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~~CONFIDENTIAL~~

SUMMARY TECHNICAL REPORT OF DIVISION 11, NDRC

VOLUME 3

FIRE WARFARE

INCENDIARIES AND FLAME THROWERS

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 11
H. M. CHADWELL, CHIEF

WASHINGTON, D. C., 1946

~~CONFIDENTIAL~~

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

- Division A—Armor and Ordnance
- Division B—Bombs, Fuels, Gases, & Chemical Problems
- Division C—Communication and Transportation
- Division D—Detection, Controls, and Instruments
- Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

- Division 1—Ballistic Research
- Division 2—Effects of Impact and Explosion
- Division 3—Rocket Ordnance
- Division 4—Ordnance Accessories
- Division 5—New Missiles
- Division 6—Sub-Surface Warfare
- Division 7—Fire Control
- Division 8—Explosives
- Division 9—Chemistry
- Division 10—Absorbents and Aerosols
- Division 11—Chemical Engineering
- Division 12—Transportation
- Division 13—Electrical Communication
- Division 14—Radar
- Division 15—Radio Coordination
- Division 16—Optics and Camouflage
- Division 17—Physics
- Division 18—War Metallurgy
- Division 19—Miscellaneous
- Applied Mathematics Panel
- Applied Psychology Panel
- Committee on Propagation
- Tropical Deterioration Administrative Committee

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

One can claim on behalf of Division 11 that the results of its work contributed directly and dramatically to the successful prosecution and triumphant termination of World War II. It was Division 11, under the leadership first of R. P. Russell, then of E. P. Stevenson, and later of H. M. Chadwell, which developed the incendiary bombs with which Japan's industrial plants were reduced to ashes. Filled with jellied gasoline, the AN-M69 incendiary was credited with the highest efficiency of any bomb against Japanese factories and dwellings. More than 40,000 tons of AN-M69 bombs were dropped on Japanese cities.

Division 11 likewise applied the use of thickened fuels to portable and mechanized flame throwers, which were employed with great success against the enemy in the Pacific. Other sections of the Division did important work in developing improved techniques for the production of oxygen for military uses, and in solving numerous other problems in the field of chemical engineering, one of the most valuable contributions being the development of new hydraulic fluids.

This Summary Technical Report of Division 11, prepared under the direction of the Division Chief and authorized by him for publication, describes the activities of the Division and its contractors. It stands as a testimonial to the imagination and resourcefulness of American scientists and industrial engineers and as a record of wartime accomplishment worthy of grateful recognition.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

FOREWORD

FOR ADMINISTRATIVE purposes and because of the diverse nature of the problems studied by Division 11 (Chemical Engineering) of NDRC, three independent sections were created: Section 11.1 (Oxygen Problems), Section 11.2 (Miscellaneous Chemical Engineering Problems), and Section 11.3 (Fire Warfare). The work of each of the three sections is presented in an individual volume of the Summary Technical Report.

This volume describes the research and development work of Section 11.3 (and its predecessor organizations) in the fields of incendiaries, flame throwers, and incendiary fuels. This work was carried out under the direction of Mr. R. P. Russell (January and February 1943), Mr. E. P. Stevenson (March 1943 to February 1945), and Dr. H. M. Chadwell (March 1945 to termination) as Chiefs of Division 11 for the periods indicated, and of Mr. N. F. Myers (January 1943 to April 1943) and Dr. H. C. Hottel (May 1943 to termination) as Chiefs of Section 11.3. Assisting them were Dr. R. H. Ewell, Dr. C. S. Keevil, and Dr. C. E. Reed as Section Technical Aides, and Mr. S. M. Jones, Dr. E. C. Kirkpatrick, Mr. R. E. Loop, and Mr. R. M. Newhall as Technical Aides on specific assignments. Whereas all the contractors working under Section 11.3 (listed in an appendix to this volume) made valuable contributions, particular mention should be made of the contributions of the Standard Oil Development Company, Factory Mutual Research Corporation, Eastman Kodak Company, Massachusetts Institute of Technology, Harvard University, and Arthur D. Little, Inc., in the fields of incendiaries, flame throwers, and incendiary fuels.

The editor, and principal contributor, of this volume was Dr. Raymond H. Ewell, Technical Aide in Section 11.3 (and its predecessor organizations) from December 1941 to January 1946. Assistant editor of the volume was Mr. Robert M. Newhall, Office of Field Service, OSRD, who was later Technical Aide in Section 11.3. Professor H. C. Hottel as Chief of Section 11.3 kept in close touch with the preparation of the volume and reviewed all material as prepared by the editors. The following authors wrote one or more sections under the supervision of the editors.

E. E. Bauer, Eastman Kodak Company
A. Bogrow, Arthur D. Little, Inc.
G. W. Engisch, Standard Oil Development Company
M. D. Haworth, Standard Oil Development Company
E. B. Hershberg, Harvard University
S. M. Hulse, Standard Oil Development Company
C. S. Keevil, Technical Aide, Section 11.3, and Section 11.3 representative at Edgewood Arsenal
W. T. Knox, Standard Oil Development Company
E. L. McMillen, Eastman Kodak Company
R. F. Messing, Office of Field Service, OSRD, and Member, Incendiary Evaluation Group, Edgewood Arsenal
K. H. Mysels, Stanford University
C. E. Reed, Technical Aide, Section 11.3
G. R. Stanbury, Ministry of Aircraft Production and Member, Incendiary Evaluation Group, Edgewood Arsenal

The coordination within the Division was supervised first by R. H. Ewell and later by D. Churchill, Jr. To all these men the Division Chief wishes to express his sincere thanks.

The developments described in this volume were carried out in close cooperation with the Chemical Warfare Service (incendiaries), the Army Ground Forces (flame throwers), and the Navy Bureau of Ordnance (flame throwers). Besides reporting work done at establishments of Section 11.3 contractors, some work on Section 11.3 developments is reported which was carried out at Army and Navy establishments, including Edgewood Arsenal, Dugway Proving Ground, Huntsville Arsenal, Eglin Field, Fort Belvoir, Fort Knox, Fort Benning, and others. Particular mention should be made of the close liaison and high degree of cooperation with the Chemical Warfare Service, without which the successful completion of many of these projects would not have been possible.

The Division Chief also wishes to acknowledge with thanks the valuable help and guidance in broad phases of the program and policy of Dr. Roger Adams, member of the NDRC.

H. M. CHADWELL
Chief, Division 11
H. C. HOTTEL
Chief, Section 11.3

CONTENTS

SUMMARY

THIS VOLUME DESCRIBES the research and development work of Section 11.3 (and its predecessor organizations) in the fields of incendiaries, flame throwers, and incendiary fuels. Chapters 1, 2, and 3 deal with incendiaries, Chapters 4, 5, 6, and 7 with flame throwers, and Chapter 8 with incendiary fuels. This program was carried out under 33 research and development contracts with 28 universities and industrial concerns as contractors. The results of this work contributed in no small measure to the successful prosecution and termination of the war, the most spectacular contributions being the incendiary bombs with which the Japanese cities were bombed and destroyed, and the thickened gasoline fuels which were used so successfully in incendiaries, flame throwers, and "blaze" bombs.

AN-M69 Incendiary Bomb. The most important single development in Section 11.3 was the AN-M69 incendiary bomb. This bomb, developed by the Standard Oil Development Co., was a small tail-ejection bomb utilizing jellied gasoline as a fuel and deriving much of its effectiveness from the tail-ejection feature. The bomb consisted essentially of a hexagonal can of thin sheet steel, $2\frac{7}{8}$ by $19\frac{1}{2}$ in., weighing 6.2 lb complete, and containing 2.6 lb of jellied gasoline. The nose contained an impact fuze with a 3 to 5 sec delay and a powder charge which ejected and ignited the fuel charge. Besides the horizontal tail-ejection principle the bomb embodied two new features in bomb design: (1) a horizontally placed impact fuze working by means of a hinged striker in lieu of an axial firing pin as commonly used in bomb fuzes, and (2) cloth tail streamers in lieu of a rigid metal tail as commonly used on bombs. Both these design features were developed in order to economize on the required length of the bomb. The bombs were filled with Napalm or polymer-type thickened gasoline containing about 90 per cent gasoline and 10 per cent of thickening agent.

The bombs were assembled in either quick-opening or aimable clusters of 100- and 500-lb sizes. The cluster produced and used in largest quantity was the M19 (E46) 500-lb size aimable cluster, containing 38 AN-M69 bombs and weighing 425 lb complete. Forty of these clusters could be carried on a B-29 bomber. When dropped the cluster falls intact in stabilized flight until it bursts open at a predetermined altitude, usually 5,000 ft. As the individual bombs impact on the target they normally come to rest in a horizontal position, and after 3 to 5 sec delay they explode, ejecting the burning fuel charge out the tail. If unobstructed, the burning fuel charge will travel up to 300 ft horizontally, and when it strikes a surface, the flaming fuel charge smears out producing a mass of flames 6 to 10 ft high.

In the form of aimable clusters the AN-M69 bomb had a degree of aimability equal to demolition bombs of the 100-lb class, and hence was suited for either area incendiary bombing in cities or for precision bombing of specific targets. The terminal velocity of the individual bombs was 220 to 230 ft/sec, practically independently of the altitude of release or of opening of the cluster. This velocity was sufficient to enable the bomb to penetrate all types of domestic roofs and the commoner types of industrial roofs.

The fire-starting efficiency of the AN-M69 bomb was thoroughly tested and found to be adequate for starting fires in all types of targets for which its use was contemplated. In fact, the tests indicated that on factories and on Japanese domestic construction the AN-M69 had the highest fire-starting efficiency per cluster, or per ton, or per bomber load of any incendiary bomb.

The principal use of AN-M69 bombs in World War II was in the bombing and destruction of the major cities of Japan in the period January to August 1945. Over 40,000 tons of AN-M69 aimable clusters were dropped on Japanese cities with results which are now well known in history. Analysis of the results indicated that a minimum density of around 125 tons/sq mile was required to completely burn out an area in a Japanese city.

M69X Incendiary Bomb. This bomb, also developed by Standard Oil Development Co., was an anti-personnel modification of the AN-M69 bomb. The nose contained a time-delay element giving time delays up to 6 minutes and a high-explosive charge which shattered the nose into more than 300 fragments. This weapon was highly lethal, particularly at distances up to 20 ft. The M69X bomb weighed 7.1 lb complete and contained 2.0 lb of thickened gasoline fuel. Its ballistic properties, penetrating power, and fire-starting efficiency did not differ significantly from those of the AN-M69 bomb. The M69X bomb was placed in production in March 1945, but none were ever used operationally.

Aimable Clusters for Incendiary Bombs. When the need for aimable clusters became apparent, the Chemical Warfare Service designed and produced the E28 (M18) cluster, which had certain disadvantages. Then the Standard Oil Development Co. developed the E18 cluster, which had other disadvantages. Finally the Chemical Warfare Service combined the best features of both these clusters into the M19 (E46) aimable cluster, which proved to be quite satisfactory and was produced and used extensively in bombing Japan.

E19 Incendiary Bomb. This bomb, developed by Harvard University and Factory Mutual Research Corp., was an 11-lb bomb combining magnesium, oil, and thermite as incendiary materials. It had an extensible metal tail, a steel nose piece, and a novel perforated metal sleeve to impart strength. The tail cone was hollow and contained a charge of white phosphorus which gave off a dense white smoke. When the tail was in the compressed position, as in a cluster, the E19 bomb was identical in size with the AN-M69 bomb, and it could be assembled in the same clusters. The E19 bomb burned with a very hot flame, but its overall fire-starting efficiency was inferior to that of the AN-M69 bomb. Its only advantage over the AN-M69 bomb was its greater penetrating power, but this factor diminished in importance as the war went on, and hence the E19 bomb was never seriously considered for production.

E9 Incendiary Bomb. This bomb developed by The Texas Co. was a 40-lb tail-ejection bomb with a time-delay, anti-personnel element. This bomb was 5 by 29$\frac{9}{16}$ in. in size (with extensible tail compressed), and contained 9.5 lb of thickened gasoline fuel and 0.8 lb of white phosphorus. It packed 14 bombs in a 500-lb size cluster. This bomb was characterized by high terminal velocity, great penetrating power, and a high degree of aimability. The anti-personnel charge contained 0.65 lb of tetrytol, and it was an exceedingly lethal weapon. The E9 bomb never reached the production stage because there was no demand for a very highly penetrating bomb in the latter stages of World War II, and the size of the bomb gave it a low fire-starting efficiency on a cluster basis compared to any of the small bombs. However, the bomb incorporated a number of novel features of design which should be of interest to future bomb designers.

One novel feature of the E9 bomb was the cluster designed for its use. Because of the intrinsic aimability of the bomb it was not necessary to assemble it in aimable clusters, and yet it was necessary to provide a cluster mechanism which would not give rise to dangerous, slowly falling metal parts. This was accomplished by making a cluster mechanism consisting of pipes of spear-like members bound together with strong metal cables. These cluster parts fell sufficiently fast that they constituted no hazard for aircraft flying below the dropping airplane. Yet the cluster was the strongest ever produced, sustaining 18 G downward stress.

Miscellaneous Incendiary Items. Besides the major incendiary bombs, a number of minor incendiary items were developed, of which three were used in World War II. A new type of burster was developed by Harvard University for the AN-M47 type of bombs embodying a tube of white phosphorus with a core of TNT or other high explosive. This burster was a replacement for the older black powder type of burster. Harvard University developed two small hand incendiaries, one a fire starter for emergency use and the other a sabotage incendiary, both of which were produced and used in the war. Both were eventually of thickened gasoline contained in a celluloid case. The M1 fire starter was a small cylinder with a match striker ignition mechanism. The H2 vest-pocket sabotage incendiary resembled a cigarette case, and was equipped with a delay incendiary pencil ignition mechanism.

Testing and Evaluation of Incendiaries. Many methods for testing incendiaries were devised and used by Section 11.3 and its contractors, ranging from small laboratory tests to large-scale tests involving model villages and factories. The most significant were the full-scale tests on the German Japanese village at Dugway Proving Ground, which was designed and supervised in construction by the NDRC Standard Oil Development Co. groups, and the model factory tests carried out by the Incendiary Evaluation Project at Edgewood Arsenal.

The full-scale tests at Dugway Proving Ground gave the first reliable indication of the effectiveness of the AN-M69 bomb on Japanese domestic structures, and the results of the tests were used by the Army Air Forces in the fall of 1943 for drawing up preliminary plans for bombing Japanese cities. The Dugway results were later checked by tests on a standardized model Japanese room by the Incendiary Evaluation Project at Edgewood Arsenal.

In the factory tests of the Incendiary Evaluation Project typical combustible objects present in factories, such as workbenches, storage bins, packing cases, cardboard cartons, and wooden partitions were tested with various bombs under realistic conditions such that a mathematical extension of the data to an actual factory layout gave absolute fire-starting probabilities, which it would require long and costly airborne tests to duplicate. These tests indicated the AN-M69 and AN-M50 bombs to be about equal, and the M74 somewhat inferior, for use in factories.

Portable Flame Throwers. In the summer of 1942 the Army M1 portable flame thrower was modified by the Standard Oil Development Co. to allow the use of the newly developed thickened fuels. The resulting M1A1 Model was used extensively during 1942 and 1943 in the Pacific War. The changes consisted of a more efficient type of fuel control valve and an increased opening and other adjustments in the pressure regulator. These changes increased the range from 20 to 25 yd for the M1 Model to 45 to 50 yd for the M1A1, and demonstrated the practicability of using thickened fuel.

The M1A1 Model left much to be desired in flame-thrower performance so that an improved portable flame thrower, the E2 Model, was developed by Standard Oil Development Co. in the winter of 1942-1943. This model embodied a cylindrical roundheaded fuel tank encircled by an oval "doughnut"-type compressed air tank. Maximum use was made of aluminum as a structural metal resulting in a large fuel capacity in relation to the gross weight. Other improvements included an improved ignition system using gasoline instead of hydrogen, diminished pressure loss in the fuel system, improved accessibility of controls and a scientifically designed carrying frame. The E2 Model had only a small superiority in range over the M1A1 Model, but it was vastly superior in full capacity, reliability, and ease of operation. The E2 Model was never put into production because of the simultaneous development of a competitive model, M2-2, by the Chemical Warfare Service.

Some work was carried out on one-shot expendable flame throwers utilizing both pistons and collapsible tubes as media for transmitting pressure to the fuel, but none were brought to the production stage.

Mechanized Flame Throwers. NDRC commenced development work on mechanized flame throwers in March 1942. During the course of this program, 11 different mechanized flame throwers, consisting of a flame gun, fuel tanks, compressed air tanks, and controls, mounted on a tank or other fighting vehicle, were developed. In addition, several experimental, long-range flame guns were developed which were not mounted on vehicles. All the flame guns, except two, used compressed air as the source of pressure. The other two, still in development at the close of World War II, used a pneumatic ram and a pump, respectively, as sources of pressure. None were developed using propellant powder as a source of pressure. Two of the complete mechanized flame throwers, E7-7 and Navy Mark I, saw combat service in the Pacific war, and another, M5-4, was in large-scale production at the end of the war. One flame gun and four of the complete mechanized units, all developed by Standard Oil Development Co., will be described separately and the other models will be mentioned only briefly.

E7 Flame Gun. This flame gun, developed by Standard Oil Development Co. in the winter of 1942-1943, was the culmination of earlier models A, B, C, and D. It was immediately successful, and it became the standard United States flame gun. It had a maximum range of over 125 yd for covering operations when applied to open trenches or fox holes, and an effective range of at least 50 yd when penetrating small enclosures such as pill box embrasures. In general principles it resembled standard portable flame throwers, but constructed much heavier and on a larger scale. A ½-in. nozzle was used on the early models and interchangeable ½-in. and ¾-in. nozzles on later models (E7R1 and E7R2). The fuel control valve was located far back of the nozzle in contrast to the pintle valve in the nozzle itself as was standard British practice. An important new feature was the use of a secondary fuel of liquid gasoline which was applied in small quantity to the main stream of thickened gasoline fuel through a porous iron annulus at the nozzle. This feature improved both range and ignition. The ignition system used atomized gasoline and a rugged high-tension spark plug. Models E7R1 and E7R2 were improved models differing only in detail from E7. This flame gun was produced by Lecourtenay Co., and used on all four of the mechanized flame throwers described below.

E7-7 Mechanized Flame Thrower. This was the first complete mechanized flame thrower developed by NDRC. It consisted of an E7 flame gun and an E7 fuel system mounted in an M5A1 light tank. The gun, fuel tanks, compressed air tanks, and controls were all contained in a self-contained, turret-basket assembly which could be placed in any M5A1 tank hull. The complete system, filled with fuel (125 gal), added 2,650 lb to the weight of the tank. This arrangement eliminated the 37-mm gun main armament of the M5A1 Tank. This unit was developed by Standard Oil Development Co., and four complete units were fabricated by Cadillac Motor Car Co. These units saw service in the Philippine Islands in June 1945, but the few results only indicated the potentialities of this type of weapon.

Navy Mark I Flame Thrower. This model is of interest as the first long-range, large-capacity mechanized flame thrower ever used in combat by U. S. Forces. The Navy Mark I Model consisted of an E7 flame gun mounted with fuel tanks, air tanks, and controls in an armored, self-contained box-like unit, weighing about 6,000 lb when filled with fuel (200 gal). The range and other operating characteristics were the same on the E7-7 Model since the E7 flame gun was used in both. This model was originally introduced for use in the cockpits of landing craft for attack of beach fortifications, but they actually were used in LVT-4 amphibious tractors. The Navy Mark I Model was developed by Standard Oil Development Co. Twenty-one units were manufactured by M. W. Kellogg Co. Six units saw service on Pelelieu Island in September-November 1944, where they were highly effective.

E14-7R2 Mechanized Flame Thrower. This model consisted of an E7R2 flame gun mounted with an E14 fuel system in an LVT-A1 amphibious tank. This unit was developed by Standard Oil Development Co., and the first unit was fabricated by Lima Locomotive Works and later units by M. W. Kellogg Co. None were ever used in combat.

