

Testing the M-69 incendiary bomb on a model enemy building

SCIENCE IN .WORLD WAR II

Office of Scientific Research and Development

Chemistry

A HISTORY of the CHEMISTRY COMPONENTS of the NATIONAL DEFENSE RESEARCH COMMITTEE 1940-1946

BY

R. ConnorW. R. KirnerD. Churchill, Jr.G. B. KistiakowskyR. H. EwellW. C. LothropC. HeimschW. A. Noyes, Jr.E. P. Stevenson

CAN A STAN

VERE

EDITED BY W. A. Noyes, Jr.

FOREWORD BY James Bryant Conant and Roger Adams

With Illustrations

An Atlantic Monthly Press Book Little, Brown and Company . Boston 1948

COPYRIGHT 1948, BY LITTLE, BROWN AND COMPANY

ALL RIGHTS RESERVED, INCLUDING THE RICHT TO REPRODUCE THIS BOOK OR PORTIONS THEREOF IN ANY FORM

FIRST EDITION

Published June 1948



111 1 1 1

ATLANTIC-LITTLE, **BROWN** BOOKS **ARE** PUBLISHED BY LITTLE, BROWN AND COMPANY IN **ASSOCIATION** WITH THE ATLANTIC MONTHLY PRESS

Printed simultaneously in Canada by McClelland and Stewart Limited

PRINTED IN THE UNITED STATES OF AMERICA

50-2168

copyright of each separate volume after ten years from the date of publication of such volume. Thereafter the volume in question will be

PUBLISHER'S NOTE

was the actual inventor.

in the public domain and dedicated to the public. This history of OSRD is intended to be a survey of the way in which certain weapons were developed, improved, or brought into use, and is not intended to be a complete documentary record of the making of the inventions that happen to be mentioned in it. Therefore the dates used, which serve to outline the general chronology, do not necessarily establish dates of conception of inventions, of their reduction to practice, or of occasions of first use. Moreover, in the interest of simplicity, credit for the development of a device is frequently given to a group identified by the name of its leader, rather than to the individual who

Under the terms of the contract for the publication of *Chemistry*

and of the other volumes in the long history of the activities of the Office of Scientific Research and Development, entitled *Science in World War II*, the publisher has agreed to waive its right under the

The authors and editor of this volume receive no royalty from its sale.

DEDICATION

This book is dedicated to the scientists, young and old, who contributed to the work described in this history. The young men, in particular, gave of their time and energy at crucial periods in their lives without seeking and receiving public acclaim and glory. They accepted orders and carried them out faithfully, often with no knowledge of ultimate objectives and often without even that satisfaction which came to older men from knowing that their work was accepted and helped to win the war. They served their country with less recognition but just as truly as did those in uniform.

Many men of the chemical divisions of OSRD gave their lives for their country. Their names belong on the Roll of Honor along with the names of those who died in battle. To these men, especially, is this volume dedicated:-

DONALD E. BOYER ROBERT S. DONE JOHN FEHRER JOHN HANUSIN CHARLES R. HOOVER ROY NELSON HURT JOHN LEONARD H. G. NELLIS CLARENCE o'BRYAN F. K. OVITZ SAM RUBEN ROY C. **WOEHRMAN**

THE AUTHORS

The histories in this volume were prepared by the several authors in collaboration with the heads of the respective administrative units of the National Defense Research Committee. The Chief of each Division and the Chairman of TDAC have assumed responsibility for the material included in his portion of the volume.

DIVISION 8 Explosives *Chief:* Ralph A. Connor, formerly Professor of Chemistry, University of Pennsylvania, and now Associate Director of Research, Rohm and Haas Company.

Authors: Ralph A. Connor.

George B. Kistiakowsky, Professor of Chemistry, Harvard University; Chief of Division 8, NRC, from 1942 to 1944:

Chemistry

division 9

Chief: Walter R. Kirner, now Director, Chemical-Biological Coordination Center, National Research Council. *Author:* Walter R. Kirner.

DIVISION 10 Absorbents and Aerosols *Chief:* William A. Noyes, Jr., Professor of Chemistry, University of Rochester.

Author: William A. Noyes, Jr.,

DIVISION II Chemical Engineering Chief: Harris M. Chadwell, now Assistant Director, The Rockefeller Foundation.
Authors: Durand Churchill, Jr., Chemical Engineer, Technical Aide to NDRC member from 1942 to 1946.
Raymond H. Ewell, Shell Chemical Corp., Technical Aide, Division II from, 1943 to 1946.
Earl P. Stevenson, Arthur D. Little, Inc.; Chief of Division II from 1943 to 1945. Х

THE AUTHORS

DIVISION 19 Miscellaneous Weapons

Chief: Harris M. Chadwell, now Assistant Director, The Rockefeller Foundation.

Author: Warren C. Lothrop, Arthur D. Little, Inc.; Member Section 19.1 from 1945 to 1946.

TROPICAL DETERIORATION ADMINISTRATIVE COMMITTEE

Chairman: Gustavus J. Esselen, Gustavus J. Esselen, Inc.

Author: Charles Heimsch, Department of Biology, Amherst College; Technical Aide, TDAC of NDRC from 1944 to 1946.

FOREWORD

CHEMISTRY today is involved in so many phases of our industrialized civilization that it is not strange to find that chemists were engaged in many activities essential to the war effort of the United States in the period 1940 to 1946. To do justice to the vital work of our profession in defending the country during the black days of war would require a survey of many industries and many Government agencies and laboratories. Such dramatic events as the establishment of the synthetic-rubber industry and the development of the atomic bomb come at once to a layman's mind when chemistry and World War II are mentioned. Incendiary bombs, improved explosives (of an unorthodox variety), and poison gas naturally occur to one thinking of the role of the chemist in modern war. So, too, would penicillin, antimalarial drugs, and blood plasma. All of these topics and many others would need to be treated in a comprehensive chemical history of World War II. Such a history would record the triumphs of American chemists, for one can say truly that our profession not only did its part in the great struggle against the Axis powers but performed almost miraculous feats in many instances.

To tell the whole story to the public of the triumphs of American chemistry in the war would be an interesting and worth-while undertaking. But this is not the objective of this volume. This is the history of one agency through which some of the chemists of the United States were mobilized for the national defense. This is an account for chemists, not for laymen. It is written on the assumption that many members of our profession would be interested in the details of the war work of the chemical components of the National Defense Research Committee. They may be interested also in the way the organization operated. Indeed, the record may prove to be of value to those concerned with organizing scientific research and development in connection with the Army and the Navy.

But in attempting to draw any lessons from the experience of the chemists of NDRC, one must always bear in mind the abnormal conditions of the period. In war, time is of the essence. "Getting there firstest with the mostest" applied in the '940'S to equipment just as it applied in the ,860's to fighting men. The very nature of a rapid mobilization in time of war (or in time of emergency preceding war) precludes the building of an organization of the usual type. There just is not time enough for the

FOREWORD

process of trial and error by which the proper places for individuals are discovered. There is not time enough to shake the team down, so to speak. That being the case, NDRC had no alternative but to create an organization with a high degree of decentralization. It resembled a university with many faculties and many almost autonomous departments, rather than an Industrial corporation. This volume records the history of the several chemical divisions. Other volumes in this series are concerned with the divisions organized around physical and engineering problems.

Co-ordination of the work of the various divisions was achieved by the labors of the members of the main Committee, the staff officers of the Chairman's Office, and through the Director of OSRD and his assistants. The policy of compartmentalization was adhered to throughout the NDRC organization in the interest of security. In general, a man was given access to classified material only to the extent that the information thus acquired would assist him in his work. The chemical problems were so closely related, however, that this policy could not be followed strictly without detriment to the work. Therefore, with certain exceptions the top men in each 'of the chemical divisions met in conference from time to time to discuss their problems. From such meetings valuable **co-operative** endeavors emerged and morale was maintained at a high level.

From the first days the members of NDRC felt the urgency of the work. Time was against them, yet only slowly did the country as a whole realize the danger and the need for speed. The first efforts of the Committee after its establishment in June 1940 were directed toward discovering what were the most pressing problems. Yet even the Army and Navy were reluctant at that time to disclose to a civilian organization all the results of the confidential investigations in their laboratories; rather, they tended to confine their suggestions, as far as chemistry was concerned, to a few fundamental problems of somewhat academic character. These and other proposals by men who had had contact with Army and Navy research were assigned by NDRC almost exclusively to university laboratories where facilities and competent staff members were available. An attempt to interest the research laboratories of industrial companies failed for the most part. Neither the need for speed nor the significance of the work of this new civilian agency was appreciated in 1940 and early 1941. The progress of the researches during 1940 and 1941 was slow since the professors were directing this new work in addition to their other duties and usually had only part-time graduate students to aid them.

After December 1941, however, the picture changed completely. Industry **co-operated** to the fullest extent and accepted research problems whenever properly equipped laboratories and trained personnel were available. The Army and the Navy revealed to the civilian scientists their important requirements in the chemical field. The NDRC program expanded rapidly

FOREWORD

until the original organization became inadequate. Reorganization resulted in the creation of Divisions 8, 9, 10, and II as separate administrative units. Division 8, under the direction first of Dr. George B. Kistiakowsky and later of Ralph Connor, was devoted exclusively to explosives and related subjects; Division 9 under Dr. W. R. Kirner to gas warfare, toxicology, analytical methods, protective ointments, and later to insecticides, repellents, and antimalarials; Division 10 under Dr. W. A. Noyes, Jr., to screening smokes, absorbents, and filters for the gas mask, testing methods, chemical warfare munitions, meteorology, insecticide dispersal, and related items; Division II, first under the direction of R. P. Russell and later of E. P. Stevenson, to chemical engineering projects such as the production of oxygen, flame throwers, and incendiaries, and to a group of miscellaneous projects of a varied character such as new hydraulic fluids, the purification of mustard gas, and antifouling paints.

The many contributions from these divisions to the war effort are described in the pages which follow, but reference may be made here to a few of them. It is of special interest to point out some of the successes of those who worked in the university laboratories, since in the early days of NDRC certain Army and Navy officers were skeptical about the ability of academic scientists to contribute in an effective way. In the field of explosives, particularly, the tradition had been that no individuals lacking special experience and training in this field could be successful. The doubts about the ability of newcomers extended beyond the universities; the Army was hesitant to consider the awarding of an explosives contract to an industrial concern without past experience with explosives manufacture, because it was believed that rapid progress by such a concern could not be accomplished without elimination of the safety factor. Actually, a new method for producing RDX was developed, based on the work of university men who had had no previous experience in explosives. The contract for putting this new process Into large-scale production was awarded to an industrial concern which had demonstrated the greatest brilliance in the development program and which had never before produced explosives.

Among other important accomplishments of the chemists mobilized through NDRC we must mention the discovery of hydraulic fluids, with very flat viscosity curves over a wide range of temperatures, which greatly simplified the problems of the Air Forces; the determination of a practical method for thickening gasoline, which resulted in revolutionary improvements in flame throwers and made possible the design of new oil-incendiary bombs; the perfection of absorbents in gas masks, both activated carbon and filters, which supplied protection for United States troops far superior to that of the enemy forces. All of these developments originated in university laboratories. Oil smokes for screening large areas during the war stemmed from the application of the basic principles of physical chemistry. xiv

It will be evident from the following pages that many of the most important ideas originated with the chemists of the contractors. This was true both of academic and of industrial laboratories. Liaison between the many individual contractors and the central organization presented certain difficulties, owing to the distance from headquarters and the relative isolation of the units. Before the United States entered the war, it was the deliberate plan to distribute the work widely so that normal functioning of university chemical departments would not be disrupted. As the work expanded, several central laboratories were established which employed many full-time senior scientists drawn from allover the United States. These central laboratories proved to be highly advantageous for the wartime period since the reduction of the number of contractors reduced the liaison work. Furthermore, the fact that these laboratories brought together many trained men insured the cross-fertilization of ideas.

Adequate liaison with the Army and the Navy research laboratories developed slowly and required time. It must be remembered that for the most part the chemical contractors of NDRC and the Army and Navy chemical laboratories had the same objectives. To a certain degree the chemists mobilized through NDRC and those employed by the Services were competitors. Petty jealousies and undue demands for credit arose, therefore, occasionally. This led to disputes between the military and civilian organizations which often resulted in unnecessary delays. Since there was no overall control of the entire research and development program, undesirable duplication could not be entirely eliminated. Nor could differences of opinion be resolved promptly. The Army and the Navy laboratories suffered because .responsibility was often assigned on the basis of rank rather than on technical competency, a difficulty which was not found in the civilian organizations. Nevertheless, the mutual relationships between the civilian and military organizations gradually reached a satisfactory stage toward the end of the war.

In conclusion, we should like to emphasize that the credit for the success of the NDRC program in chemistry is due primarily to the division chiefs, the section heads, and the directors of the contractors' laboratories. To their untiring efforts, as well as to the efforts of the many able men who followed their lead to the disregard of all personal advantage, the country owes a great debt of gratitude.

JAMES BRYANT CONANT

Chairman, National Defense Research Committee President, Harvard University

ROGER ADAMS

Member, National Defense Research Committee Chairman, Department 01 Chemi University of Illinois

PREFACE

T HAS been said tritely and somewhat facetiously that World War I was the chemist's war whereas World War II was the physicist's war. Such statements may impress the lay public and lead to the belief that the role of the chemist in the recent conflict was a minor one. The subjects most popularized in the press are the atomic bomb, radar, penicillin, and DDT. The first two of these have been associated in the mind of the public with physics rather than with chemistry, and the third and fourth are often ascribed to biologists. And yet it is probably true that more chemists than physicists worked on the atomic bomb and that final success in the separation of the elements and in the development of the bomb itself was due fully as much to the contributions of chemical engineers and of chemists as to the efforts of the physicists. Penicillin production on a large scale was mainly a chemical problem. DDT, both for production and for methods of use, was largely in the hands of chemists.

The role of the chemist in the recent conflict was, therefore, very important if not spectacular. Indeed the development and manufacture of every item used by the Armed Services depended to some degree on the chemist. Whether it be textiles, glass, steel, rubber, or leather, the chemist played a part in devising processes, controls, and standards; but in addition to the contributions which the chemist made as part of his routine stock in trade, there were other major contributions in the form of munitions which played a vital part in the attainment of victory. Flame throwers, incendiaries, screening smokes, and explosives were developed by chemists and chemical engineers as instruments of war, but a host of other problems were solved by the chemists. Paints which would prevent ship bottoms from becoming covered with barnacles, ways of preventing mold in the tropics, hydraulic fluids, units for supplying oxygen for welding in Theaters of Operation: these are a few of the many problems which chemists were called upon to solve.

This history is written with the object of permitting chemists to learn what their fellow chemists did during the war. Since we are confining our attention to various component parts of the National Defense Research Committee, this history omits the atomic bomb and penicillin as well as those Vast contributions by chemists in industry and in laboratories directly under the control of the Armed Services except insofar as such work may be re-

10

lated in some way or other to work carried on by NDRC. This book is written for chemists and chemical engineers, and no effort is made to avoid technical terms. On the other hand, it does not contain technical details of the type which will be found in the Summary Technical Reports. In other words, it is a history of work done by chemists and is designed to be read by chemists.

