against Bombing remained unchanged in its personnel and its Executive Officer. On 1 November 1941, Mr. Burnham Kelly was appointed Assistant Executive Officer and he remained in that capacity until the end of the work. On 1 July 1943, in order to clarify the objectives of the Committee and avoid requests for information which the Committee was unable to furnish, its name was changed from the Committee on Passive Protection Against Bombing to the Committee on Fortification Design.

The Committee and its Executive Officer did not in themselves conduct any direct experimenting nor make any appreciable amount of direct interpretation of the experimental results. By far the largest part of the experimental work and the interpretation thereof was carried on at Princeton University by a group of physicists and engineers assembled there; this work was augmented substantially at Princeton by the assistance of other personnel at the Princeton University Station of Division 2 of the National Defense Research Committee; some other National Defense Research Committee contractors, notably the University of Illinois and the Massachusetts Institute of Technology, provided collateral information, as did the Humble Oil and Refining Company on subcontract from the National Academy of Sciences and the Geophysical Research Corporation on a voluntary basis. The extensive field tests required in the concrete penetration program and the earth-shock program were made possible through the provision of proving grounds and targets by the U. S. Army Corps of Engineers and Ordnance Department. At such trials, representatives of the Committee were not only present as observers and recorders but indeed, generally speaking, initiated and planned the programs which were later carried through.

The Committee was fortunate in having available, almost from the first days of its existence, two versatile, energetic, and capable scientists, Professor H. P. Robertson, who was theoretical physicist for the Committee, and Professor Walker Bleakney, who was experimental physicist. Professor H. P. Robertson was influential in the thinking of the Committee even for some time after he left Princeton University to undertake foreign service in October 1942. Professor Walker Bleakney remained an active force until the end of the work. In addition to these two leaders, it is necessary to mention a few others who took prominent parts in the work of the Committee. These are especially Dr. R. A. Beth and his assistant, Mr. J. G. Stipe, Jr., employees of the Committee who were responsible for the work on terminal ballistics of concrete, assisted further by Mr. J. T. Pittenger; Dr. C. W. Lampson and his assistant, Dr. George T. Reynolds, employees of the Princeton University Station of Division 2, NDRC, who directed the work on the measurement of transients and the field work in connection with underground explosions, both at Princeton and in Oklahoma; Dr. C. W. Curtis, of the Princeton University Station, and Mr. R. J. Slutz, Technical Aide of Division 2, NDRC; Mr. David Mayer, Mr. R. J. Hansen, and Mr. N. C. Dahl, three engineers for the Committee who took an active hand in various tests, both at Princeton and in the field, participating in planning as well as in execution; and Messrs. D. G. Kretsinger and M. E. DeReus, who were responsible for concrete production, the study of properties of concrete and the like. The Executive Officer is deeply indebted to his assistant Mr. Burnham Kelly whose loyalty, industry, and intelligence were indispensable.

(A very considerable number of other people in NDRC and other groups gave major support to the work of the Committee.) It would be quite difficult and probably meaningless to attempt to name them all, but special thanks should perhaps be rendered to Dr. A. H. Taub of the Princeton University Station, Division 2, NDRC, Dr. N. M. Newmark of the University of Illinois, Dr. W. M. Rust, Jr., of the Humble Oil and Refining Company, and Dr. B. B. Weatherby of the Geophysical Research Corporation.

It would be possible to write a considerably more extended list of persons who had made significant contributions to one or

GENERAL HISTORY OF RESEARCH DONE

It will be clearest in studying the history of this Committee to deal with its fields of interest one by one, and a later section of this report will treat the work in that way. However, a somewhat better orientation for the programs and a better understanding of the reasons for them can be obtained if at first we sketch briefly the work as it progressed from year to year.

1940–1941

In the year 1940 when our work began, war in which the United States would be engaged seemed rather remote and any idea that our lands might be attacked by enemy aircraft seemed quite out of the question. Nonetheless, persons with foresight had given a directive to the Chief of Engineers calling for him to study the protection of installations both military and civil against bombing. It was in the execution of this directive that the contract with the National Academy of Sciences was made, and for this reason it was necessary at the outset for the Committee to decide where the emphasis of its work should lie, whether it was to study primarily the question of fortification design or primarily the question of civilian defense, or both. After appropriate discussion with the representatives of the War Department, it was concluded that the emphasis should lie on fortifications, and it was not until the following year that any serious independent attention was given to the problem of civilian protection, although the Committee had access through the Office of Scientific Research and Development, after that agency was set up, to its opposite numbers in the Ministry of Home Security in England. These people under the leadership of Dr. R. E. Stradling were already intensively engaged on experiments which were to lead to definitive solutions of the problems of civilian defense and to relieve our Committee from the necessity of much work which we should otherwise have had later to undertake.

From a reasonable amount of previous qualitative evidence, it was concluded early in the work that a fortification which was strong enough to prevent a given projectile from getting within its walls would be strong enough to resist the secondary effects of the explosion of any such projectile. This original assumption has at the present time been subject to extensive tests which on the whole verify its original validity. It was accordingly decided that the first emphasis of the Committee should be laid upon the problem of providing walls or roofs sufficiently resistant to prevent perforation by a projectile. Such walls could be conceived of as being made of steel or concrete or of earth. Because there was already a considerable amount of evidence from the Army and Navy proving grounds on the terminal ballistics of steel and because concrete seemed to be the material which would be most frequently used in a heavy fortification, it was concluded that the first emphasis should lie on the terminal ballistics of reinforced concrete.

As a first step in this work Professor H. P. Robertson undertook a general survey of previous literature on terminal ballistics and his report[1] remains the definitive statement of the Committee on this subject. It was probably surprising to everyone to discover that although extensive use of concrete had been made in fortifications and notably in the Maginot line and the West Wall, so far as we could discover from documents available to us, there had been no very serious experimental work on terminal ballistics of concrete from the time of the Metz Committee, 1835. In view of the early period in which this work was done and the many uncertainties which surround it, it was concluded that a serious program should be entered into on the terminal ballistics of concrete. This program developed into a major part of the work of the Committee over the whole four years of its existence, and as a result a very substantial body of data and some reasonably reliable interpretation of these data will be available to our successors. Those who have been most

[1] *Terminal Ballistics*, by H. P. Robertson. January 1941.

intimately associated with this work believe that a very considerable amount of further data is needed and that a good deal more time can profitably be spent upon its interpretation but that the data which have been accumulated are quite reliable so far as they go.

The first work of the Committee in the year 1940-1941 was at the small scale of calibers .30 and .45 on model targets designed and built at Princeton with considerable advice on concrete properties from Professor R. W. Carlson of the Massachusetts Institute of Technology. Additional data were afforded in this year by trials conducted by the U. S. Navy at the Dahlgren Proving Ground at model scales consistent with the use of 3″ and 6″ projectiles, and by some full-scale bombing tests conducted by the Corps of Engineers with the assistance of the Ordnance Department and the Air Forces at the Edgewood Arsenal. The small-scale tests conducted at Princeton required the development of new projectiles and design of proper restraint for the targets and included the first studies of the effect of concrete properties on the impact phenomena.

It was recognized from the outset that sole reliance could not be placed on defeating the projectile and preventing its entering the fortification. In this year no serious effort was made by the Committee to study the phenomena of detonation in earth or at some distance from the target in air, although in its first reports it did review the British work in these fields insofar as it had at that time come to its attention.

Finally, in the first year the Committee spent some time on engineering design of various peripheral burster slabs which might be expected to keep a bomb from entering the earth near the side walls of a fortification. It was recognized that a detonation in earth near the walls might be quite damaging. It was believed that it might be more economical to put material into a burster surrounding the fortification which would prevent the bomb from getting too near, rather than to make the walls thick enough to resist any such detonation. Finally, some small-scale tests were entered into to get first approximations to the effect of detonation in air but in contact with the walls or roofs of the fortification.

1941–1942

In the early stages of 1941-1942 the work continued along the lines laid down in 1940 and 1941, though at a considerably accelerated pace. In September 1941, Professor H. P. Robertson and Professor J. E. Burchard went on a mission to the United Kingdom accompanied by Lt. Col. S. B. Smith (then Mr. S. B. Smith). This party returned to the United States only shortly before the Japanese attack upon Pearl Harbor. What they had learned in the United Kingdom caused them to introduce several new programs, especially in connection with the measurement of transients and the study of earth shocks. The Japanese attack and the subsequent reaction of the American public led the Committee to believe, with the concurrence of the War Department, that certain trials were also necessary in connection with civilian defense, if only to verify the conclusions which had been reached by the British both from laboratory experiments and in the crucible of the blitz. In undertaking these experiments related to civilian defense, the Committee did not in the least alter its view that its principal objective lay in helping in the design of fortifications; and this view coincided with the facts, which have since been established by the course of events. The work of 1941-1942 can be summed up as follows:

1. A very considerable extension of work on the terminal ballistics of concrete, including full-scale trials at Fort Cronkhite in California, through the joint efforts of the Corps of Engineers, the Panama Canal Zone, the Ordnance Department and the Committee, and the beginning of a very large set of terminal ballistic tests using projectiles up to 155 mm and employing a total of 34 targets, which were built by the Corps of Engineers at the Aberdeen Proving Ground in accordance with speci-

fications laid down by the Committee. These tests, begun in 1941-1942, were not fully reported until the following year by Dr. Beth and Mr. Stipe, who also were in charge of the conduct of the tests.