M5-4 (E12-7R1) Mechanized Flame Thrower. This model, designed by Standard Oil Development Co. and manufactured by M. W. Kellogg Co., consisted of an E7R1 flame gun and an E12 fuel system in an M4A1 or M4A3 medium tank. The fuel and air tanks were housed in both the hull and turret basket so that it was not a self-contained, turret-basket assembly as the E7-7. The fuel capacity was 315 gal compared to 125 gal for the E7-7. As in the E7-7, the flame thrower displaced the normal main armament of the tank. The performance of this model was essentially the same as the E7-7 Model. The MS-4 was standardized by the Army for large-scale production, and about 75 units had been completed and about 600 were on order at the close of World War II. None were ever used in combat.

Other Mechanized Flame-Thrower Models. Model E8, developed by C. F. Braun and Co., was mounted in an M5A1 light tank with stationary turret body. Model I-3, developed by Shell Development Co., was a simplified flame gun which was never mounted on a vehicle.

Model E9, developed by Standard Oil Co. (Indiana), had an original design flame gun with ¼-in. and ¾-in. interchangeable nozzles mounted in an M5A1 light tank and equipped with a 1,200-gal armored fuel trailer. Model E13-13, developed by Morgan Construction Co., used a pneumatic ram as the source of pressure with an E13 flame gun of the pintle valve type and an E13 fuel system mounted in an M4A1 medium tank. Model E13R1-13R2, developed by Massachusetts Institute of Technology, was a modified form of the E13-13 Model, only using compressed air instead of a pneumatic ram as the source of pressure. Model 19-19, which was being developed by the State University of Iowa when World War II ended, was the first United States design to retain the normal main armament of the tank and still provide a long-range effective flame thrower as an auxiliary. After studying several possible locations for installation of such a flame thrower in the M4A3 medium tank, a location on the port side of the turret was selected for further development. Model E20-20 (Ordnance designation T33), which was in development jointly by Standard Oil Development Co., Chemical Warfare Service, and Ordnance Department at the close of the war, was similar to the M5-4 Model, except that the main tank armament was retained and the flame gun was mounted coaxially with the tank's 76-mm gun. If the war had continued, the E20-20 Model would probably have replaced the then standard M5-4 Model. A pump-operated flame thrower was in development by Eastman Kodak Co. at the close of World War II.

Flame Thrower Servicing Units. Model E8 flame-thrower servicing unit, developed by Standard Oil Development Co. and Davey Compressor Co., comprised a thickened fuel mixing tank, fuel storage tanks, an air compressor, and air storage tanks mounted on an Army truck. A power take-off from the truck engine provided power. This unit provided complete field servicing facilities for flame throwers. Sixty-five units were made, of which some were sent to the field. The mixer and compressor were also mounted separately as palletized units for carrying in small landing craft. Other fuel mixing units were developed by other contractors for use with portable flame throwers and for shipboard use for filling "blaze" bombs.

E1 Anti-Personnel Tank Projector. This unit, the purpose of which was to harass infantry attacking tanks at close range, consisted of a small tank filled with a spontaneously inflammable liquid mixture of phosphorus and sulfur, and fitted with a nozzle controlled from inside the tank. The phosphorus fuel had a strong anti-personnel effect, and also produced a thick white smoke.

Studies on Flame-Thrower Design. Extensive studies were made by Massachusetts Institute of Technology, Factory Mutual Research Corp., Standard Oil Development Co., Eastman Kodak Co., and other contractors on the fundamentals of design and fuel properties which determine flame-thrower performance. These studies contributed materially to the efficient design of many of the flame throwers described herein.

Fuels for Incendiaries and Flame Throwers. The type of fuel used most widely in the above weapons was jellied or thickened gasoline. The value of thickened fuel in incendiaries and flame throwers was demonstrated by the early fundamental work at MIT and Standard Oil Development Co. The most important agent for thickening gasoline developed in World War II was "Napalm," an aluminum soap of naphthenic, oleic and coconut oil acids. Napalm was a cooperative development resulting from the coordinated efforts of Harvard University, Nuodex Products Co., Eastman Kodak Co., and the Standard Oil Development Co. About 80,000,000 lb of Napalm were produced and used in many applications. Napalm is a generic term, and the composition can vary widely, although the most commonly used acid composition contained 25 per cent naphthenic acid, 25 per cent oleic acid, 50 per cent coconut oil acids. The successful commercial production of this material involved coprecipitation and drying to form a dry granular powder resembling some commercial soap powders. The variables in the production of Napalm were thoroughly studied, and this resulted in the production of a reliable, uniform product.

The use of Napalm on shipboard for filling "blaze" bombs led to the desirability of having a liquid thickening agent which could be mixed with gasoline in a continuous two-stream operation. Several liquid thickening agents were studied, of which aluminum cresylate (plus stearic acid dissolved in gasoline) was the most promising.

Early in World War II thickening agents which were based on isobutyl methacrylate polymers fortified with sodium soaps were developed by E. I. du Pont de Nemours and Co., Ammonia Department, for filling incendiary bombs.

Fortified fuels for use in both incendiary bombs and flame throwers were studied by several contractors. The principal advantages sought were greater fierceness of burning and more difficult extinguishment by water compared to thickened gasoline. Most of these consisted of hydrocarbon base fuels with added finely divided metals, such as magnesium, and/or oxidizing agents, such as nitrates.

Self-igniting fuels were the subject of study by Arthur D. Little, Inc., and other contractors. The most useful one discovered was a liquid eutectic mixture of phosphorus and sulfur mentioned in connection with the E1 Anti-Personnel Tank projector.

An extensive program of fundamental studies on the rheological properties of thickened gasoline was carried out by Eastman Kodak Co., which permitted a sound, scientific approach to many of the problems involved in the manufacture and use of Napalm. While many interesting and scientifically valuable results were obtained, little correlation with the performance of incendiary bombs and flame throwers was discovered.

Chapter 1

INCENDIARY BOMBS AND CLUSTERS

1.1 INTRODUCTION

INCENDIARY BOMBS WERE used in World War II by all belligerents, but most effectively by the British, United States and German air forces. Incendiary bombs were used against three principal types of targets:

1. Heavy domestic construction as in Germany or Great Britain.
2. Light domestic construction as in Japan and other parts of the Orient.
3. Factories, warehouses and other precision bombing targets. In the attack of British cities, the German air force used 10 to 30 per cent incendiary bombs. Profiting by this example, the British air force used 30 to 70 per cent incendiaries in their attack of German cities. In the attack of Japanese cities, the United States air force used essentially 100 per cent incendiary bombs. In the attack of factory targets by precision bombing, the U.S. air force used incendiary bombs in variable amounts, ranging all the way from 0 to 100 per cent, but usually around 20 to 50 per cent.

For the purpose of orientation the principal incendiaries used or developed to an advanced stage in World War II may be classified as follows.

1. Small incendiary bombs, 2 to 11 lb.
   - 2-lb United States magnesium bomb, AN-M52.
   - 2.2-lb German magnesium bomb, B1.
   - 4-lb British magnesium bomb, Mark IV.
   - 4-lb United States magnesium bomb, AN-M50.
   - 4-lb United States therm-8 bomb, AN-M54.
   - 5-lb German magnesium bomb, B2.2.
   - 6-lb United States gasoline gel bomb, AN-M69.
   - 6-lb United States gasoline gel bomb, M69X.
   - 8-lb United States pyrotechnic gel bomb, M74.
   - 11-lb United States magnesium bomb, E19.
2. Medium-sized incendiary bombs, 18 to 40 lb.
   - 18-lb British magnesium dust bomb, Mark I.
   - 20-lb British naphthalene jet bomb, J20.
   - 30-lb British gasoline gel bomb, Mark IV.
   - 30-lb British liquid gasoline jet bomb, J30.
   - 40-lb United States gasoline gel bomb, E9.
3. Large incendiary bombs, 70 to 550 lb.
   - 70-lb U.S. gasoline gel bomb, AN-M47.
   - 75-lb German fire-pot bomb, Sprengbrand C.50.
   - 90-lb German benzene-phosphorus bomb, Brand C.50.
   - 240-lb German benzene-phosphorus bomb, Brand C.250.
   - 240-lb German gasoline gel bomb, Flam C.250.
   - 250-lb British gasoline gel bomb, Mark II.
   - 400-lb British gasoline gel bomb, Mark I.
   - 500-lb U.S. pyrotechnic gel bomb, AN-M76.
   - 550-lb German gasoline gel bomb, Flam C.500.
4. Super incendiaries, over 550 lb.
   - 1,000-lb British gasoline gel bomb, Mark I.
   - 4,000-lb British gasoline gel bomb.
   - United States jettisonable gasoline tanks (fire bombs), 75- to 300-gal capacity.
5. Miscellaneous small incendiaries.
   - Incendiary leaves, United States and British.
   - Sabotage incendiaries (for hand placement).

This list includes both service types and the principal bombs in development at the close of the World War II. Not included in the list are (1) numerous abortive experimental incendiary bombs, (2) numerous minor variants of the above bombs, (3) Japanese, Italian, French, and Russian incendiary bombs, none of which were significant in World War II.

The first two categories of incendiary bombs, namely small and medium-sized bombs, are ordinarily provided and used in containers or clusters of some description. Such clusters may be either the quick-opening or short-delay type which open almost immediately below the airplane, or the aimable or projectile type, which are stabilized and provided with a time or barometric fuze allowing them to be dropped intact for thousands of feet before opening. The third and fourth categories, namely large incendiary bombs and super incendiaries, are ordinarily hung individually on either internal or external bomb racks. However, the AN-M47 bomb is usually loaded in multiple suspension with two to six bombs hung on a single bomb station.

Incendiary bombs may also be classified according to the mode of functioning as follows.

1. Static functioning type, which burns where it comes to rest.
   a. With undirected combustion, e.g., magnesium bombs.
   b. With directed combustion, e.g., jet bombs.
2. Distributive type, which throws incendiary material some distance from the point of initial impact or the point of rest.
   a. Instantaneous firing type. (1) Bursting type, which bursts the incendiary bomb, dispersing chunks of the incendiary charge outwards and downwards in a conical pattern due to the downward inertia, e.g., AN-M47 bomb. (2) Tail-ejection type, which ejects the incendiary charge out the tail somewhere between the roof and floor of the target, e.g., M74.
   b. Delayed firing type. Tail-ejection type, which ejects the incendiary charge out the tail laterally after a time delay sufficient to allow the bomb to come to rest, e.g., AN-M69 bomb.

An incendiary bomb consists essentially of some sort of casing filled with an incendiary material. Materials which have been most prominent in the development of incendiary bombs in World War II are the following:

	Btu per lb
Magnesium	10,800
Gasoline gel, United States motor gasoline	16,000 to 17,000
Gasoline gel, British high benzol	17,000 to 18,500
Pyrotechnic gel, several types	12,000

Incendiary bombs containing gasoline gel are frequently referred to as oil incendiary bombs. This is really a misnomer, but the term has become established through usage. A number of other incendiary materials were investigated which proved to be of little or no value as primary incendiary materials, of which the following might be mentioned:

	Btu per lb
Thermite, including many variants	1,400
White phosphorus	10,500
Celluloid	7,200

1.2 AN-M69, 6-LB OIL INCENDIARY BOMB

1.2.1 Introduction

Development of this bomb was initiated in October 1941 by the Standard Oil Development Co. under Contract OEMsr-183 (later superseded by Contract OEMsr-354). This development was started as a consequence of a letter from General H. H. Arnold to Vannevar Bush on September 24, 1941, emphasizing the serious shortage of magnesium and requesting the development of a substitute for magnesium as an incendiary material. This project was later formalized as Service Project CWS-21 from the Chemical Warfare Service on October 7, and the work was carried out in direct collaboration with the Chemical Warfare Service.

Following a review of the various incendiary bomb designs in use or in development in the fall of 1941, exploratory work on the new bomb developed the following basic conceptions.

1. Use of some petroleum product as the incendiary material because of the high heat of combustion, 17,500 to 19,500 Btu per lb.

2. Use of fuel in the form of a gel or other semi-solid, in order to control the rate of burning.

3. Tail ejection of fuel charge, in order to project the fuel charge into a favorable location for starting a fire.

4. Delay fuze, in order to allow the bomb to come to rest on its side and eject the fuel charge horizontally.

5. Horizontally placed fuze, in order to economize on the available length of the bomb.

6. Use of a comparatively thin metal case, in order to yield as high a charge/weight ratio as possible.

7. Cloth streamer tails, in order to stabilize the bomb and slow it down to a striking velocity appropriate for the thin case, and to accomplish this as economically as possible with respect to length of the bomb.

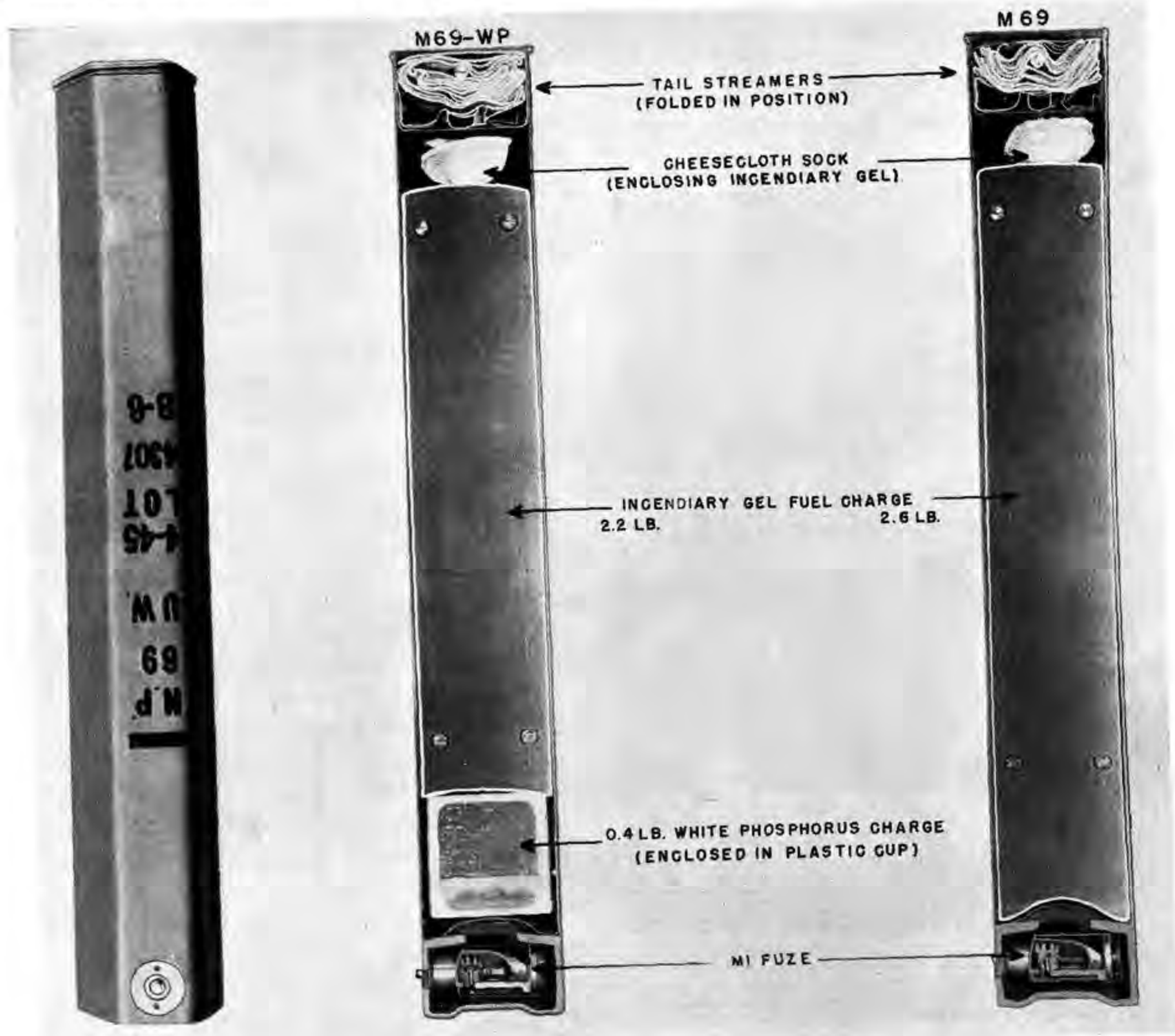


FIGURE 1. AN-M69 incendiary bomb, external and cross-section views. Model M69-WP (center view) was in production at end of World War II but was never used.

1.2.2 Description

Brief Description.[1,2,3,4,5] As finally developed and produced, the AN-M69 incendiary bomb consists of a hexagonal thin steel case, 19½ in. in length, before release of tail streamers, and 2⅞ in. across the flats, weighing 6.2 lb complete and containing about 2.6 lb of gasoline gel (Figure 1). The principal components are briefly described below.

1. Casing, hexagonal in shape, made of 19-gauge steel, butt-welded, extending the entire length of the bomb. In later production beginning May 1945, the tail end of the casing was rounded.[6,7]

2. Nose cup, made of 13-gauge steel, brazed into the nose end of the casing. It forms a flat

nose and serves to house the fuze and two containers of powder.

3. Fuze, bomb, M1, of the inertia type, embodying a 3- to 5-second delay train (Figure 2).[8,9] The components of the fuze include a base and a hinged striker made of aluminum, a hinge pin, a spring, a firing pin, a primer cap, a delay spitter fuze, a black powder-magnesium powder booster charge in a celluloid cup, a safety plunger unit, and a cylindrical fuze case.

FIGURE 2. Detail of nose end of AN-M69 incendiary bomb. (Model with WP cup illustrated.)

The fuze is screwed into a threaded hole in the side of the casing and nose cup, and it rests directly on the indented bottom of the nose cup. The outside face of the fuze bears an arrow which should point towards the tail of the bomb. In late 1944 an all-ways fuze was developed for the M69 bomb, but the stability of the bomb was such that it was not needed and it never went into production (see Section 2.7).

4. Powder containers, two in number, made of celluloid and filled with an ejection-ignition charge consisting of a mixture of black powder and magnesium powder. The two powder containers fit into the nose cup on either side of the fuze.

5. Impact diaphragm assembly, made of 3/16-in. steel, consisting of a hexagonal member resting on the nose cup, and an impact plug resting loosely in a hole in the hexagonal member. The impact diaphragm assembly takes the impact force of the fuel charge when the bomb strikes and yet allows ready venting of the ejection-ignition charge when the bomb fires.

6. Sealing diaphragm, made of 34-gauge sheet steel, which covers the impact diaphragm assembly and nose cups, and is brazed into the bomb assembly between the casing and the nose cup. The sealing diaphragm forms a hermetical seal for the nose end of the casing, and is supported by the impact diaphragm for strength.

7. Tail cup, made of 26-gauge sheet steel, crimped into the tail end of the casing similar to a tin-can seal, providing a hermetical seal for the tail end of the casing.

8. Tail retainer assembly, made of sheet steel, consisting of a tail retainer cup welded to the bottom of the tail cup, a tail retainer disk which snaps over the tail retainer cup and holds the tail streamer in place, and a tail retainer clip which is wedged across the tail cup in a way so that the tail retainer assembly cannot come out in case the weld between the tail retainer cup and the tail cup should fail.

9. Tail streamers, four in number, each 3x40 in. long, made of mildew-proofed sheeting. The streamers are held in the tail cup by the tail retainer disk, and are folded loosely in the cup.

10. Gasoline gel filling, 2.6 lb in weight, contained in a cheesecloth sack. The gasoline gel may be either of the Napalm type (NP) or the isobutyl methacrylate type (IM).

11. WP cup, screwed-top plastic cup containing 6 oz of cast white phosphorus, which is located between the sealing diaphragm and the gasoline gel fuel charge.[10,11,12] This component was introduced in the spring of 1945 after approximately 20,000,000 AN-M69 bombs of the above description had already been made without it. This model of the AN-M69 weighed 6.4

lb complete and contained 2.2 lb of gasoline gel. None was ever used operationally.