Since the National Defense Research Committee was established as a civilian organization to help the Armed Services, relationships to the Army and to the Navy are of paramount importance. To say that such relationships were always along flower-bordered paths would be a misstatement. It is important that these difficulties be stated fairly and without animosity as a guide to those who may meet similar problems in the future. At the outset, it may be said that by the end of the war most of the important conflicts had been resolved.

W. A. NOYES, JR.

CONTENTS

Dedication	viii
Foreword	XI
Preface	XV

PART ONE-Introduction

I	The Organization of the National Defense	
	Research Committee: General Plan	3

PART TWO-History of Division 8

II	Introduction to the History of Division 8	15
III	The History of Division 8 Central Laboratories	26
IV	Synthetic Work on Explosives	35
V	Research on Detonation and Shock Waves	58
VI	Evaluation of Explosives and Munitions	76
VII	Development of Explosive Compositions and	
	Devices	90
VIII	Molded Composite Propellants	96
IX	Application of Molded Composite Propellant	I15
Х	Propellants Based on Nitrocellulose	124
XI	Tracers and Igniters	137

PART THREE-History of Division 9

XII	Relationships of NDRC to the Armed Services	
	and to Allied Countries in Chemical Warfare	141
XIII	The Organization of Division 9	155
XIV	Synthesis and Stabilization of Chemical War-	
	fare Agents	157
XV	Protective Clothing and Ointments	206

X VI II	CONT	ents
XVI	The Detection, Identification, and Analysis of Chemical Warfare Agents	216
XVII	The Toxicity and Vesicancy of Chemical War- fare Agents	
XVIII	The Physiological Mechanism of Action of Chemical Warfare Agents	249
PART FOUR-	History of Division 10	
XIX	General Scope of Division 10 Activities	261
XX	The Filtration of Aerosols	265
XXI	Screening Smokes	274
XXII	Chemical Warfare Munitions - Toxic Aerosols	292
XXIII	Gas Mask Absorbents and Related Problems	296
XXIV	Offensive Chemical Warfare and Related	
	Problems	318
XXV	Insecticide Dispersal	333
PART FIVE-	History of Division 11	
XXVI	The Organization of Division 11	343
XXVII	The Oxygen Program	345
XXVIII	Miscellaneous Chemical Engineering Problems	372
XXIX	Incendiary Bombs	388
XXX	Incendiary Fuels	410
XXXI	History of NDRC Flame-Thrower Develop- ment	420
PART SIX - H	istory of Division 19	
XXXII	Weapons for Sabotage	43 ¹
PART SEVEN	- History of Tropical Deterioration Committee	
XXXIII	The Study of Tropical Deterioration	445
Epilogue		479
Appendices		483
Indices		507

ILLUSTRATIONS

	Testing the M-69 incendiary bomb on a model enemy build- ing Frontisp	piece
	Relation between diaphragm deformation of "damage" gages and the proximity of a submarine explosion (FIGURE I)	82
	SNAFU (figure 2)	
	University of Chicago Toxicity Laboratory (FIGURE 3)	244
	The "Benesh Gassing Chamber" (FIGURE 4)	245
	Hession smoke generator (FIGURE 5)	282
)	Smoke screen from TBM-I plane showing tactical use in amphibious operation (FIGURE 6)	283
	Double canister, "breather" type test machine (FIGURE 7)	304
	Goat fitted with gas mask for field tests (FIGURE 8)	305
	"Mechanical Goat" for field tests of gas mask canisters (FIGURE 9)	3 ⁰ 5
	Keyes Unit with built-in liquid oxygen pump (FIGURE 10)	356
	Collins Unit (FIGURE II)	357
	Sectional models of AN-M-69 and M-69-WP bombs (FIGURE 12)	394
	E6R2 aimable cluster for the M-69 bomb (FIGURE 13)	395
	Operator with E-2 portable flame thrower (FIGURE 14)	422
	Tank equipped with protective flame device (FIGURE IS)	

Part One: Introduction

CHAPTER I

THE ORGANIZATION OF THE NATIONAL DEFENSE RESEARCH COMMITTEE: GENERAL PLAN

W. A. NOYES, JR.

THE SUMMER OF 1940

THE WAR in Europe started in September 1939, but the history of the next few months resembled that of the thirty months following August 1914 very closely. The United States was unprepared, both morally and materially, for war. The conflict seemed remote, and many, if not most, Americans believed that this country could and should avoid all participation. This attitude was strengthened, if anything, by the period sometimes referred to as the "phony war" which followed the conquest of Poland.

Startling events occurred during the spring of 1940: the fall of Denmark and of Norway, the conquest of the Lowlands, the entrance of Italy into the war on the side of the Axis, and finally the fall of France. The United Kingdom was left alone as a protection in Europe of the way of life in which Americans believed.

The consternation which swept this country after the fall of France cannot, even then, be said to have awakened Americans to the inevitableness of global war. Action was slow in crystallizing, and decisive steps toward preparation for armed participation were little more than idle talk. In view of the general lethargy, it is to the lasting credit of a small group of leading scientists that steps were taken to mobilize the scientific talent of the United States during June 1940 - even before France capitulated.

The early organization of the National Defense Research Committee concerns us only insofar as it pertains to chemistry and to chemical engineering. The first meeting of NDRC was held in Washington on June 18, 1940. The **National** Defense Research Committee was formally established on the 27th of that month under the Council of National Defense. The "Order Estab-

ORGANIZATION OF NDRC

CHEMISTRY

lishing the National Defense Research Committee" was signed by President Roosevelt and by several Members of the Cabinet. It may be quoted, in part, as follows: "The Committee shall correlate and support scientific research on the mechanisms and devices of warfare, except those relating to problems of flight included in the field of activities of the National Advisory Committee on Aeronautics. It shall aid and supplement the experimental and research activities of the War and Navy Departments, and may conduct research for the creation and improvement of instrumentalities, methods, and materials of warfare."

Dr. Vannevar Bush, President of the Carnegie Institution of Washington, became the first Chairman of NDRC, and Dr. James Bryant Conant, President of Harvard University and an eminent organic chemist, agreed to organize Division B and be its first Chairman. Division B had the somewhat awe-inspiring title of "Bombs, Fuels, Gases, Chemical Problems."

The first informal meetings of NDRC were held on June 18 and June 25, 1940, in Washington. At the second of these meetings Dr. Roger Adams and Dr. W. K. Lewis were approved as top men in Division B. The first official meeting was held on July 2, 1940, in Washington. It should be noted in retrospect that Selective Service was not yet in operation, that although appropriations for the War and Navy Departments had been raised above the rock-bottom levels reached during the depths of the depression, the intensification of research and production by the Army and Navy had yet to occur. Skeleton staffs were still in vogue in Washington offices and few reserve officers had been called to active service. Even the National Guard was not called to the colors until the following fall.

In spite of the state of mind of the country, the response of scientific men to invitations to serve was immediate and enthusiastic. If certain academic institutions and companies expressed unwillingness to release personnel to NDRC during these early days, the general atmosphere and the newness of NDRC should be remembered.

The BIRTH of division B

The first informal meeting establishing the broad outlines of the organization of Division B was held in Washington on July 11, 1940, with Drs. Conant, Adams, and Lewis in attendance. A later conference on the same day was held with Major General W. C. Baker, Chief of the Chemical Warfare Service, and Major M. E. Barker, Chief of the Technical Division. The next day, the three key members of Division B visited the Naval Research Laboratory with Rear Admiral H. G. Bowen, and visited Colonel K. F. Adamson, of Army Ordnance.

A conference on explosives was held July 18, 1940, at 1530 P Street NW,

Washington.' A further conference considered the possibility of a fundamental physical-chemical study of high explosives!

The first meeting at which positive steps were taken to give definite character to the organization of Division B was held at the time of the American Chemical Society meeting in Detroit on September 8, 1940.'

The formal organization as of September 12, 1940, can be seen at a glance **from** the Organization Chart of that date, given in Appendix A.

Several other important problems had been received by the first of October, and on October 3, r940, Dr. W. K. Lewis called together a large group of physical chemists and chemical engineers at 1530 P Street NW, Washington. This meeting was exploratory in character, and useful leads were sought for solving some of these problems.

The first large meeting attended by the Chairman, Vice-Chairmen, Section Chairmen, Technical Aides, and many Official Investigators of Division B was held on December 14 and r5, 1940, at the home of the President of Harvard University. A second large meeting of this type was held in the Lord Baltimore Hotel, Baltimore, Maryland, on April 25 and 26, 194', after the return of Dr. Conant from England.

Beginning with the summer of 1941, after Dr. Adams became Chairman of Division B, regular monthly meetings were held by the Technical Aides, the Section Chairmen, and some Subsection Chairmen. These meetings were unique in NDRC and served to form a nucleus of men well acquainted with the broad aspects of defense problems in chemistry and in chemical engineering.

The relationships of Division B and its successors to British agencies will be discussed elsewhere, but a brief mention of this important matter should be made at this time. The British Empire had entered the war in September 1939, and prior to the formation of NDRC, British scientists had acquired much experience on war matters. Numerous visits of NDRC personnel to **Canada** occurred throughout the war, and these contacts were most helpful m educating American scientists on war matters.

Of particular importance was the visit of Dr. Conant to England from February to April, 1941. He was able to ascertain the progress British scientists had made, and to bring back many important problems. This contact and later ones made by other American scientists saved a large amount of tIme in obtaining the necessary background for effective work. F. L. Hovde, Assistant to the President, University of Rochester, and now President of

t Dr. J. B. Conant, Harvard University, Chairman; Colonel K. F. Adamson, Army Ordnance; Dr. T. L. Da.vis, Massachusetts Institute of Technology; Dr. W. W. 'Farnum, Indian Head Naval Station; Dr. George C. Hale, Picatinny Arsenal; Commander J. H. Hoover, Naval Research Laboratory; Dr. W. K. Lewis. Massachusetts Institute of Technology; Dr. W. H. Rodebush, University of Illinois; Dr. C. G. Storm, Army Ordnance: Dr. W. W. Thompson, Naval Proving Ground.

^aJ. B. Conant, T. L. Davis, W. K. Lewis, W. H. Rodebush, R. C. Totman. Roger Adams, H. M. Chadwell, J. B. Conant, W. R. Kirner, W. K. Lewis.

OIIGANIZATION OF NDRC

CHEMISTRY

Purdue University, accompanied Dr. Conant on his trip to England, and remained there to establish the NDRC Mission at the U.S. Embassy, 1 Grosvenor Square, London.

The Washington office of Division B was established at the Carnegie Institution of Washington, 1530 P Street NW, in September 1940: but had become seriously overcrowded by June 1942, and Division B, with such parts of the administrative overhead as pertained to that Division, moved, at the invitation of Harvard University, to Dumbarton Oaks, 1703 Thirty-second Street NW. The building which was used at Dumbarton was seriously overcrowded also for many months prior to the termination of the war, but when one considers the handicaps suffered by many governmental agencies in Washington during the war period, one can feel that Division B was better off than most.

During 1940 Division B was one of the five divisions in NDRC, although there were other appendages, at least one of which was dealing with atomic energy. The form of organization remained essentially unchanged until the summer of 1941, when the Office of Scientific Research and Development was established with an organization chart approved by President Roosevelt and dated August 20, 1941. Dr. Bush became Director of OSRD, and Dr. Conant became Chairman of NDRC. NDRC now consisted of four Divisions, with Dr. Roger Adams as Chairman of Division B, the one in which we are interested. The internal organization of Division B was not changed appreciably at the time OSRD was established, although new sections were continually being added and the number of contracts grew by leaps and bounds. The Organization Chart of September r, 1942, in AppendiX A shows the structure just prior to the final reorganization in December 1942.

GENERAL ADMINISTRATION

Certain general matters relating to the organization should be emphasized. Impatience at the slowness of obtaining action was often voiced, but many necessary formalities had to be gone through in setting up a new Government agency, particularly since NDRC was to perform research on instruments of war. The obtaining of clearances was one of the chief bottlenecks in starting the program. Clearance for one of the best-known chemists was delayed because his name was confused with that of another man whose loyalty was suspect. In some instances men were allowed to start work while awaiting clearance and on the personal responsibility of some member of the organization.

During World War I the chemists, particularly those dealing with chemical warfare, had been brought togetber at American University and at Catho-

4 Dr. H. M. Chadwell, Professor of Chemistry, Tufts College, representing Dr. Conant; Dr. W. R. Kirner, representing Dr. Adams; and Dr. T. K. Sherwood. representing Dr. Lewis. **lic** University in the District of Columbia. Those responsible for the policies of NDRC decided, rather, to utilize existing research facilities and to have the research conducted by contract with academic institutions, research institutes, and industries. This lack of centralization had the advantages of getting the work started rapidly, of allowing key men to continue part of their peacetime activities, and of avoiding much of the red tape inherent either in military or in other governmental establishments. The most obvious disadvantage lay in the difficulties of maintaining the necessary personal contacts for co-ordination and direction of the work.

The legal details involved in granting Government contracts to research institutions and industries had to be clarified. The form of contract, particularly as regards methods of payment for salaries and materials and as to patent rights, demanded careful study. Indeed, the patent clauses were frequently a source of friction since often a company would supply information which it had obtained in peacetime pursuits. Usually such difficulties were resolved in a spirit of good will and with the evident desire on the part of everyone to help the country in a time of emergency. Only in the case of a very few companies was the patent clause a stumbling block which was never overcome.

The compensation to be paid to administrative personnel was the subject of much debate and indecision. In fact, this difficulty arose again and again to plague the powers that be. At the start, key administrative personnel such as the Chairman of NDRC, Division Chairmen, Section Chairmen, and Contractors' Technical Representatives all worked without compensation, that is, they retained their peacetime positions, for which they received full pay, and devoted spare time to NDRC for which they received no pay other than for travel. It was obvious that university professors, whose routine duties take only a few hours per week, could stop peacetime research and devote the time thus freed to the Government. Inevitably, most of the administrative posts were filled at the start by academic men serving without pay.

Much administrative work could be handled in Washington by full-time personnel only, serving mostly as Technical Aides to the Division and Section Chairmen. Again, it was easier to obtain academic men on leave of absence than to obtain men from industries which were loath to disrupt working organizations.

With some notable exceptions, therefore, the administration of NDRC **Was** staffed by men from academic circles, although many research contracts, as We shall see, were placed in industrial concerns. As time went on, partly for legal reasons and partly because it seemed unfair to ask academic institutions to pay full salaries for men who were in residence only a few days a **month**, the administrative posts came to be filled more and more by full-time Civil Service employees. Nevertheless, many positions were held throughout the war by men working without Government pay.

7

8

CHEMISTRY

The first Chairman of NDRC, who later became Director of OSRD, established the principle of "No profit, no loss" for scientists engaged on war work. That is, they were paid salaries equal to those which they had been receiving, plus additional amounts to compensate for increased living costs in case they were forced to move to new locations. Academic men were paid for twelve months per year at the same monthly rate they received for the academic year. This principle was applied approximately both to Civil Service and to contract employees at the beginning, even though it worked some obvious injustices. Academic salaries throughout the country are far from uniform, and the general scale is lower in the South and West than it is in the East. Consequently, two men of equal experience and ability might receive widely different stipends when employed side by side in NDRC.