2. An interest in the problem of revetment panels or blast-protection walls which raised questions as to the dynamics of structures, including whether or not they would overturn under impulsive loads and what sort of stresses might be expected in the target under impulsive loads. This led to a statement of the theory of impulsive loading by Professor Robertson.
3. The beginning of a study of underearth phenomena in connection with a set of vertical walls set forward some distance from the basic fortification walls for the purpose of absorbing the shock of an underground detonation. These first small-scale tests conducted by Mr. David Mayer blossomed into the large underground program of subsequent years.
4. The beginning of what became a large program, principally under NDRC auspices, of the measurement of shock in air under the general direction of Dr. C. W. Lampson, resulting in the planning and construction of a large mobile laboratory for the simultaneous measurement of many transients.
5. Concern with the problem of explosion in confined spaces and the study of what could be done to diminish the effects when, despite precautions, a bomb did enter a structure. This had a further extension in the development of a study of what would happen to a many-storied building due to the uplift caused by detonation inside of one of the lower stories. This program was initiated principally at the suggestion of the British, and was carried through some pilot-model stages only to be abandoned the following year as the turn of the war relaxed the interest in civilian defense matters.

6. A considerable study of the penetration to be expected by German incendiary bombs into various types of structures. This program was undertaken to supply information desired by the National Bureau of Standards in connection with a more extensive study it was making of incendiary defense.
7. The introduction to this country of the British reinforced concrete standardized shelter with some modification in its design to make it more consistent with American practice, and full-scale tests of these shelters under two different foundation conditions.
8. The study of damage to American wood frame houses due to detonation of bombs in air at various distances therefrom. Certain observations in the United Kingdom had led us to believe that American wood frame houses might be more resistant to collapse from blast than British brick buildings. Since the degree of resistance would affect civilian defense policy, three full-scale houses were constructed and tested at the Aberdeen Proving Ground and a report was subsequently rendered on the probability of casualty to a person occupying various positions in such a dwelling.
9. Advice on the problem of glass protection. This was a problem which never concerned the Committee deeply but upon which it was required to touch from time to time.
10. It is perhaps symptomatic of the state of mind of the nation in this year to point out that the Committee was required to furnish scientific consulting services to the Technical Committee of the Office of Civilian Defense, to the Committee on Conservation of Cultural Resources of the National Resources Planning Board, and to the Interdepartmental Advisory Committee on Protection, of the Public Building Administration. The results of the work of the Committee on Conservation of Cultural Re-

sources were summed up in a report by that Committee *Protection of Cultural Resources Against the Hazards of War*. The results of the work of the Interdepartmental Advisory Committee on Protection, which was established under directive from the President, was a book entitled *Air Raid Protection Code for Federal Buildings and Their Contents*. As of this writing, this book is still believed to be the most reliable publication in its field.

The emphasis of this text would suggest that the activities of the Committee in 1941-1942 were largely diverted from the problem of fortification design to that of civilian defense. This was not in fact the case. The greater amount of funds and of personnel continued to be expended on the problem of defeating an explosive projectile by a fortification. The largest emphasis as in the preceding year lay on the terminal ballistics of concrete, but there was a very considerable expansion of work on the effect of underground explosion and some study of the effects of impulsive loading on structural systems.

1942–1943

In 1942-1943 the military situation had so far changed that except for occasional advice to the Central Technical Board of the Office of Civilian Defense and disposition of a certain number of civilian defense projects which had hung over, the entire resources of the Committee could be expended on the problem of fortification design.

During this year Professor W. Bleakney, Professor H. L. Bowman, and Mr. N. C. Dahl went on missions to the United Kingdom. It was already becoming realized that information which the Committee had at its disposal might prove to be even more useful in planning attack than it would be for defensive purposes, at least so far as this country and this war were concerned. Much of the emphasis of the visits of Professors Bleakney and Bowman and Mr. Dahl was therefore directed toward this problem.

In the field of terminal ballistics of concrete, the year was spent in completing the large-scale tests at the Aberdeen Proving Ground, in extending the conclusions to cover the effects of shell fire as well as those of bombs, and in studying the behavior of slab combinations, comparing monolithic construction with laminated, for the indications were that such great thicknesses of concrete are required to defeat a modern bomb or projectile as to make it almost essential from a practical point of view that this concrete be poured in laminae.

The shock-wave work continued with greater intensity and it was in this year that a large number of pilot-model tests were made at Princeton, to study and to plan the extensive set of tests in Oklahoma which took place in 1943-1944.

Further attention was given to the problem of impact loading, remote effects, and design for impulsive loads. Experiments conducted in this field were not encouraging as to the useful conclusions of a limited experimentation, and it was the general feeling of the Committee that there would be very little profit in or necessity for exploring such methods of design, as it was felt that structures adequate to resist the local effects of impact and explosion would in all cases also be capable of resisting remote effects. Nonetheless, because of the Corps of Engineers' continued interest in this sort of study, arrangements were made with the Office of Scientific Research and Development whereby Professor J. B. Wilbur, of the Massachusetts Institute of Technology, would conduct independent studies in this field. His reports were made available to the Corps of Engineers through the National Defense Research Committee. At the same time, further NDRC studies were conducted on the effects of impact on various simple concrete structures such as beams and columns. These were prosecuted at the University of Illinois and reports thereon are available through the NDRC.

Because of a continued civilian interest in the effects of bombing and because of the very considerable amount of misinformation which was being circulated through irresponsible sources, it was considered desirable to produce a popular book at the junior engineering level which would attempt to give the generally accepted facts about the effects of bombs, and which would be intended for rather wide circulation by the Office of Civilian Defense. This was our final contribution to the art of civilian defense.[2]

The tendency of this year was, then, to withdraw from the field of civilian defense and to draw increasing attention to the utility of all our data in planning the attack. This was accomplished in part by professional advice which various representatives of the Committee were from time to time called upon to render to the Air Forces and to others interested in planning the attack, and in part through placing at the disposal of Division 2, NDRC, with the consent of the Chief of Engineers, the pertinent data we had assembled. These data were then incorporated in a loose leaf manual formerly entitled *Effects of Impact and Explosion*, and recently changed to *Weapon Data—Fire, Impact, Explosion*, prepared for and circulated to the Services by Division 2, NDRC. In considering the accomplishments of the Committee this somewhat indirect result should by no means be underestimated, because the NDRC compilation has had extensive circulation and use.

Finally, at the end of this year an Appendix to the Final Report was issued entitled *Terminal Ballistics and Explosive Effects*. This book of some 170 pages added up all the information the Committee had by then obtained, either by itself or through NDRC or Service sources, in compact form and largely in the form of graphs, nomograms and tables. Very little which has been accomplished in the final year would result in substantial changes in that report. However, some small corrections might have to be made, and in the fields of earth shock and earth penetration, substantial additions are available from work carried on in 1943-1944.

[2] *Fundamental Principles of Structural ARP*, by J. E. Burchard, Washington, D. C. 1943 (Restricted).

1943–1944

The work of 1943-1944 was directed pointedly at filling certain gaps in our information, with full knowledge that the defensive crisis was past and that we were putting together what would be needed to leave a reasonably clear record for our successors. One new field was investigated to a slight extent, that of penetration in soils. The previous work in concrete having proved inadequate on the side of study of concrete properties, a considerable effort was made on the concrete properties survey. Finally the large series of tests in Oklahoma was completed. These last consisted of studying the effects of detonating appropriately scaled charges in earth at varying distances from targets of five scales. The charge for the full-scale target was 1000 lb. of TNT, while a few charges of 3200 lb. of amatol were also detonated. At the conclusion of this year, a large number of interim reports were rendered, as described in more detail later.

The above chronological survey will perhaps have illustrated with sufficient clarity what the principal contributions of the Committee can be said to have been. They may be summarized as follows:

1. Evaluation of prior literature of terminal ballistics.
2. Working up of pertinent data on the terminal ballistics of steel, principally taken from Service sources with some small additions from our own work or that of NDRC.
3. A very large addition to the data on and interpretation of the local effects of impact and explosion on reinforced concrete. This will perhaps be looked upon by most people as the major contribution of the Committee.
4. Preliminary studies in the much neglected field of the penetration of projectiles into earth.
5. Initiation of studies in this country on the characteristics of detonations in air and the measurement of their physical effects. This work was not of major importance to the Committee and was soon carried forward much more

vigorously by Divisions 2 and 8 of NDRC and by the U. S. Army Ordnance Department.

6. A major study of the effects of detonation of explosives in earth. This is believed to provide the first large body of data in this field.
7. Studies on the dynamic effects of impact on structures. These were indecisive, but it is believed they were carried far enough to indicate that in the present state of the art of fortification design the more elaborate studies necessary to produce firm conclusions might not prove justifiable.
8. Contribution to the knowledge of civilian defense items, including especially:
   (a) Evaluation of the resistance of American frame houses to blast and earth shock.
   (b) The adoption of standard reinforced concrete surface shelters for civilians.
   (c) Tests on the penetration to be expected into American buildings by enemy incendiary bombs.
9. Contribution to the general technical background of civilian defense, especially through the Central Technical Committee of the Office of Civilian Defense, the Interdepartmental Advisory Committee on Protection, and the Committee on Conservation of Cultural Resources.
10. Contribution to the art of attack, especially from the air but also by gun fire:
    (a) Through the personal services of consultants furnished by the Committee to the appropriate military establishments.
    (b) Through the NDRC publication formerly entitled *Effects of Impact and Explosion* and now changed to *Weapon Data—Fire, Impact, Explosion*, and the CPPAB publication *Terminal Ballistics and Explosive Effects*.