Details of Design.[1,2] The following presents further details regarding each of the components of the bomb outlined above, including the factors which led to the final selection of characteristics and, wherever pertinent, various alternatives which were tried and discarded:

1. Casing. The casing was made hexagonal in shape for efficient clustering and to provide a firm abutment between adjacent bombs in order to keep the safety plungers of all bombs depressed while in clusters. A later model produced in 1945 was made round at the tail end to facilitate seaming.[6,7] Electrically butt-welded tubing was selected instead of seamless tubing, since the former was equivalent in strength for this particular bomb and could be butt-welded directly in the hexagonal form, whereas seamless tubing was more limited in supply and also had to be especially formed to the hexagonal shape over a mandrel. Lap welding was not suitable because it gave an unsymmetrical distribution of stresses which resulted in splitting on impact. The thickness of sheet steel was selected as 19 gauge, since 20 gauge proved to be not quite strong enough for impact on concrete at terminal velocity, and 18 gauge was considered heavier than necessary. The corners of the hexagonal case were rounded in order to eliminate thinning and consequent splitting at the corners of the case on impact. Low carbon steel, SAE 1010 or its equivalent, was used since this was the most available grade of steel and was adequate for the purpose. Obviously, the grade of steel, the thickness used, and the striking velocity of the bomb are interdependent factors, but this particular combination proved to be satisfactory.

2. Nose cup. For this component 13-gauge steel, SAE 1010 or its equivalent, was selected on the same general basis as the casing. The nose cup was brazed into the nose end of the casing by a continuous copper brazing method in a hydrogen atmosphere, with the thin sealing diaphragm placed between the nose cup and the casing before brazing so that all three components were brazed together. This process depends on the surface tension of the molten copper to make a perfect hermetical seal, and it was found superior to silver soldering and other competitive processes. The brazing process also annealed the casing, relieving stresses by the butt-welding process. The bottom of the nose cup was indented for the purpose of supporting the fuze.

3. Fuze, bomb, M1.[8,9] The principal components of the fuze, namely, the base and the hinged striker, were made of aluminum alloy by die casting because this was the simplest method of making them. Alternative models made of brass or pressed steel were discarded. The base contained recesses for the primer cap, the delay spitter fuze, and the safety plunger unit, and the hinged striker accommodated the firing pin. These two principal components were assembled by means of the hinge pin and the spring, and the whole assembly inserted into the cylindrical fuze case. Four different primer caps were tried: New No. 4, Mark V, M26, and No. 209B. The last was found to be the best. The New No. 4 primer was rejected because of a high rate of deterioration at high temperatures; the Mark V primer was also subject to deterioration but was fairly satisfactory; the M26 primer required a stabbing type firing pin and was too sensitive. A delay fuze was desired in order to allow the bomb to come to rest on its side before firing, and for this purpose Ensign-Bickford lead-coated spitter fuze, providing a 3- to 5-sec delay, was selected. In order to insure transmission of ignition from the primer to the spitter fuze it was found necessary to place a small dab of match composition on the receiving end of the spitter fuze. In order to insure transmission of ignition from the spitter fuze to the booster charge on the back of the fuze it was necessary to extend the spitter fuze beyond the end of its channel in the fuze base and bend it upwards ½ in. into the middle of the booster charge. The safety plunger unit was the standard British-United States design used in the 4-lb magnesium and other incendiary bombs. The firing pin was of the round-headed type, 0.040-in. radius, made of SAE 1112 steel. Numerous tests showed that this type of firing pin was more reliable than the sharp-pointed stabbing type. The sensitivity of the fuze depends on the weight of the hinged striker and the strength of the spring. The spring selected

was a 3-turn spring made of 0.055-in. spring steel wire. This combination gave zero probability of firing when dropped two feet onto concrete and 100 per cent probability at six feet. The booster charge located at the back of the fuze consisted of one gram of a mixture of 50 per cent A-4 black powder and 50 per cent Grade B magnesium powder in a flat celluloid cup.

4. Ejection-ignition charge consisted of 0.27 oz A-4 black powder and 0.23 oz Grade B magnesium powder. Black powder alone did not give reliable ignition of the fuel charge at low temperatures. Various grades of aluminum and magnesium powder were tried to overcome this, and Grade B linseed oil-coated magnesium powder was found to be the best.

5. Impact diaphragm was made in a two-piece assembly embodying a loose center plug after tests showed that a solid impact diaphragm was frequently held by a collapsed or distorted casing and interfered with ignition of the fuel charge.

6. Sealing diaphragm was selected of a thickness (34 gauge) which would stand rough treatment during assembly and still be thin enough to rupture reliably with the ejection-ignition charge selected. Bursting pressure was 450-550 lb per sq in.

7. Tail cup was crimped into the casing in standard seaming machinery used in the canning industry. Although the hexagonal closure gave some difficulties, it was used during 1943 and 1944, but in 1945 a round closure was adopted for easier seaming. It was necessary to control hardness of the tail cup from 55 to 70 on Rockwell B scale in order to get proper seaming. A vinylite seaming compound was used in the seam to insure gas-tightness.

8. Tail-retainer assembly was adopted which spread the tail streamers to the periphery of the tail cup, after early models with a central tail suspension gave a large percentage of unstable bombs. The tail retainer clip was devised as an added precaution after it was found that the weld between the tail retainer cup and the tail cup sometimes failed.

9. Tail streamers of bombs in quick-opening clusters were made of surgical gauze in early models, but the switch to aimable clusters in 1943 necessitated changing the tails to cotton sheeting.[13] When the bombs are clustered, the last 3 in. of the tail streamers are turned back outside the bomb to enable the wind to whip the tails out reliably and rapidly when released from the cluster. The tails were mildew-proofed by dipping in a naphtha solution of copper naphthenate containing one per cent by weight of copper.

10. Gasoline gel fillings will be described in the next section.

11. WP cup was made of either Bakelite or Catalin plastic. The thickness and quality of the plastic were selected in order not to break with ordinary handling of the bombs and clusters, yet break reliably on impact at terminal velocity. The white phosphorus is not intended to aid in ignition of the fuel charge, but only to provide smoke for the purpose of interfering with fire-fighting. The wet phosphorus tended to develop cracks in the plastic by action of phosphorus acids; therefore sodium acetate was added as a buffer.

Fillings for Bomb. Many types of thickened or bodied gasoline fuels were studied as filling for the AN-M69 bomb. The heat contents (Btu) of all these fuels were essentially the same and all fuels showed some degree of effectiveness in starting fires, but comparative burning tests showed certain fuels to be significantly superior to others. The principal requirements, in addition to fire-starting effectiveness, were (1) sufficient strength to withstand ejection without excessive shattering, (2) consistency which would give a burning time of 5 to 10 min when spread in a ¼ in. thick pad, (3) ease of ignition by the M69 ejection-ignition charge at temperatures down to 40 degrees below zero, (4) availability of required raw materials, and (5) ease of manufacture.

The three principal fuels which were used for filling AN-M69 bombs were the following.

Napalm Filling (NP Type II)	
Napalm thickener	9.0%
Gasoline	91.0%

IM Filling	
Isobutyl methacrylate polymer NR	5.0%
Fatty acids (stearic acid)	2.5%
Naphthenic acid	2.5%
Aqueous solution of caustic soda (40%)	3.0%
Gasoline	87.0%

IM Filling (IM Type III)	
Isobutyl methacrylate polymer AE	2.0%
Fatty acids (stearic acid)	3.0%
Naphthenic acid	3.0%
Aqueous solution of caustic soda (40%)	4.5%
Gasoline	87.5%

Other satisfactory fillings which involved fewer critical materials than the NP or IM fillings, but which were never used in production, were the following.

S.O.D. Formula 122[1, 2]	
Stearic acid	3.5%
Rosin	1.8%
Cottonseed oil	3.0%
Aqueous solution of caustic soda (33%)	3.3%
Gasoline	88.4%

Cellucotton Filling	
Cellucotton chunks	10-15%
Gasoline	85-90%

Clusters of AN-M69 Bombs. For efficient carriage in bombardment aircraft small bombs must be carried in some sort of cluster or bomb container. During World War II, AN-M69 incendiary bombs were manufactured and supplied to the theaters of operation in the following 5 clusters.

1. AN-M12, 100-lb size, quick-opening cluster, consisting of 14 AN-M69 bombs assembled in a M4 cluster adapter (Fig. 3).[14] This cluster has an actual weight of 105 lb and measures 8.4 in. maximum width and 39.3 in. maximum length. The size of the cluster is approximately that of a 100-lb GP bomb, and it will fit on practically all 100-lb bomb stations.

FIGURE 3. AN-M12, 100-lb size, quick-opening cluster of AN-M69 incendiary bombs. AN-M13, 500-lb quick-opening cluster is similar in construction and appearance.

2. AN-M13, 500-lb size quick-opening cluster consisting of 60 AN-M69 bombs assembled in a M7 cluster adapter.[15] This cluster has an actual weight of 425 lb and measures 17 in. maximum width and 58.9 in. maximum length. The size of the cluster is somewhat wider than a 500-lb GP bomb, but nevertheless it will fit on practically all 500-lb bomb stations.

3. E28 (also called M18 or E6R2), 500-lb size aimable cluster consisting of 38 AN-M69 incendiary bombs assembled in a E6R2 cluster adapter (Figures 4 and 5).[16] The actual weight of the cluster is 350 lb and it measures 14.7 in. maximum width and 59.0 in. maximum length. The size of the cluster is practically the same as a 500-lb GP bomb, and it will fit on practically all 500-lb bomb stations. This cluster was used in the initial incendiary attacks on Japanese cities.

FIGURE 4. E28, 500-lb size aimable cluster of AN-M69 incendiary bombs.

4. E36, 500-lb size aimable cluster consisting of 38 AN-M69 incendiary bombs assembled in an E21 cluster adapter. This cluster is a variation of the E28 cluster and its weight and dimensions are the same as the E28 cluster. The E36 cluster was produced in relatively small quantities between production of the E28 and M19 clusters.

5. M19 (E46), 500-lb size aimable cluster containing 38 AN-M69 bombs assembled in a M23 (E23) cluster adapter (Figure 6). The actual weight of the cluster is 425 lb and it measures 14.8 in. maximum width and 59.5 in. maximum length. The size of the cluster is practically the same as a 500-lb GP bomb, and it will fit on practically all 500-lb bomb stations. This cluster was the principal one used in the incendiary attacks on Japanese cities (Figure 7).

FIGURE 5. B29 load of 40 E28 aimable clusters of AN-M69 incendiary bombs.

FIGURE 6. M19, 500-lb size, aimable cluster of AN-M69 incendiary bombs.

1.2.3

Performance Data

Mode of Functioning. When a cluster of AN-M69 bombs is dropped from an airplane the following sequence of actions takes place.

1. After dropping some distance, depending on the type of cluster, the cluster breaks open, releasing the individual bombs.

2. The wind catches the tail streamers, pulling them out to their full length, thereby stabilizing the bomb so that it falls nose down.

3. When the cluster disperses, the bombs are armed as the safety plungers are relieved from contact with adjacent bombs.

4. On impact the striker passes through the space occupied by the safety plunger before arming, and the firing pin strikes the primer cap.

5. The flash from the primer cap ignites the spitter fuze.

6. After 3 to 5 sec delay the spitter fuze ignites the booster charge attached to the back of the fuze.

7. The booster charge in turn ignites the main ejection-ignition charge contained in the two celluloid powder containers.

8. The explosion of these charges ruptures the sealing diaphragm, ejecting the impact

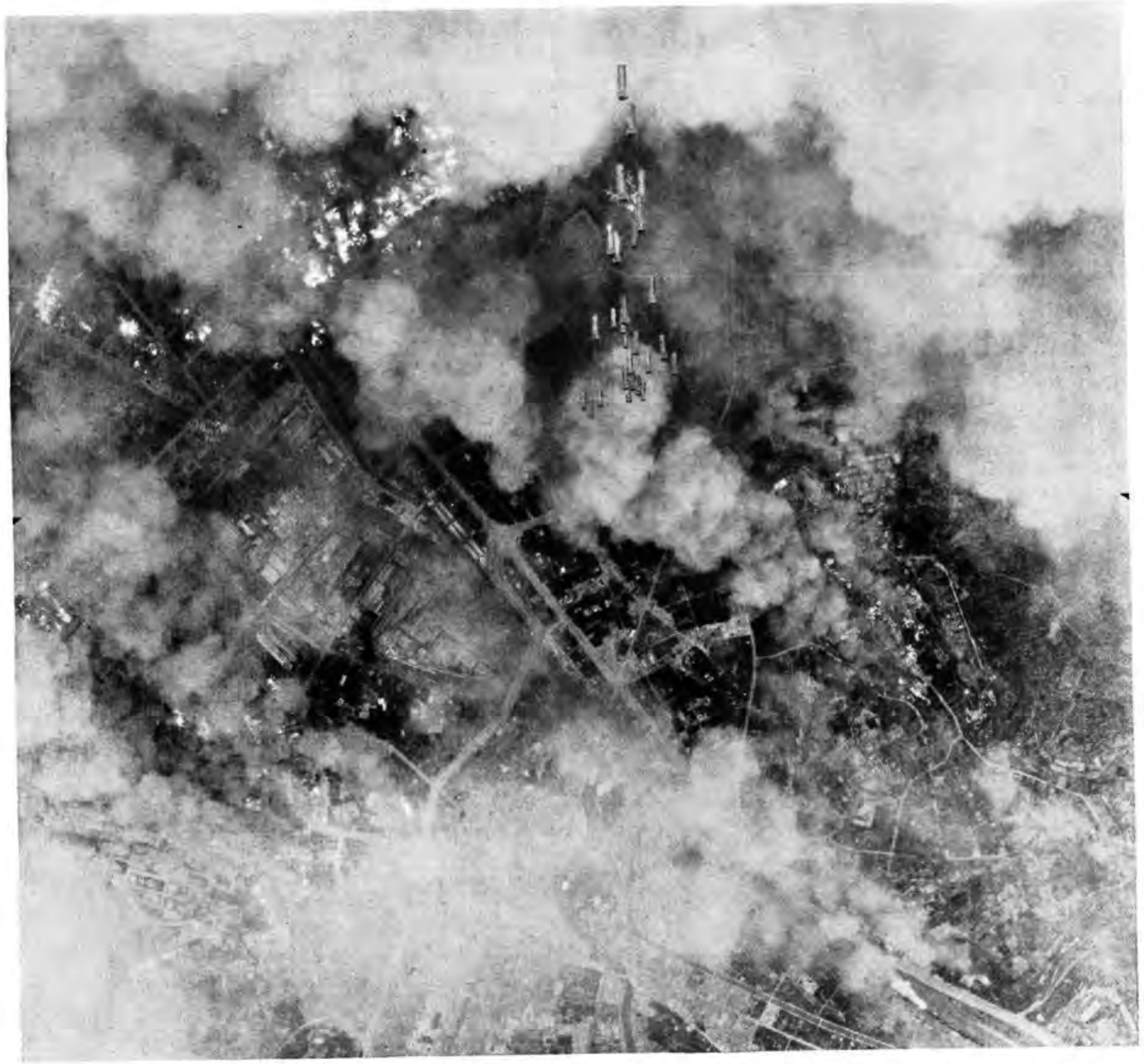


FIGURE 7. Salvo of M19 aimable clusters dropped from a B-29 over Yokohama. Photo shows 28 clusters, although a full load for a B-29 would be 40 clusters.

plug, fuel charge, tail cup and streamers, and simultaneously igniting the fuel charge. Burning magnesium particles from the ejection-ignition charge insure ignition of the fuel charge.

9. The flaming fuel charge in the sock is thrown through the air for distances up to 300 ft until it strikes an obstruction (Figure 8). On impact the fuel charge smears over the surface of the object struck, instantly producing a mass of flames 6 to 8 ft high. The pattern of distribution of the fuel depends on the nature and distance of the object struck and on the consistency of the fuel.

10. In the case of bombs containing the WP cup, this cup is ruptured when the bomb impacts and upon ejection of the fuel charge the phosphorus charge is broken up into many small particles. The burning particles of phosphorus produce a thick white smoke practically instantaneously.

Per Cent Functioning. The per cent functioning of AN-M69 bombs increased steadily with improvements in design of bombs and clusters and in production technique during 1943 and 1944. Table 1 gives some representative figures on the performance of bombs in M19 aimable

FIGURE 8. AN-M69 incendiary bombs, firing at workbench target, illustrating horizontal projection of fuel.

clusters, dropped at Eglin Field during the period October 11, 1944 to February 8, 1945.[17] These data are not sufficiently extensive to yield any reliable correlation with altitude of release on opening, even though the single group from 30,000 ft is the lowest figure. The relatively high percentage of flat landers from 30,000 ft is probably due to tail streamers being torn off as a result of the greater velocity of the clusters at opening and the resultant greater stress on the tail streamers when they come out. The per cent of air bursts (0.2 per cent) is of negligible proportions, although this was not true in the earlier E28 and E36 clusters, which had explosive opening mechanisms instead of a mechanical opening mechanism.

The per cent functioning from quick-opening clusters is somewhat higher than that from aimable clusters because of the smaller stress on the bombs on release from the cluster and because of the greater time of flight available for stabilization of the bombs.

Fuze failures (0.4 per cent) are also negligibly small. This satisfactory function is the result of many minor improvements in the design and production technique of the M1 fuze, and it attests to the fundamental soundness of the design of this fuze.

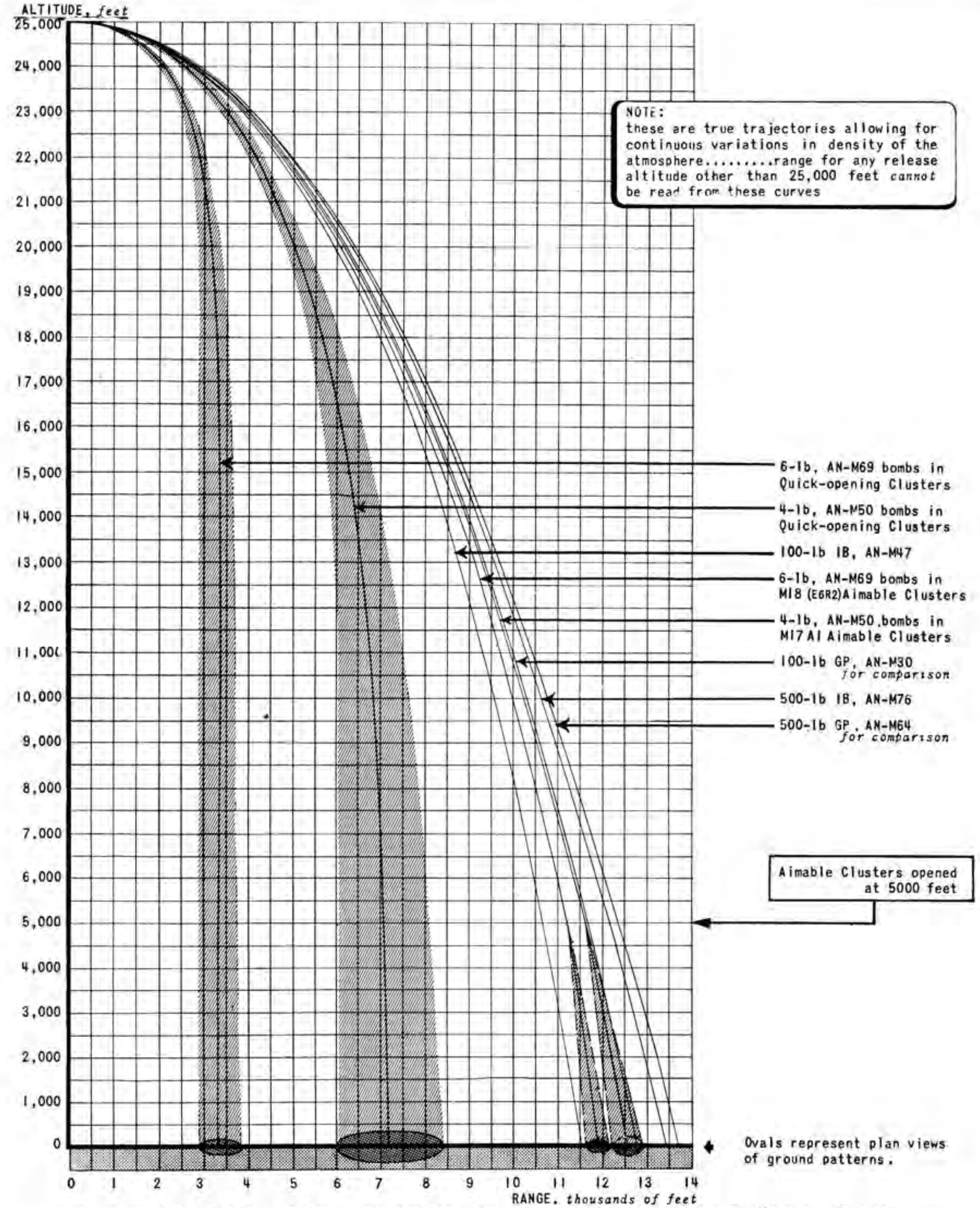
Ballistic Characteristics. A novel feature of the AN-M69 incendiary bomb is the cloth streamer tail. This type of tail imparts a high degree of stability to the bomb and also has such a positive drag that on release from a cluster the individual bombs are very quickly stabilized and slowed to their normal terminal velocity. For this reason the striking velocity of this bomb is practically uniform at 220-230 ft per sec from quick-opening clusters dropped from 3,000 ft or higher, or from aimable clusters opened at 3,000 ft or higher. This figure has been determined both by observations of bombs in flight and by wind-tunnel measurements. If quick-opening clusters are dropped from less than 3,000 ft the bombs strike at less than 220-230 ft per sec, and if aimable clusters are opened at less than 3,000 ft the bombs strike at more than 220-230 ft per sec.