For young men, many of whom began working for NDRC just after receiving academic degrees, the salaries were roughly comparable to those paid in industry. In a few instances men working in academic institutions were allowed to submit NDRC work in theses for advanced degrees.

Since the highest Civil Service salary is below many paid in industry or even in some academic institutions, a few members of the organization made real financial sacrifices while working for the Government. Inevitably, however, some salaries were increased during the war as certain men showed marked ability and attained increased responsibilities.

Thus the salary problem was very complex, but it seems to have been handled as fairly and as equitably as could be expected. The scientists did not get rich, and neither did they suffer any material loss.

TECHNICAL AIDES

The Technical Aides in Washington maintained contacts with the Armed Services, performed numerous administrative duties, ensured co-ordination of work within the Sections and Divisions, and performed many annoying routine functions, at least some of which should not have fallen to the lot of technical men. Some of these functions maybe described in passing.

As the demands of the Armed Services increased, the danger of losing scientists through Selective Service also increased. And yet the success of NDRC and of the war effort in general depended on retaining scientific men in the laboratory. Many of these men were young and vulnerable to the draft. A large amount of time was necessarily spent in ensuring deferments of scientists, and although NDRC lost only a few men, these duties were very time-consuming and annoying.

The contractors purchased equipment of various sorts ranging from thermometers to trucks and even airplanes. This equipment was paid for on vouchers submitted by the contractors and these vouchers had to be approved in the Washington office of the proper Section or Division. Disposal of prop-

oaGANIZATION OF NDRC

erty on contracts which terminated, transfers from one contract to another, and large amounts of detail concerned with estimates of funds needed, stipends to be paid assistants and Technical Representatives or Official Investigators, all necessitated a large amount of correspondence. The editi.ng and distribution of the many different reports constituted one of the main tasks of Technical Aides. The wide geographical distribution of the contracts made the handling of business details and the direction of the technical work difficult without periodic visits by representatives of the Washington offices. The old saying "Join the Navy and see the world" -could have been applied equally well to NDRC. A statistically minded person might amuse himself by trying to estimate the travel mileage of NDRC personnel. It would be stupendous.

SERVICE PROJECTS

While no legal restriction prevented NDRC from working on nearly anything related to the war effort, early problems nearly all derived from Service Projects. If some branch of the Army or Navy had a problem on which work was desired, a request was forwarded to the Army or Navy liaison officer for NORC. This officer then transmitted the request to the Executive Secretary ofNDRC (later of OSRD), who in turn asked the proper Division whether it was willing to undertake the work. After NDRC had accepted a Service Project, the proper Division was free to assign the work to existing contracts or to start new contracts if needed.

Service Projects were given symbols indicating the branch of the Service originating the project, followed by a serial number. Thus CWS-I, etc., were all assigned to NDRC by the Chemical Warfare Service. Navy Projects began with N followed by a letter designating a bureau or laboratory. Thus NO-I, etc., were Navy Bureau of Ordnance projects; NL-BI, etc., were from Naval Research Laboratory; NS-I, etc., were from Navy Bureau of Ships.

The Service Projects varied greatly in breadth. Some of them dealt with highly specific problems. Others were so broad as to cover a whole range of activities. Certain branches of the Armed Services took the attitude that NDRC had no right to work on subjects not specifically authorized. To hamper thus the activities of scientific men would have nullified their value **was** scarcely in order during wartime. As time went on, the restrictions were **cither** ignored or removed and most Divisions felt free to attack those phases of a problem which seemed most important. The responsibility for prevent-Ulg undue wastage of effort lay mainly with Section and Division Chiefs.

Let us next examine the way NDRC functioned after receiving a Service Project and assigning it to a Division. The Divisions varied considerably in

ORGANIZATION OF NDRC

internal organization and in ways of doing business. All of them had plan. ning boards or steering committees which met at various intervals. Usually, the members came from such widely separated localities that frequent meetings were impossible and much of the business was conducted by mail, telegraph, and long-distance telephone.

The Division Chief and his Technical Aides were responsible for finding a laboratory where the desired work could be carried out. Negotiations were conducted covering the terms of the contract, i. e., amount of money (based on estimates of the number of persons to be employed and on requirements for apparatus and supplies), duration of the contract, work to be accomplished, etc. The terms were approved by the steering committee of the Division and the contract proposal submitted to the National Defense Research Committee for approval. After favorable action the institution received a letter of intent which permitted it to begin work even before receipt of the contract. In a few instances very urgent work was started without any formal agreement and in anticipation of action on a request for funds.

When a Service Project was established, one or more Army and Navy liaison officers for that project were designated by the Service branch concerned. It was through such officers that direct contact was maintained with the Army and Navy by Division and Section Chairmen. Gradually personal relationships developed between other persons at lower echelons in NDRC, the Army, and the Navy. In this way, those actually doing the work on both sides dealt with each other directly, thus avoiding much red tape and misunderstanding. Indeed there were many areas in which, by the end of the war, the military and civilian organizations were so intertwined that the programs had become truly unified.

THE CONTRACT SYSTEM

Each contract was under the supervision of an Official Investigator or Contractor's Technical Representative, usually a faculty member of a university or a responsible official of an industrial company. Until July 1942 such men served without pay. Thereafter, part or all of the salary, depending on circumstances, of the Technical Representative was paid by the Government under the contract. The research assistants and other employees were paid by the contractor, who, in turn, was reimbursed by the Government.

There were several advantages to the system of research by contract over that in Government laboratories. The existing research facilities of the country could often be used, although sometimes new laboratories had to be built and outfitted. Men employed under contracts did not need to be subjected to the delay of obtaining Civil Service appointments and they could be paid according to accepted salary scales for the duties performed. Not the least advantage lay in the possibility of giving contracts for periods long enough guarantee contInwty of effort. Thus the uncertainties attendant upon the and of the Government fiscal year were avoided.

THE FINAL REORGANIZATION

The work of the National Defense Research Committee had become so **complex** by the fall of r942 that each of the four original Divisions was **covering** a vast amount of unrelated material. The structure had become too **cumbersome** for efficient operation, and a simplification and a redefinition of **responsibility** were essential. The final major **reorganization** of the National **Defense** Research Committee occurred in December 1942, and thereafter **only** minor changes took place until the end of the war.

The reorganization of December 1942 led to the formation of four new Divisions: 8, 9, 10, and 11, all resulting from the old Division B as listed in Appendix A. These Divisions covered a wide variety of subjects, Division 11 being particularly heterogeneous in that it covered many miscellaneous and more of less unrelated problems. Division r9 and the Tropical Deterioration Administrative Committee, both of which are treated in the present volume, ongm.ated more or less from the activities of Division B, and derived some of thelf personnel from that Division. On the other hand, these organizations were formed for special purposes and the histories of their origins are best included in the chapters devoted to them.

The National Defense Research Committee as organized in December 194² was ^a supervisory body to which the various Divisions reported. Its membership IS shown in Appendix B.

The National Defense Research Committee determined general policy, passed on appropriation requests, and was responsible through its chairman to the Director of OSRD for the technical program. Since the subjects covered in the mneteen DIVISIOns of the National Defense Research Committee were very broad and comprehensive it was essential for subcommittees to be appointed to review the programs of specific Divisions. The ones organized for the DiVIsions formed from Division B are shown in Appendix A.

The Subcommittees of NDRC met with Division Chiefs and Technical Aides to survey the program, to make recommendations concerning future action, and t₀ bein a position to report to t^he parent Committee on the desirability of appropriation requests. From time to time, the Division Chiefs often accompanied by Technical Aides and Division Members, appeared be-(are the main Committee to review programs and justify expenditures. Dr. urg Adams, as former Chalfman of DIVISIOn B, was the representative of Chalfman, NDRC, in dealing with Divisions 8 9 10 and 11 but the UVISIO.ns were essentially autonomous, and proceeded with little restraint From higher echelons.

10

CHEMISTRY

Responsibilities of divisions 8, 9, 10, and 11 Following december 1942

The various Sections of Division B were distributed among Divisions 8, 9, 10, and 11, probably without adequate delineation of functions. The organizations which resulted resembled the old form of the parent Division very slightly, but the actual conduct of the work changed less than appeared on the surface. It was ruled that all positions with administrative responsibility had to be filled either by WOt (without compensation) or by Civil Service appointees. Few WOC appointees were available, since academic institutions were feeling the financial pinch due to decreased enrollments. Full- or parttime contract employees were not allowed to hold administrative positions, so that institutions were unable to recover salaries of such persons from the Government. For a time, men employed under contract were allowed to serve as Division Members, that is, they served on the planning committees which determined the policies and programs of the Divisions. Division Members always refrained from participating in any action which involved contracts in institutions where they were employed or where they had been employed during recent years. After March r945 it was ruled that Division Members could not be contract employees under any contract being administered by the Division. In some instances employees under a contract in one Division were Division Members of another Division. Thus all Division Chiefs, Technical Aides, and Division Members were either WaC or Civil Service appointees after March r945.

Since many of the scientists in Divisions 8, 9, ro, and 11 were also official investigators under contracts, and since few were willing or able to assume **Wac** or Civil Service appointments, the formal organizations of the three Divisions consisted mainly of the Division Chief, the Technical Aides, and the steering committees. Divisions 8 and rr were formally organized into more than one Section, each with its Section Chief. Division ro had one such Section. The real scientific work was done as before by contract employees.

As time went on, the number of contracts decreased markedly. In some instances small contracts were terminated because the work was completed; in other instances the work could be carried on more expeditiously by large groups. Beginning on March 1, 1945, some contracts were transferred **to** the Army and N avy and ceased to be administered by NDRC.

Division 8 was given the title of "Explosives." Details of the accomplishments of this Division will be found in the chapters devoted to it. Essentially, • it covered work in the synthesis, testing, and production of explosives, including underwater explosives, gun propellants, propellants for rockets, and high explosives for use in shells and bombs. Part of this work, particularly

ORGANIZATION OF NDRC

on the effects of explosives on the surroundings, air, and water, was separated out and became a separate Division at a later date.

Division 9 was given the title of "Chemistry." It will be necessary to consult the chapters devoted to the accomplishments of this Division for details of its program, but we may state its domain in broad terms. Work in synthetic organic chemistry (chemical warfare agents), analytical methods, and protective devices applied to the persistent type of chemical warfare agent, bio-assay, and purification, stabilization, and physiological mechanisms of action of chemical warfare agents was assigned to Division 9. During the latter part of the war several problems on insecticides, insect repellents, rodenticides, and antimalarial agents received much attention. Some of these subjects bordered on or even overlapped work of Divisions 10 and rr and of the Committee on Medical Research. Generally speaking, 9 was the Organic and Biochemistry Division.

The title of Division 10 "Absorbents and Aerosols" was, as things worked out, very misleading. The parent Sections had been formed to deal with the component parts of the gas mask canister and with smokes in general. Section B-S had already worked extensively on screening smokes and Section B-6 on new agents. As time went on, Division 10 covered the following subjects: gas mask absorbents, gas mask filters, testing methods for gas mask canisters, screening smokes, meteorology, certain inorganic problems, munitions for smokes and chemical warfare, insecticide dispersal. Generally speaking, Division 10 was the Physical Chemistry Division, but it contained a lot of chemical and even mechanical engineering. Irs work overlapped at several points the fields covered by Divisions 9 and rr.

As is evident from the titles of the Sections from which it was formed, the subject matter of Division 11 defies description, even though it was called "Chemical Engineering." Flame throwers, incendiaries, oxygen-generating and -storage equipment, paints, hydraulic fluids for gun-recoil mechanisms and airplanes, purification processes for chemical warfare agents, and many other problems all came into this Division at some time or another. As time went on, the lines of demarcation between Division rr and Divisions 9 and 10 became sharper, and an unconscious redistribution of responsibility occurred. Some subjects placed originally in Division rr never really belonged there.

ADMINISTRATIVE OFFICES

After the reorganization of December 1942, Dr. Adams, representing the Chairman of the National Defense Research Committee, and the central offices of Divisions 8, 9, 10, and rr continued to be housed at Dumbarton Oaks, although some Section offices and certain Technical Aides were located in cities other than Washington.

CHEMISTRY

One feature of these combined headquarters was the Reports Library, of which Dr. Louise Kelley, Professor of Chemistry at Goucher College, was in charge. Dr. Kelley was assisted from February 1943 to August 1945 by Dr. Elizabeth Ballard. The Library had the function of distributing reports from the Armed Services and from Allied organizations to the various scientists in these Divisions. This work reached a very large magnitude at its peak. It was of immense service to the scientific personnel of the various Divisions, since requests were frequently received for reports dealing with specific subjects. This **meant** that extensive indices covering all of the reports had to be maintained.

In addition, Dr. Chadwell, as Chief Technical Aide to Division B, had R. A. Bowman, Jr., as Administrative Assistant. The Administrative Assistant was responsible for the mail room and Division B files and the employment of clerical and fiscal personnel. In addition he handled arrangements for travel, reservations for hotel rooms for scientists visiting Washington, and promotions, etc., for clerical and fiscal employees of Division B. Mr. Bowman was succeeded by Marcia D. Campbell, who in turn was succeeded by Adele Endres.

Captain R. A. Lavender, U.S.N., had charge of all patent matters for OSRD, but a Division B representative was Lieutenant (later Captain and later still Major) B. A. Bull, CWS, who continued to serve Divisions 8, 9,10, 11, and 19 until the end of the war. Major Bull was assisted for a time by F. T. Williams, who was later commissioned as an officer in the Navy.

From August 1942 until the formation of the four Divisions, Division B had a representative in the Office of the Chief, Technical Division, Chemical. Warfare Service. It was his duty to aid in the transmittal of information between Division B and that Service.

Most of the essential parts of Division B which had to do with administrative procedure can be found in the organization chart of September 1, 1942, in Appendix A. It should be emphasized, of course, that while Division B was housed separately from most of the offices of OSRD, the general administrative overhead of the parent organization handled many matters directly. Thus, the Scientific Personnel Office was responsible for all matters pertaining to the Selective Service system and for appointments and promotions of scientific personnel. The office of the Executive Secretary handled contract matters, although much of this was done on recommendation from Division B or its successors.

Part Two: History of Division 8

CHAPTER II

INTRODUCTION TO THE HISTORY OF DIVISION 8

G. B. KISTIAKOWSKY AND RALPH CONNOR

ACKNOWLEDGMENT

LHE FORMER Chiefs of Division 8, in writing these chapters, have been motivated largely by the consideration owed to some **hundreds** of young scientists who participated in the work of the Division; This history is the final gesture that we can make to express our appreciation of the confidence and loyalty of our young coworkers, to discharge our obligation to justify their work, and to provide a permanent record of the trying times we shared with as fine a group, technically and personally, as ever worked in a **common cause**.