(c) Through the use of these and the other reports of the Committee in the preparation of widely distributed reports of other organizations. A few examples of such reports are:

Performance of Bombs and Projectiles against Shore Installations, U. S. Navy Bureau of Ordnance Pamphlet 1172. (Confidential).

Data on Functional Characteristics of Bombs by Fano and others, Ballistic Research Laboratory Report No. 477, Aberdeen Proving Ground, Ordnance Dept. (Restricted).

Terminal Ballistic Data, Volume I: *Bombing*, Volume II *Artillery Fire*, Office of Chief of Ordnance, U. S. Army. (Restricted).

Data Sheets, Armament Design Department, British Ministry of Supply. (Br. Secret).

Selection of Bombs and Fuses for Attack of Industrial Targets, U. S. Navy Op-16-V Report A6. (Confidential).

11. Contribution of personnel. It is not an exaggeration in dealing with the contributions of this Committee to point with pride to the considerable number of civilians previously unskilled in this work who have subsequently left our employ to take on a more active role as field service consultants, usually, but not always, to the Air Forces, in all the theaters of operations. It is difficult here to separate the contribution made by our Committee from that made by the Princeton University Station of Division 2 of the NDRC, with whom we have worked so harmoniously almost from the beginning. Of our own personnel, the following are now working in some such field capacity full time: Professor H. P. Robertson, Messrs. David Mayer, R. J. Hansen, and N. C. Dahl, and Professor N. M. Newmark, while as a result of our close relations with Division 2, a very much larger num-

ber of people have been subjected at Princeton to the same environment with the deliberate purpose of making them ready for field work. Thirty-five men are now out in the field following such training. It is very likely that if an objective score could be tallied and if the score were to be kept only upon its effect upon this war, two contributions would stand foremost:

(1) The work of Dr. R. A. Beth and his colleagues in evaluating the resistance of concrete to penetration and

(2) The anonymous work done since they have left us by the above-mentioned field personnel.

This in effect concludes a rehearsal of the activities of our Committee. The following section deals in somewhat more detail with the principal subjects listed immediately above.

ANALYSIS OF PRINCIPAL PROJECTS

1. *Literature Survey*

As a natural first interest a survey was made of past experience in the field of terminal ballistics resulting in *Terminal Ballistics, A Preliminary Report*, by H. P. Robertson, dated January 1941. This report, though made so early, remains the basic report of its kind which has been rendered by the Committee. In it Robertson surveys the general theories of penetration, the problem of rupture (scabbing) and of perforation without rupture, and the effect on penetration of the physical properties of the target. He provides a substantial bibliography of those references from which material was actually used in preparing the report, beginning with Robins in 1742 and concluding with British ARP publications of 1939. The principal authors cited include Robins, Euler, Morin, Poncelet, Piobert, Didion, Martin de Brettes, v. Wuich, Résal, Levi-Civita, Pétry, Nobile de Giorgi, Cranz, Thompson, Scott, Peres, Milota, Gaede, Vieser, Heidinger, Skramtajew, Montigny, Speth, Bazant, Gailer, Harosy, and Hayes.

2. *Terminal Ballistics of Concrete*

This study was intended to reveal the relations between mass, shape, velocity and angle of incidence of a projectile (usually non-deformable) and its penetration into massive concrete or perforation through slabs of concrete (including the phenomenon of scabbing), and to study further how these relations might be affected by changes in the properties either of the concrete itself or of its reinforcement. Beginning with small-scale shots on model concretes at Princeton University, the study ultimately embraced consideration of rather random results from full-scale bombing tests at Edgewood Arsenal (deformable projectiles) and more carefully measured results over the full gamut of scales (AP bomb test at Aberdeen which was made with 12″ projectiles; 3″ and 6″ projectile tests on 3/16- and 3/8-scale models at Dahlgreen Proving Ground of the Navy; full-scale (16″) projectile tests at Fort Cronkhite, California; and the large P and E tests designed by the Committee and carried out at Aberdeen Proving Ground with the assistance of the Ordnance Department and the Corps of Engineers, and ranging over scales from caliber .45 to 155 mm, obliquities from 0° to 35°, impact velocities from 600 to 3000 ft/sec, and concrete compressive strengths from 4000 to 6500 psi). The P and E tests at Aberdeen were followed by an extensive series of carefully controlled tests at Princeton using caliber .50 projectiles of various types, and studying both penetration and perforation of concretes varying in compressive strength from 900 to 8000 psi, a large variety of reinforcing designs, concrete aggregates, and other concrete properties over a wide range of projectile velocities and obliquities and target thickness. The results of these tests together with the results of the first concrete properties survey threw light on the effect of concrete properties on both penetration and perforation. In the course of this work a number of ad hōc trials were also made, usually to answer a direct inquiry from the Chief of Engineers as to specific mixtures of concrete or admixtures thereto, proprietary materials, or special forms of reinforcement. Finally, some exploration was made as to the effect of laminating the resisting slab as a desirable practical measure for field construction of massive fortifications, and as to the probable resistance of combined materials, especially concrete and armor.

In addition to the extensive experimenting with inert projectiles, attention was paid to the effect of subsequent detonation of the explosive carried by the bomb or shell. These studies ranged from detonations on the surface through detonations of explosive placed in the craters formed by the use of inert impact to the use of live projectiles fuzed to detonate following penetration.

This work was from the outset and to its completion under the direction of Dr. R. A. Beth, who had notable assistance from Mr. J. Gordon Stipe, Jr.

A. 27 April 1941: *Terminal Ballistics II—Experimental Study of Penetration in Concrete*, by Walker Bleakney and Richard A. Beth.

This first interim report on the subject describes the small-scale experimental work up to the date of publication, and deals at some length with the preliminary problems which had to be solved, such as the difficulty of designing model concrete, the design of proper targets of massive concrete, the development of a model projectile, and the preparation of necessary apparatus, including guns and velocity-measuring devices such as chronographs and ballistic pendulums. It contains a summary of the penetration data obtained in these first experiments, including the details of about 180 rounds of caliber .45 at velocities ranging between 800 ft/sec and 2400 ft/sec with the majority of shots made at 1000-2000 ft/sec. The targets were principally concrete blocks up to five months old, but included some granite, a few younger concrete blocks and a few slabs. The report also includes a statement on the dimensional analysis of penetration and a very preliminary statement on methods of calculating penetrations in concrete.

Part I of the Final Report for 1941 gives more complete data and discussion.

B. November 1941: *Penetration of Projectiles in Concrete*, by Richard A. Beth. Interim Report No. 3, 1941-1942.

A discussion of the possible "scale effect" for concrete penetration. This effect results when, at a given velocity and for a given concrete, the penetrations of similar projectiles are other than proportional to their calibers.

C. January 1942: *Velocity Measurements at Fort Cronkhite California*, by Walker Bleakney. Interim Report No. 4, 1941-1942.

Tests were initiated by the Corps of Engineers and the Panama Canal Zone for firing of 16″ projectiles at bomb velocities against targets appropriate in scale and ranging from 13′ to 23′ thick. Difficulties were encountered on the site in measuring the impact velocities and the services of the Committee were invoked. Professor Bleakney took the necessary apparatus to California, set it up, and supervised the first measurements. This report deals only with the method of measurement and the results obtained for velocity. The corresponding data on penetration are not discussed here but are, of course, incorporated in subsequent reports by Dr. Beth.

D. 19 February 1942: *Suggestions for Procedure at Forthcoming Penetration and Explosion Tests on Concrete Slabs*, by Walker Bleakney and Richard A. Beth. Interim Report No. 7, 1941-1942.

Previous experience with large-scale proving-ground tests (AP bomb test at Aberdeen and Fort Cronkhite test) had indicated the necessity for a carefully planned and coordinated procedure. Since the program about to be embarked upon at Aberdeen (P and E tests) was the most elaborate one yet planned and was probably the last set of large-scale tests which would be possible in the war, this report was written to set forth the desirable procedures for the forthcoming tests.

These procedures were followed in all essential details when the tests were made.

E. February 1942: *Perforation Tests on Gunite and Concrete Slabs with Cal .30 and Cal .50 AP Projectiles*, by Richard A. Beth. Interim Report No. 5, 1941-1942.

At the request of the Chief of Engineers, penetration tests were made on a special material, Gunite, poured by its sponsor into targets as required by the Committee. This report deals with these specific results. They are also incorporated into the larger studies of the Committee.