The trajectory followed by AN-M69 bombs depends strongly on the type of cluster involved (Figure 9). When released from quick-opening clusters the bombs rapidly lose their forward component and soon drop practically vertically.

TABLE 1. Functioning of AN-M69 incendiary bombs in M19 aimable clusters.

Altitude of release, ft	10,000	10,000	15,000	30,000	15,000	....
Altitude of opening, ft	3,000	5,000	5,000	5,000	7,500	....
Clusters dropped	7	13	7	14	9	50
Bombs dropped	266	494	266	532	342	1,900
Bombs recovered	261	473	247	504	325	1,810
Bombs functioned O.K.	254	450	241	474	314	1,733
Number of air bursts	0	0	0	0	4	4
Number of duds on ground	7	23	6	30	7	73
Flat landers	0	9	3	18	7	37
Lightly struck primers	0	8	0	2	0	10
Fuze failures	0	6	1	1	0	8
No apparent cause	7	0	2	9	0	18
Per cent functioning*	97.3	95.1	97.6	94.0	96.6	95.7

*On recovery basis.



SOURCE: Based on data supplied by the Ballistic Research Laboratory, Aberdeen Proving Ground, Aberdeen, Maryland

FIGURE 9. Trajectories of AN-M69 incendiary bombs in quick-opening and aimable clusters, together with other bombs for comparison.

Therefore, their trail in mils and time of flight are quite large compared to large bombs. In the case of aimable clusters the intact cluster falls essentially the same as a large demolition bomb down to the point of separation, whereupon the individual bombs are released and follow a nearly vertical trajectory to the ground. A few illustrative data are shown in Table 2.

TABLE 2. Ballistic data for clusters of AN-M69 incendiary bombs.*

	AN-M69 in AN-M12 or AN-M13 quick-opening clusters	AN-M69 in M19 aimable cluster opening at 5,000 ft	AN-M69 in E28 aimable cluster opening at 5,000 ft	AN-M64 500-lb GP bombs (for comparison)
Release altitude 10,000 ft				
Trail in mils	2,440	859	....	61
Dropping angle, degrees	8.7	33.9	....	41.4
Time of flight, sec	54.4	41.7	....	25.7
Release altitude 25,000 ft				
Trail in mils	1,467	463	329	68
Dropping angle, degrees	7.7	24.0	25.4	28.7
Time of flight, sec	105.6	61.9	54.8	41.9

*For airplane speed of 250 mph.

The AN-M69 bomb has been shown to have the highest flight stability of any small incendiary bomb. This is an interesting result since originally the cloth tails were adopted as a supposedly poor substitute for a metal tail, in order to economize on the length of the bomb. For a considerable number of E28 aimable clusters released at 30,000 ft and opened at 5,000 ft, the average angle of impact on the ground was 13 degrees from vertical. The distribution of impact angles is shown in Table 3.

TABLE 3. Impact angles of AN-M69 incendiary bomb from E28 aimable clusters.

Angle of impact from vertical	Percentage of M69 bombs with given impact angle
0–10°	76
11–20°	6
21–30°	2
31–40°	2
41–50°	4
51–60°	2
61–70°	4
71–80°	0
81–90°	4

While the AN-M69 has a high stability and excellent reproducibility of trajectory, it is adversely affected by cross winds due to its low velocity.

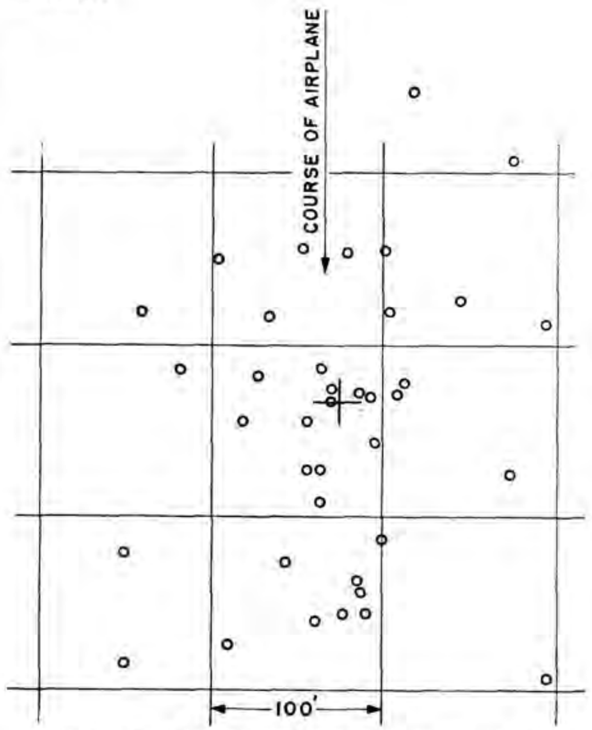


FIGURE 10. Typical dispersion pattern of M19 aimable cluster of AN-M69 incendiary bombs, released from 20,000 ft and opened at 5,000 ft. Circles indicate bombs and cross indicates center of impact. Grid is 100 ft sq. Center of impact was 1,080 ft behind AN-M64, 500-lb GP bomb.

Cluster Dispersion Patterns.[17, 18, 19, 20, 21] The ground pattern given by the dispersion of a cluster of small incendiary bombs is an elongated oval or racetrack-shaped pattern (Figure 10). In the case of quick-opening clusters the pattern is several times as long as it is wide, while in the case of aimable clusters the elongation is not so pronounced. The dispersion patterns for the several clusters of AN-M69 bombs are as follows.

	Dimensions of racetrack figure which includes 90% of the bombs
Quick-opening clusters (dropped from 10,000 ft)	400 x 1000 ft
E28 Cluster (dropped from 20,000 ft, opened at 5,000 ft)	340 x 510 ft
M19 Cluster (dropped from 20,000 ft, opened at 5,000 ft)	240 x 360 ft

The dispersion pattern is substantially the same for 100-lb or 500-lb quick-opening clusters. In all these dispersion patterns the distribution is fairly uniform throughout most of the pattern area with a thinning out at the edges. For this latter reason the dimensions of the dispersion pattern are specified to contain 90 per cent of the bombs.

Penetrating Power.[22, 23, 24, 25, 26, 27] The penetrating power of the AN-M69 incendiary bomb, at its normal striking velocity of 220-230 ft per sec, can be classed as fair or moderate compared to other incendiary bombs. It will penetrate practically all light and medium-weight roofs including the following.

Wood planking, about 1 in.
Slate on wood battens or wood sheathing.
Tile on wood battens.
Hollow tile slabs, 2½-3½ in. thick, with or without 2-4-in. cinder concrete for drainage.
Lightweight concrete slabs, 2½-3½ in. thick, with or without 2-4-in. cinder concrete for drainage.

However, the bomb will not penetrate reinforced structural concrete 3 in. or more thick. Of the industrial targets encountered in World War II approximately 80-85 per cent in Germany and 90-95 per cent in Japan had roofs penetrable by AN-M69 bombs.

Fire Starting Efficiency. The fire starting efficiency of small incendiary bombs can be evaluated by a variety of methods, which will be outlined in somewhat greater detail in Chapter 3. Following are a few examples of the fire starting efficiency of the AN-M69 bomb against some typical targets.

1. Factory workbench with a wooden tote-box underneath.[28] This setup was ignited by the fuel charge from an AN-M69 bomb whenever the major portion of the fuel charge was deposited on or near the box.

2. Stack of wooden packing boxes.[28] This setup was ignited by the fuel charge from an AN-M69 bomb whenever the major portion of the fuel charge was deposited on or near it.

3. German houses at Dugway Proving Ground.[23, 27, 29] In the tests on these targets resultant fires were classified as follows.

Fire classification	Definition of fire
A1	Beyond fire-guard control in 0-2 min
A2	Beyond fire-guard control in 2-4 min
A3	Beyond fire-guard control in 4-6 min
B	Beyond fire-guard control in 6 min or more
C	Nondestructive fire

The fires resulting from functioning M69 hits on German houses were as follows.

Fire classification	Percentage of fires: Inside hits	Percentage of fires: Ejection hits
A1	16%	0
A2	11%	0
A3	10%	0
B	16%	11%
C	47%	89%

4. Japanese houses at Dugway Proving Ground.[23, 30, 31] Using the same classification of fires as in (3), the fires resulting from functioning M69 hits on Japanese houses were as follows.

Fire classification	Percentage of fires: Inside hits	Percentage of fires: Ejection hits
A1	32%	4%
A2	22%	2%
A3	14%	13%
B	13%	31%
C	19%	50%

Figure 11 shows the action of the M69 in a Japanese-type house similar to the Dugway houses.

For a more extensive discussion of the methods and results of testing AN-M69 and other incendiary bombs see Chapter 3. The results of these tests were used to make preliminary estimates of the quantities of incendiary bombs required to destroy Japanese cities.[32, 33, 34, 35]

1.2.4 Operational Results

AN-M69 incendiary bombs were used operationally by the following U.S. Army Air Forces and Bomber Commands.

	Base	Location of targets
5th Air Force	Southwest Pacific	New Guinea, New Britain, etc.
7th Air Force	Central Pacific	Ponape, Truk, Marianas, Palau and other Pacific Islands
10th Air Force	India	Burma
12th Air Force	Italy	Italy and Germany
14th Air Force	China	China and Formosa
15th Air Force	Italy	Italy and Germany
XX Bomber Command	India and China	China and Japan
XXI Bomber Command	Marianas Is.	Japan

FIGURE 11. Destruction of a Japanese type house by a single AN-M69 incendiary bomb. Pictures were taken at 0, 10, 15, and 20 min after firing of bomb.

The use of this bomb by all these units was of minor importance, except that of the XXI Bomber Command. However, some incidents worthy of note are the burning of Ponape Town in February-March 1944 by the 7th Air Force, the destruction of supply dumps in Italy in 1943 by the 12th Air Force, and the burning of Changsha in October 1944 by the 14th Air Force.

The chief use of AN-M69 bombs was in the great incendiary offensive against the major Japanese cities by the XXI Bomber Command from the Marianas Islands bases. The first of these attacks was on Nagoya on January 6, 1945, and the first significant one was the historic attack on Tokyo on March 9, 1945 (Figures 13, 14). Figure 12 illustrates the burning of Toyama, a city of 150,000 population, on August 1, 1945, by means of AN-M69 bombs. Although a complete review of these attacks is beyond the scope of this report, Table 4 summarizes the first 27 attacks on Japanese cities.

TABLE 4. Incendiary attacks on Japanese cities.

City	Date	No. of B-29's attacking	Square miles destroyed*	Tons AN-M69 IB	Tons AN-M50 IB	Tons AN-M47 IB	Tons AN-M76 IB	Tons M74 IB	Tons HE & Frags	Total tons dropped†
Nagoya	1/6/45	57	0.2	138	0	0	0	0	12	150
Kobe	2/4/45	69	0.1	167	0	0	0	0	14	181
Tokyo	2/25/45	172	0.7	437	0	0	0	0	44	481
Tokyo	3/9/45	279	12.5	1,624	0	129	0	0	0	1,753
Nagoya	3/11/45	285	2.0	1,772	0	114	0	0	0	1,886
Osaka	3/13/45	274	6.6	1,782	0	56	0	0	0	1,838
Kobe	3/16/45	306	2.9	695	1,178	0	352	0	20	2,245
Nagoya	3/18/45	290	2.4	289	105	972	467	0	19	1,852
Tokyo	4/13/45	327	9.3	1,929	0	226	0	0	0	2,155
Kawasaki	4/15/45	194	2.9	812	0	312	0	0	40	1,164
Tokyo	4/15/45	109	8.6	462	0	325	0	0	15	802
Nagoya	5/14/45	472	3.1	2,679	0	0	0	0	0	2,679
Nagoya	5/16/45	457	3.8	81	3,134	129	0	0	0	3,344
Tokyo	5/23/45	520	22.1‡	3,004	45	789	0	0	0	3,838
Tokyo	5/25/45	464		1,406	877	643	328	3	4	3,261
Yokohama	5/29/45	464	6.9	1,899	19	778	0	0	0	2,696
Osaka	6/1/45	458	3.3	743	627	1,348	0	0	94	2,812
Kobe	6/5/45	474	4.4	1,004	860	1,147	0	0	82	3,093
Osaka	6/7/45	409	2.3§	574	0	1,061	0	204	804	2,643
Osaka	6/15/45	444	2.7§	74	2,375	514	0	0	0	2,963
Kagoshima	6/17/45	117	2.0	476	7	360	0	0	0	843
Omuta	6/17/45	116	0.1	393	0	407	0	0	0	800
Hamamatsu	6/17/45	130	1.3	523	7	419	0	0	0	949
Yokkaichi	6/17/45	89	1.2	208	18	356	0	0	0	582
Toyohashi	6/19/45	136	1.7	558	7	426	0	0	0	991
Fukuoka	6/19/45	221	1.3	781	0	797	0	0	0	1,578
Shizuoka	6/19/45	123	2.3	531	0	375	0	0	0	906
Totals				25,041	9,259	11,683	1,147	207	1,148	48,485

*These areas are actual built-up areas omitting rivers, canals, parks, wide boulevards, firebreaks, etc. The overall areas, including open spaces, would be 20% to 40% larger. For example, the overall area destroyed in the Tokyo attack of 3/9/45 was 17 to 18 sq miles.

†These are the total tons dropped on or near the target city, but frequently a large percentage of the tonnage given did not actually fall within the built-up area of the target city.

‡No cover available between these two attacks.

§Includes a small area destroyed in adjacent Amagosaki.

The attacks in this table comprise about one-half the incendiary bomb tonnage dropped on Japanese cities. It will be noted that the AN-M69 bomb was the principal incendiary used, with the AN-M47 and AN-M50 bombs following in importance. Several issues of *Impact* review the results of the incendiary attacks of Japanese cities.[36, 37, 38] An analysis of some of these attacks is given below in Section 3.6.

1.3 M69X, 6-LB OIL INCENDIARY BOMB, X-TYPE

1.3.1 Introduction

Development of this bomb was initiated in May 1942 by the Standard Oil Development Co. under Contract OEMsr-354. The purpose of the project was to develop a modification of the AN-M69 incendiary bomb embodying a delayed-action, anti-personnel element as a deterrent to fire-fighters (see Chapter 3).

1.3.2 Description

Many of the components of the M69X bomb are identical with those in the AN-M69 (Figures 15 and 16).[7, 39, 40] The principal points of difference between the two bombs are:

1. Gross weight of M69X is 7.1 lb compared with 6.2 lb for AN-M69 (or 6.4 lb for AN-M69 with WP cup).
2. External appearance of M69X is nearly identical with AN-M69, except that the fuze hole is moved $2\frac{3}{8}$ in. towards the tail in M69X to make room for the fragmentation unit, and a waterproofing rubber patch covers the out-

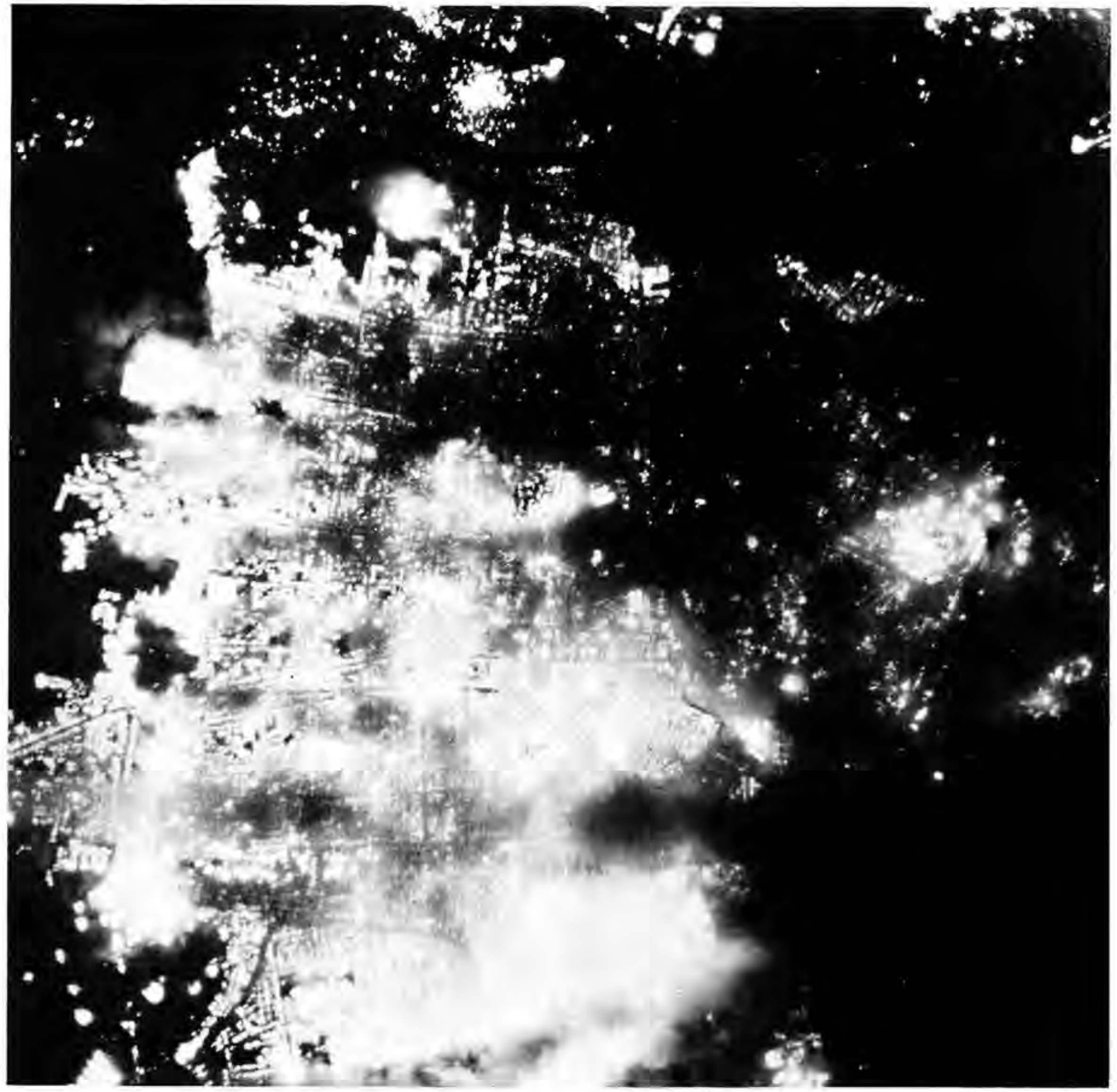


FIGURE 12. Toyama, Japan, burning on the night of August 1, 1945, following an attack by AN-M69 incendiary bombs. This city of 150,000 population was one of the most completely destroyed cities in Japan, over 95 per cent.

side face of the fuze. Otherwise the casing is identical with that of the final model AN-M69.

3. A hexagonal steel liner, 0.059 in. thick, $2\frac{1}{2}$ in. high, is brazed to the inside of the casing below the fuze cup for strengthening.

4. Fuze cup is made of 11-gauge steel instead of 13-gauge steel as in AN-M69, because of added strength requirement. Also, fuze cup has 3/22-in. hole in bottom for transmission of powder flash to the delay fuze of the fragmentation unit.