In preparing the Division 8 history it has not been possible, in the space allocated, to describe the contributions of each individual. Usually a group is designated by reference to the senior man; this is done solely to identify the group as concisely as possible with the hope that the reader will realize that credit is shared by all the participants. In order to make it possible to determine the general field of activities of each worker, these groups are identified and the names listed of all the technical workers who participated on a fulltime basis for more than six months. These lists may be found at the end of the appropriate chapter; if one group participated in activities which are described in different chapters, the group is listed after only one chapter and not repeated.

The names of personnel under each contract have been supplied by the contractors; it is significant that letters forwarding these lists have repeatedly contained the statement that credit should be assigned to groups - not to individuals. It is indeed true that every successful project was the result of co-operative efforts which usually involved more than one laboratory. The splendid spirit of co-operation, interlaboratory as well as intralaboratory, greatly facilitated the work of the Division.

Part Five: History of Division

CHAPTER XXVI

THE ORGANIZATION OF DIVISION //

E. P. STEVENSON AND D. CHURCHILL, JR.

THE Sections which eventually formed part of Division 11 had their origins in the summer of r940 when Dr. W. K. Lewis, of the Massachusetts Institute of Technology, Vice-Chairman of Division B, in association with Dr. Roger Adams, of the University of Illinois, also a Vice-Chairman of Division B, called upon Dr. T. K. Sherwood to take charge of projects in the field of Chemical Engineering. By the summer of 1941 Division B had been organized into eight different sections, and in August E. P. Stevenson, President of Arthur D. Little, Inc., was appointed a Member of Division B and made Chairman of several of the sections which ultimately formed part of Division 11. A list of these sections and of their key personnel as of September 1, 1942, is given on pages 486-491.

When Division II was first organized on December 9,1942, R. P. Russell was designated Chief, but he served in that capacity only until about March I, 1943, when he was succeeded by E. P. Stevenson. Mr. Stevenson continued to serve as Chief of Division Ir during its period of greatest activity, but resigned about February I, 1945, when he was succeeded by Dr. H. M. Chadwell.

Mr. Russell rearranged the sections from which Division II was formed and placed all of the Technical Aides in one pool serving the Division as a whole rather than individual sections. This arrangement continued until about April I, 1944, when Mr. Stevenson, who was then Chief, restored the original sectional distribution of the Technical Aides and at the same time designated D. Churchill, Jr., as a Divisional Technical Aide. At the same time, Division Members were eliminated and each Section was given its own steering committee, consisting of several Section Members.

By the time Dr. Chadwell succeeded Mr. Stevenson as Chief of the Division, the program had begun to be curtailed, and the system of Division CHEMISTRY

Members was restored, although only five were named: E. R. Gilliland, Deputy Chief, E. P. Stevenson, and the Chiefs of the three Sections, J. H. Rushton, T. K. Sherwood, and H. C. Hottel.

During an extended period of time beginning about the middle of 1943 and lasting to the fall of 1945, Division 11 had a representative statlOned in the Office of the Chief, Technical Division, Chemical Warfare Service, at Edgewood Arsenal. The first such representative was Dr. E. C. Kirkpatrick who served on a part-time basis. He commuted from Wilmington, Delaware where he devoted a substantial fraction of his time to the du Pont - Company: He was succeeded during the summer of 1943 by Dr. C. S. Keevil who resided at Edgewood full time and who aided very materially in mam-

taining excellent contacts between Division II and the Service.

Division 11 also had other very intimate contacts With various branches of the Army and Navy. Some of these were maintained by the overhead personnel and some by contract employees. Some were overseas in various Theaters of Operation. The details of these contacts will be found in the following chapters.

The organization of Division 11, which consisted of three SectIOns during the height of its activity from about April 15, 1944, to about February 15, 1945, is given in Appendix J.

The History of Division II covers a lot of heterogeneous and unrelated activities. Of these, by far the largest single program, concerned the generation and use of oxygen and is given in Chapter XXVII as the History of Section II.I. Section II.2 dealt with miscellaneous chemical engineering problems. Its history is given in Chapter XXVIII, and it will be found that a wide variety of different topics has been covered. Section 11.3 covered flame warfare in general, and its history is subdivided into Chapter XXIX, "Incendiary Bombs," Chapter XXX, "Incendiary Fuels," and Chapter XXXI, "The History of NDRC Flame-Thrower Development."

Certain parts of original Division B were included in Division 19, but for a time they were essentially part of the Sections which formed Division II. The same may be said concerning activities related to the problems of the Quartermaster Corps.

CHAPTER XXVII

THE OXYGEN PROGRAM

E. P. STEVENSON

REASONS FOR THE PROGRAM

THE oxygen program had its inception in the immediate needs of three branches of the Services and a long-range project of the Navy. The **immediate** needs were for relatively lightweight field generating units, either skid or truck mounted, to supply compressed oxygen of high purity for **general** repair uses at forward bases and for aviators; the long-range Navy project was that of underwater propulsion of submarines using a gas turbine with liquid oxygen or its equivalent as a secondary fuel. This project called for means to generate, during the night! y surface operation, a large part or all of the oxygen needed while the submarine was at sea. It posed an **extreme problem** in design, and the challenge offered was indirectly useful **in** connection With other projects. The initial program largely centered in the submarine propulsion project.

INCEPTION OF PROGRAM AND PRELIMINARY CONTRACTS

A beginning was made in the fall of 1940 when, at the instigation of NDRC, Commander R. P. Briscoe, of Naval Research Laboratory, wrote to Dr. W. M. Latimer, of the University of California, submitting tentative specifications for a liquid oxygen plant to be operated on a submarine. Work on this project was actually initiated at the Massachusetts Institute of Technology under the direction of Dr. F. G. Keyes, for the development of hightweight liquid-air rectification equipment based on a cycle using helium as a secondary refrigerant. This project also involved the design study of a free-piston compressor, a novel reciprocating expander, and a new type of dual-functioning heat-exchange and air-cleanup system.

A somewhat paralleling project was undertaken in the following spring by the University of California, under the immediate direction of Dr. W. F. **Giauque**, to cover sp.ecifically the possibility of meeting the Navy's specilication through the deSign of a cascade system embodying various features of a hquid-air unit previously built by Dr. Giauque. It was appreciated from

¹ The leehnical personnel for each contract (usually identified in the **text** by the name of the Technical Representative) are listed at the end of the chapter.

344

INCENDIARY BOMBS

CHAPTER XXIX

INCENDIARY BOMBS

E. P. STEVENSON

REASONS FOR THE **PROGRAM**

WHEN work on incendiaries was undertaken by NDRC in the summer of 1941, the large-scale use of incendiary bombs was a relatively new concept. The effectiveness of the incendiary as a weapon of attack had been shown during the blitz on England, where destruction per ton of incendiaries dropped was about five times as great as the damage from a ton of high-explosive bombs. The only American incendiary bombs available at the time were the AN-M-so, 4-pound magnesium bomb, and the AN-M-S4, 4-pound thermite bomb, intended as a substitute for the AN-M-so.

Projects for the development of incendiary materials and contamers were first set up by NDRC at Harvard, Brown, and Chicago Universities. Following a letter from General H. H. Arnold to Dr. Vannevar Bush. emphaSIZing the shortage of magnesium, NDRC in September r941 orgamzed an enlarged program for development of incendiary munitions which were to be at least as effective as the German Kilo magnesium bomb and readIly capable of mass production without utilizing important strategic materials or facilities.

INVESTIGATIONS OF THICKENING AGENTS FOR LIQUID FUELS

When a Service project was received from the Chemical Warfa.re Service on October 7, 1941, exploratory work on new bombs and incendiary materials had already begun. A group at Harvard University ¹ under the direction of Dr. L. F. Fieser was experimenting with gasolme, thickened or "jellied" by addition of rubber, as a fuel. This combination proved to be an effective incendiary material since it had a high heat of combustion, was easily ignited, and gave a controlled burning rate. To augment the program, Dr. G. B. Wilkes at the Massachusetts Institute of Technology started fundamental studies of the ignition of wood by incendiary materials, and the Standard Oil Development Company, under R. P. Russell, made available the services of a large group for development of fuels and munitions. Shortly thereafter, Arthur D. Little, Inc., joined the incendiary develop-

¹ The technical personnel for each contract (usually identified in the text by the name of the Technical Representative) are listed at the end of the chapter.

JDent groups and E. P. Stevenson took general charge of the NDRC incendiary program.

When the beginning of the war in the Pacific in December 1941 cut off the supply of rubber, an intensive search for a substitute thickening agent began. Three lines of investigation were initiated. The Harvard group, working with the staff of Arthur D. Little, Inc., investigated the potentialities of aluminum naphthenate as a thickening agent. The thickener was JDodified by addition of the aluminum soaps of coconut acids. The Standard Oil Development Company (SOD) simultaneously developed a sodium soap gasoline thickener, and the du Pont Company developed a thickener based on isobutyl methacrylate polymer. Early incendiary tests showed the methacrylate thickener to be somewhat superior to existing aluminum and sodium soap thickeners, and the first production of "jellied" gasoline bombs utilized this formula. The du Pont Company, under Dr. J. C. Woodhouse, continued actively in its studies of methacrylate-based formulas, and these were the main source of jellied gasoline for the first year of production.

Although aluminum soap thickeners were, at this time, unsuitable because of necessary high mixing temperatures, unreliable thickening, and instability, work on them continued at the Nuodex Products Company, Inc., SOD, Arthur D. Little, Inc., and Harvard. Arthur D. Little, Inc., found that commercial aluminum naphthenate, after purification **by** alcohol or acetone extraction, gave reliable thickening. SOD produced a powdered aluminum soap of cottonseed fatty acids (oleic, linoleic, and palmitic), which gelled in gasoline by stirring at ambient temperatures but which oxidized when exposed to the air. Harvard mixed the aluminum soaps of naphthenic and coconut acids to produce a stable thickener which was extruded into the gasoline, and by a long series of subsequent experiments established the optimum ratio of acids finally adopted in the product christened Napalm.

Nuodex Products Company, Inc., with Arthur Minich as director, applied its previous experience with aluminum soaps and produced Napalm (2 parts coconut acids, I part oleic acid, and I part naphthenic acid) by coprecipitation. The product was a granular, nonagglomerating powder which could be produced commercially in large quantities with existing facilities, solvated readily in gasoline, and was reasonably resistant to oxidation. More than 80,000,000 pounds of Napalm were produced commercially during the war for incendiary bomb and flame-thrower fuels. A more complete account of the development of incendiary fuels will be found in Chapter XXX.

DEVELOPMENT OF THE AN-M-69 BOMB

While research work on thickening agents for gasoline was being carried out in the fall of 1941 the Standard Oil Development Company undertook the development and design of a small incendiary bomb utilizing gasoline jelly as a fuel. Messrs. H. G. M. Fischer and R. P. Russell acted as

CHEMISTRY

general leaders of the devdopment group, with N. F. Myers in active charge of the work. Preliminary tests to find the amount of fuel necessary to stan a fire in an attic, when the fuel was placed at various distances from eaves revealed the importance of creating a munition which would project the fuel into a favorable location. Gasoline was considered one of the best incendiary fuels because of the high heat of combustion (17,500 to 19,500 BTU per pound). The use of the fuel in the form of a gel or semisolid was found to be superior since a controlled rate of burning then resulted. To allow the bomb to come to rest on its side and then eject the fuel horizontally from the tail of the bomb, a delay element in the fuze was indicated. A high fuel-charge-to-total-weight ratio was to be achieved by use of a comparatively thin metal case as a container for the fuel, by placing the fuze horizontally so as to occupy less space, and by using cloth streamer tails which would reduce the velocity to permit desirable structure penetration without destroving the mechanism of the bomb and without adding unnecessary bulk to the munition.

Two similar bombs embodying the above features were first developed, one weighing about 5 pounds and the other 7.5 pounds. The final model, illustrated in Figure 12, represented a compromise between the two previous bombs and weighed 6.2 pounds. Complete data for the bomb are included in the accompanying Table (see p. 405). The bomb was designed so that after it is separated from the cluster (see later discussion) the tail streamers are caught by the wind and pulled out to their full length, thereby stabilizing the bomb in flight. The safety plungers are also relieved from contact with adjacent bombs when the cluster disperses, and the bombs are then fully armed. On impact the striker, previously held away from the primer cap by a steel spring, falls forward and the firing pin strikes the primer cap. When the flash from the primer cap ignites the spitter fuze, the spitter begins to burn and after 3-5 seconds ignites the booster charge at the back of the fuze. By this time, the bomb has usually reached its final resting position, either on its side or stuck more or less venically into the floor boards. When the booster charge ignites, its flash in turn fires the main ejection-ignition charge contained in two nitrocellulose powder bags. The explosion of these charges ruptures the sealing diaphragm and ejects the fuel charge, together with the tail cup and streamers, from the tail end of the bomb. The burning magnesium particles in the ejection-ignition charge insure ignition of the gasoline fuel. The flaming fuel is held together in a sock and is thrown for approximately 50 yards or until it strikes an obstruction. The jellied gasoline smears over the object struck and initiates a fire if the object is sufficiendy combustible.

The filling used in the SOD bomb was gasoline-thickened either with Napalm or with isobutyl methacrylate polymer. The compositions varied from time to time; the following are typical formulas: INCENDIARY BOMBS

Napalm Filling

Napalm thickener Gasoline

9.0 percent

1M Filling

Isobutyl methacrylate polymer	5.0 percent
Fatty acids (stearic acid)	2.5
Naphthenic acid	2.5
Aqueous solution of caustic soda -	3.0
(40 percent)	
Gasoline -	87.0

Several experimental lots of the gasoline-jelly bomb were used in testing work. Vanous mechanical improvements to increase the reliability of functioning were incorporated in the design as information was obtained from the testing work.

In order to simulate the performance of the bomb when dropped from aircraft, a mortar was constructed at SOD and used to fire the bombs downward onto a target at any chosen velocity. The mortar was mounted on a movable crane placed over an abandoned "hydrogenation stall," so that the point of impact of the bomb on the structure below could be closely controlled. Various sections of typical enemy domestic and industrial structures were employed to test the penetration, functioning, and fire-raising characteristics of the 6-pound oil bomb, which was later to be designated the M-69. Over 20,000 bombs were tested by Standard Oil Development Company before the final design was standardized.

development of burster for the M-47 bomb

While the small gasoline-jelly bomb was being developed by SOD, Drs. Fleser and Hershberg of Harvard were at work on development of a suitable **filling** and burster mechanism for the 70-pound AN-M-47 bomb. The first trials were made using the conventional black-powder central burster but it was soon found that this was not entirely satisfactory because of poo: fuel distribution. When a bomb filled with gasoline jelly was ruptured by a black-powder burster, a weak spot at a seam or near the tail yielded sufficiendy to relieve the pressure, and thus only a portion of the fuel was ejected while the remainder burned in the bomb or in the crater below. A fasteracting explosive, TNT-tetryl, on the other hand, was found to burst containers of fuel fairly uniformly and could be adapted to give gobs of appropriate size for best incendiary action. The problem then remained to find a suitable igniter for the gasoline gel. Among those tried were powdered and **grained** magnesium, sodium, potassium, sodium-potassium alloy, zinc

39**2**

CHEMISTRY

dimethyl, silicon ethyl, phosphorus, and pyrophoric metals. Phosphorus Was selected as the most suitable material and in the final model the central TNT-tetryl burster was surrounded by white phosphorus placed in a larger tube. This burster-igniter combination was turned over to the Chemical Warfare Service for completion of development, and after modification eventually was standardized as the M-9–M-13 burster-igniter. Many of these units were produced and used in AN-M-47 bombs in the bombing of Germany and Japan. The same principle was adopted in developing bursters for the AN-M-76, Soo-pound incendiary bomb, and for the JettIsonable belly tanks used effectively in tactical warfare.