F. April 1942: *AP Bomb Test—Comment*, by Richard A. Beth. Interim Report No. 9, 1941-1942.

As part of the program of determining the terminal ballistics of concrete, the Corps of Engineers caused to be constructed at Aberdeen Proving Ground vertical slabs of three thicknesses, 26″, 60″, and 81″. Each of the three slabs was 30 feet square and had five types of reinforcements, one at the center and one at each of the corners. 12″ AP projectiles were fired at approximately 1000 ft/sec and obliquity of approximately 20° at the center of each of the five regions on each slab and appropriate measurements taken of penetration, crater, and scab. In addition, dynamic strain gages designed and installed by Professor A. C. Ruge were used in an effort to get a picture of the dynamic behavior of the slabs under impact. High-speed motion pictures were used as an additional tool, especially for the measurement of entrance and exit velocities. Tests were made on 27-30 June 1941. The results were reported by the U. S. Engineer Office, Baltimore, Maryland, by Dr. Ruge, and by the Waugh Laboratories. On request of the Chief of Engineers, Dr. Beth provided his comment for the Committee. It includes a partial analysis of the data obtained, derives entrance and exit velocities so far as these could be derived and attempts to interpret the data from the strain gage readings. The general penetration data are included in the analysis of the over-all problem afforded in later Committee reports.

G. June 1942: *A Brief Summary of Recent Data on Penetration in Concrete at Various Scales*, by Richard A. Beth. Interim Report No. 18, 1941-1942.

This report summarizes the principal experimental data which was obtained during the previous year on the penetration of non-deforming projectiles in concrete. Of these the principal ones were:

AP Bomb Test, Aberdeen Proving Ground, 27-30 June 1941.

Additional sets of cubes at Princeton University.

Shots at 37 mm and 75 mm on Bombproof B, Aberdeen Proving Ground, 5-6 September 1941.

Shots from 16″ rifles at Fort Cronkhite, California, 8 January and 1 March 1942.

Shots on 12 of the 34 slabs of the P and E test at Aberdeen Proving Ground.

The purpose of the report was to make the experimental results available for design purposes immediately, since it was expected that the averaged values here given would not be changed materially by further experiments and more careful analyses. The report also contains some preliminary data on scabbing and perforation but no generalizations were attempted in this field.

H. January 1943: *Penetration and Explosion Tests on Concrete Slabs—Report I: Data*, by Richard A. Beth and J. Gordon Stipe, Jr. Interim Report No. 20, 1942-1943.

I. January 1943: *Penetration and Explosion Tests on Concrete Slabs—Report II: Crater Profiles*, by J. Gordon Stipe, Jr. Interim Report No. 21, 1942-1943.

The purpose of the tests described in these two reports was to determine limiting conditions and collateral information on penetration and explosion of 37 mm, 75 mm, and 155 mm uncapped projectiles for varying thicknesses of concrete slabs.

For this purpose 39 slabs were cast. Five were made and tested at Princeton, three for 37 mm and two for caliber .50 projectiles. The remaining 34 were made and tested at Aberdeen Proving Ground, including ten for 37 mm projectiles, ten for 75 mm projectiles and ten for 155 mm projectiles. At each of these three scales the ten slabs consisted of five thin and five thick slabs, the thick slabs being 2.5 times the thickness of the thin slabs. In addition to these slabs there were four slabs of special design. Two of these were similar to the others in all details except for the addition of a metal plate on the rear face designed to prevent scabbing. The other two were a thin and a thick slab at the 155 mm scale reinforced with many small bars instead of a smaller number of large bars.

In each group, two of the slabs were tested by normal firing at approximately 65 days' age, two by normal firing at six months' age and one by oblique firing at six months' age. Generally speaking, 9 to 15 rounds were fired at each slab over velocities ranging from the lowest practicable to above the perforation limit of the slab. In addition, a series of 37 mm shots was taken at velocities ranging from 600 to 3000 ft/sec on each of the slabs tested at the two largest scales to provide a direct comparison for the penetration at the different scales. Comparison shots with special caliber .45 bullets were fired at a number of the targets. Efforts were made to determine perforation, scabbing, and sticking limit velocities by bracketing. Careful attention was given to concrete properties and to measurement of crater profiles. Specially designed charges were detonated in many of the inert craters. In some cases live ammunition was fired. Finally there were some departures from the general program as the evidence seemed to dictate and space was left for additional shots at the end, not contemplated in the original program.

This program, with targets designed by the Committee and with the firing and measurements directed by Dr. Beth, yielded an enormous amount of carefully accumulated data. In order that these raw data could be available in useful form at the earliest possible date the subject reports attempt no extensive analysis although some preliminary graphs are provided which might aid in interpolatory estimates. The synthesis of these and other data into more usable rules, graphs and formulae and the considerations of their bearing on the theory of the physical phenomena involved in penetration and perforation of concrete were reserved for later reports. Nonetheless these reports contain the largest reservoir of good data on this subject of which the Committee has any cognizance and they will, therefore, doubtless constitute fundamental sources for the student for many years to come.

J. 27 February 1943: *Plastiment Concrete Penetration Tests,* by R. A. Beth and J. T. Pittenger. Interim Memorandum M-7, 1942-1943.

At the request of the Chief of Engineers comparative small caliber tests were made to determine how the addition of a small amount of Plastiment admixture might affect the penetration resistance of concrete. This memorandum reports the results, which were not spectacular either way.

K. April 1943: *Soil Cement Penetration Tests,* by R. A. Beth and J. T. Pittenger. Interim Memorandum M-8, 1942-1943.

This report describes tests for small caliber penetration of hand-rammed soil-cement blocks, made as a result of request from the Office of Civilian Defense and showing that the material was not particularly effective.

L. May 1943: *Resistance of Laminated Concrete Slabs to Perforation,* by Robert J. Hansen. Interim Memorandum M-9, 1942-1943.

This memorandum describes the result of two sets of tests at 37 mm scale designed to show what loss of effectiveness in resisting projectile impact might be expected if the same thickness of slab be provided in continuous laminae instead of monolithically. If the loss were to be small, there might be considerable practical advantage in field work. On the basis of the meager data available, it appeared that the lowering of limit velocity by only a few layers was not greater than 5% for each construction joint.

M. July 1944: *Repeated Fire and Edge Fire Effects on Small Concrete Slabs,* by J. Gordon Stipe, Jr. Interim Memorandum M-12, 1943-1944.

The title is self-descriptive. The memorandum gives the number of rounds required for perforation of reinforced concrete slabs by repeated fire attack for two thicknesses of concrete and for different distances from the slab edge. Two reinforcing schemes were used and the number of slabs tested was limited.

N. 30 June 1944: *Composite Slabs,* by J. Gordon Stipe, Jr. Interim Memorandum M-13, 1943-1944.

Based on the data available to the author, this memorandum gives a method for estimating the perforation proof-thickness of slabs composed of concrete and steel, soil and concrete, and of the three materials.

O. July 1944: *Concrete Properties Survey—Effect of Concrete Properties on Penetration Resistance,* by Richard A. Beth, J. Gordon Stipe, Jr., M. E. DeReus, John T. Pittenger. Interim Report No. 27, 1943-1944.

P. *Concrete Properties Survey, Appendix A—Preparation and Physical Tests of Concrete,* by M. E. DeReus. Interim Report No. 27, 1943-1944.

Q. *Concrete Properties Survey, Appendix B—Penetration Data,* by Richard A. Beth, J. Gordon Stipe, Jr., and John T. Pittenger. Interim Report No. 27, 1943-1944.

These reports deal with tests in massive concrete, using caliber .50 model-scale projectiles to determine the effect of concrete properties on penetration resistance. They cover the results from 154 cube targets made of some 75 different concretes with projectiles fired at normal incidence and at velocities from 600 to 2000 ft/sec. The earlier Concrete Properties Survey data given in Part I of the 1941 Final Report of the Committee were not so extensive or so accurate as the present work and are therefore to be regarded as auxiliary and preliminary to the data reported here. The report provides an analysis of the effect of various concrete properties on the significant parameter in a new empirical formula for penetration derived from the ballistic data. So far as the work of the Committee is concerned these reports are the definitive statement on this part of the problem.

R. 30 June 1944: *Ballistic Tests of Small Concrete Slabs,* by J. Gordon Stipe, Jr., M. E. DeReus, John T. Pittenger, and Robert J. Hansen—Interim Report No. 28, 1943-1944.

S. 30 June 1944: *Ballistic Tests of Small Concrete Slabs, Appendix A—Tables of Data,* by J. Gordon Stipe, Jr., M. E. DeReus, John T. Pittenger, and Robert J. Hansen. Interim Report No. 28, 1943-1944.

These two reports deal with an extended series of tests on the perforation and scabbing of small concrete slabs by caliber .50 model-scale projectiles. The tests were planned to supplement the information obtained in the large-scale Penetration and Explosion Tests as reported in Interim Report No. 20, particularly with respect to the effect of slab thickness, concrete strength, aggregate gradation, various schemes of reinforcement, scab plates, and obliquity of incidence.

T. 30 June 1944: *Contact Explosions on Concrete,* by D. G. Kretsinger. Interim Report No. 29, 1943-1944.

This report summarizes the results of tests with small-scale explosions to determine effect of contact explosions on slabs of varying compressive strengths, effect of projectile impact and contact explosions on spaced concrete slabs, effect of method and amount of reinforcing steel in concrete slabs attacked by contact explosions and effect of intimacy of contact on damage to concrete slabs by different explosions.

The above reports constitute all the formal material presented by the Committee in independent form on this subject. In addition to these, it will be desirable to make reference to the final reports of the Committee, each of which takes account of the state of the art at the time of making the report.