5. Delay fuze unit consisting of one to six ft of Ensign-Bickford safety fuze coiled helically and housed in a thin steel cup. One end of this delay fuze is fitted with a piece of Navy quickmatch to catch the powder flash, and the other end is crimped into a special M106 detonator. This type of delay fuze burns at a rate of either 30 or 60 sec per foot. Delays of approximately $1\frac{1}{2}$, 4, and 6 min are provided in quantities of 40 per cent, 40 per cent, and 20 per cent, respectively.

FIGURE 13. Nihonbashi District in Tokyo before incendiary attack. Note the intermingling of 10 to 20 per cent modern concrete buildings with 80 to 90 per cent wooden Japanese type buildings.

6. HE unit consisting of an HE cup, made of 13-gauge steel, containing $4\frac{1}{2}$ oz (130 g) of pressed tetryl. This unit is press-fitted in place in the nose end of the casing. A rubber gasket is compressed in place between the delay fuze container and the HE cup, providing moisture-proof protection for the delay fuze unit.

7. Rubber patch cemented to the rubber ring on the outside face of the Ml fuze for the moistureproofing. This moistureproofing was found necessary due to the hygroscopicity of the black powder in the delay fuze.

8. Gasoline gel filling is 2.0 lb instead of 2.6 lb in AN-M69.

9. WP cup is similar to that of AN-M69, except that it is shorter and contains 3 oz of white phosphorus instead of 6 oz, as in AN-M69.

10. Booster charge in Ml fuze is 1.0 g A-4 powder instead 1 g of 50-50 mixture of A-4 powder and magnesium powder, to avoid instantaneous firing of the HE charge.

Clusters of M69X Bomb. Only one type of cluster of M69X bombs was manufactured and supplied to the field: M21(E74), 500-lb size aimable cluster containing 38 M69X bombs, assembled in a M23(E23) cluster adapter. This cluster is identical in appearance with the M19 cluster of AN-M69 bombs, but it weighs 465 lb due to the greater weight of the M69X bombs. These clusters were never used operationally.

1.3.3 Performance Data

Mode of Functioning.[7, 39] The functioning of the M69X bomb is the same as that of the AN-M69, with the following additional actions.

1. The flash from the main ejection-ignition charge ignites one end of the delay fuze.

2. When the ejection-ignition charge ejects the fuel charge, the empty bomb case is propelled in the opposite direction so that the bomb case and the fire are usually some distance apart.

3. After a variable delay of $1\frac{1}{2}$ to 6 min the delay fuze initiates the detonator, which ex-

FIGURE 14. Nihonbashi District in Tokyo after attack of March 9, 1945, with AN-M69 incendiary bombs. The area in this picture is within one mile of the area shown in Figure 13 and has the same type of construction. Note the gutted shells of modern concrete buildings and complete destruction of the Japanese type buildings (*Life* photograph).

plodes the tetryl charge.

4. The explosion of the tetryl charge fragments the entire nose end of the bomb including HE cup, fuze cup, fuze, impact diaphragm, and the bottom one-third of the casing, producing over 400 metal fragments.

Per Cent Functioning.[7, 41, 42, 43] Table 5 gives functioning data observed from 30 M21 aimable clusters of M69X bombs dropped at Eglin Field, Florida, from altitudes of 12,000 to 30,000 ft, opening at 5,000 ft, in January-March 1945. It will be noted that 36 out of 71 complete duds were due to striking on soft earth, which is no fault of the bomb. Later production models of M69X bombs showed somewhat better functioning than that shown in Table 5.

TABLE 5. Functioning of M69X incendiary bombs.

Number of M69X bombs recovered		939
Number functioned properly with respect to both incendiary and fragmentation actions		856
Number of air-burst bombs		5
Number of duds on ground		78
Analysis of duds on ground		
Complete duds		71
Flat landers	28	
Tails torn off	4	
Lightly struck primer	36	
Fuze failures	3	
Incendiary duds, fragmentation O.K.		3
Fragmentation duds, incendiary O.K.		4
Total		78
Overall per cent functioning (recovery basis)		91.2%
Overall per cent functioning, eliminating lightly struck primers consequent on impact in soft earth		94.8%

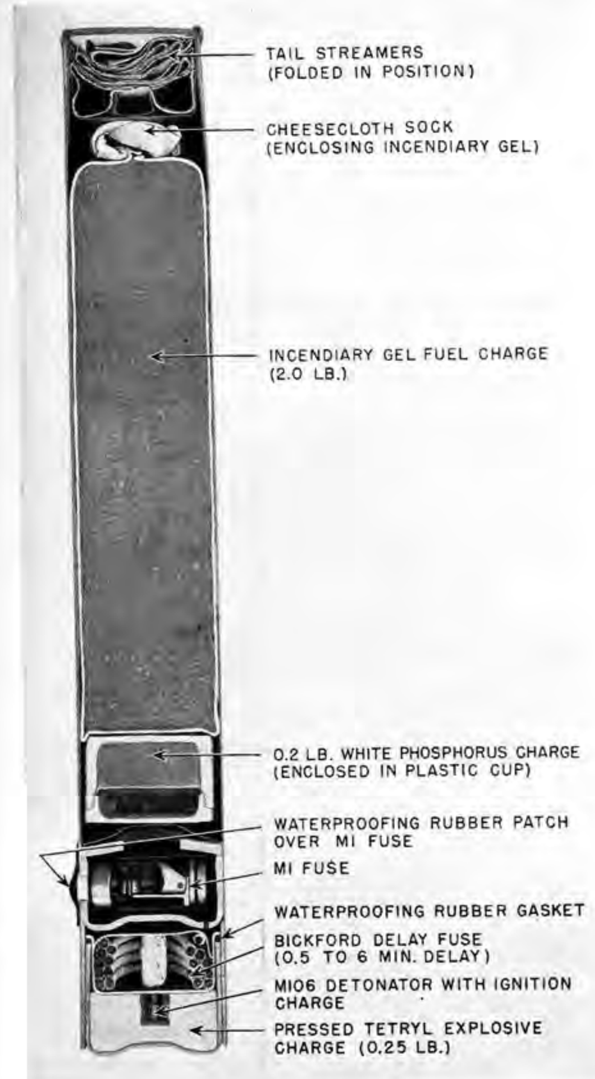


FIGURE 15. M69X incendiary bomb. External view is practically the same as AN-M69 bombs.

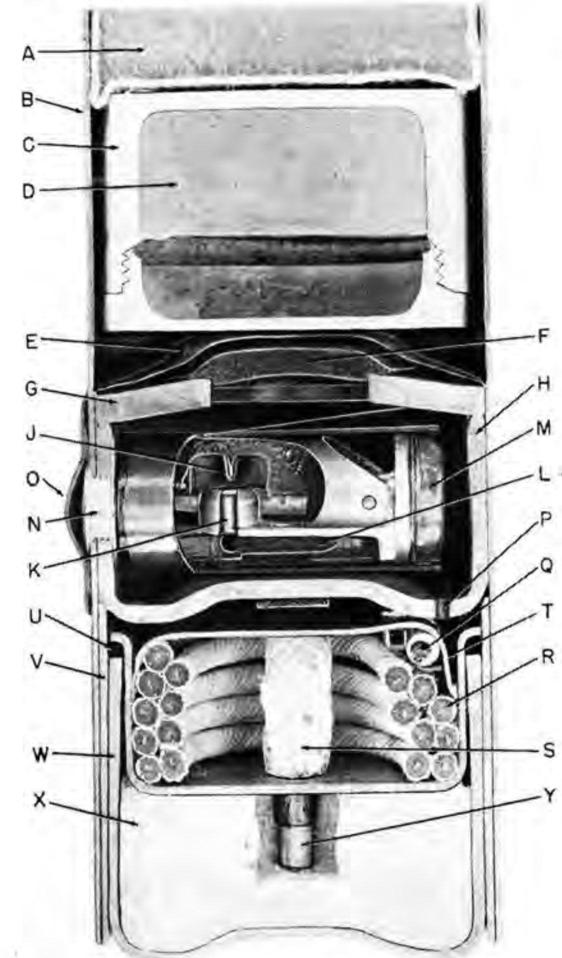


FIGURE 16. Detail of nose end of M69X incendiary bomb.

Ballistic Characteristics.[7, 26, 41, 44, 45] Because of the heavier weight the normal striking velocity of the M69X bomb is 240-250 ft per sec, i.e., about 20 ft per sec higher than the AN-M69. The trajectory of the M21 cluster is similar to that of the M19 cluster, but on account of the greater weight of the former it has a somewhat greater range, about 300 ft when dropped from 20,000 ft and opened at 5,000 ft. This would mean that from 20,000 ft its trail would be about 15 mils less. The M69X bomb is somewhat more stable than the AN-M69 due to its greater nose-heaviness.

Cluster Dispersion.[7, 26, 41, 44, 45] When dropped from 20,000 ft and opened at 5,000 ft, the M21 cluster gives a dispersion pattern (containing 90 per cent of bombs) approximately 200x300 ft, compared with 240x360 ft for the M19 cluster of AN-M69 bombs.

Penetrating Power.[7, 26, 44] In view of its greater weight and greater striking velocity the M69X has about 35 per cent greater impact energy than the AN-M69. However, this does not change the penetration picture greatly, compared to the AN-M69. Both the M69X and the AN-M69 will penetrate all types of light roofs, but neither will penetrate 3-in., or thicker, reinforced structural concrete. There are very few intermediate types of roofs penetrable by

M69X that are not also penetrated by the AN-M69. In actual flight tests at Dugway Proving Ground on Japanese structures no marked difference was observed.

Fire Starting Efficiency.[7] Although the M69X contains 23 per cent less gasoline gel than the AN-M69, it was not possible to detect any appreciable difference in the relative fire starting efficiency of these two bombs against typical combustible targets. Any location in which an AN-M69 fuel charge will start a fire, will also be ignited by an M69X fuel charge, although sometimes it takes a little longer to reach a given stage of development of the fire.

Fragmentation.[7, 46] The explosion of the tetryl charge fragments the entire nose end of the bomb, including the HE cup, fuze cup, fuze, impact diaphragm, and the bottom one-third of the casing (Figures 17 and 18). Over 400

FIGURE 17. Explosion of M69X incendiary bomb lying on top of the ground, showing force of explosion.

fragments are produced ranging in size from several milligrams up to 2 oz and having velocities up to 4,500 ft per sec. An analysis of the fragment coverage showed that a 6-ft man at a distance of 10 ft from the bomb would have a 22 per cent chance of being hit fatally and an additional 22 per cent chance of being injured not fatally or a 44 per cent chance of being disabled at least temporarily (Figure 19). In addition, the shock of the explosion will probably incapacitate a man for several minutes even if he is not hit (based on the results of tests with live goats). However, tests showed that the blast of the explosion did not adversely affect fires burning 3 ft or more away from the HE unit.

Moistureproof Characteristics.[7, 47] In order to make the M69X moistureproof independently of its shipping container, the M1 fuze and HE-delay fuze assembly must be especially waterproofed.

The M1 fuze is waterproofed by the use of a vulcanized Neoprene type GN patch $1\frac{5}{8}$-in. diameter and 0.020 in. thick, cemented to a neoprene type GN ring 3/16 in. wide, 1 17/32 in. OD and 0.015 in. thick, which is vulcanized to the casing around the hole.

The HE-delay fuze assembly is waterproofed by the use of a soft vulcanized Neoprene type GN rectangular gasket, 3/32 in. thick, $\frac{1}{4}$ to $\frac{3}{8}$ in. wide, placed under the lip of the delay fuze cup so that the leading edge of the HE cup rests against the gasket as the HE cup is pressed flush with the end of the casing.

Both the M1 fuze and HE-delay fuze assembly were subjected to a 24-hr submergence test under 6 ft of water and a 7-day storage test at 100 per cent humidity with cyclical temperatures varying every 12 hr from 70 to 125 F. The following results were observed.

1. M1 fuze showed 97 per cent performance out of 266 tested in the submergence test and 97.7 per cent performance out of 87 tested in the storage test.
2. HE-delay fuze assembly showed 98.3 per cent performance out of 120 tested in the submergence test and 100 per cent performance out of 35 tested in the storage test.

1.3.4 Final Status

Production of M69X bombs in M21 clusters was begun in March 1945, and clusters reached operational bases in the Marianas Islands in July 1945, but there is no record of their ever having been used operationally. This bomb

FIGURE 18. Fragments recovered from explosion of M69X incendiary bomb.

would undoubtedly have been more effective, possibly twice as effective, as the AN-M69 bomb for incendiary attacks on Japanese cities.

1.4 AIMABLE CLUSTERS FOR AN-M69 TYPE BOMBS

1.4.1 Introduction

Aimable or projectile clusters of incendiary bombs, which drop as a unit to a predetermined height where they are opened by a mechanical time fuze, were first developed and used by the Germans in 1941. The idea was later adopted by the British (1942) and still later by the United States (1943). The first United States aimable cluster of AN-M69 bombs was the E28 cluster, also called M18 or E6R2, developed by the Chemical Warfare Service in 1943. This cluster had several disadvantages: (1) its trail was larger than desirable, (2) its flight characteristics were not reproducible, (3) it produced about 3 per cent of air-burst bombs due to the shock of opening, and (4) about 5 per cent of the clusters failed to open due to failures of the single mechanical time fuze. The E28 cluster is shown in Figure 20.

weighed 125 lb gross and contained 45 AN-M69 bombs, compared to 38 in the E28 cluster (Figure 20). The principal components of the E18 cluster are as follows: (1) hemi-

it was believed necessary to increase the length from the standard 59 in. for 500-lb size bombs and clusters to 69 in., which was suitable for nearly all airplanes until the advent of the B-29

FIGURE 20. Experimental models of aimable clusters of AN-M69 incendiary bombs. Left to right, British No. 20 cluster, E18 cluster, and E28 cluster.

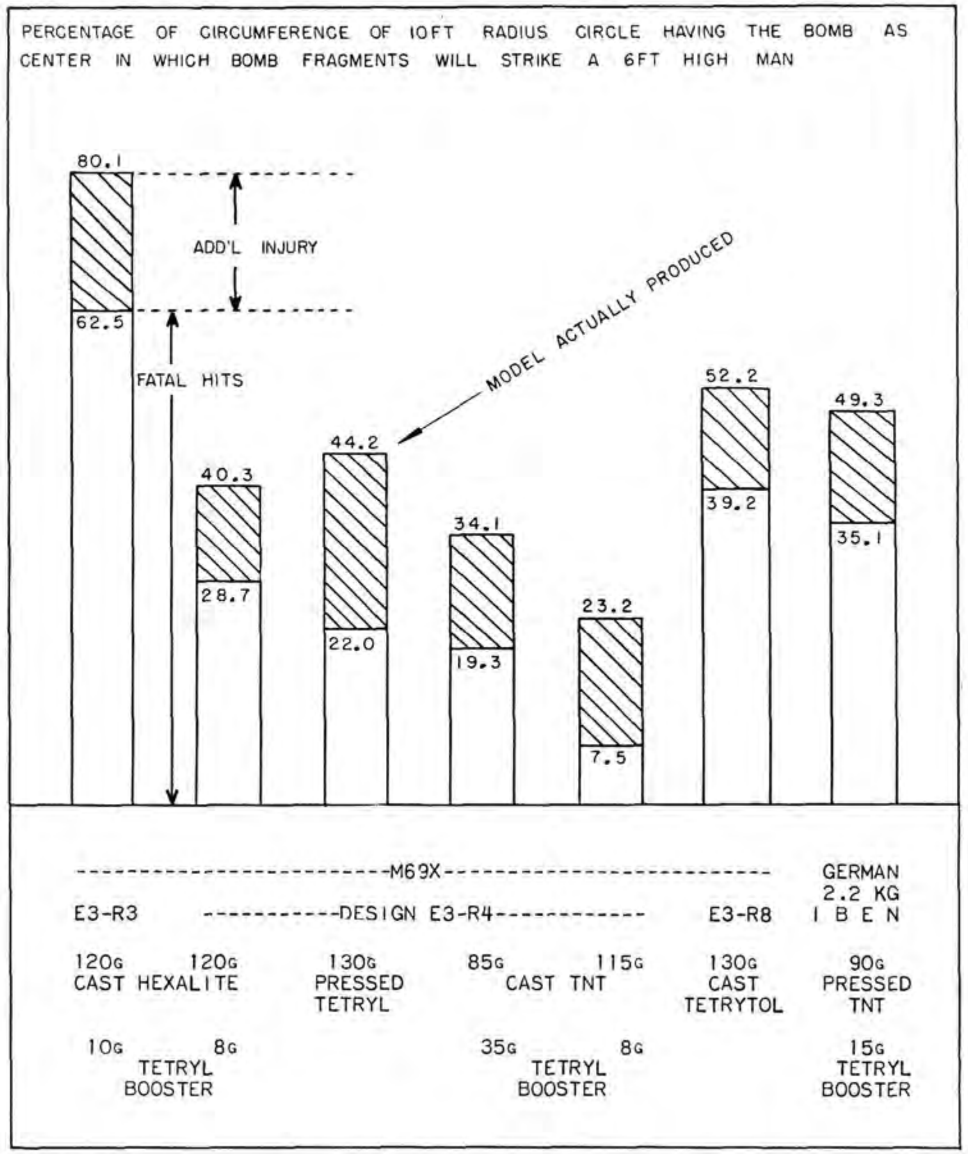


FIGURE 19. Anti-personnel effect of fragments from explosion of M69X incendiary bomb.

1.4.2 E18 Aimable Cluster

In order to overcome the disadvantage of the E28 cluster, the development of the E18 aimable clusters was begun in January 1944 by the Standard Oil Development Co. under Contract OEMsr-354. The E18 cluster (also called C1 cluster) was 14.4 in. diameter and 69.0 in. in length, weighed 425 lb gross and contained 45 AN-M69 bombs, compared to 38 in the E28 cluster (Figure 20). The principal components of the E18 cluster are as follows: (1) hemispherical nose fairing of sheet steel, (2) two hemicylindrical cover sheets, (3) top suspension bar, (4) bottom bar, and (5) tail assembly, including fairing, box-type tail fins, cylindrical tail shroud and two tail fuze adapters. The method of opening was by Primacord bursters similar to the E28 cluster.

In order to produce a well-streamlined cluster, it was believed necessary to increase the length from the standard 59 in. for 500-lb size bombs and clusters to 69 in., which was suitable for nearly all airplanes until the advent of the B-29

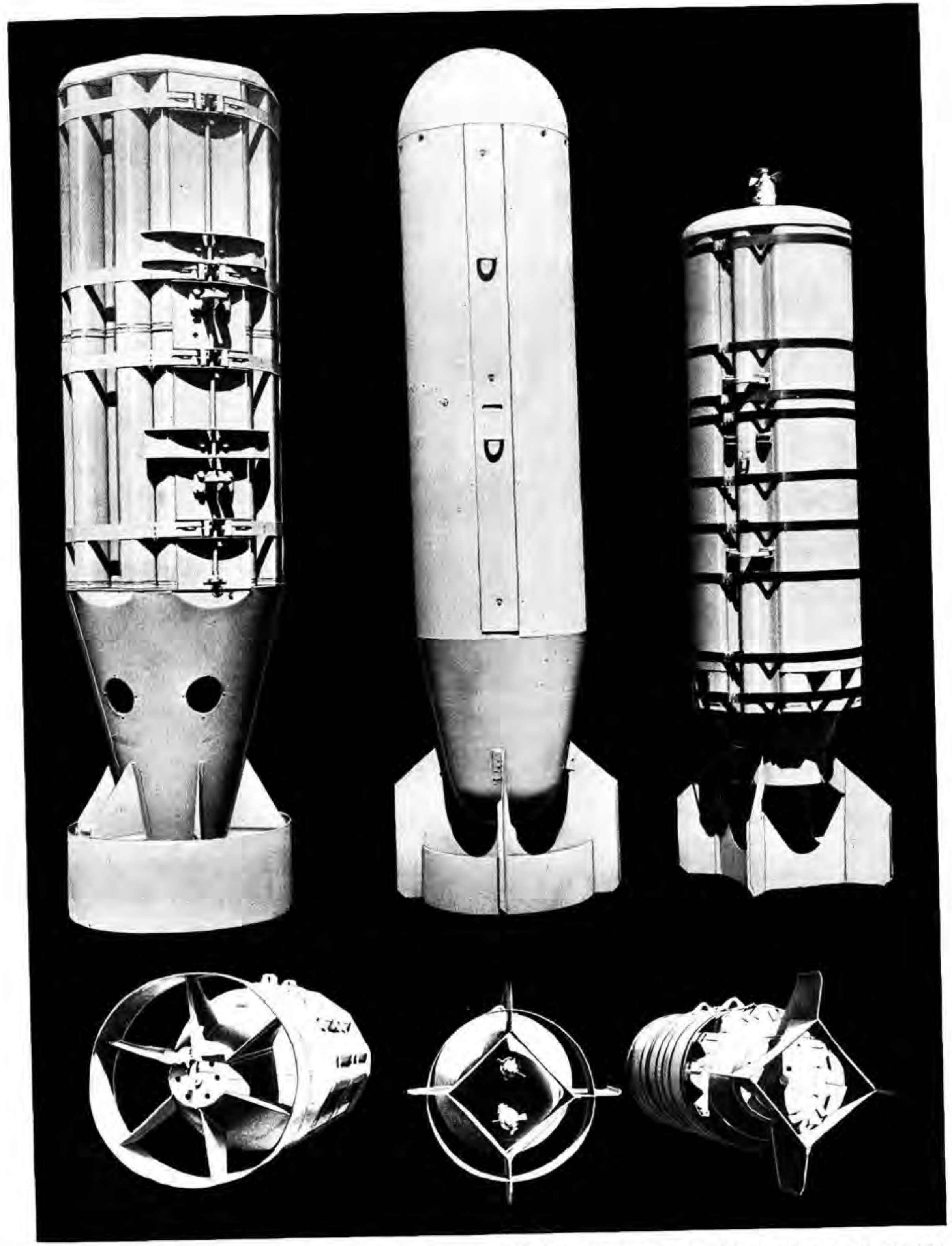


FIGURE 20. Experimental models of aimable clusters of AN-M69 incendiary bombs. Left to right, British No. 20 cluster, E18 cluster, and E28 cluster.

and B-32. The resulting cluster proved to be ballistically superior, but the excessive length prevented efficient loading on 500-lb bomb stations in B-29 and B-32 airplanes. For this reason the E18 cluster was never standardized or produced.