INCENDIARY TESTS AT JEFFERSON PROVING GROUND

By the early summer of 1942 the 6-pound jellied-gasoline bomb and the experimental AN-M-47 burster were available in sufficient quantity for airborne testing on condemned farm huildings at Jefferson Proving Ground, Madison, Indiana. The tests showed that the gasoline-jelly bomb developed by SOD was a superior fire starter among the small bombs tested, and that the TNT-white phosphorus burster for the AN-M-47 was an Improvement over the black-powder burster. On the basis of these results, the small jelly bomb was standardized as the AN-M-S6 (later the AN-M-69) and the Air Forces and CWS decided to put it into large-scale produc. tion.

Although the Jefferson tests added to the knowledge of functioning of the bombs in an airborne attack, the nonrepresentative character of the target led to some question as to the significance of the results. The **Standard** Oil Development Company, therefore, originated extensive research into the types of construction occurring in German and Japanese buildings, and on the basis of information obtained from several experienced consultants designed various sections of houses which were used in mortar testing as described previously. The results verified the previous findings that the AN-M-69 fuel charge showed a much higher expectancy of **reaching** a vulnerable location and hence starting a fire than small bombs whose **action** was limited to the region in which they landed.

TESTS AT DUGWAY PROVING GROUND

As research continued, it appeared advisable to construct a large group of typical German and Japanese houses for actual airborne bombing trials. During February 1943 plans for this project were prepared by SOD With the aid of architects who had practiced in Germany and Japan. When the project was turned over to CWS in March 1943, the SOD group continued to hold a principal role as architect-engineers. After Dugway Proving INCENDIARY BOMBS

Ground in Utah was chosen as the site because of the high freq 393 days 0^f clear VISI^{bil}Ity, construction was begun on March 29, 1943 ^{uprov} o^f the f0^l oWing seven wee^ks, the **entire** target consisting of 12 tWo-f^{unn}g Japanese houses and 6 adjoining German houses was completed and am ^{uy} ready for testing. The wood used in the structures was chosen so ma^de slmu ate ^lum^ber use^d **in** German and Japanese construction as close!^{as} to possible. A shipment of Russian spruce was located on the West C^y as s^h**IPPe**^d across the continent to New Jersey for milling, and finally ^{re-} shipped to Utah as finished structural members. This wood was used in the Japanese dwellings to **simulate** "hinoki," which is used extensively in Japanese constructIOn. H. A. Řícards of SOD undertook a 2s,000-mile search of the West Coast and Hawaiian Islands to collect an adequate supply of the Japanese straw floor **mats**, **known** as "tatami," used in the dwellings. RKO studIOS and other organizatIOns were called upon to furnish authentic designs of German furniture for the houses.

An extensive series of tests using the AN-M-so, AN-M-S2, AN-M-S4' and AN-M- 69 bombs was conducted at the Dugway site from May 17 to September I, 1943. The wood, which was the main source of combustible material in the houses, was originally conditioned to a moisture content appropriate for German and Japanese dwellings, *i. e.*, about IS percent. As tests progressed, however, the arid climate dried out the wood somewhat, particularly the lighter members which play an especially important part in 11lidatIOn of fire.

A few trials with the AN-M-S4' 4-pound thermite bomb, gave very poor results and further operations did not include this munition. The relative ratings of the other bombs on the German and Japanese dwellings were det.ermined using a **fire** scale in which any **fire** beyond control of the well-tramed and properly equipped **fire** guards in 6 minutes was classified an A fire; a **fire** which was ultimately destructive if unattended was a B fire' and a fire. judged.nondestructive was a C fire. Using this basis, the **fires** resulting **11** functIOning hits on the German and Japanese houses were as follows:

Fire	German Houses Japanese House		erman Houses		ses	
Classification	AN-M-50	AN-M-52	AN-M-69	AN-M-50	AN-M-52	AN-M-69
A B C	0% 26 74	0% 18 82	37% 16 47		26% 14 60	68% 13 19

• It will be noted that although the probability of a quick fire is greater the more combustible Japanese structures, there is nevertheless a significant proportion (37 percent) of A fires resulting from AN-M- $_69$ hits on German dwellings. The potentialities of incendiary warfare in a coun-

394

CHEMISTRy

try of crowded cities were further emphasized by near-eonflagration Con_ ditions which occurred several times throughout the tests.

Using the results of the Dugway trials as a basis, plans for the bombing of Japan with the **AN–M-69** were drawn up by the Army Air Forces in the fall of 1943. Dr. R. H. Ewell, Technical Aide, Section 11.3, working directly with the Air Force, and Professor H. C. Hottel, Chief, Section II'3 working with CWS, contributed to the preparation of these plans.

BRITISH-AMERICAN **CO-OPERATION** IN DEVELOPMENT AND TESTING

In the fall of r942 Mr. Russell of SOD and Dr. Ewell went to England to present a summary of the tests at Jefferson Proving Ground and to discuss the use of the gasoline-jelly bomb in European raids. The latter suggestion was not adopted, however, partly because the AN-M-69 bomb showed poor functioning due to inadequate production control, and partly because of the British viewpoint that a large fire bomb was required to initiate fires in German attics. About a year later Mr. Myers of SOD and Professor Hottel also visited England to present the new picture of performance of small incendiary bombs gained from the Dugway tests of r943 and to discuss methods of evaluation of incendiaries. The British testing agencies had just completed a few German-type structures somewhat similar to those at Dugway and they later added Japanese-type structures to their test program. The results of the tests in these structures, in contrast to the Dugway results, indicated that quick fires could not be obtained when an M-69 bomb ejected fuel into the eaves of a simulated German dwelling or within a Japanese room, and that the M-50 magnesium bomb would not start a destructive fire in a German attic.

A mission of British incendiary experts, including Group Captain F. G. S. Mitchell, MAP, Wing Commander E. A. Howell, RAF Staff, Professor G. I. Finch, MHS, G. R. Stanbury, MAP, and H. Elder, MHS, therefore -visited the U.S. in November 1944, to inspect facilities and discuss the differences in results. A later visit by Mr. Llewellyn, Building Research Station, who had supervised testing work in the United Kingdom, assisted greatly in resolving the differences. In general, it was concluded that: (r) the hits in the German structures at Dugway probably presented an unduly favorable picture of the rapidity of fire growth, since the few quick fires which were obtained resulted from bombs lodging in small but readily combustible places; and (2) the tests carried out in the Japanese structures in Great Britain gave less favorable results than those at Dugway, because of the combined effects of a higher average moisture content, a less combustible species of wood, and differences in construction, the net effect of which was to make the test structure in the United Kingdom a poorer incendiary target.



FIGURE 12. Sectional models of AN-M-69 and M-69-WP bombs



INCENDIARY BOMBS

development of M-69X bomb

The development of a modification of the AN-M-69 bomb containing an antipersonnel explosive element was started by SOD after the main testing work with the regular AN-M-69 had been completed. It was believed that if a part or all of the incendiary bombs contained the "X" charge, the fire fighters would be deterred from acting to save the structure in which the bomb hit. As final! y designed, the M-69X had the same outside dimensions as the AN-M-69, but part of the jellied-gasoline fuel charge was displaced by a terryl charge in the nose of the bomb. Through this change the weight of jellied gasoline was reduced from **2.6** pounds in the AN-M-69 to 2.2 pounds in the M-69X, but the decrease in fuel content did not significantly change the fire-starting ability of the bomb.

The M-69X was constructed so that as the main ejection-ignition charge forces the fuel from the bomb case, a delay fuze leading to the tetryl charge is also ignited. After a variable delay of $1\frac{1}{2}$ to 6 minutes, the explosion of the X charge fragments the entire nose end of the bomb, including the heavy HE cup, fuze cup, fuze, impact diaphragm, and the bottom third of the casing, producing over 400 metal fragments. Despite the fact that the shock of the explosion would probably incapacitate a man for several minutes even if he was not hit by a fragment, tests showed that the blast would not adversely affect fires burning 3 feet or more away from the HE unit. Large-scale production of the M-69X was not begun until March 1945, and although shipments reached operational bases in the Marianas Islands in July 1945, there is no record of the bomb's having been used operationally.

Associated with the development of the M-69X was a second modification of the AN-M-69, whereby a closed plastic cup containing white phosphorus was inserted between the sealing diaphragm and the fuel charge (see Figure 12). When the fuel is ejected from the bomb, the force of the explosion breaks the cup and spatters the white phosphorus about the area. Fire fighting is then hampered by the obscuration and irritation resulting from breathing the white phosphorus smoke. Just as in the M-69X the weight of the fuel charge was decreased by the addition of the phosphorus cup, but again tests failed to show a real difference in fire-starting efficiency of the gel.

AIMABLE CLUSTERS

Small incendiary bombs are Ordinarily used in containers or clusters in which a number of the bombs are closely bundled. Such clusters may be either the quick-opening or short-delay type which opens and scatters the bombs almost immediately below the airplane, or the aimable or delayopening type, which is stable in flight and falls as a unit to within a few

INCENDIARY BOMBS

CHEMISTR.Y

thousand feet of the ground before opening and scattering the bombs (see Figure 13). Small incendiary bombs were used in quickoOpening clusters in the U.S. until the fall of 1943, when the Air Force ruled that parts from quickoOpening clusters constituted a major hazard to the planes following in formation **flight**. Aimable clusters were required therefore for all munitions. The E28 (also called M-18 and E6R2), Soo-pound aimable cluster for the AN-M-69 bomb, had been developed by CWS; however, its flight trajectory was not reproducible; it gave about 3 percent of air-burst bombs due to the shock of opening; and about S percent of the clusters failed to open at all. A request by the Air Force in November 1943 for rush production of 10,000 E28 clusters for use by the 20th Bomber Command in China necessitated manufacture of the cluster despite its recognized deficiencies. In cooOperation with CWS, SOD assumed full responsibility for production and inspection of the order, and completed delivery **in** I¹/₂ months.

In January 1944, SOD began development of a modified aimable cluster (E18) for the M-69 bomb which was more streamlined, was longer, contained 4S instead of 38 bombs, and had a reliable mechanical opening device. Although the E18 cluster was **suitable** for loading in most airplanes, it was too long to permit efficient loading in the new B-29 and B-32 airplanes, and for this reason the cluster was never standardized.

Using these developments as a basis, CWS designed a new cluster, the E46 or M-19, which functioned reliably, gave a reproducible trajectory, and had a mechanical opening device which delivered the bombs with a minimum of air bursts and tail damage. The M-19 was produced in large quantities and used extensively in the bombing of Japan in 1945.

WORK. OF INCENDIARy-EVALUATION PROJECT

In the early spring of 1944 CWS and NDRC agreed upon establishment of a joint project for evaluation of incendiaries by an impartial group of engineers. The Joint CW8-NDRC Incendiary-Evaluation Project, which was formed for this purpose, drew personnel from the Chemical Warfare Service Technical Command, Factory Mutual Research Corporation, Massachusetts Institute of Technology, Division 11 of NDRC, the Office of Field Service of OSRD, and the British Ministry of Aircraft Production. Their assignment was to study the relative performances of small incendiary bombs against industrial targets, although work on Japanese domestic structures was included to some extent.

After preliminary test work in the laboratories of Factory Mutual, the group, under the direction of Dr. Keevil, was transferred to Edgewood Arsenal in October 1944. The facilities provided included a large fireproof test building above which a mortar was mounted on a tower to permit firing

bombs into targets placed within the building. After selecting five Combustible objects as being generally typical of factory occupancies, many tests were performed with standard and experimental munitions to establish the probability of fire if the bomb hit in or near the various targets. These data were then combined with the probability of a bomb hitting in the various locations, if it entered at random into a building in which the combustible objects were present, to give the over-all probability of fire. This type of analysis again led to the conclusion that a munition which projects fuel horizontally after entering a structure shows a greater probability of starting a fire than a bomb of the same size which is effective only within the region immediately surrounding the bomb.

An important function of the Evaluation Group was to make an intercomparison of the three small incendiary munitions of chief interest, the magnesium AN-M-so, the tail-ejection, delay-fused AN-M-69, and the tail-ejection instantaneous-fuzed M-74, developed by CWS. By means of the instantaneous fuzing, the M-74 ejected the gel from the bomb case by the time the bomb was a few feet through the roof, whereupon the gel descended without a large horizontal component. The M-74 also differed from the AN-M-69 in that it was filled with PT-I-C fuel (a paste of magnesium powder, oil, isobutyl methacrylate polymer, and gasoline), had a metal popoOut tail, and an all-ways fuze which was activated regardless of the angle at which the bomb struck. As stated previously, it was found that as between the instantaneous and delay-fuzed tail-ejection bombs, the horizontal target-seeking action associated with delay-fuzing constituted an advantage which outweighed all other differences between the bombs. The same tests indicated great promise for a magnesium bomb which could be stowed more efficiently than the AN-M-so because of the very large number which could be carried per plane load.

In order to evaluate the performance of the AN-M-47 70-pound oil incendiary bomb and other large bombs which are not easily fired from a mortar, airborne drops on a target building were employed. A large test **building** which contained the three common types of **industrial** roofs was constructed at Eglin Field, Florida, by NDRC in early 1944. One section of the building had a wood sawtooth roof, the middle section had a concrete-tile roof, and the third part was a three-story re-enforced-concrete structure, Penetration, fire-evaluation, and functionary tests with the AN-M-69, AN-M-47, M-74, and E9 bombs were conducted at Eglin Field during the following year. A duplicate of this building was constructed by CWS at Edgewood Arsenal in the fall of **1944**, and the various wooden targets used in static and mortar-evaluation tests were placed within the building to observe the **incendiary** action of the various bombs.

CHEMISTRY

AN-23 project in photointerpretation

During the fall of 1944 the AN-23 group,² under the direction of Dr. V. Rojansky, was formed as a joint Division 2-Division 11 effort to appraise the effectiveness of various munitions through interpretations of data from aerial photographs of enemy industrial targets taken before and after bombing raids. Following a visit to Photointerpretation installations in England and other Air Force bases in Europe in late 1944, the members of AN-23 analyzed the amassed data in Washington during 1945. Comparisons of effectiveness between incendiary and high-explosive bombs showed the definite superiority of the incendiary bomb per unit weight against industrial targets, particularly in the aircraft industry. The M-47, which was the incendiary used to the greatest extent in Europe, was found to be twelve times better than the 500-pound HE bomb against combustible buildings, and one-and-a-half times as effective against noncombustible or fire-resistive buildings. Only a sinall amount of data concerning the AN- $M-5_0$ incendiary bomb (in M-I7 clusters) was obtained, but it indicated that this incendiary was, on a weight basis, as good as the AN-M-47 against industrial buildings.