U. Final Report 1940-1941

V. Final Report 1941-1942

W. Final Report 1942-1943, with

X. Appendix to Final Report 1942-1943, *Terminal Ballistics and Explosive Effects*

This appendix combined with reports made since June 1943 constitutes the final findings made by the Committee on this subject. It is believed that most students can follow all the essential work of the Committee in this field by consulting the following of the aforementioned reports: A, G, H, I, L, M, N, O, P, Q, R, S, T, U, X, and by referring to the appropriate data sheets in a report of Division 2, NDRC formerly entitled *Effects of Impact and Explosion* and now changed to *Weapon Data—Fire, Impact, Explosion*.

3. *Penetration in Soils*

Though earthworks undoubtedly constitute a very large portion of all fortifications, especially those of a field nature, the work of the Committee was not strongly directed towards the study of earth until 1943. At that time, as a result partly of interest in the attack on enemy earthworks and partly as a result of a direct inquiry from the Chief of Engineers, the Committee made a survey of what was then known, and incorporated these findings in the Appendix to the Final Report 1942-43 *Terminal Ballistics and Explosive Effects*.

This study revealed the very sketchy nature of the available information. Accordingly in the year 1943-44, such time as was available from studies of higher priority was devoted to establishing at least a preliminary knowledge of the factors governing penetration in soils. This information is recapitulated in *Pene-*

tration in Soils, by J. Gordon Stipe, Jr., Interim Report 30, 1943-44. This report covers studies of penetration of caliber .50 bullets of various types into sand, loam, and clay, and perforation of parapets of these materials. Data on penetration of bombs and large caliber projectiles available from other sources are considered and correlated with the small caliber penetration data.

4. *Air Blast*

Save for a few minor reports, which are dealt with elsewhere in this summary and which, in general, treat of the effects of blast on a specific target, the reader is referred to the bibliographies of Divisions 2 and 8 of the National Defense Research Committee for reports on explosions in air.

5. *Detonation in Earth*

As a result of the first Edgewood bombing trials, it was realized that bombs which penetrated the earth near to a fortification wall and detonated there might be very destructive. Attention was paid in the very first Final Report to methods of avoiding this danger, but these early studies were entirely in the field of design and relied upon the provision of a burster which would stop the bomb from getting near enough to the fortification wall to do damage. The next step in this study was to consider replacement of the horizontal burster by a vertical wall separated by a suitable space from the main wall and intended to take up the shock without deterioration of the main wall. These early trials at the model scale at Princeton showed clearly that the problem was very complex and would need fundamental study; such fundamental study would, moreover, have to be supplemented by a considerable amount of experimentation with specific targets; time and cost considerations would require that these be models. It was accordingly essential to determine what scale relations would have to be considered in model testing. This led to the two general lines of further attack: one would endeavor to measure the transients arising in earth (pressure, acceleration, velocity, displacement) and the permanent displacement resulting from the detonation at various depths in various soils of various amounts of a standard explosive and how these would vary with distance from the charge; another would attempt, by studying a suitable standard target at many scales up to full size, to determine the relation of these transients to damage and whether scale effects occurred. Both of these culminated in the large-scale tests in Oklahoma which were conducted in the late fall and winter of 1943.

Insofar as the measurements were concerned, the work has always been under the general direction of Dr. C. W. Lampson, with specially strong assistance from Dr. G. T. Reynolds. Mr. David Mayer was the principal in the work on targets with strong assistance from Messrs. D. G. Kretsinger and M. E. DeReus, and occasional concentrated help as well from Messrs. N. C. Dahl and R. J. Hansen.

A. March 1942: *Preliminary Measurements of Earth Pressures and Movements under Detonation*, by L. W. Blau, W. M. Rust, Jr., W. D. Mounce and J. M. Lohse. Interim Report 8, 1941-42.

Three preliminary memoranda from the Humble Oil and Refining Company on the measurement of earth displacement and pressure in the neighborhood of an explosion of dynamite. These tests were of an exploratory nature and yielded results which define the magnitude of the quantities and the nature of the experimental difficulties.

B. May 1942: *Report on Exploratory Tests on Underground Bursters*, by D. G. Kretsinger and David Mayer. Interim Report 10, 1941-42.

Report on preliminary tests at model scale (3/40) of the use of vertical bursters in various combinations to protect five foot (prototype) principal fortification walls against the detonation of a prototype charge of 1185 pounds of TNT at various nearby distances from the protective wall.

C. June 1942: *Preliminary Measurements of Earth Pressures from the Explosion of Small Charges of TNT*, by C. W. Lampson. Interim Report 16, 1941-42.

Report with oscillograms of measurements with quartz pressure gages made on the face of vertical concrete slabs to obtain the pressure-time relation for small charges of TNT (½ lb.) set in earth at various distances from the target.

D. September 1942: *Measurements of Earth Pressures and Movements under Detonation*, by W. M. Rust, Jr., and W. D. Mounce. Interim Report 19, 1942-43, with Preface by C. W. Lampson. Sequel to A.

Description of apparatus for measurement of pressure and of displacement, and a report of the results of these measurements at various distances from charges of 2.5 pounds of 60% gelatin and of 50–1000 pounds of TNT.

E. October 1942: *Proposal for Expansion of Program on Underground Explosions*, by David Mayer. Interim Memorandum M-3, 1942-43.

Proposal for the program which, with but minor modifications of detail, was subsequently adopted and worked through at Camp Gruber, Oklahoma.

F. November 1942: *Pilot Tests for Humble Program . . . Investigations of Type of Target and of Target Distances*, by David Mayer. Interim Memorandum M-4, 1942-43.

Report on model-scale experiments at Princeton which led to selection of targets for Camp Gruber program and of the distances at which charges were to be detonated.

G. June 1944: *Effects of Underground Explosions*, Interim Report 26, 1943-44.

Vol. I. *Subsurface and Target Phenomena*, by C. W. Lampson

Vol. II. *Subsurface and Surface Phenomena*

Part I. Work of Geophysical Research Corporation

Part II. Work of Humble Oil and Refining Company

Summary by C. W. Lampson

Vol. III. *Resulting Damage to Structures*, by David Mayer and N. C. Dahl.

As a sequel to E and F, and with the assistance of the Corps of Engineers, the Ordnance Department, the Humble Oil and Refining Company, the Geophysical Research Corporation,[8] and the Princeton University Station of Division 2, NDRC, an elaborate set of tests lasting many months was carried on at Camp Gruber, Oklahoma. These involved several targets at each of 5 scales from 1/5 to full size, the latter being very massive. Detonations were made of appropriate charges ranging from a few pounds of TNT to 3200 pounds of amatol. These detonations were initiated at several different critical distances from the targets. Other charges were detonated for comparison in free earth. Comparison was made between light-cased charges and bombs of equivalent charge weights. Careful measurements were made of the velocity, acceleration, displacement, and pressure as functions of time and distance from the charge, as well as measurements of the permanent displacement and of the effects upon the various targets. These lengthy reports also include a comparison of this work with that done at smaller scales at Princeton.

As in the case of Terminal Ballistics of Concrete, certain pertinent data related to explosions in earth have been incorporated in *Terminal Ballistics and Explosive Effects*, the Appendix to the Final Report for 1942-43, and in *Weapon Data—Fire, Impact, Explosion*, a report by Division 2, NDRC. These two reports, together with all the reports listed above, will have to be consulted by the student. Report G represents the final statement of the Committee insofar as its work was carried.

6. *Dynamic Effects of Impact on Structures*

The Committee's original impression that the remote effects of impact or explosion were not very significant has not been

[8] The reports by this group were published by NDRC, reports A-160 and A-238 *Effects of Sub-Surface Detonation in Earth*, Parts I and II, by B. B. Weatherby.

changed by the evidence which has come before it. Nonetheless its directive included the instructions to provide a "rational method of design." Design engineers in particular have throughout the life of the Committee been consistent in their insistence that we provide such a method of design.

The problem is very complicated, involving as it does a difficult dynamic analysis of a complicated structure (where even the simple structure is hard to handle), uncertainty as to the forces applied and the duration of the application, and uncertainty as to whether the behavior of the resistant material is elastic or plastic or, as is most probable, both. Methods which have been proposed have often led by calculation to results which called for amounts of material quite ridiculous in view of the known performance of lesser amounts.

The Committee feels that it has not come to grips with this problem but that it is quite unnecessary to do so in order to design a satisfactory fortification.

Its contributions have been of two sorts:

(a) A few theoretical papers on simple problems of dynamic loading, plus a limited number of experiments made to afford others data on which to develop their theories.

(b) The stimulation of engineering thinking through contracts made on its behalf by NDRC with the Massachusetts Institute of Technology (Dr. J. B. Wilbur) and the University of Illinois (Drs. F. E. Richart and N. M. Newmark). The work of these two groups will be found in reports of Division 2, NDRC.

A. January 1941: *Memorandum on Motion of Target Block on Impact by Projectile*, by H. P. Robertson.

The simple overturning problem under dynamic load analyzed to assist the engineers in problems of blast walls.

B. February 1942: *Memo on Rotation Under Impact and Blast*, by H. P. Robertson. Interim Report 6, 1941-42.

Generalization of the previous memorandum.

C. June 1942: *Free Recoil of a Target and Its Effect on Stopping Power*, by Walker Bleakney. Interim Report 17, 1941-42.

A qualitative discussion of the reason why nets or elastic structures are ineffective against bombs or projectiles. Results of some typical experiments and demonstration that the results therefrom confirm predictions from the theory of the mechanics of penetration.