For comparative purposes some British No. 20 clusters were made and tested in parallel with the E18 and E28 clusters (Figure 20). This cluster was 18.0 in. in diameter and 67.3 in. in length, weighed 450 lb gross, and contained 62 AN-M69 bombs. A major difference from the E18 and E28 clusters was the method of opening, which was of the mechanical type instead of the explosive type. The British No. 20 cluster was really of the 1,000-lb size and had to be restricted to 1,000-lb bomb stations in loading on airplanes.

TABLE 6. Comparative data on aimable clusters.

	E28	E18	British No. 20
Cluster weight, lb	350	425	450
Cluster diameter, in.	14.2	14.4	18.0
Cluster length, in.	59.4	69.0	67.3
No. of AN-M69 bombs in cluster	38	45	62
Terminal velocity, ft/sec	675	1,000	515
Trail behind AN-M64, ft*	2,550	335	2,855
Trail angle, mils*	179	135	189
Circular probable error, mils*	30	15	50-75
Cluster pattern, ft	350x450	300x450	300x300
AN-M69 bomb performance*			
% Air-burst bombs	2.4	1.0	0
% Tails torn off	1.7	6.4	1.0
% Flat landers, other causes	2.8	1.6	2.0
% Fuze failures	1.5	0	0

*For release from 30,000 ft, opening at 5,000 ft, and true airspeed of 250 miles per hr for dropping airplane.

Table 6 gives some comparative data on the E28, E18, and British No. 20 clusters.[48] These data lead to the following conclusions:

1. The E18 cluster has excellent range, reproducibility of trajectory, and other desirable ballistic characteristics. In fact, its range is nearly identical with that of the AN-M64, 500-lb GP bomb.

2. The British No. 20 has poor ballistic characteristics.

3. The E18 cluster causes an excessive number of AN-M69 tails to be torn off, owing obviously to the high velocity of the cluster at time of opening.

4. The British No. 20 cluster causes no air-burst bombs, probably because of the mechanical type of opening instead of the explosive type of opening.

1.4.3 M19 (E46) Aimable Cluster

On the basis of these conclusions the Chemical Warfare Service developed a new aimable cluster, the M19 (E46), combining the best qualities of the E18 and British No. 20 clusters, and retaining the 59-in. standard length for 500-lb size bombs (Figures 6 and 21).[5, 17, 49, 50, 51, 52, 53] The M19 cluster had a blunt rounded nose fairing, a streamlined tail with shroud and twin tail fuzes similar to the E18, and a mechanical type opening which was simpler than the British No. 20 mechanism. This produced a cluster which still had a somewhat undesirably high trail, but its trajectory was very reproducible. The cluster released the bombs with a minimum of air bursts and tail damage, and the twin tail fuzes insured practically 100 per cent functioning of the clusters. Figure 10 shows the dispersion pattern of this cluster when dropped from 20,000 ft and opened at 5,000 ft. The M19 (E46) cluster was produced in large quantities and used extensively in bombing Japan in 1945.

FIGURE 21. Detail of tail end of M19 aimable cluster showing twin tail fuzes and tail shroud construction. For overall external view of this cluster see Figure 6.

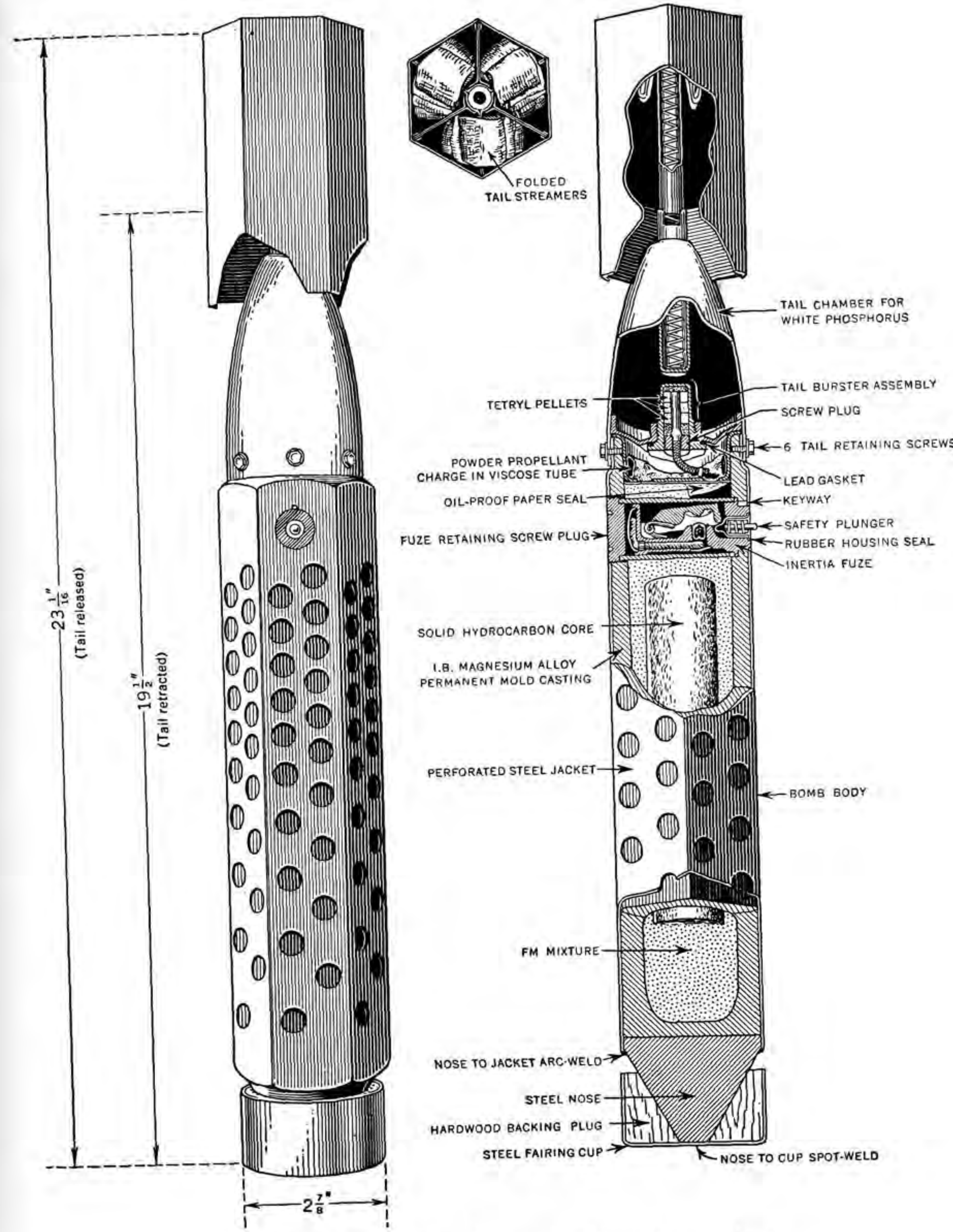


FIGURE 22. E19 incendiary bomb, external and phantom views.

1.5 E19, 11-LB MAGNESIUM INCENDIARY BOMB

1.5.1 Introduction

The E19 bomb was originally conceived as a more potent fire-raiser than the AN-M50 for use on German domestic construction. Later, with the development of aimable clusters, its possible use on factory targets in precision bombing was considered. The E19 was a bomb of the same external dimensions as the AN-M69 bomb, but heavier, and had a terminal velocity of about 650 ft per sec, so that its penetrating power was adequate for either use. As compared to existing small incendiary bombs, the E19 has higher penetrating power, in addition to the special features, in that the bomb is propelled to a favorable site after impact, and that the flame resists the action of ordinary extinguishers and is screened from fire fighters by an obscuring phosphorus smoke.

1.5.2 Description

The E19 is identical in outside dimensions to the AN-M69, namely 19½ in. long by 2⅞ in. across the hexagonal flats (Figure 22).[54, 55] It consists essentially of a magnesium body enclosed in a perforated steel sleeve welded to a steel nose-piece, filled with a mixture of several incendiary materials, and fitted with a spring-out metal tail. The gross weight is 11 lb.

The bomb is a thin-walled magnesium shell encased in a perforated steel sleeve welded to a steel nose-piece. The principal incendiary filling has the following composition:

Flake aluminum	14.8%	Sulfur	1.6%
Sodium nitrate	14.8%	Motor oil	7.1%
Barium nitrate	11.7%	Thermite	50.0%

For a further description of this mixture see Section 8.7. This mixture is loaded under compression into an annulus surrounding a case of solid hydrocarbon wax. A perforated steel diaphragm holds both fillings in place. The incendiary filling is satisfactorily ignited under light confinement by a flash of black powder from the fuze; and no first-fire mixture is required. The mixture of finely divided metal and oxidizing agents burns with an intense heat sufficient to ignite the magnesium casing and to crack the hydrocarbon wax to volatile gases. The result is a combined jet and magnesium bomb. The perforated diaphragm or propellant cup keeps the filling in place and promotes the development of an internal pressure sufficient to force jets of flame to issue from successive perforations in the steel sleeve. Thus, intensely hot flames, in a series of radial jets, issue from the bomb over a period of 3 to 4 min, and a residual flame and heat effect from the more slowly burning magnesium metal persists much longer. The total heat release is greater than that of the M50 bomb on the basis of either cluster volume or weight and about equals that of the M69 bomb on a cluster basis.[56, 57]

The fuze is very similar to the M1 fuze used in the AN-M69 bomb. The fuze is waterproofed by a rubber sleeve enclosing the safety plunger.

The tail contains a charge of phosphorus which is dispersed by a central burster. A parting charge separates the tail and the main bomb body after a 3-sec delay.

The E19 bomb is loaded in the same clusters as the AN-M69 bomb, but since the E19 is heavier than the M69, the nose and tail weights of the E23 cluster adapter can be omitted.

1.5.3 Performance Data

The action of the E19 is illustrated in Figure 23. After impact there is a 3-sec delay train in the fuze similar to the action of the M69. After coming to rest an igniter charge of 0.6 g of black powder leads the flash to a separating charge of 7 to 8 g of black powder, which then shears off the tail and, at the same time, ignites the bomb and kicks it in the opposite direction with sufficient force to cause it to come to rest against a wall or other obstacle. The bomb thus has an advantageous feature of tending to come to rest in a site favorable for starting a fire. The tail assembly comprises a streamlined canister loaded with phosphorus, with an extensible extruded magnesium fin-tail making for economy of load in the cluster. The canister carries an explosive charge that operates a few seconds after the tail has been separated from the body of the bomb.

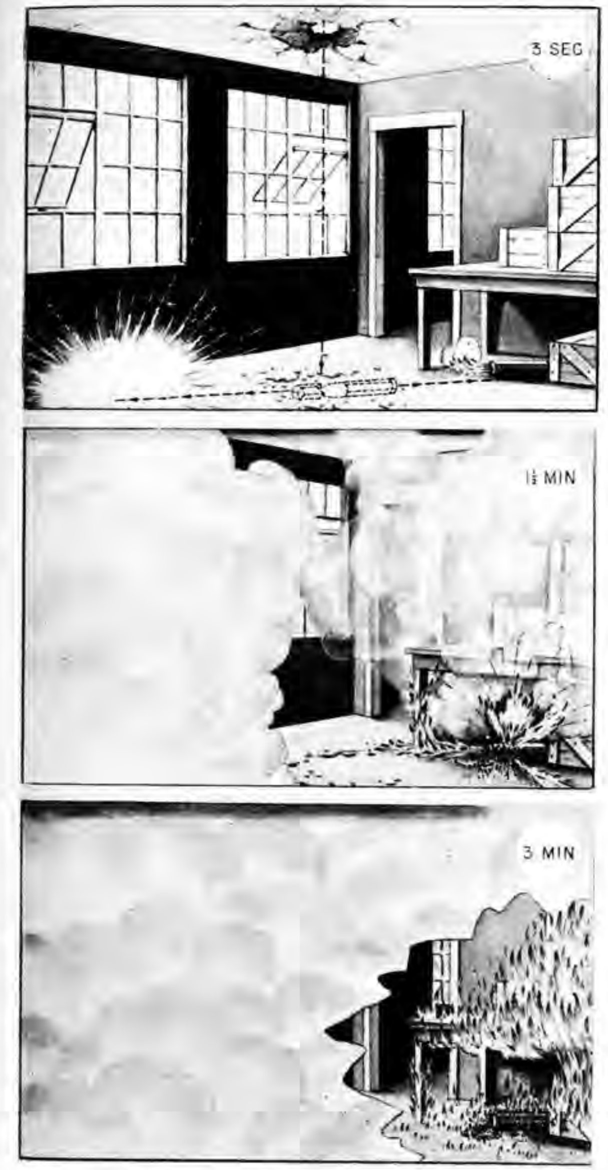


FIGURE 23. Action of E19 incendiary bomb. Note the jet-like flames issuing through the perforated bomb case in the middle view.

Thus, in the normal case the tail explodes at some distance from the body and produces an obscuring screen offering a considerable deterrent to the fire-fighter. In addition, the sudden release of a shower of burning phosphorus produces an explosion wave capable of shattering windows and blowing out doors and frames. The burning phosphorus tends to ignite any readily inflammable material in the area with consequent increase in room temperature and accentuation of the action of the bomb proper.

Penetration tests with bombs fired at velocities up to 650 ft per sec indicate that in the majority of instances the tail stays in place even when the bomb penetrates a thick concrete roof or suffers abrupt setback on a concrete slab. It will penetrate up to 6 in. of singly reinforced concrete slab, unless it hits directly over a reinforcing rod. In some instances of severe punishment, for example in a glancing hit, the tail may be ripped off the body on impact and prior to the operation of the separating charge. However, the bomb is ignited by the fuze even though the tail is lost on impact.

All of the dropping tests indicate that the bomb has excellent ballistics. Its center of gravity is 8$\frac{1}{16}$ in. from the nose, while its metacenter is 9⅛ in. In the event that a lower penetration is required, the striking velocity can be controlled by the addition of three tail streamers of Class A binding tape, each ¾ in. wide, looped over the struts of the sliding tail vane and fastened with wire staples. The foot streamers of this material, which is much more effective than sheeting, reduce the terminal velocity to approximately 500 ft per sec when the bombs are released from the cluster at a level above 8,000 ft. The ends of the streamers are dipped into heavy lacquer to prevent them from fraying.

1.5.4 Final Status

Although development of the E19 was satisfactorily completed, the decision was reached not to put the bomb in production, because of the absence of evidence that enough targets existed on which it would show performance superior to existing bombs.

1.6 E9, 40-LB OIL INCENDIARY BOMB

1.6.1 Introduction

Development of this bomb was initiated in February 1943 by The Texas Co. under Contract OEMsr-898. The request for a bomb of this intermediate size came from the Chemical Officer of the Eighth Air Force in England.

The basic conception was to develop a medium-size bomb which would have good ballistics, would penetrate a substantial target, and carry the maximum amount of incendiary fuel. The bomb was intended for use in high-altitude precision bombing, and was to be carried in a cluster that would utilize fully the space available on the 500-lb bomb station of American planes. 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. Thus the bomb would be a highly aimable all-purpose medium-size bomb. It would have far greater penetrating power than the M50 4-lb magnesium bomb, the M69 6-lb oil bomb, or the M47 100-lb oil bomb, and would contain a substantial amount of incendiary fuel.

A preliminary design study attempted to meet the required properties in a bursting-type bomb. Concurrently the Chemical Warfare Service had been designing a tail-ejection bomb in this same size range and with some of the same features. On March 31, 1943, at a conference at Edgewood Arsenal, the two designs were amalgamated with the CWS tail-ejection model predominating in the combined model. This project was then turned over to The Texas Co. for development. A principal subcontractor under The Texas Co. was the Foster-Wheeler Corp., which had the primary responsibility for the mechanical design.

FIGURE 24. E9 incendiary bomb, external and cutaway views. Cutaway view does not have gel filling, white phosphorus, ejection charge, burster charge, or HE charge in place; otherwise bomb is complete.

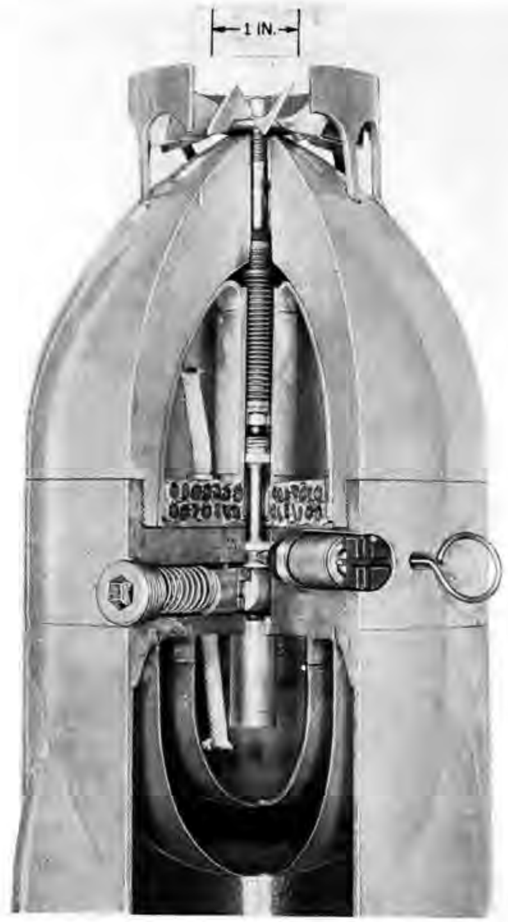


FIGURE 25. Detail of nose end of E9 incendiary bomb.

1.6.2 Description

Brief Description. As finally produced in limited procurement for test purposes the E9 bomb consisted of a heavy steel nose, an hexagonal steel case, and an extensible metal tail (Figures 24 and 25). The overall dimensions were such that fourteen bombs, in two banks of seven, formed a cluster which utilized fully the space available on a 500-lb bomb station. Attached to the nose was an arming vane which permitted an out-of-line detonator to slip into position only after the bomb was separated from the cluster and had fallen away from the airplane. Contained in the nose were a delay train and blasting cap and a high-explosive charge. The heavy nose shell screwed into a forged steel base plate, which carried the out-of-line detonator and the safety pin that prevented arming of the bombs while clustered. Attached to the other side of the base plate were two steel domes and the steel case which contained the incendiary fuel. The inner dome contained the ejection charge, and the space between the two held the white phosphorus. The far end of the hexagonal case was rounded, and attached to it was a thin conical section which carried the extensible metal tail.