OTHER INCENDIARY MUNITIONS

In addition to the bombs mentioned previously, the Fire Warfare Section carried out the development of several other incendiary bombs. This was done in part on the theory that several strings to a bow are desirable, but largely in consequence of inadequate knowledge of what targets might be expected. As events proved, structures in Germany and Japan were at least as vulnerable as had been anticipated, but had they turned out to be considerably more resistant from the standpoint either of penetration or of fire resistance, bombs such as the E9 and E19 would have been required.

development of E9 bomb

The E9 bomb was developed by the Texas Company. The Foster Wheeler Corporation and the Standard Products Company assisted in the design and construction of experimental versions. S. M. Jones served as a Special Technical Aide to Section 11.3 on this project. Research was initiated in February 1943 upon receipt of a request from the Eighth Air Force for an intermediate-sized bomb which would have good ballistics, would penetrate a substantial target, and would carry the maximum amount of incendiary fuel.

2 Drs. H. F. Bohnenblust. G. W. King, J. Neyman, and H. L. Webb. and Messrs. E. B. Gerry and R. J. Hensen.

INCENDIARY BOMBS

It was planned to incorporate a charge of white phosphorus in addition to the incendiary gel, and to include a **high-explosive** element that would cause fragmentation of the nose. Primarily, however, the bomb was to be highly aimable so as to be suitable for high-altitude precision bombing.

A preliminary design study attempted to meet the requirements in a bursting-type bomb. Concurrently, the Chemical Warfare Service had been designing a tail-ejection bomb in the same size range and with some of the same features. At a conference between Texas Company representatives and CWS in March 1943. the two designs were amalgamated in a tail-ejection model and the project was turned over to the Texas Company for completion of development.

The E9 bomb, as produced in pilot quantities for test purposes, had a heavy steel nose, hexagonal steel case, and an extensible metal tail. The overall dimensions were chosen so that fourteen bombs, in two banks of seven, formed a cluster which fully utilized the space available on a 500-pound bomb station. An arming vane attached to the nose permitted an out-of-line detonator to slip into position after the bomb separated from the cluster and fell away from the plane. A delay train, blasting cap, and highexplosive charge were contained in the nose which screwed into a base plate holding the detonator and safety pin. Attached to the other side of the base plate were two domes, one containing the ejection charge and the other white phosphorus, and the steel case holding the incendiary fuel. The end of the case was rounded, and attached to it was a thin conical section carrying the extensible metal tail. The only fillings which could be used were those capable of being introduced through the small hole in the tail cone. Despite the fact that an extensive series of tests showed that a fuel charge consisting of cylindrical wads of cellucotton saturated with gasoline or other liquid fuel was the most promising, the construction necessitated use of thickened gasoline which could be admitted through the small hole. The weight of incendiary gel which could be carried was 9.5 pounds.

Although the E9 was originally intended for use in 500-pound quickopening clusters, the Air Force ruling against the use of **quick-opening** clusters because of the danger from slowly falling metal components necessitated design of a new cluster adapter. Since ordinary aimable clusters require a nose fairing and a tail and since there was no room to add these parts to the cluster of E9 bombs, it became necessary to devise an adapter which would open quickly but would fall nearly as rapidly as the bombs. This was accomplished by using a small number of strong streamlined components and by replacing the conventional steel straps with low-air-drag cables attached to the main cluster bar. The essential parts of this design were the main cluster bar containing the mechanism to open the cluster, stiffening bars, javelins to keep the bombs from sliding back and forth, and cables to hold the cluster together. CHEMISTRy

DEVELOPMENT OF E19 BOMB

The development of the EI9, II-pound magnesium bomb, was undertaken joindy by the Factory Mutual Research Corporation, under the direc tion of Mr. Thompson, and Harvard University, with Drs. Fieser and Hershberg directing the work. The Morgan Construction Company, represented by Mr. Strickland Kneass, J1., assisted in solution of mechanical engineering problems associated with the development and production of the EI9. The bomb was first conceived as a more potent fire weapon than the AN-M-so for use on German domestic structures, and was later considered for possible use in precision bombing of factory targets. As finally produced, the EI9 had the same outside dimensions as the AN-M-69, and consisted essentially of a magnesium body enclosed in a perforated steel sleeve welded to a steel nosepiece. The magnesium bomb body was filled with a special incendiary mixture (thermite, flake aluminum, motor oil, sodium nitrate, and barium nitrate), and had a core of solid hydrocarbon wax. The tail contained a white phosphorus charge which was dispersed by a central burster. The gross weight was II pounds.

After impact, a 3-second delay in the fuze of the EI9 permits the bomb to come to rest. After this short interval, the force of the separating charge shears off the tail end of the bomb containing the white phosphorus 'charge and, at the same time, kicks the main body of the bomb in the opposite direction with sufficient force to cause it to come to rest against some obstacle in a site more favorable for starting a fire. The separating charge also ignites the filling of the bomb, which then melts the magnesium body and also cracks the hydrocarbon wax to volatile gases. The 'gases create enough pressure within the bomb so that, as the magnesium melts, jets of flame about I foot long issue from the successive perforations in the steel sleeve. Intensely hot flames thus are given forth from the bomb during the first two minutes of burning, and afterwards a pile of hot glowing magnesium remains. Meanwhile, the bursting charge in the tail section which has been separated from the bomb body is activated, and disperses the phosphorus charge, thus effectively hindering the activities of fire fighters.

The performance tests with the EI9 bomb have indicated that it has excellent ballistics and high penetrating power. Although the development of the bomb was fully completed during the war, it was not put into largescale production because of the lack of evidence that enough targets existed on which it would show performance superior to existing bombs.

There were many other contributors to the incendiary programs. Their names are listed for reference at the end of this chapter.

INCENDIARY BOMBS

USE OF INCENDIARY MUNITIONS

The NDRC incendiary development items which achieved widest use during the war were the AN-M-69 oil incendiary bomb and the M-9-M-13 burster for the AN-M-47 bomb. As pointed out in the results of the AN-23 analyses, the AN-M-47 bomb was found to be very effective in attacks on German industrial targets. No records of the bombing of Italy and Germany with the AN-M-69 bomb are available, but it is known that the AN-M-69 bomb was used to only a very slight extent. Both the AN-M-69 and the AN-M-47 were used widely in Pacific Warfare, most prominendy in bombing of Japanese home islands by the 21st Bomber Command.

The first important operational use of the AN-M-69 bomb was in March **1944**, when the Seventh Air Force attacked the town of Ponape on Ponape Island, producing extensive fire damage with about 20 tons of bombs. The first AN-M-69 bombs fell on Japan on January 6, 194S, when Nagoya was attacked by the 21st Bomber Command with 138 tons of bombs. This attack was a high-altitude (2S,000 feet) mission, and the destruction achieved was only 0.2 square mile. Further relatively small attacks on Kobe and Tokyo occurred on February 4 and February 2S, 194S.

Large-scale all-incendiary attacks on Japan began with the historic raid on Tokyo on March 9, I94S. With 279 B-29 bombers, carrying 129 tons of AN-M-47 incendiary bombs as pathfinders to mark aiming points, and 1,624 tons of AN-M-69 incendiary bombs as the main load, about IS square miles of the center of the city were destroyed. To quote the official report of the 20th Air Force, "Never before or since has so much destruction resulted from any single bombardment mission regardless of the number of airplanes or type of bombs employed." Although the target area consisted primarily of two-story wooden buildings, structures of all types including concrete, brick, and steel frame were completely gutted. Fire fighting was of litde or no value in combating a blaze of such proportions. In addition to wrecking buildings, the conflagration destroyed automobiles parked on streets in the target area, bent and twisted steel poles, severed electric and telephone service, damaged trolley wires, and otherwise harmed the war economy of Tokyo.

The Tokyo raid was followed quickly by large and successful attacks on Nagoya, Osaka, Kobe, and again Nagoya, all employing a large proportion of AN-M-69 bombs (see Table, p. 408, which includes raids up to June 19, 1945)' Since these attacks exhausted the supply of incendiaries in the Marianas, raids during the ensuing two months were very limited. When large-scale bombing was resumed on May IS, all of the major cities of Japan, except Hiroshima, Nagasaki, and Kyoto were effectively destroyed. In the five major raids on Tokyo, a total of S6 square miles, or over So

CHEMISTRY

percent of the built-up area of the city, was completely burned out. Ground surveys since the end of the war have revealed the effectiveness of the incendiary raids both in destroying industrial installations and in disrupting the activities of the factory workers.

CONTRACTORS AND THEIR PERSONNEL*

Brown University; C. A. Kraus Organic and inorganic incendiaries

Chicago, University of; M. S. Kharasch Organic and inorganic incendiaries

E. 1. du Pont de Nemours and Co., Inc., Ammonia Department; J. C. Woodhouse Fuel and thickening agents

H. R. Dittmar E. C. Kirkpatrick D. E. Strain

Eastman Kodak Company; E. E. Bauer and E. K. Carver Fuel and thickening agents

D. Andrews	H E. Goldberg	A. E. Quinn
G. Broughton	E. L. McMillen	O. Sandvik
B. B. Burritt, Jr.	E. E. Moyer	J. R. Van Wazer, Jr.
J. J. De Voldre	J. R. Peer	C. F. Vilbrant

n

Factory Mutual Research Corporation; N. J. Thompson Evaluation of incendiaries; organic and inorganic incendiaries

R. E. Lally

E. A. Blair	Morrill Daki
A. J. Brown	A. L. Kling

Ferro Enamel Corporation; G. H. McIntyre Napalm and other thickening agents

S. B. Elliott

R. H. McCaffrey

Foster Wheeler Corporation; S. N. Arnold Eg incendiary bomb

Harvard University; L. F. Fieser and E. B. Hershberg Organic and inorganic incendiaries; burster for M-47 bomb

E. R. Coburn	G. C. Harris	F. C. Novello
J. L. Crenshaw	Morley Morganna	S. T. Putnam

• The contractor, the Technical Representative supervising the work for the contractor (with a few exceptions), the subject of the work, and the technical personnel are given in the order named.

INCENDIARY BOMBS

Arthur D. Little, Inc. Organic and inorganic incendiaries

F. S. Bacon H. J. Billings A. Bogrow S. E. Cairneross J. J. Clancy Mrs. H. A. Corey J. de Piccolellis G. Feick, III	M. G. Gray Miss C. Harion L. R. B. Hervey H. W. Hosmer Miss R. G. Jackson M. Knöbel A. Latham, Jr.	C. J. Matthew H. O. McMahon J. B. Nugent W. J. Smith M. H. Streeter E. Washken T. L. Wheeler
Monsanto Chemical Comp Organic and inorganic ind	pany; T. S. Carswell cendiaries	
N. A. Koop	T. S. Lawton	H. K. Nason
Morgan Construction Con Flame throwers; organic	npany; Myles Morgan and inorganic incendiaries	
R. E. Comptois	A. E. Erickson	Strickland Kneass, Jr.
Nuodex Products Compar Napalm and other thicke R. A. Allan	ny; A. Minich ning agents	
Standard Oil Developmer Flame throwers; oil ince	nt Company; R. P. Russell and and aries, gasoline-gel bombs	nd H. G. M. Fischer s; thickening agents
 A. Beerbower R. L. Betts R. H. Brewer V. J. Cantlupe J. O. Collins L. M. Cooper R. W. Emery G. W. Englisch 	J. F. Garrard G. H. Garraway C. C. Hale M. D. Haworth H. S. Hulse E. G. Kinsman W. T. Knox, Jr.	F. Marancik G. L. Matheson N. F. Myers H. A. Ricards, Jr. J. K. Roberts J. C. Roediger F. R. Russell
Standard Products Comp Eg bomb	any; F. R. Valpey	
Stanford University; J. V Fuel and thickening age	V. McBain nts	
R. H. Coe	H. H. Pomeroy	G. H. Smith

К. П. СОЕ	п. п. гошегоу	or in pinni
S. S. Marsden, Jr.	L. B. Rogers	E. B. Working
C. G. McGee	George Shreve	R. D. Zentner
K. J. Mysels		

404

Texas C₀mpany; W. E. Kuhn Oil incendiaries, Eg bo∞b

Victor Chemical Works; H. Adler Organic and in erganic incendiaries

Th₀∞as M. Beck Ge₀rge Klein



T ABLE I

PHYSICAL CHARACTERISTICS OF AMERICAN INCENDIARY BOMBS

Ι.	Gasoline-Gel Bombs			
	Designation, inc. Nominal	Ioo-Ib. AN-M-47A2	6-lb. AN-M-69 ²	6-lb. M-69X
	Weight and Number	AN-M-47A3		
	Actual Weight, lb.	72 ¹ , 73'	6.2	7.0
	Dimensions:			
	Diameter; in.	8.12, 8.12	2.87	2.87
	Length; in.	48.9, 51.9	'9.5	19.5
	Weight of Charge			
	(Incendiary)	40 lb.	2.6 lb.	2.2 lb.
	Other Charges	M-I2 Burster:	Black Powder 0.27 oz.	Black Powder 0.27 oz.
		Black Powder 7.8 oz.	Mag. Powder 0.23 oz.	Mag. Powder 0.23 oz.
		Mag. Powder 7.4 oz.		TetryI 4.6 oz.
		M-I3-M-9, Burster-Igniter		
		W.P., 21 oz.; TNT, 24 oz.		
		Tetryl, 0.07 oz.		
	Total Heat Liberated (BTU)	669,000 (includes heat of W.P.)	44,000	37,000
	Fusing, Type, and Number	Nose Impact M-I26AI or	Nose Inertia;	Nose Inertia;
		M-ro8	M-I	M-I
	Striking Velocity from 20,000 ft.,			
	ft/see.	740	230	245
	Cluster Sizes and Types	Not clustered but some-	sao-lb. size, Aimable	Clustered with
		times loaded by multi-	Ioo-Ib. size}QUiCk-	AN-M-69
		ple suspension on Ioo-Ib.	500-lb. size opening	(Tail ejection)
		and 500-lb. stations	(Tail ejection)	
		(Burster type)		

2.	Magnesium Alloy and Thermate		
	Designation, inc. Nominal	4-lb. AN-M-50A2	4-lb. AN-M-soXA3
	Weight and Number		(antipersonnel explosive nose)
	Actual Weights, lb.	3.6	3.7
	Dimensions:		
	Diameter, in.	1.69	1.69
	Length, in.	21.3	21.3
	Weight of Charge	1.1 lb. Mag. alloy	I.0S lb. Mag. alloy
	(Incendiary)	0.6 lb. Therm-64C	0.6 lb. Therm-64C
	Other Charges	First Fires 0.71 oz.	First Fire 8 0.71 oz.
			Tetryl (type A) 1.4 oz.
			Tetryl (type B) 1.6 oz.
	Total Heat Liberated (BTU)	13,100	12,300
	Fusing, Type and Number	Tail Inertia	Tail Inertia
	Striking Velocity from 20,000 ft.,		
	ft/sec.	420	4 ² S
	Cluster Sizes and Types	soc-lb. size, Aimable	Clustered with
		Ioc-Ib. size}qUick-	AN-M-soA2
	Designation, inc. Nominal	Soc-lb. size opening	
	Weight and Number	2-lb. AN-M-S2AI'	4-lb. AN-MS4
	Actual Weights, lb.	1.7	3.7
	Dimensions:		
	Diameter, in.	1,69	* 1.69
	Length, in.	14.2	21.3
	Weight of Charge	0.9S lb. Mag. alloy	1.6 lb. Thermate
	(Incendiary)	0.5 lb. Therm-64C	
	Other Charges	First Fire 8 0.7 oz.	First Fire 8 0.7 oz.
	Total Heat Liberated (BTU)	11,200'	2600
	Fusing, Type and Number	Tail Ineltia	Tail Inertia