D. June 1942: *The Reaction of Thin Beams and Slabs to Impact Loads—Part I: General Theory*, by H. P. Robertson and R. J. Slutz. Interim Report 13, 1941-42.

Self-explanatory title.

E. June 1942: *The Reaction of Thin Beams and Slabs to Impact Loads—Part II: Beams*, by H. P. Robertson and R. J. Slutz. Interim Report 14, 1941-42.

The effect of impact loads on simply-supported and cantilever beams, or slabs acting as beams within the elastic limit. As such it is an extension to dynamic loading of the usual approximate theory of the behavior of beams under static loads.

F. June 1944: *Impulse Delivered to a Plane Slab by a Contact Explosion*, by D. G. Kretsinger. Interim Memorandum M-11, 1943-44.

Results of quantitative measurements made on a pendulum in answer to a request for data on this point by the Chief of Engineers.

7. *Contributions to Knowledge of Civilian Defense*

A. August 1941: *Suggestions Based on Observations of Results of Tests at Edgewood Arsenal* 21 *May* 1941, by F. E. Richart and N. M. Newmark. Interim Report 1, 1941-42.

Suggestions by two well known engineers as to construction details which would make civilian reinforced concrete buildings more resistant.

B. October 1941: *Design of Typical Interior Floor Panel of Reinforced Concrete Industrial Building.* Interim Report 2, 1941-42.

Further suggestions along the same lines in response to specific request from Chief of Engineers.

C. May 1942: *Incendiary Bomb Test,* by R. J. Hansen. Interim Report 11, 1941-42 and *Appendix B* thereto.

Report on penetration of German incendiaries through various types of American roofs as the result of tests carried on following request by the Office of Civilian Defense, Public Buildings Administration, and the National Bureau of Standards.

D. December 1942: *Fundamental Principles of Structural ARP,* by J. E. Burchard.

Popular treatment of the main things a civilian engineer needs to know about the effects of impact and explosion.

E. February 1943: *The Use of Bamboo for Reinforcement in Concrete,* by N. C. Dahl. Interim Report 22, 1942-43.

Evaluation of the use of bamboo in concrete to answer inquiries from the Office of Civilian Defense.

F. April 1943: *Static Detonation Trials of Three Framed Houses at Area J, Aberdeen Proving Ground, December 19, 1942 to January 11, 1943,* by J. E. Burchard, H. L. Beckwith, E. N. Gelotte and N. C. Dahl.

Full description of three American frame houses built at Aberdeen and the damage done to them by detonations in air and earth, principally the former, of large charges of explosive at distances ranging from 500 to 18 feet from the target.

G. May 1943: *Relative Safety of Basements and Upper Stories of Frame Houses in Air Raids,* by Henry Scheffé. Interim Report 24, 1942-43.

A statistical treatment of the probability of casualty based on the evidence in the preceding report and existing data on fragment distribution.

8. *Miscellaneous*

The student who wishes best to follow the thinking and work of the Committee in more detail than afforded by this report, but in less detail than would be required by study of all the bibliographical references, might well confine himself to study of the Final Reports for the years 1940-41, 1941-42, and 1942-43, and especially to the Appendix to the last, *Terminal Ballistics and Explosive Effects*; to the pertinent sheets from the Division 2, NDRC report *Weapon Data—Fire, Impact, Explosion*; to *Fundamental Principles of Structural ARP*; and to CFD Memorandum M-10 by Drs. Walker Bleakney and A. H. Taub entitled *Remarks on Fortification Design*.

SUGGESTED FURTHER RESEARCH

We leave this problem with much undone. It is appropriate that we should leave some record of what we wish we had been able to do. The text which follows attempts to provide that record. This is not an easy task. If we confine ourselves to a list of subjects, it may prove less comprehensible to the reader or our successor than our own familiarity would lead us to suspect. If we are elaborate, we run the risk that obsolescence may make us seem ridiculous. Of the two evils the latter seems the lesser.

In lieu of the usual apology, let us say, what we hope is obvious, that we recognize that present trends in weapon design, if projected very far, are capable individually or in combination of making present fortifications obsolete and of rendering a large part of our work only of academic interest in the future. Let it be noted that we are not aware of the information which will be available to us from our enemies at the war's end. Let it be admitted that we make no claim toward skill in prognostication of what new developments will be or how they will affect present design practice.

The framework of these notes is that of a short span of time. They are concerned principally with those items to which we should have given more attention in these years past, had there been more time for that attention. If, by the time they are needed, our methods and our thought are obsolete, this will be apparent to our successors who will be tolerant of our ignorance. No serious harm will have been done.

Each of the persons who has been engaged in this work has his own ideas as to what else he might profitably have done. Each has his own opinion as to the emphasis which should be laid on the various possible lines.

In order to arrive at this text, the Committee has consulted with all those who have contributed most importantly to our past work and who are now available.[4] Each has written his own independent impressions as to the desirable contents of this note.

The total of these impressions reveals no dichotomy with respect to the subjects to be covered and only a reasonable difference of opinion as to relative importance.

The editor had first to decide whether to issue the notes as a composite and therefore anonymous or team document or to publish each suggestion separately, associated with the name of its author. The latter has of course the advantage that the reader may to each in the words of Jefferson, "ascribe the faith and merit he chooses."[5] Since this would result in considerable repetition, since the reader will in any event assign his own emphasis in terms of his times, and since we have always acted as a team, we conclude to ring down the curtain in the way we began.

The limitations of the suggestions are then that they do not have the advice of some of our most distinguished collaborators, that they deal principally with work which should be done now were the war to continue long and were the defensive to become

[4] Including R. A. Beth, W. Bleakney, C. W. Curtis, D. G. Kretsinger, C. W. Lampson, J. G. Stipe, Jr., and A. H. Taub. It unfortunately excludes N. C. Dahl, R. J. Hansen, David Mayer, N. M. Newmark, G. T. Reynolds, H. P. Robertson, and M. P. White, all of whom are on foreign duty.

[5] Autobiography, 6 January 1821. Jefferson was of course referring not to a scientific matter, but to the pedigree of his wife's family.

our role, and that they are principally concerned with the major interest of this Committee, the design of heavy fortifications.

Terminal Ballistics—General

From a fundamental point of view the greatest weakness in our present knowledge of terminal ballistics is the lack of adequate ideas concerning the forces resisting the projectile. This applies really to all materials, to steel as well as to concrete. A quantitative understanding of the force function and the variables on which it depends would solve many extremely practical problems; in fact all practical answers based on extrapolations of empirical formulae will continue to be uncertain until such an understanding provides an integrated rational basis covering all aspects. There are certain problems which cannot be answered even empirically at present because of this lack; among these are problems connected with the time of penetration (optimum fuzing) and with the conditions under which deformation or rupture of bombs or shells will occur.

There are two paths open for attaining the required understanding:

1. By analysis of present and future penetration data. This reduces to a kind of "cut-and-try" of various possible force laws or the attempt to deduce their form from the penetration curves as observed.

2. By physical experiment designed to measure phenomena and record time *during* penetration followed by a careful analysis to deduce general force laws from the observations.

Up to the present, terminal ballistics work has proceeded generally along the lines of *1*. The measurements correspond to *integrals* of the equation of motion $F = ma$. From these it is not possible rigorously to deduce the form of the force function F. This is not possible even under the assumption that the resisting force depends only on the values of x (position) and v (velocity) during the motion. It is doubtful whether even this simplifying assumption is true, although it seems to be the only one considered by previous workers.[6] Under two still more restrictive assumptions, the problem can be solved completely,[7] namely, that the force F depends *only* on either (a) the velocity v (Sectional Pressure Theories), or (b) the depth x (Sectional Energy Theories). In each of these cases the force F during penetration may be deduced from a knowledge of the measured maximum penetrations for all striking velocities. The results in neither case, however, agree with the observed variation of penetration with projectile mass or with caliber (scale effect).

Present work in this direction consists of the attempt to make use not only of the observed penetration-velocity curves, but also the observed dependence on mass and caliber in order to evaluate F under the assumption that F depends on x and v jointly in some prescribed way, e.g., that $F = a(x) + b(x)v^2$. The latter can be integrated explicitly, and the functions $a(x)$ and $b(x)$ can be evaluated from sufficiently accurate penetration-velocity measurements (curves) for different masses and calibers. The work is tedious and involved, and it is not yet clear whether consistent results will be obtained for both the mass analysis and the caliber analysis. If the results are consistent, good estimates of the time of penetration and of the maximum deforming force acting on a projectile will be possible. Extrapolations from the resulting penetration formula would be correspondingly strengthened.

This work should be continued, not only for its inherent promise, but also because it will be a guide to future penetration experiments, particularly with respect to devising controlled experiments on the effect of projectile mass and the effect of caliber and the way in which the results are to be evaluated. Until such clearer ideas are obtained, either by this approach on the basis

[6] See *Terminal Ballistics I*, by H. P. Robertson, January 1941.

[7] See *Penetration Theory: Estimates of Velocity and Time During Penetration*, internal report PMR6, Princeton University Station, Division 2, NDRC, 15 March 1944.

of present data, or by approach *2*, it does not seem worth while to conduct further penetration tests for theoretical purposes.

There are of course tests for many specific practical purposes which may be desirable from time to time.