Pertinent data on the final design are as follows.

Diameter	5 in.
Length, tail collapsed	29 9/16 in.
Length, tail extended	33¾ in.
Weight empty	29.7 lb
Weight loaded	40.5 lb
Weight of incendiary	
(13% Napalm-gasoline)	9.5 lb
Weight of WP	0.8 lb
Weight of tetrytol	0.65 lb
Weight of booster charge	
A-4 black powder	2 g
Composition of ejection charge	
75-mm FMH smokeless	
Cannon powder	20 g
A-4 black powder	6 g
Oiled magnesium powder	9 g
Center of gravity, distance from nose	11.1 in.

Details of Design. 1. Nose. The nose of the E9 bomb was a steel forging, shaped into an ogive to provide maximum thickness at the point where impact occurred. A ⅜-in. hole provided for the shaft of the vane arming fuze mechanism to pass through the nose. Attached to the outer surface was a guard ring which protected the arming vane. There were also two sockets for the special wrench with which the nose was screwed onto the base plate.

2. Base plate. This was a steel forging, which carried the out-of-line detonator and the safety plunger. Through it passed the striker pin.

3. HE cup. A spun steel cup, designed to fit snugly into the nose, contained the tetrytol.

4. Delay fuze. A coil of Bickford fuze, contained in a shallow metal cup, fitted inside the nose and into a recess in the base plate. Burning of the delay was initiated by the black-powder ejection charge in the dome.

5. Out-of-line detonator. This was a spring-loaded element which slid into position after the striker pin had withdrawn sufficiently following rotation of the arming vane.

6. Safety pin. A spring-loaded pin was held in position to prevent retraction of the striker pin when the bombs were clustered. When the cluster opened and the bombs separated, the safety pin was thrown out of the way.

7. Booster charge. This was contained in a cellophane cup, in line with the primer and in contact with the black powder in the dome. Its function was to ensure rapid and complete ignition of the black powder.

8. Powder dome. This was a light steel dome, brazed to the base plate and scored to facilitate rupture of the dome near its base.

9. WP dome. The white phosphorus was contained in the space between the inner and outer domes.

10. Casing. The casing was of steel ⅛-in. thick, formed from tubing which was left round at both ends for attachment to the base plate and tail cone. The intermediate portion was hexagonal, which facilitated clustering and provided a snug fit to hold the safety pin in place, and also increased the fuel capacity by about 3 per cent.

11. Tail cone. This was a light-gauge tapered shell which was blown off when the bomb functioned.

12. Extensible tail. A finned metal tail was attached to a post which seated into a recess in the tail cone. By means of a coiled spring the tail was extended when the bombs broke out of the cluster.

Fillings for Bomb. The only fillings that could be used were those capable of being introduced through the small hole in the tail cone. Gasoline gel containing thirteen per cent Napalm was used in the bombs made for test purposes. An extensive series of tests was conducted to determine the optimum fuel for the E9 bomb. After small-scale laboratory tests had established a preliminary order of merit, a full-scale field test mortar was used for evaluating the fillings. The mortar had the same capacities as the regular bomb and utilized the same rupturable domes and cones. A concrete block framework was erected 36 ft from the mortar. Sound ¼-in. plywood was mounted on the framework for each shot. A fuel was rated according to the percentage of the plywood target burned within a ten-minute period.

The following fuels are recommended in the order of preference.

1. 12% cellucotton in 5 cylindrical wads, 42 in. long and 3 in. in diameter.
   58.5% turpentine.
   19.5% furfural extract from lube oil.
   10% magnesium, type B, 40/100 mesh.
2. 15% cellucotton in 5 cylindrical wads, 42 in. long and 3 in. in diameter.
   85% turpentine
3. 12% cellucotton in 5 cylindrical wads, 42 in. long and 3 in. in diameter.
   58.5% turpentine.
   19.5% furfural extract from lube oil.
   10% ammonium nitrate.
4. 4% polyisobutyl methacrylate polymer containing 0.3% methacrylic acid.
   1% 40% aqueous sodium hydroxide.
   20% toluene.
   75% gasoline.
5. 13% Napalm thickener, type B.
   87% gasoline.

It can be noted that a wadding or solid type of filling produced the best results. The use of this material, however, would involve a redesign whereby a full 5-in. diameter opening could be employed. The design of a satisfactorily strong and leak-proof connection or seal of this size was not worked out during this investigation. It is believed, however, that this type of filling would offer more promise than the standard types of thickened gasoline.

1.6.3 E53 Cluster of E9 Bombs

The E9 bomb was originally intended for use in a quick-opening cluster of the 500-lb size. When the Air Forces ruled against the use of quick-opening clusters for release from planes flying in large formations, because of the danger from slowly falling metal components, there was a general trend toward delayed-opening aimable clusters. These require a nose fairing and a tail to give good ballistics. Since there was no room to add these components to the cluster of E9 bombs it became necessary to devise an adapter which would open quickly and consist of parts that 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. This adapter was known as the E26 cluster adapter, and the complete cluster of 14 E9 bombs was designated the E53 cluster.

The essential features of the E26 cluster adapter and E53 cluster are illustrated in Figures 26 and 27. The principal components are briefly described as follows.

FIGURE 26. E53, 500-lb size, quick-opening cluster of E9 incendiary bombs.

1. Main cluster bar. This is a hollow steel tube 2 in. in diameter, with a heavy rounded nose and an extensible finned metal tail. It contains the mechanism which opens the cluster, and permanently attached to it are the four steel cables that hold the bombs until the cluster opens. It is fitted with a hoisting lug and with

FIGURE 27. Detail of nose end of E53 cluster.

carrying lugs for attachment to a standard bomb shackle.

2. Stiffening bars. Two lengths of 1-in. pipe, weighted at one end, and provided with light metal tails, are placed 120 degrees from each other and from the main cluster bar. These serve to hold all bombs firmly in position when the cables are tightened.

3. Javelins. These are three slender steel rods which serve to prevent the central bombs from sliding forward or backward in relation to the outer bombs. One end of each is enlarged and the other end has a flat disk which engages the tails of the rear bombs in the cluster. The three javelins are placed around the two central bombs at intervals of 120 degrees.

4. Cables. These are 5/32-in. woven steel airplane cables, fitted with threaded connectors by which they can be drawn up tightly against the bombs. One end is permanently locked into position inside the main cluster bar. The other end is held by a latch until released by the functioning of the cluster opening mechanism.

5. Cluster release mechanism. In the nose of the main cluster bar is a fuze, consisting of a cocked firing pin, a 1½-sec delay pellet and a charge of black powder contained in a steel cylinder. The firing pin is prevented from moving by a rotating safety pin which cannot turn until the arming wire pulls out as the cluster leaves the airplane. Pressure developed by the burning of the black powder is applied to a piston. Beyond the piston is a steel rod carrying 4 integral steel latches which hold the free ends of the cables. When the powder burns, the moving piston causes the rod to slide within the main cluster bar, releasing the free ends of the cables and opening the cluster. The four cables then fall with the main bar to which they were attached.

The E26 adapter weighs 58 lb, and the complete E53 cluster of 14 E9 bombs weighs 618 lb. It is noteworthy that this cluster adapter, weighing less than 10 per cent of the total weight of the cluster, was strong enough to meet the latest requirements for strength of clusters as prescribed by the Joint Aircraft Committee in the spring of 1945. New clusters were required to withstand a stress equal to 18 g (18 times the force of gravity) in a vertical direction, 7.5 g fore and aft, and 3 g sideways. None of the clusters in common use by the U.S. Air Forces at the end of World War II could meet these requirements, despite the fact that the relative weight of their adapters was in general much greater than 10 per cent of the total. The novel features of the E26 cluster adapter should be kept in mind in future work on bomb clusters.

1.6.4 Performance Data

Mode of Functioning. When an E53 cluster is dropped the following sequence of actions takes place:

As the cluster leaves the bomb bay the arming wire pulls out of the safety pin, permitting it to rotate and free the spring-loaded striker pin of the cluster fuze. The striker pin moves forward, firing a primer which in turn ignites a delay composition that burns through in about 1½ sec. A small charge of black powder then is ignited and moves a piston and the steel rod which carries the four latches that have locked the free ends of the cables in place. When these are released the cluster disintegrates and the 14 bombs are free to fall individually. The extensible tail on the main cluster bar springs out and the bar, with the four steel cables attached to it, falls rapidly, as do all other members of the adapter.

As the bombs separate, each safety pin is thrown out and the propeller arming vane rotates rapidly. This action draws the firing pin toward the nose end of the bomb and soon permits the out-of-line detonator to slide into the firing position. When the bomb strikes the target the firing pin is driven back into the primer-detonator. This fires the booster charge which ignites the black powder ejection charge. The domes are ruptured and the pressure causes the tail cone and bomb tail cone and bomb tail to part from the case, ejecting the gel and white phosphorus. The Bickford delay fuze starts to burn and after approximately 2 min the high-explosive charge shatters the nose and part of the casing.

Per Cent Functioning. Ten clusters of bombs with inert filling in the HE cup were dropped from 20,000 ft onto the clay flats at Dugway Proving Ground. The bombs penetrated from 8 to 14 ft into the clay, and no gel was observed to emerge above the ground level. By probing, it was found that several of the bombs had functioned. However, two bombs were found which had malfunctioned because of deformation of the firing pin.

Fifteen clusters of bombs complete with live HE in the nose were dropped from 20,000 ft onto the industrial target building at Eglin Field, Florida. Several complete duds were found, and in a few instances instantaneous detonation of the high-explosive charge occurred when the bomb hit the target area.

It appears that some further development would be required to insure a satisfactorily high percentage of functioning. Minor changes would be needed to strengthen the firing pin assembly and to prevent the arming vane from bending without transmitting the required thrust to the firing pin. Further study to prevent premature detonation of the HE charge is also indicated. It is believed that the pressure built up in the inner dome causes a flash which sometimes bypasses the Bickford fuze and sets off the blasting cap. The fact that completely satisfactory functioning occurred in some instances suggests that the troubles encountered could be overcome by minor changes in the construction of the bomb.

Ballistic Characteristics. When properly launched in high-level flight, the E9 bomb exhibited excellent ballistic properties. The trail angle was small compared to most other incendiary bombs and was well within the scope of the standard bombsights, being almost exactly the same as for the M38A2 practice bomb. It was apparent that the design was successful in yielding a bomb that was suitable for precision bombing from high altitude. When released from the cluster, some of the bombs were thrown out at random and exhibited a certain amount of preliminary tumbling and yawing before assuming true flight. This resulted in a separation of the bombs and caused some of them to fall a considerable distance behind the others. It is believed that if a suitable bomb rack were available to release all bombs individually in true flight the ballistic characteristics would leave little to be desired.

Cluster Dispersion Patterns. Ten E53 clusters were dropped from 20,000 ft onto the clay flats at Dugway Proving Ground. One cluster did not open. Of the 14 bombs in a cluster, between 8 and 12 fell into an area the width of which varied from 100 yd to 150 yd and the length varied from 100 yd to 375 yd. From one to three bombs usually landed about 600 yd to the rear, and in three instances from one to three additional bombs landed approximately 1,200 yd to the rear. When the impact patterns of these clusters were superimposed upon a line through the leading bomb in each cluster, it was found that 55 per cent of the bombs fell within an area measuring 200x200 yd, 80 per cent were within an area 200 yd wide by 775 yd long (Figure 28).

The leading bombs in each cluster fell near the M38A2 practice bomb, and most of the bombs were consistently grouped within a reasonable distance of the practice bomb. This is evidence that the E9 bomb, when properly launched, has excellent ballistics; and also indicates a high degree of aimability for the cluster, despite the fact that a few of the bombs usually fell far to the rear. Clusters of other incendiary bombs frequently gave tighter and more uniform patterns, but their centers of impact varied widely with respect to the aiming point where the M38A2 bomb landed. When considered in terms of a stick of clusters from

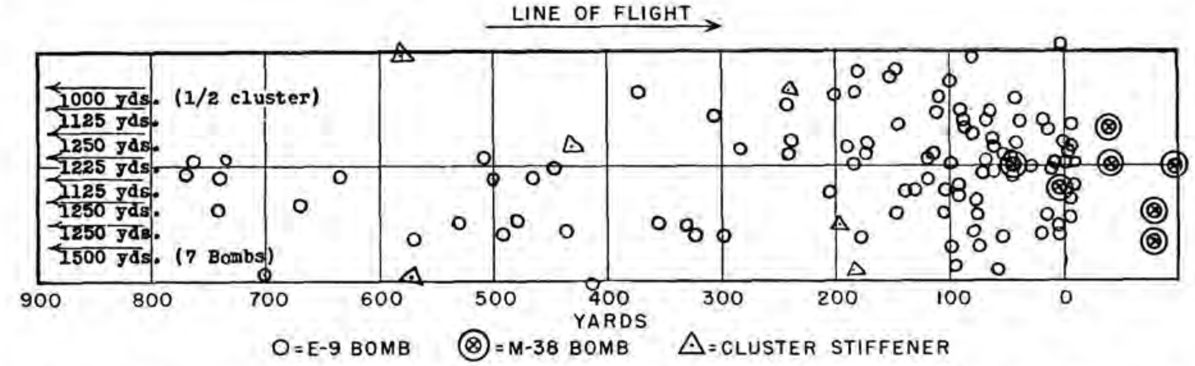


FIGURE 28. Superposition of impact patterns of nine E53 clusters of E9 incendiary bombs dropped from 20,000 ft.

a single plane, or many clusters from a group of planes, the dispersion pattern of the E53 cluster appeared satisfactory. The high intrinsic aimability of the E9 bomb increases the probability that some bombs will hit a specific target, even though a few will trail considerably.

Release from Fighter Planes. E53 clusters were released from P-51 fighter planes at 350 mph at an angle of 30 degrees from 3,000 ft elevation in a glide bombing attack. All the bombs hit close to the target in a pattern about 200 ft by 300 ft. The E53 cluster is probably the only incendiary bomb cluster which could be used for low-level or glide bombing attacks.

Penetrating Power. A number of hits were obtained on the industrial target building at Eglin Field, Florida. One bomb penetrated the 6-in. reinforced concrete roof slab and an 8-in. reinforced concrete floor, and then ejected its gel and disintegrated from premature detonation of its high-explosive charge. A second bomb showed similar penetration of roof and floor, but failed to function. Upon hitting the next lower floor the nose assembly parted from the case. Two bombs which hit light roof construction penetrated cleanly and also went through a plain 6-in. concrete floor, coming to rest about 1 ft below the floor. The incendiary gel was ejected; one HE charge detonated prematurely and the other after the intended delay. No instance of rupture of the bomb case upon impact was noted, and there were no failures of the nose and case to hold together until after the roof had been penetrated by the bomb.

When impacting on sand or clay, in drops from high altitude, the E9 bomb penetrated 12 ft or more into the ground. Ejection occurred after the bomb had gone some distance below the surface, and no incendiary results were to be expected.

Fire Starting Efficiency. The end of World War II came before tests could be run to evaluate the fire starting efficiency of the E9 bomb when actually dropped onto combustible targets. The test mortar, used to determine the optimum fuel for the bomb, simulated the original design in which a delay element permitted the bomb to come to rest before ejection occurred. The final design omitted the delay, so that ejection occurred in a few hundredths of a second after the first impact. But this permitted a bomb that hit on the ground to penetrate to the point where no gel was discharged above the surface; hence, only direct hits on structures would be significant. From the meager data available it appeared that ejection of gel would occur while the bomb was still in flight after penetrating roofs and floors equivalent to the 6-in. roof and 8-in. floor actually penetrated in two instances. Or, after penetrating a light roof in a one-story building the bomb would go through a 6-in. floor and eject its gel upward from its final position just below the floor.

Neither of these modes of functioning was favorable to the starting of a fire, as compared to the horizontal ejection of gel that was originally planned. However, with approximately 10 lb of incendiary gel being ejected, there would be a good chance that several gobs of substantial size would be thrown against combustible material. Moreover, the chance of starting several simultaneous fires which would be mutually supporting increased with the amount of fuel in the bomb. Hence it may be said that the E9 bomb would probably prove to be an effective fire starter, and would be especially valuable for the attack on selected targets where precision bombing and the ability to penetrate a substantial roof were necessary.

It appears unlikely that a bomb of this type could be constructed which would regularly hold together until it came to rest before ejection. The E9 showed no sign of failure in penetrating the roof and floor slab, but in one instance the nose separated from the casing when the next floor was encountered. In slowing down as it passes through roofs and floors, the bomb is certain to turn so that the next impact will not be taken on the nose and in line with the central axis of the bomb. When that occurs, breakup is to be expected. Hence it appears necessary to have the bomb function instantaneously, and a more rapid ejection than was achieved in the E9 would have some advantages. Hits on the ground might not be a total loss, and hits on one-story factories would result in gel being ejected between roof and floor without having to depend on there being a heavy concrete floor to stop the bomb where its gel would still be ejected inside the structure.

TABLE 7. Fragmentation of E9 incendiary bomb.

Description	Number	Weight
Unfragmented portion of case	1	6 lb, 15 oz
Large fragments, ½ lb and over	8	5 lb, 12 oz
Medium fragments, 1-8 oz	40	5 lb, 15 oz
Small fragments, 0.2-1 oz	100	2 lb, 2 oz
Small fragments, 0.2 oz and smaller	1,000 approx.	2 lb, 10 oz
Total	1,150 approx.	22 lb, 12 oz

Original weight of metal, 24 lb, 3 oz
Recovery, 94.1%

Fragmentation. A test made in a fragmentation chamber at Edgewood Arsenal gave results shown in Table 7. The detonation of the E9 anti-personnel element makes a very impressive noise, and in field trials fragments were found ½ mile from the point of explosion.

1.6.5 Final Status

When World War II ended, some minor problems remained to be solved in perfecting the E9 bomb and the E53 cluster. In summarizing this development, the following conclusions appear to be justified.

1. The E9 is a medium-sized incendiary bomb which has excellent ballistic characteristics. It can be aimed with current bombsights and has a small trail angle compared to most of the other incendiary bombs.
2. The penetrating power on reinforced concrete exceeds the stated requirements for this bomb, and the performance after penetration appears satisfactory.
3. The quantity of incendiary fuel per cluster is greater than for any other comparable cluster of bombs using gelled fuel.
4. A lethal anti-personnel charge was successfully incorporated, but some further work is required to prevent premature functioning of the HE.
5. Some changes in details of the bomb-fuze mechanism are needed to prevent malfunctioning on impact.
6. The E26 cluster adapter is capable of releasing the bombs with a minimum of tumbling. It utilizes all the space available in a 500-lb bomb station, and its components fall rapidly enough to clear lower flying planes in a formation.
7. The E53 cluster is suitable for high-level, low-level, and glide bombing.
8. The E9 bomb and E53 cluster are adequately safe to handle, transport, and store.

1.7 E3, 25-LB OIL INCENDIARY BOMB

Development of this bomb was initiated in April 1942 by Harvard University under Contract OEMsr-179. The objective was to develop a medium-sized incendiary bomb which would be an improvement on the AN-M46, 30-lb bomb, from the point of view of flight stability and functioning, and on the AN-M47, 70-lb bomb, from the point of view of clustering and loading efficiency. The E3 bomb could be considered either as a small version of the AN-M47 bomb,

or as an improved version of the AN-M46 bomb. Some impetus also came from the British 30-lb petrol gel bomb, which was of the same size class. The E3 bomb can be considered as a precursor of the E9, 40-lb oil incendiary bomb (see Section 1.6).

The E3 bomb was of the 25-lb class and of the bursting type. It was intended to be clustered 14 in a 500-lb size quick-opening cluster. The bomb consisted of a hexagonal sheet steel case with an ogival nose and a conical tail section fitted with a fixed hexagonal steel fin. A central burster was of the WP-HE type as in the AN-M47 bomb. The filling was 13.5 per cent Napalm gasoline gel. The nose was fitted with an AN-M110 arming vane type fuze. The overall dimensions were 4¾ in. across the hexagonal flats by 26¾ in. long. The filled weight was 23.5 lb, of which 11 lb was gasoline gel. The proposed 500-lb size cluster would have been approximately 14¼x58 in. and would have weighed approximately 375 lb.