	G 11 XI 1 C 20 000 G		(20)
	Striking Velocity from 20,000 ft.,		420
	ft./sec.	340	
	Cluster Sizes and Types	soo-lb. size, Aimable	roo-lb. size}QUiCk-
		Ioc-lb. size quick-	soo-lb. size opening
3.	PT Mixtures	Soc-lb. size opening	
	Designation, inc. Nominal	• · · · ·	
	Weight and Number	Io-lb. M-74	Soc-lb. AN-M-76
	Actual Weight, lb.	8.4	475
	Dimensions:		
	Diameter, in.	2.87	14.18
	Length, in.	19.5	S9-2
	Weight of Charge (Incendiary)	2.8 lb. PT-I mixture	17S lb. PT-I mixture
	Other Charges	White Phos. 6.0 oz.	Tetryl 1.2 lb.
	C	Mag. Powder 0.11 oz.	White Phos. 9.0 lb.
		Black Powder 0.07 oz.	
	Total Heat Liberated (BTU)	38.000 (includes heat of	2,210,000 (includes heat of
	The first designed (Die)	White Phos.)	White Phos.)
	Fusing, Type and Number	Nose Inertia: M-I42	Nose Impact AN-M-I03
		,	Tail Inertia AN-M-IOIA2
	Striking Velocity from 20.000 ft.		
	ft/sec.	420	965
	Cluster Sizes and Types	soc-lb_size_ Aimable	Not clustered
	Studier Dized und Types	Ioo-Ib size auick-	(Burster type)
		Soc lb size opening	(Buister type)
		Soc-io. size opening	

(Tail ejection)

Weight given is for this bomb with M-13-M-9 burster-igniter and M-126A1 fuze. The M-12 burster weighs 3 lb. less than the M-13-M-9 burster-igniterj the M-108 fuze, 0.5 lb. less than M-126A1 fuze. ² New type AN-M-69 in production has gross weight of 6.4 lb. and contains 2.2 lb. of gasoline gel, 6.0 oz. of white phosphorus. and liberates 41,000 BTU. ⁸ First Fire is the agent for initiating combustion of main filling. ⁴ Several redesigns of this bomb are under consideration for standardization.

TABLE 2

INCENDIARY ATIACKS ON JAPANESE CITIES

(The areas indicated are actual built-up areas omitting rivers, canals, parks, wide boulevards, firebreaks, etc. The over-all areas, including those open spaces, would be 20 to 40 percent larger. The totals indicated are the total tons dropped on or near the target city; frequently a large percentage of the tonnage given did not actually fall within the built-up area of the target city.)

City	Day	No. of B-29'S	Sq. Mi. Destroyed	Tons AN–M-69	Tons AN-M-50	Tons AN-M-47	Tons AN-M-76	Tons M-74	Tons HE& Frags.	Total Tons
Nagoya	1-6	57	0.2	t38	0	0	0	0	12	'5°
Kobe	2-4	69	0.1	167	0	0	0	0	14	181
Tokyo	2-25	'72	0.7	437	0	0	0	0	44	481
Tokyo	3-9	279	12.5	1,624	0	129	0	0	0	1,753
Nagoya	3-II	285	2.0	1,772	0	II4	0	0	0	1,886
Osaka	3-13	274	6.6	1,782	0	56	0	0	0	1,838
Kobe	3-16	306	2.9	695	1,178	0	352	0	20	2,245
Nagoya	3-18	290	2.4	289	105	972	467	0	'9	1,852
Tokyo	4-13	327	9.3	1,929	0	226	0	0	0	2,155
Kawasaki	4-15	'94	2.9	812	0	3'2	0	0	40	1,164
Tokyo	4-15	109	8.6	462	0	325	0	0	15	802
Nagoya	5-14	. 472	3.1	2,679	0	0	0	0	0	2,679
Nagoya	5-16	457	3.8	81	3,134	129	0	0	0	3,344
Tokyo	5-23	520	22.1	3,004	45	789	0	0	0	3,838
Tokyo	5-25	464	22.1.	r,406	877	643	328	3	4	3,261
Yokohama	5-29	464	6.9	1,899	'9	778	0	0	0	2,696
Osaka	6-1	458	3.3	743	627	1,348	0	0	94	2,812
Kobe	6-5	474	4.4	1,004	860	1,147	0	0	82	3,093
Osaka	6-7	4°9	2.3 "	574	• 0	1,061	0	204	804	2,643

TABLE 2	(Continued)
---------	-------------

City	Day	No. of B-29's	Sq. Mi. Destroyed	Tons AN–M-69	Tons AN-M-50	Tons AN- M-47	Tons AN-M-76	Tons M-74	Tons HE&	Total Tons
									Frags.	
Osaka	6-15	444	2.7"	74	2,375	5,4	0	0	0	2,963
Kogoshima	6-17	"7.	2.0	476	7	360	0	0	0	843
Omuta	6-17	II6	0.1	393	0	407	0	0	0	Boo
Hamamatsu	6-17	'30	1.3	5 ² 3	7	419	0	0	0	949
Yokkaichi	6-17	89	1.2	208	18	356	0	0	0	582
Toyohashi	6-19	136	1.7	558	7	426	0	0	0	991
Fukuoka	6-19	221	1.3	781	0	797	0	0	0	1,578
Shizuoka	6-19	123	22.3	531	0	375	0	0	0	906
				25.04	9.259	II.683	1,147	207	1.148	48,485

• No cover available during these two attacks.

b Includes a small area destroyed in adjacent Amagasaki.

CHAPTER XXX

INCENDIARY FUELS

E. P. STEVENSqN

. COMPARATIVE tests on thickening agents for petroleum available in May 1942 indicated the du Pont isobutyl methacrylate material (p. 389) to be best, but it was recognized that supplies of this might be inadequate, particularly when the new small gasoline-jelly incendiary bomb (M-69) came into full production. Moreover, it was realized that little was known of the rheological properties responsible for the great success of the thickened gels in resisting the undesirable breakup of ungelled hydrocarbons both in bomb and in Rame thrower.

The above reasons led to the establishment of a number of new contracts in the spring of 1942.1 These fell primarily into two classes: those for development work with firms expected by the Chemical Warfare Service to manufacture thickening agents at a later date and those for work of a more fundamental nature. Contracts for work on Napalm were accepted by Nuodex Products Company, which had already contributed to the original discovery of Napalm, the Harshaw Chemical Company, and Ferro Enamel Corporation. The work of E. I. du Pont de Nemours and Company (Ammonia Department) was continued by the acceptance of an NDRC contract for the investigation of methacrylate thickeners. In the second class, contracts were made with Eastman Kodak Company (Department of Manufacturing Experiments) and du Pont Company (Engineering Department) for the investigation of the rheological behavior of thickening agents both in hydrocarbons and in vesicants. The contract at Massachusetts Institute of Technology, at first under the direction of Professor Hottel and later T. V. Moore, also worked along these lines. As a result of their contracts for the development of a small incendiary bomb and an improved Rame thrower, the Standard Oil Development Company from time to time als,0 did work upon thickening agents.

Napalm, which developed from earlier experiments on the aluminum fatty-acid soaps, is prepared by the aqueous coprecipitation with aluminum sulfate solution of the mixed sodium soaps of naphthenic, oleic, and coconutoil acids in the ratio 1:1:2. A granular precipitate, which can be filtered, washed, and dried readily, is obtained. The thickened fuel itself can be

1 The technical personnel for each contract (usually identified in the text by the name of the Technical Representative) are listed at the end of the chapter.

INCENDIARY FUELS

prepared easily from this by stirring the soap into gasoline or other petroleum hydrocarbon at room temperature.'

Thus, for a 6 percent Napalm at a temperature of $70-80^{\circ}$ F., from 0.5 to 10 mmute.s are required to reach the stir or set time of the fuel, *i. e.*, the point at which the Napalm particles are so swollen that settling can no longer occur. The gel, thus produced, is usually. an amber-colored, slightly cloudy, somewhat ngId Jelly, having *Row* propertieS deCidedly different from those of an ordinary hydrocarbon.

PROPERTIES OF ALUMINUM SOAP GELS AS THICKENING AGENTS

.Dr. Carver and his coworkers at Eastinan Kodak Company soon recog-Dlzed that the supenor performance of the aluminum soap gels in the Rame thrower and incendiary bomb could be correlated with their **unusual** rheological properties. When an ordinary, often termed a "Newtonian," liquid, such as lubricating oil\ is caused to *Row* through a capillary tube under pressure, the *Row* is directly proportional to the pressure as long as the turbulent *Row* range is not reached. This is not true for Napalm gels, which show propo!tionately more *Row* at high than at low pressures, *e. g.*, a thousandfold increase of flow rate of a 6 percent gel in a **1**/2-inch pipe requires only a 25 percent increase of pressure. Such gels are said to be anomalous or pseudoplastic in their flow characteristics.

By means of high-speed motion pictures (2000 frames per second), smallscale model flame throwers, and the use of several different types of viscosimeters to elucidate the non-Newtonian flow of the thickened fuels, it was possible to show that their better performance in incendiary weapons was due to their ability to flow readily (almost as well as the pure hydrocarbon) under high shearing stresses, such as are met in discharge through the flame-thrower nozzle or during ejection from the M-69, and yet resist flow at the relatively low shearing stresses operative when the burning jet or gob.of material is traveling through the air. Thus, in spite of some uncertainties concerning the viscosity measurements on such gels, it is possible to show conclusively that satisfactory incendiary gels possess very high viscosities (1000 to 100,000 poises) at low rates of shear, and that these gradually decrease as the rate of shear is increased until at the highest shear rates (approximately 100,000 reciprocal seconds) the viscosities are of the order of 0.1 to 3 poises.

Another factor of importance was found to **be** the extensibility or stringiness of the gel. This was measured experimentally by the length to which a given gel can be stretched or extended at a **fixed** constant rate before rupture

² This was the significant difference from the British thickened fuel, FRAS, which required digestion of the aluminum stearate used with the gasoline at 120–130° F.

INCENDIARY FUELS

CHEMISTRY

occurs. The isobutyl-methacrylate-fortified soap gels tend to lack stringiness or be "short." Such short gels, while satisfactory in incendiary bombs, do not behave well in flame throwers, the rod of fuel issuing from the nozzle pulling apart into separate small chunks which offer so great a surface that drag, owing to air resistance, reduces range.

DIFFICULTIES EXPERIENCED IN THE **MANUFACTURE** AND USE OF NAPALM

During the course of the above investigations it became abundantly clear that the gels studied were not stable or reproducible. Similar observations were made by several contractors. Ultimately these difficulties were traced to three main causes, progressive oxidation of the Napalm owing to the presence of the double bond in the oleic acid component, the hygroscopic nature of Napalm (the absorbed water causing breakdown of the gel), and the differences in manufacturing procedures followed by the Chemical Warfare Service producers. As a result, the Napalm shipped to the war theaters in 1943 was far from uniform, and in some cases, owing to excessive oxidation, was even insoluble in gasoline and hence useless. In any event, it was almost impossible for the using troops to predict what jelly viscosity and hence what flame-thrower range would be obtained with any new Napalm shipment used. Furthermore, examination of bombs filled with some early batches of Napalm after periods of six months or more showed that in many cases the gels had dropped in consistency almost to that of pure gasoline, with re' sultant bad flash burn on functioning.

With the co-operation of the Technical Division, Chemical Warfare Service, this situation was improved through early 1943 until by the winter of r943-44 it was much less serious. Intensive work on the Eastman Kodak Company, Ferro Enamel Corporation, and Shell Development Company contracts indicated the cause and cures of the oxidation trouble.

Heavy metals, in particular iron and manganese, as impurities in the aluminum sulfate used, were shown by Dr. G. Broughton (Eastman Kodak) and S. B. Elliott (Ferro Enamel) to act as catalysts for the oxidation of the oleic acid radical, the presence of sufficiently large percentages even causing spontaneous oxidation in the Napalm driers. Specification of metal contents of the alums used and incorporation of an inhibitor, alpha' naphthol, caused this trouble to disappear. The effect of moisture on Napalm gels, suspected by several producers, was demonstrated definitely by extensive studies made by drying samples of the soap at various relative humidities. As a result of these studies, the Chemical Warfare Service introduced a moisture limitation into its Napalm specification and commenced to pack all Napalm destined for flame-thrower use in hermetically sealed metal cans. During this period

extensive surveillance tests were carried out both at Eastman Kodak Company and at Standard Oil Development Company. It was concluded that Napalm was satisfactory as regards stability both for incendiary bomb and for flame-thrower use.

The third difficulty, differences in the thickening power and behavior of Napalm made by different manufacturers, was much more troublesome to overcome and was not indeed fully solved at the end of the war. The urgency with which Napalm had been demanded resulted in its production from somewhat sketchy specifications by a number of manufacturers without the usual pilot plant stage of development. Thus no suitable viscosimeter was available for rapid measurement of the consistency of gasoline gels and hence of the thickening power of a given Napalm sample. Largely at the insistence of Myers and Dr. Betts of SOD, the Gardner Mobilometer was adopted and proved to be a fortunate choice, rapid in operation and relatively insensitive to certain rheological effects causing trouble with other instruments. In addition, each manufacturer possessed somewhat different plant facilities and adapted the precipitation process to the equipment available. The resillt was that all manufacturers had little difficulty in producing Napalm which would pass specifications, but the resulting products were different in many respects, e. g., setting time, variation of consistency with concentration, and susceptibility to water and other additives. A unit in the field, therefore, might receive a can of Napalm which, according to the manufacturer producing it, when made up in the 4.2 percent concentration specified for the flame thrower, might vary fivefold in setting time and threefold in consistency. By limiting the Napalm packaged for flame throwers to two manufacturers (Nuodex Products, Inc., and the Imperial Paper and Color Corporation), and later to one, this variability was overcome to a large degree, but it was still embarrassing to plants @ling incendiary bombs.

APPOINTMENT OF A FUELS COMMITTEE

During this attempt to secure greater uniformity and improve manufactur, ing conditions, a committee was appointed in the summer of 1943 by the Chief of Division 11 to visit most of the Napalm-producing plants and NDRC contracts on thickening agents, to leport on its findings, and to make recommendations. This committee consisted of Drs. Betts and Broughton and Me. Byfield. As a result, future work was placed under the close supervision of Dr. Carver as chairman of a Fuels Committee, responsible for all NDRC activities on flame-thrower and incendiary fuels. This committee enjoyed the closest relations with the Technical Command (CWS) and with the NDRC groups working on the design of bombs and flame throwers.