Terminal Ballistics—Concrete

The most important question on which there is still no information is that of bomb break-up against concrete. There is a need for controlled tests on the deformation and rupture of GP bombs against various thicknesses and strengths of reinforced concrete. Obliquity and striking velocity should be varied; the striking velocity should be tested considerably above the perforation limit for each slab in order to find the effect on deformation of the bomb. Means should be found to project the bombs from guns, and probably tests against various thicknesses of armor and steel should be performed at the same time for the same purpose, once the gun, range, and facilities are available. It goes without saying that any such program should take advantage of existing information on penetration of "non-deforming" projectiles.

As a first step, attention might be focused on the measurement of the total time of penetration; while this is also an integral of the equation of motion, it is not so easily observed as the distance of penetration (maximum) or even as the striking velocity. Quite elaborate physical apparatus is required to measure the total time of penetration, and in devising means for doing this the still more basic question of measuring position or velocity as a function of time *during* penetration should be kept in mind as the ultimate objective.

Attempts have been made, both here and in England, to record photographically the shadow of the base of a projectile entering steel by sweeping it across a photosensitive plate at a known time rate. The shadow image is not sharp and two differentiations are required to deduce decelerations and forces. Improvements in technique are undoubtedly possible, and the method should not be abandoned unless something obviously better can be devised to take its place.

The electromagnetic method of recording velocity as a function of time during penetration in non-magnetic, non-conducting media[8] should be followed up and developed unless and until something better can be devised to take its place. It has the advantage that only one differentiation is required to deduce decelerations and forces. It is the only promising way which has so far been suggested for getting times of penetration (fuzing problems) and a direct measure of the force acting on the projectile (deformation and rupture problems; projectile and bomb design). Even if the old approach *1* of attempting to deduce the resisting force from measured integrals of the equation of motion should give encouraging results, it would be extremely important to be able to check them against direct observations of velocity as a function of time during penetration. In fact, no theory of penetration will rest on a secure base until such direct observations are in accord with it.

Work should also be done to modify the electromagnetic method for experiments on penetration in soil and other materials. The problem of optimum fuze setting for bombs striking earth is urgent, and a promising approach would be to use a series (say 5 to 10) of solenoids spaced a radius apart and connected alternately in opposition. A magnetized projectile moving at uniform velocity along the axis of the coils would produce a trace very much like a sine wave in the region covered by the coils, the peaks being proportional to the velocity, and the period corresponding to the time required by the bullet to cover a distance equal to the coil diameter. By embedding the coils in soil and using a small-caliber model projectile, a very good idea could probably be obtained of both velocity and position as a function of time during penetration. This experiment would have certain advantages over the two coil method devised

[8] See Princeton Monthly Reports Nos. 11, 17, and 28, Princeton University Station, Division 2, NDRC.

for concrete; the problem of stabilizing the magnetization of the projectile would be less severe because the shock on entering the target is not so strong; the method is self-checking in that the velocities as deduced from the height of the peaks should be consistent with the positions as represented by successive axis crossings of the trace. Some difficulties may arise from the tendency of bullets to curve in soil, and some coils may have to be replaced if they are struck; some modifications of the analysis may have to be made for the end coils—possibly a slightly different spacing or coil diameter toward the end would facilitate the analysis.

In connection with fuzing problems for anti-concrete projectiles and bombs it would be helpful to determine the time of perforation of concrete slabs for velocities ranging from the perforation-limit-velocity to much higher values. One method of doing this would be to take high-speed movies with camera set in the plane of the slab so that the field of view covers 30 to 40 feet of the projectile path in front of the slab and an equal distance in back. The time of perforation as well as both the striking and residual velocities should be obtainable from the films. It goes without saying that the results would be of interest in connection with any proposed theory of perforation.

Another piece of work which should be completed is the evaluation of residual velocities from the high-speed motion pictures taken during the Penetration and Explosion Tests.[9] These residual velocities would be helpful in predicting the penetration of successive concrete slabs, whether they be double or multiple fortification walls or successive floors to be perforated by a bomb. A knowledge of the residual energies would also have a bearing on any theories of concrete perforation which may be devised.

[9] Penetration and Explosion Tests on Concrete Slabs, reported in detail in PPAB Interim Reports Nos. 7, 18, 20, and 21. Prints of the high speed motion pictures taken during these tests are on file in the Office of the Chief of Engineers.

Additional experiments appear also to be required on the following subjects:

1. The effect of repeated fire and especially its relation to reinforcement
2. The effect of hypervelocity
3. The effect of very low velocities on thin slabs
4. Extensions of study of scale effect
5. Extensions of study of effect of other projectiles, especially those with quite low or quite high values of caliber density (w/d^3)
6. Extensions of the work on spaced protection.

Terminal Ballistics—Steel

The problems for steel are basically the same as those for concrete despite the much greater amount of work which has been done in steel. They are further complicated by difficulties attendant upon getting a projectile which will really be nondeforming and perhaps somewhat simplified by the nature of the material itself. At risk of some repetition, it appears wise to make a statement about further work on terminal ballistics of steel which will stand, independent of the previous statements about concrete.

During the past two years an immense amount of useful data concerning the perforating ability of standard Service projectiles has been accumulated. Very little information is available, however, covering the behavior of bombs against steel. (In the case of either projectiles or bombs, correlation of the existing empirical data is difficult, partly because there is inadequate knowledge of the forces resisting perforation, but mainly because too little is known as to how and when bombs or projectiles deform and as to the effect of this deformation on penetration.)

There are two approaches to a study of the forces acting during penetration. The most direct is by a measurement of the deceleration of the projectile during impact. This measurement requires ingenuity and extreme care in experimental technique and a considerable time would probably elapse before significant results were obtained. The measurements would supplement work of this type now being carried out at the Naval Research Laboratory in Washington. The forces acting on a projectile can also be inferred from values for the limit and residual energies of a non-deforming projectile. (Data of this type have already been obtained at model scale for wide variations in projectile and plate parameters for normal impact against homogeneous armor.) Under conditions where a non-deforming projectile is possible, these data should be extended to include oblique impact. Penetration measurements in massive armor should be made so that by comparison with perforation limit values, the effects due to the surface of the plate can be determined.

Data for the non-deforming projectile are of direct interest in the design of fortifications since this ideal type gives optimum performance from the point of view of attack. It seems at present impossible, however, to design a projectile which will not undergo break-up at high velocities and large angles of obliquity. For these conditions, the present meager data on the perforation limit of deformed or shattered projectiles should be extended, and as quantitative knowledge is obtained for the forces acting on the projectile, it should be applied to better projectile design.

Perforation data should be available for unconventional projectile types, such as are used with hypervelocity weapons. Empirical data are at hand for particular present-day projectiles of this type, but little is known at hypervelocities of the effects of caps or variations in the weight of the steel base supporting a tungsten carbide core. Firings to determine the results of varying the weights and shapes of these elements should be carried out.

There is need for data on the performance of bombs against armor. Since little is known of the factors controlling break-up of bombs, an answer to this question should first be obtained with regular bombs at full scale, but model-scale work might also be carried out for extending and correlating the results.

Terminal Ballistics—Soils

The most important and recurring question here has to do with penetration as a function of time. Direct full-scale experiments can be performed by the Services by dropping bombs with various fuzings (including duds) and carefully surveying the results as to craters formed and penetrations achieved.

The investigation of the scale effect in this medium is also of importance. Small-scale experiments are relatively easy to perform but until the scale effect has been determined, one is uncertain about the permissible extrapolation.

Finally, soils offer in greater measure than most materials the enormous difficulty of relating the properties of the test materials to those to be found in the field. Elaborate experiments in this field are perhaps beyond the scope of those interested in fortification design, and very desirable correlations may have to wait for further advances in the sciences of geology and soil mechanics.

Terminal Ballistics—New Materials

One important subject which has received relatively little attention is the development of new materials to be used in protective construction. The development of plastic protection against small calibers (and to some extent against shaped charges) is an important contribution to the general problem of protection which has concerned the Committee. Further developmental work on this and any other promising materials should be pushed.

The importance of this field may be magnified by progress which is being made in this war by both sides in the design of concrete-piercing projectiles. Work along this line should be of great interest to the Corps of Engineers, who are charged with the problem of fortification design. Experiments on possible means of breaking up the high-charge concrete-piercing type of projectiles could be performed; these means might involve the use of armor or other hard facing, or the use of one or more layers of stones, such as granite, one or two calibers in size, to break up larger projectiles after the fashion of plastic protection for small calibers, even though tentative experiments along this line at Edgewood Arsenal early in the war were not encouraging. Initiation of the delay fuze some distance before the wall would be effective, although it is hard to see how any suitable means could be devised.

Explosions—General

The situation in the field of explosions will depend in large measure on what will be accomplished during the rest of the war by various agencies of the NDRC. Certain programs are now in hand for studying these effects and future programs should be drawn up with the results of these in mind.

At the moment, and assuming no further progress, the following fundamental considerations seem important.

The phenomena associated with explosions may be classified into three groups:

1. Those associated with the point of detonation.
2. Those associated with the transmitting medium.
3. Those associated with the structure subject to a contact or near miss explosion.

The designer of a fortification must have knowledge of all three for he wants to answer questions such as "How must a structure be built in order to resist the explosive effects of a given bomb or shell at a given distance from the structure?"

The three groups of problems are interrelated mainly through the second group. The explosion sets up a pressure wave in the transmitting medium and this in turn interacts with the structure. Questions associated with the first group of phenomena may be formulated as follows: How does the pressure wave from the charge depend on the method of detonation, the shape of the charge, the type of explosive, and the type of case?

The work to date has shown that these variables affect the quantities characterizing the pressure wave, such as peak pressure and impulse. Considerable progress has been made in studying the variations produced by changing the type of explosive in standard-shape bombs. However, insufficient attention has been paid to the problem of the optimum shape of bomb. The program suggested below is a start in this direction. It is realized that the bomb designer must always keep in mind the fact that the exterior ballistics of the bomb must be good, but much could still be done within the limitations imposed by this requirement.

The problems involved in measuring the pressure wave from an explosion in the various transmitting media such as air, earth and water are not all solved. The present techniques involve complicated electronic apparatus which will stand continued improvement. It is not impossible that simpler devices, such as mechanical ones, may be able to determine some characteristics of the pressure wave sufficiently accurately for design purposes. To design such a device is an extremely difficult undertaking but it is a very worthwhile one.

The theory of the propagation of pressure waves of finite amplitude is in its infancy. It is important for it enables one to predict the future shape of the wave in terms of its past history. Thus it would be an invaluable aid in designing and evaluating various modifications of the phenomena associated with the detonation. It is also necessary in order to understand the effect of a pressure wave on an actual structure, for the structure when subjected to such a wave responds by sending out reflected waves in the medium, and by knowing the interaction of the incident and reflected waves we can deduce the actual pressure on the structure as a function of time.

The mathematical theory involved here is extremely difficult and recondite. The most promising method of attack would be one which combines theory and experiment. Such techniques have been developed at Princeton University Station of Division 2, NDRC.

The problems involved in group *3* are essentially problems on the reflection, transmission and diffraction of pressure waves. At present almost nothing is known regarding the last of these except in the approximation where the waves may be considered acoustic (that is, of infinitesimal amplitude). A program such as that outlined below would give such information. If the structure and the transmitting medium are such that they are acoustically mismatched (that is the density times the velocity of sound of one is very different from that of the other, as is the case for a concrete or steel wall if the transmitting medium is air or water) then the waves in the structure may be neglected and it may be considered as either a rigid body, an elastic body or a plastic one, and sufficiently accurate estimates may be made of the pressure acting on the structure.

At present, semi-empirical rules exist which state that if the pressure or impulse in the wave impinging on certain structural elements exceeds certain fixed quantities, the element will fail. The range of validity of these rules and their extension to other structural elements can be obtained most readily by a combination of theory and experiment, the latter involving model studies.

Considerable progress has been made in studying theoretically the reflection phenomena involved when waves of finite amplitude impinge on "infinitely rigid" surfaces. However, much remains to be done in this field, and in particular the phenomena of Mach reflection, which provides a mechanism whereby oblique reflection of weak shocks gives higher pressures than even "head-on" reflections, should be studied further.

The field of transmission and reflection of shocks in structures is important, for it involves such a phenomenon as scabbing of concrete. The advantages and disadvantages of using structural elements of a number of materials, some good transmitters and some bad, should be studied and then would fall under this category.

In the case of contact explosions in air, earth and water, the transmitting medium is the structure itself. The effect of this type of explosion has not been studied nearly so extensively as has the effect of more remote explosions. Some studies have been initiated by the Committee on the impulse delivered by a contact bare charge to a rigid body, and the size of charge necessary to scab a given concrete slab supported in various ways (Interim Report No. 29 and Interim Memorandum M-11). Both types of study should be extended and correlated, for there is almost no other work in this field. The extensions should include the effect of confinement by a case, the effect of the medium surrounding the charge, and the effect of the shape of the charge. The latter involves studying the effect of the nature of the surface of contact between charge and target.

Experience to date indicates that when it is necessary to relate explosions to their effects on targets, model studies guided by some theoretical work offer the most profitable method of attack.

Explosions—Contact

A beginning and only a beginning has been made in studying the effect of contact explosions in air or in earth against concrete. No definitive picture of the phenomena involved has been produced and a program to produce one would be very much worth while.

Explosions—Air

In view of the continued work by NDRC, it does not seem desirable to consider the possible fields of interest in detail. A partial list would include:

Blast: (Fundamental Study)

(1) Study of the effect of obstacles on blast.
- a. Diffraction around wall (infinite in length)
- b. Diffraction around square baffle
- c. Diffraction around arbitrary shapes
- d. Blast traps in tunnels

(2) Effect of shape of charge on character of blast wave.
  a. Spherical charge
  b. Disc charge
  c. Rod charge

(3) Effect of oxygen content of explosive on character of blast wave.
  a. Oxygen-balanced charge
  b. Oxygen-deficient charge
  c. Oxygen-surplus charge

(4) Theoretical study of spherical decay of blast waves in air.
  a. Free space
  b. Half space

Blast: (Applied Topics)

(1) Effect on models.
  a. Buildings
  b. Cities
  c. Details of structures

(2) Effect of confinement.

(3) Effect of very large explosions.

Explosions—Earth

As in the case of explosions in air, further work by NDRC will justify only a list here. In this medium the same problems of defining the material arise as exist in the case of penetration in soil.

Earth Phenomena: (Fundamental Studies)

(1) Effect of wide variety of soils on magnitude and decay of earth pressures, motion and acceleration
(2) Effect of depth of burial of charge
(3) Effect at various depths from fixed charge
(4) Effect of shape of charge
(5) Effect of type of explosive
(6) Transmission from air to earth of shock from charges above ground

(7) Accumulation of data on crater sizes from various sizes and depths of charge
(8) Further studies of effect of stratification of sub-surface materials

Earth Phenomena: (Applied Topics)

(1) Model tests to determine damage relations between walls supported on four sides and walls supported on two sides
(2) Effect on retaining walls and embankments (brick and timber)
(3) Effect on piers and pilings
(4) Further studies on surface structures (walls, columns, etc.)
(5) Effect of very large explosions.

Structural Analysis—Rational Design

It is only natural that the engineer who must design fortifications would like to be able to make calculations supported by as much experimental evidence as is available to him, for example, when he designs simple static structures (or even indeterminate structures) by the standard approximations.

In the absence of such well-established methods, however, it will be far better for the engineer to rely on valid empiricism rather than on calculations which may by their complexity conceal the enormous assumptions they make. There are widespread differences of opinion on the design of structures to withstand shock of impact and explosion. The question of plastic design versus elastic design is still open and ought to be settled. Such a program could well be part of peace-time engineering studies, since the whole field of dynamic analysis of indeterminate structures is in an unsatisfactory state. Initial studies of interest for general civilian purposes might involve energy releases lower in amount than those characteristic of projectile impact or explosion, and could then be extended to the faster actions characteristic of military force. If such studies are undertaken (and they might well be encouraged), the progress of the investigations should be followed closely by those whose continuing duty it is to design fortifications.

Structural Combinations

Only a very limited amount of work has been done in the field of studying what can be accomplished by laminated structures, structures with articulated joints, or structures made up of a combination of materials. In this field, planned progress could be made if the fundamentals of the phenomena of penetration and explosion were thoroughly known and if rigorous methods of structural analysis were available. In the meanwhile, one can proceed only by ingenuity. Various bracketing trials might be made through model techniques.

Improved Projectiles and Fuzes

Though this field is strictly speaking not a concern of this Committee our experience in defense indicates that constant attention should be paid by the defenders to developments in:

1. Anti-concrete shells
2. Zero-acceleration fuzes
3. Shaped charges
4. Plaster shots
5. Follow-through projectiles
6. Increased accuracy of aim.

Conclusion

The foregoing paragraph merely points up the fact that the designer of a fortification is likely to meet his test in the first days of war. If his designs are obsolete, he may well have lost the war for his side. It is often easier in wartime to recover ground lost to the enemy in peace time in other fields, where the effects are not so immediately felt as they are when a key fortification falls.

This is but to say that perhaps the most important part of fortification research is keeping abreast of developments in weapons or possible tactics which may emasculate an entire fortification design. Part of this can be done through detailed following of intelligence and even assisting in the planning of intelligence; part through the closest knowledge of technical developments in those parts of our services which are entrusted with designing weapons, and in the forces which plan our attack.

But this will probably not be sufficient. The defender should use his own imagination as well. He should attempt to think of ways by which his own designs can be defeated. He should not hesitate to test these ways even though the experts in weapons and tactics say that the weapons and tactics he proposes are quite impossible. In this role, the defender stands as amateur but very often the amateur has the original idea which his ignorance does not inhibit. That an active attitude in this direction is a valuable asset has been demonstrated time and again in the history of science and engineering.

It seems quite likely that a relatively small amount of money expended annually in the study of this problem will yield more results than a large amount spent freely when our nation is on the verge of war. For the fortification designer indeed, when this crisis has been reached, it is already too late. A continuing program involving at least the advice of a council of able men is strongly urged.

It is an unpleasant task towards the end of a grim decade to be writing for hypothetical successors who may again have to face the problems we have faced. It would be comforting to believe that all this is unnecessary and that the men of good will are to prevail. But it was no war-lover who advised "In times of peace prepare for war." The quality of the preparations rather than their quantity will determine whether the men of good will are so supported that good will may prevail. This quality will depend almost entirely on a continuing rather than a spasmodic program of research.

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