Under the guidance of the Fuels Committee, the years 1944-45 saw steady progress in the knowledge of the aluminum soap thickening agents. Messrs.

412

CHEMISTR.Y

G. G. Unkefer and J. Dickenson at Harshaw Chemical Company investi_ gated thorough!y the effect of changing acid ratios, precipitating conditions, etc. and were able to place the manufacture of Napalm upon a more logical basis. At a later date they did preliminary work upon a soap gel formed *in situ* by mixing together solutions in hydrocarbons of aluminum cresylate and fatty acid.³ This was considered promising enough to warrant a separate contract with California Research Corporation, which manufactured the two constituents on a pilot plant basis. However, the end of the war came before the new fuel could undergo full-scale fire bomb trials.

Another promising two-component thickening agent for fire bomb use, aqueous sodium aluminate and fatty acids, was also investigated at Harshaw Chemical Company, but, again, the end of the war came too soon for largescale tests. Theoretical work on the fatty-acid aluminum soaps, which showed that they were essentially association polymers of high molecular weight, was conducted at Stanford University under Dr. McBain. A study of oxidation inhibitors, made by Mr. White at the Shell Development Company **labo**ratories, led to the uncovering of certain extraordinarily effective compounds of this class, but the ready availability of alpha naphthol, together with its proven adequacy, led to its retention by the Chemical Warfare Service.

While work on the chemical preparation and aspects of the fuels was going on under the above auspices, rheological work was continued under the Eastman Kodak contract. Dr. Van Wazer built and operated a viscosimeter of novel design in which a gel could be subjected to a suddenly applied stress and the strain measured by optical magnification. An oscillating viscosimeter, in which the elastic properties of the gel could be measured under a variety of shearing conditions, was also made by Dr. Sandvik and Mr. Goldberg, and led to new insight into the rheological behavior of the gels. It became increasingly clear that nearly every thickening agent, when analyzed exhaustively, behaved differently with regard to certain properties, e. q., some showed thixotropic properties while others did not, but that all satisfactory agents were identical in showing the properties mentioned earlier, namely, non-Newtonian flow and stringiness or elasticity. At this point, therefore, rheological work, which was seen to be increasingly complex, was abandoned. More practical aspects, however, such as measurements of pressure drop, occurring on flow through pipes (important for flame-thrower design), and mechanization of the Gardner Mobilometer, were continued by Dr. McMillen. Dr. Bauer also devised a simple viscosimeter for testing flamethrower fuels in the field.

• This thickening agent was sugg.sted originally by Dr. Alexander of the British Petroleum Warfare Department.

INCENDIAR.Y FUELS

COLLABORATION WITH BRmSH PETROLEUM W **ARFARE** DEPARTMENT

The large amount of **work** done by the British Petroleum Warfare Department on thickening **agents**, with consequent need for liaison in this field, and the desirability of having someone in the European Theater with a detailed knowledge of the Napalm project, led to the appointment of Dr. Broughton to the London Mission of OSRD in March 1944. This appointment supplemented the valuable liaison work already initiated by Dr. Joel H. Hildebrand in the London Mission. This contact with the Petroleum Warfare Department and the Ministry of Aircraft Production resulted in very close technical co-operation in the **incendiary** bomb and flame-thrower fields for the rest of the **war**. In addition, when Napalm mixing was performed on a manufacturing scale in England and France, NDRC knowledge was made immediately available.

ULTIMATE ROLE OF NAPALM IN INCENDIARY WEAPONS

Napalm was used extensively as a thickening agent for gasoline fillings for the M-69 and M-47 bombs. Tests carried out by the CWS Technical Command showed that Gardner consistencies of 500-1 roo gave satisfactory performance in the M-69. The lower limit of 700 was set to allow for decrease of consistency on aging. This corresponds to a 9 percent Napalm gel. In the M-47, an II.5 percent gel was used, the higher consistency being required because of the greater shearing force applied to the fuel on the bursting of this bomb. Large numbers of M-69's were dropped in the incendiary raids on Japan, while larger tonnages of the M-47 were dropped in 1944 In the European Theater.

Application of Napalm in flame-thrower fuels was more difficult and led to more troubles than in the incendiary bombs, largely because field mixing was employed. Variability of the Napalm supplied, its ready absorption of moisture when exposed to air, and occasional occurrence of a gasoline which reacted with Napalm to give a fuel of low consistency were the chief causes of trouble. In the European Theater of Operations these difficulties were overcome by using a factory-premixed fuel, but while this was advocated by certain Chemical Warfare Service units in the Pacific, field-mixed fuel continued to be employed. The recommended mix for the portable flame thrower, M-IAI or M-2, was 4.2 percent Napalm in ordinary motor gasoline, readily prepared by adding one of the hermetically sealed cans (5¹/₄ pounds) to 20 gallons of gasoline. For small quantities of fuel, little apparatus was required other than openhead drums and wooden paddles. Care was necessary to keep the gasoline above 60° F., otherWlse mixing times became pro-

414

416

CHEMISTRY

hibitively long. If low gasoline temperatures were unavoidable, the addition of $\frac{1}{2}$ percent xylenol would allow mixing at temperatures as low as 30° F. and at the same time give a fuel of more ready pourability for a given Gardner consistency than would a pure Napalm gel. For these reasons the Napalm-xylenol mixtures found considerable use in the field during the later stages of the war. The use of 4.2 percent Napalm (manufactured by Imperial Paper and Color Corporation) produced a consistency of 75-100 grams, which prolonged tests by Eastman Kodak Company and by several Service agencies indicated gave optimum long-range performance in the portable flame thrower. However, for the larger vehicle-mounted or mechanized flame thrower (nozzle diameters 0.5 to 1.0 inches), a fuel of somewhat higher consistency is optimum. Tests by the Flame Thrower Evaluation Group (a joint CW5-NDRC group) and the Flame Attack Section of the Medical Division, Chemical Warfare Service, at Edgewood Arsenal indicated an optimum fuel consistency of 200-250 grams Gardner for maximum lethality, effective range, ease of handling, and aimability. This higher consistency, together with the greater quantities of fuel required, led to the co-operative development of the Mark I field-mixing unit by Standard Oil Development Company and Davey Compressor Company during 1944. This unit was capable of delivering 550 gallons of mixed fuel per hour (see Chap. ter XXXI).

In the later stages of the war particularly, enormous quantities of thickened fuel were used for filling the droppable fuel tanks known as blaze or fire bombs. The Navy was interested in an incendiary fuel to be used in flame bombs for aerial attack. This type of bomb, using Napalm-thickened fuel, was extensively employed by tactical air forces in the European Theater and played an important role in the ultimate break through the western defenses of Germany. The optimum consistency for this application was 200-400 grams Gardner. Lower consistencies resulted in too much Bash burn and higher consistencies in incomplete ignition of the fuel. Much of the fuel used in the European Theater was mixed by National Oil Refineries, Ltd., at Llandarcy, Wales. Using soaps from a number of manufacturers, concentrations of 5.7 to 6.7 percent were required to obtain the desired consistency, and stability was generally satisfactory over a five-month surveillance period.

DEVELOPMENT OF FIELD-MIXING EQUIPMENT

For Navy use a thickener was required which could be mixed continuously with gasoline on the deck of an aircraft carrier, since the tanks had to be filled on the planes just prior to take-off. This led to considerable co-operative work on the development and testing of an especially rapid-setting Napalm for use in an injector-type mixer developed by National Foam Systems, Inc. It also led to the work on aluminum cresylate-fatty-acid thickeners, already

INCENDIARY FUELS

mentioned, since these would have provided ideal mixing systems for Navy use.

In the spring of 1944 insistent demand for a small, portable Napalm mixing unit led to development of a continuous-mixing device for Napalm and gasoline by Ferro Enamel Corporation, under subcontract with the Eastman Kodak Company. While this was not perfect, it was decided, in March 1945, to undertake manufacture of a revised model. The Transition Office of OSRD took charge, and production was assigned to Cleaver-Brooks Company of Milwaukee on purchase order from Eastman Kodak Company. This work was under the leadership of John Chamberlin.

It was found that after the FeIro mixer had been redesigned to eliminate some defects pointed out by the Chemical Warfare Service, the unit was too heavy and cumbersome to be useful. In the meantime, an alternate form of mixer, consisting of a gasoline-engine-driven pump for circulating the Napalm-gasoline mix in an openhead drum until gelation occurs, had been developed by Cleaver-Brooks. This unit was somewhat similar to the one built independently by Messrs. Peer and Burritt at Eastman Kodak. This equipment, designated as the Err mixer, appeared so promising that six units were produced and were being tested by the Armed Forces at the close of the war.

. In the case of the large mechanized flame throwers it was necessary to develop means for refilling and repressurizing in the field. To this end the Standard Oil Development Company, in collaboration with Davey Compressor Company, produced the E8 servicing unit.

MISCELLANEOUS RESEARCH PROJECTS

While the above summarizes the main trend of work on thickened fuels, many facets have perforce been left untouched. Many compounds were suggested for use as thickeners, and received tests of lesser or greater extent according to their promise. Considerable work was done upon addition agents such as silica gel and peptizers, and the work done upon Napalm specifications in order to insure a satisfactory product was of major importance. In this connection mention should be made of the studies of Arthur D. Little, Inc., over a considerable period of time, of the properties of phosphorusphosphorus sesquisulfide mixtures as flame-thrower fuels, including a good deal of fieldwork on the lethal properties of such fuel with thickened gasoline. This fuel was intended originally for use in a one-shot, throwaway flame thrower, but was ultimately accepted by the Chemical Warfare Service for use in a tank protective device, which is described in Chapter XXXI and illustrated in Figure 14. However, it is hoped that the above will serve to indicate briefly the ground covered and the importance of the work in making readily available a thickener of satisfactory performance and stability.

CONTRACTORS AND THEIR PERSONNEL*

California Research Corporation Fuel and thickening agents

G. C. Brock A. G. Orr

W. H. ShifHer

Davey Compressor Company; P. H. Davey Flame throwers

H. S. Hulse W. H. Van Horn W. W. Warner

E. I. du Pont de Nemours and Company, Inc., Ammonia Department; J. C. Wood. house

The personnel of this contractor are listed at the end of Chapter XXIX.

- E. I. du Pont de Nemours and Company, Inc., Engineering Department; T. H. Chilton
- Rheological properties of thickening agents

The personnel of this contractor are listed at the end of Chapter XXVIII.

Eastman Kodak Company; E. E. Bauer and E. K. Carver

The personnel of this contractor are listed at the end of Chapter XXIX.

Ferro Enamel Corporation; G. H. McIntyre

The personnel of this contractor are listed at the end of Chapter XXIX.

Harshaw Chemical Company; G. G. Unkefer Napalm and other thickening agents

John Dickensen K. E. Long

Captain J. A. Southern

Arthur D. Little, Inc.

The personnel of this contractor are listed at the end of Chapter XXIX.

Massachusetts Institute of Technology; T. V. Moore and H. C. Hottel Flame throwers; general incendiary studies

Mrs. J. Addelson	N. Grossman	B. J. Ready
A. W. Adkins	W. A. Klemm	Leonard Russum
G. A. Agoston	T. A. La Cava	L. V. Uhrig
J. A. Bock	R. Messing	Miss Phyllis White
A. Byfield	H. E. Odiorne	G. B. Wilkes
B. Chertow	William Pitts	F. A. Wolfe

* The contractor, the Technical Representative supervising the work for the contractor (with a few exceptions), the subject of the work, and the technical personnel are given in the order named.

INCENDIARY FUELS

Nuodex Products Company; A. Minich

The personnel of this contractor are listed at the end of Chapter XXIX.

Shell Development Company Flame throwers

R. D. Dawson	R. L. Iglehart	E. R. White
H. Harvey	T. W. Rosebaugh	

Standard Oil Development Company; H. G. M. Fischer and R. P. Russell The personnel of this contractor are listed at the end of Chapter XXIX.

APPENDIX |

PERSONNEL OF DIVISION II, NDRC

CHEMICAL ENGINEERING

Organization During Period April '5, '944, to February '5, '945

Chief: E. P. Stevenson Technical Aide: D. Churchill, Jr.

SECTION 11.1 **OXYGEN PROBLEMS**

Chief:	J. H. Rushton
Members:	T. H. Chilton, C. C. Furnas, W. R. Hainsworth
Technical Aides:	H. B. Goff, S. S. Prentiss
Consultants:	S. C. Collins, B. F. Dodge, P. C. Keith, F. G. Keyes, W. E
	Lobo, F. J. Metzger

SECTION 11.2

MISCELLANEOUS CHEMICAL ENGINEERING PROBLEMS

Chief:	T. K. Sherwood
Members:	G. H. B. Davis, H. C. Hottel, W. K. Lewis, A. J. Weith
Technical Aide:	R. C. Wilcox
Consultants:	C. K. Drinker, D. B. Williams

SECTION II.3 FIRE WARFARE'

Chief:	H. C. Hottel
Members:	E. K. Carver, L. F. Fieser, H. F. Johnstone, T. V. Moore,
	N. F. Myers, R. P. Russell, N. J. Thompson
Technical Aides:	R. H. Ewell, S. M. Jones, C. S. Keevil, R. E. Loop, C. E. Reed
Consultants:	H. Adler, H. Bond, H. O. Forrest, C. Goldsmith, E. C. Kirk-
	. patrick, W. E. Kuhn, B. Laiming, R. S. Moulton

DIVISION MEMBERS AND TECHNICAL AIDES WITH APPROXIMATE DATES OF SERVICE

MEMBERS

E. R. Gilliland	2/ 15/ 45-	R. P. Russell	3/1/43-6/5/44
H.C. Hottel	3/25/44-	T. K. Sherwood	12/9/42-
H. F. Johnstone	5/2/44-5/3/45	E. P. Stevenson	2/ 15/ 45-
W. K. Lewis	12/9/42-		

1 Originally 'Incendiaries and Petroleum 'VarfaTe."

APPENDIX J

TECHNICAL AIDES

M. Newhall

D. Babcock W. W. Beck A. Byfield D. Churchill, Jr. S. C. Collins D. R. Dewey W. Dietz R. H. Ewell C. C. Furnas	12/9/42-1/24/43 8/r/42-11/23/42 7/1/42-2/29/44 8/19/42-5/31/46 6/1/42-12/31/43 7/2/42-7/23/43 9/27/43-6/2/44 12/8/41-5/3r/46	S. M. Jones C. S. Keevil R. E. Loop R. M. Newhal S. S. Prentiss C. E. Reed J. H. Rushton F. E. Vinal
C. C. Furnas	12/ 8/ 41-5/3r/ 46 9/ 23/ 41- 10/ r/ 45	F. E. Vinal R. C. Wilcox
H. B. Goff	2/1/44-7/1/45	

4/27/45-7/1/45 II/ r/ 43-5/3r/ 46 10/4/44-8/31/45 10/30/45-5/31/46 2/4/42-5/31/46 3/18/44-5/31/46 10/26/42-5/31/46 9/16/42-7/27/43 3/16/42-10/2/45

5°3