Only two rather crude models of this bomb were ever dropped in flight tests. One dropped from 2,500 ft at Jefferson Proving Ground showed good flight characteristics, and the other dropped from 2,500 ft at Edgewood Arsenal yawed badly. These results left the flight characteristics in doubt, so that this project was held in abeyance for some time and was later revived in the development of the E9, 40-lb incendiary bomb.

1.8 E20, 500-LB OIL INCENDIARY BOMB

Development of this bomb was initiated in April 1943 by Harvard University under Contract OEMsr-179. The objective was to develop a large incendiary bomb with a cast-iron case, instead of steel, in order to reduce the force necessary to open the case and thereby prevent dispersion of fuel in such small particles as characterized the performance of the steel-case bomb.

The E20 bomb was very similar to the AN-M76 500-lb incendiary bomb, which in turn is externally identical with the AN-M64 500-lb GP bomb. The principal differences between the E20 and AN-M76 bombs are:

1. The E20 bomb casing is made of cast iron instead of steel.
2. The E20 casing is slightly thicker, with a minimum wall thickness of 0.5 in. and a maximum nose wall thickness of 1.5 in. compared with 0.3 in. and 1.25 in., respectively, for the AN-M76 casing.
3. The E20 bomb used a 9/16 in. tetrytol burster compared with a ⅞ in. burster in the AN-M76 bomb.
4. E20 bombs were filled with Napalm type I, methacrylate type I and PT1 fillings, although part of the purpose of using the cast-iron case was to be able to use the Napalm and IM types of filling.

When fired statically the E20 bomb, filled with Napalm type 1 and with 9/16-in. tetrytol burster, dispersed burning gel over an area 100 ft x 200 ft. There were 297 fires burning after 5 min and 46 fires after 11 min. The casing broke into many small pieces.

When dropped on buildings from 4,000-5,000 ft, the bomb functioned satisfactorily on striking light roofs. One bomb penetrated a lightweight, concrete tile roof and also a 3-in. concrete slab floor, depositing gel on the first floor over an area 120 ft x 180 ft, with 235 fires burning after 5 min. However, when striking a 7-in. reinforced-concrete slab the bomb broke up so badly that satisfactory penetration and functioning on heavy-roofed buildings seemed doubtful. The E20 bomb is therefore not a substitute for the AN-M76 in this respect.

When dropped 10 ft and 20 ft onto concrete, the bomb broke into 6 to 18 pieces. This fact ruled out the bomb from a safety point of view, and further development was discontinued.

1.9 E22, 500-LB OIL INCENDIARY BOMB

Development of the bomb was initiated in April 1945 by the Factory Mutual Research Corp. under Contract OEMsr-257. The objective was to develop a large incendiary bomb of the tail-ejection type, using cellucotton as the bodying agent for gasoline fuel instead of gelling agents such as Napalm.

The E22 bomb was an attempt to develop a large tail-ejection type incendiary bomb to meet the requirement for a 500-lb size incendiary bomb. This bomb used the casing of the AN-M64 500-lb GP bomb, modified somewhat, and therefore was externally identical with the AN-M76 500-lb incendiary bomb.

The principal components of the E22 bomb were the following.

1. The AN-M64 bomb case scored to a depth of 9/32 in. clear around at the base of the tail cone (2/3 thickness of the casing).

2. A nose burster consisting of a steel wall 1¾ in. in diameter by 18¾ in. long extending inside the bomb case and filled with 250 g of 70 per cent A4 black powder and 30 per cent coarse magnesium flakes.

3. A cylindrical tail canister containing 5 lb of white phosphorus.

4. A main filling consisting of 92 cellucotton rolls, 4 in. x 4 in., covered with cheesecloth and 17 gal, or 110 lb, of gasoline. Gel type fillings could also be used.

5. An AN-M103 nose fuze, with the charge reduced from 50 g to 5 g of tetryl, set for instantaneous firing.

6. An AN-M101 A2 tail fuze and M115 burster containing 100 g of tetryl, set for 0.025-sec time delay.

The gross weight of the bomb was about 375 lb, and the external dimensions and appearance were identical with the AN-M64 and AN-M76 bombs.

On functioning, the burster charge blew off the scored tail section and ejected the gasoline-soaked cellucotton rolls. The spectacular action earned this bomb the name volcano bomb. In static tests about 92 per cent of the cellucotton units were ejected whole with 85 per cent ignition. At the end of 10 min 57 fires were still burning. There was a large flash burn of excess gasoline at the time of ejection, but this was estimated to consume less than 10 per cent of the gasoline in the bomb. The white phosphorus canister in the tail was burst by the M115 burster and produced an instantaneous white smoke.

Dropping tests were few and inconclusive. A total of 10 bombs were dropped from 5,000 ft altitude, of which 3 hit a building and 7 hit onto ground. The bombs which hit buildings seemed to fragment the case rather than simply eject the contents, and there was an unusually large amount of flash burn. Also the cellucotton rolls were shredded and shattered more than in the static tests. However, in one case there were 56 fires burning at the end of 5 min. The general conclusion was that the bombs did not function the same or as promisingly in the dropping tests as in the static tests. One bomb penetrated two floors of 7 in. and 8 in. of concrete respectively, showing its penetrating power to be comparable to the AN-M64 or AN-M76 bombs. The bombs striking onto ground did not add any pertinent data.

Although the results were not conclusive, the development was discontinued at this point in view of the AN-M76 filling the limited requirements for this class of incendiary bombs.

1.10 PLASTIC INCENDIARY BOMB

Development of this bomb was initiated in December 1941 by the Monsanto Chemical Co. under Contract OEMsr-198. The objective was to develop a small incendiary bomb utilizing cellulose nitrate plastic as an incendiary material.

Two principal types of bombs were developed under this project.

1. Bombs in which the cellulose nitrate plastic served as a combustible casing for a therm-8 filling, i.e., the plastic was intended to be an improved substitute for the steel casing in the AN-M54 type of incendiary bomb.

2. Bombs in which the cellulose nitrate plastic was the primary incendiary material with only enough therm-8 filling to assist the burning of the plastic.

The various bombs developed under this project were hexagonal in shape, 1¾ in. across the flats by 10 in. long, or roughly half of the length of the AN-M50 and AN-M54 standard bombs.

Many variants of bombs of the first type were tried, and the most important and final model had the components described below.

Plastic casing, hexagonal, 1¾ in. across flats by 10 in. long, with inside bore of 1¼ in. or 1½ in., giving a minimum wall thickness of ¼ in. or ⅛ in., respectively.

Steel nose plug, with hexagonal section ¼ in. thick and a ⅝-in. long section extending inside the plastic casing.

Plastic tail plug, made of Resinox plastic, 1¼ in. in diameter, 3¼ in. long, bored internally to take the firing pin, spring, and primer holder from the AN-M54 bomb.

Filling of 5 pellets of therm-8, each 1 in. thick, and 1 first-fire pellet.

Cloth tape tail streamer, 1 in. wide, 30 in. long. Various other bombs with tails and bombs without tails were also tried.

The gross weight of a bomb of this description was 2¼ lb; the burning time was 2½ min.

Drop tests from 1,000 ft onto concrete resulted in breaking and malfunctioning of these bombs, although the flight stability was good. Somewhat better performance on drop tests was obtained by wire reinforcing in the plastic and by use of layer-cloth, tail streamers, and parachutes, but the results were still discouraging. These results caused abandonment of this type of bomb.

Bombs of the second type were similar to those of the first type, except that the bore of the plastic casing was reduced to ½ in., making the bomb primarily a plastic bomb with just enough therm-8 to assist the burning of the cellulose nitrate. These bombs weighed only 1.6 lb compared to 2.25 lb for the first type, so that it was felt the bomb was sufficiently nose heavy with the steel nose plug that the cloth tail could be omitted. Drop tests from 1,000 ft onto concrete showed adequate strength and apparently good flight stability. However, drop tests from 5,000 ft and 10,000 ft showed very poor flight stability, many bombs tumbling badly.

In view of these test results development of this bomb was discontinued in the summer of 1942. Furthermore, comparative burning tests showed that the fire starting capacity of this bomb was quite low, reflecting the relatively low heat of combustion of cellulose nitrate (7,200 Btu per lb).

Chapter 2

MISCELLANEOUS INCENDIARY ITEMS

2.1 INTRODUCTION

This chapter describes miscellaneous developments in the incendiary field, including a new type of burster for large incendiary bombs which was utilized in the AN-M47 and AN-M76 bombs, several small incendiaries for sabotage and other miscellaneous purposes, an all-ways fuze for M69 type bombs, incendiary leaves, and certain modifications of some standard incendiary bombs. Most of these developments could be described as minor, except the new type burster for large incendiary bombs.

2.2 BURSTER-IGNITER FOR M47 TYPE BOMBS

2.2.1 Introduction

All the incendiary bombs used in World War II were exploded by either base-ejection or central charges of black powder. Chemical bombs, on the other hand, scattered their contents by means of a central burster, usually of tetryl. The phosphorus bombs or shells constructed in this manner were poor incendiaries at best, and the bursting charge was so great that most of the contents were broken into very small particles. With the development of gasoline fuels thickened by rubber or Napalm, a new and comparatively difficult problem of ignition and distribution arose. It was necessary to distribute the burning gel in gobs sufficiently large to start fires under average conditions. Very large lumps may burn for a long time, but they represent an inefficient distribution, while very fine pieces of gel are too short-lived to be effective.

It was found that the M47 series of 100-lb chemical bombs, which make efficient containers for incendiary material, burst unevenly under slowly increasing pressure such as produced by a black powder burst. Usually there was one weak spot at a seam or near the tail that would rupture sufficiently to release the pressure and eject only a portion of the fuel, while the remainder burned either in the bomb or in the crater below. This was verified by high-speed motion pictures (800-1200 frames a sec) with the M47 100-lb bomb having a 0.032-in. wall, and the same effect was later observed, to a lesser degree, with the M47A1 bomb having a 0.050-in. wall. Bombs loaded with chemical agents did not exhibit this fault, for the liquid transmitted the pressure practically undiminished, but the jellied fuels absorbed much of the energy, causing a slower transmission of the bursting energy to the case.

2.2.2 Description

It was observed that light-wall gallon cans used to test experimental batches of thickened fuel were effectively scattered by one or more detonators. From this observation it was reasoned that a high-explosive central core of primacord or TNT-tetryl should act similarly, and this was found to be the case. A means having been found for distributing the gelled fuel evenly and in regulated size, a large number of igniters were then examined in order to effect ignition of the gel. Among those tried were powdered and grained magnesium, sodium, potassium, sodium-potassium alloy, zinc dimethyl, silicon ethyl, phosphorus, and pyrophoric metals. Larger scale tests were then made on zinc dimethyl and phosphorus confined in an annular tube surrounding the central explosive core. Phosphorus was found to be the better of the two, and from practical considerations of manufacture and loading it was selected as the igniter to be used in conjunction with the high-explosive burster.[1,2]

The experimental model is shown in Figure 1. In this unit the central explosive core 31 consists of TNT pellets, contained in a bakelite tube with one or more booster pellets of the more sensitive tetryl at either end. Light brass or aluminum caps retain the pellets in the tube and permit firing the tube at either end. The

burster is held against the fuze by the coil spring 32 which is an integral part of the outer housing. Considerable leeway is permitted in the gap between the fuze and the end of the burster, and reliable firing is obtainable with gaps of from 1/8 to 1/4 in. in length. Two pounds of phosphorus is contained in the annular space between the inner burster well and the outer tube. A seal made by the lead washer 26, together with a luting of pipe dope (hydraulic cement ground with linseed oil), retains the phosphorus.

The burster-igniter as described above was never produced, but after some delay the Chemical Warfare Service modified it somewhat and it was standardized and produced as the AN-M13 burster and AN-M9 igniter for use in AN-M47 series bombs.[4,5,6] These items were produced and supplied separately so that each was made a sealed unit, with the result that the total wall thickness required to be ruptured was increased so much that the production models never equalled the experimental models in performance. The AN-M13 burster is a plastic or aluminum tube, 0.45 in. diameter, 36 in. long,

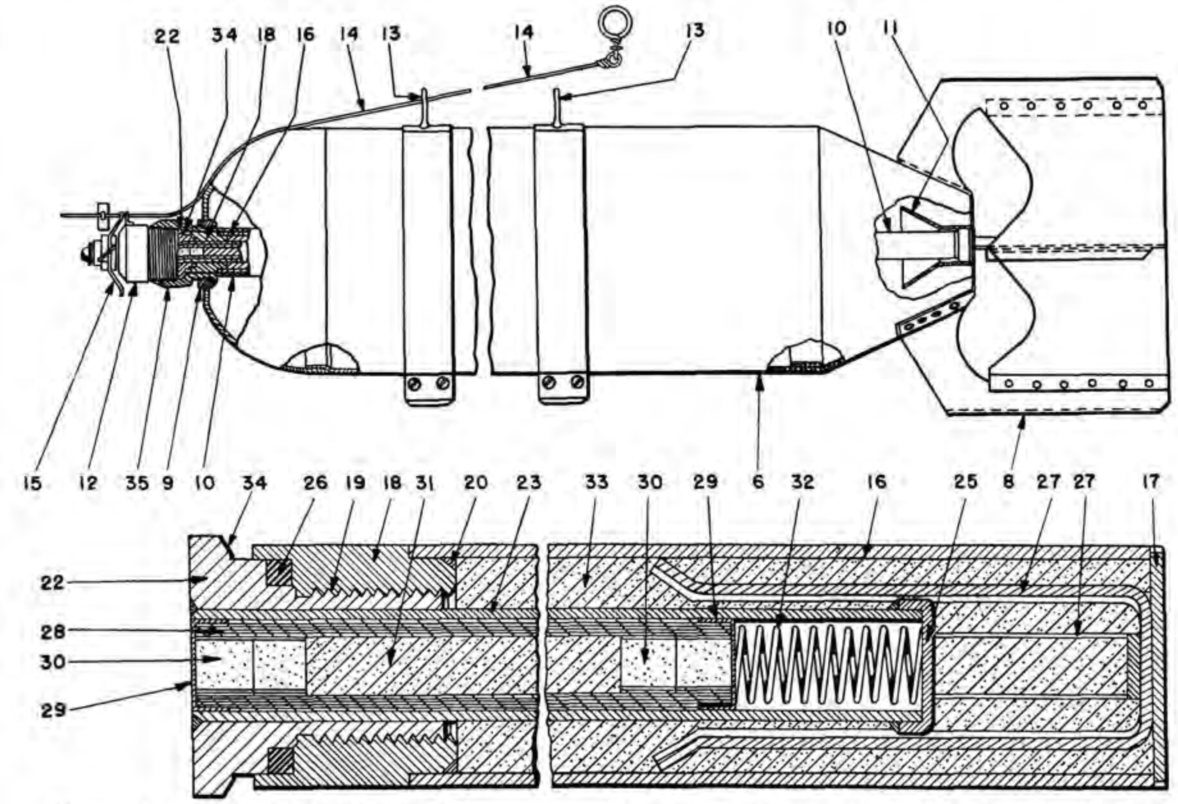


Figure 1. WP-HE burster-igniter in place in AN-M47 incendiary bomb and detailed cross section.

The phosphorus was loaded by either the wet method (under water) or the dry method (under carbon dioxide).[3] The latter method was preferred and largely used in production, because of the lessened chance for corrosion. The phosphorus was loaded and sealed into the burster well in the factory, and the sealed tube of explosive was inserted into the central well in the field at the time of arming.

filled with TNT pellets containing tetryl pellets at each end. The AN-M9 igniter is a steel tube, 38.5 in. long, filled with 1.6 lb of white phosphorus (WP), and containing a steel well, 0.454-in. inside diameter, to receive the AN-M13 burster. This combination was used extensively in AN-M47 bombs in bombing Germany and Japan. The AN-M12 black powder-magnesium powder burster was also used in this bomb. Tests at Eglin Field failed to show conclusive superiority for either of these competitive bursters.

This same principle was adopted for use in the AN-M76, 500-lb incendiary bomb. This bomb was a standard 500-lb[7] bomb case filled with 180 lb of PT incendiary gel. The M14 burster and M5 igniter for the AN-M76 bomb were of the same type as the AN-M13-M9 combination used in the AN-M47 bomb. The M14 burster contained one lb of tetrytol, and the M5 igniter contained 9 lb of white phosphorus. This combination worked quite successfully in this bomb. The AN-M76 bomb was used to a limited extent in bombing Germany and Japan.

Another application of this burster-igniter principle was used by the Chemical Warfare Service in the burster-igniter for the jettisonable belly tanks, or fire bombs, filled with Napalm gasoline gel, which were used so effectively in Europe and the Pacific.

2.2.3 Performance Data

This type of burster is always instantaneous firing. In testing this type of burster a sharp distinction must be made among three methods of testing:

1. Firing of statically placed bombs, in which the fuel is thrown outwards and upwards in a fairly circular pattern with the bomb at the center (Figure 2). A typical burst of this type would cover an area about 150 ft across and would yield about 50 gobs of gel which would still be burning after 10 min.

FIGURE 2. Static burst of AN-M47 incendiary bomb using WP-HE burster-igniter.

2. Bombs dropped from airplanes onto earth, in which the bomb makes a crater and most of the fuel is thrown forward and upwards in an elliptical pattern with the bomb at one end. The area covered was about 50x100 ft, although this varied with the angle and speed of impact.

3. Bombs dropped from airplanes onto buildings, in which the bomb bursts 8 to 15 ft below the roof and the fuel is thrown downwards and outwards in a conical pattern onto the floor below.

Figure 2 shows a burst of type (1). Bombs were frequently tested by method (2) in the early days of World War II, and some limited conclusions could be drawn. Tests by methods (1) and (2) in 1942 indicated a marked superiority of the WP-HE burster over the black powder-magnesium powder burster,[8, 9, 10] and this led to the decision to use the former. However, only tests by method (3) are really significant in determining the effectiveness of a bomb. Tests by this method at Eglin Field in 1944[11, 12, 13] failed to show any marked superiority of the AN-M13-M9 burster-igniter combination over the AN-M12 black powder-magnesium powder burster. It is possible that a better adjustment of HE charge and wall thickness of material in the AN-M13-M9 combination might have given the superior results shown by the experimental model.

2.3 SABOTAGE INCENDIARIES AND FIRE STARTERS

2.3.1 Introduction

Small pocket-size incendiaries of this type are used as sabotage incendiaries, usually placed by hand, and for starting campfires in the field, or for heating and cooking in emergencies. The following NDRC contractors developed incendiaries of this type:

Harvard University, Contract OEMsr-179; Factory Mutual Research Corp., Contract OEMsr-257; and University of Chicago, Contract OEMsr-113. The first two contractors later worked directly with the Office of Strategic Services in this line of development.

All incendiaries of this type consist essentially of a combustible case, filled with some incendiary material, and fitted with some sort of igniter.

2.3.2 M1, Fire Starter

This unit, developed by Harvard University, consists of a cylindrical celluloid case, $3 \times 1\frac{1}{2}$-in. diameter, filled with 33 g of Napalm gasoline gel, and fitted with a match-head and scratcher igniter (Figure 3).[14, 15, 16, 17, 18, 19] The gross weight of the unit is 77 g, its heat output is about 1,700 Btu, and it burns for 7 to 9 min. The match-head composition is 50 per cent potassium chlorate, 30 per cent antimony sulfide, 20 per cent dextrin, and water to give a stiff paste. The scratcher composition is 50 per cent red phosphorus, 30 per cent 50-80 mesh sand, 20 per cent dextrin, and water to give a stiff paste. The complete unit is waterproofed with a coating of vinylite.

FIGURE 3. M1 fire starter (Harvard Candle), assembly and construction.

The fire starter is ignited simply by rubbing the scratcher on the match-head. This unit was tested in a packing box test where two packing boxes are placed with 10x25-in. faces, $1\frac{1}{2}$ in. apart. The M1 fire starter started a continuing fire in this test setup, while some other small incendiaries which weighed more would not do so. This test was successful with either dry or wet wood. Other simple wood-burning tests were used in which the M1 fire starter showed up to advantage compared to other incendiaries of similar weight.

This incendiary, originally called the Harvard Candle, was standardized as the M1 fire starter in 1942 and produced in some quantities. There is no record of its use in the field.

2.3.3 H2, Vest-Pocket Sabotage Incendiary

This device, developed by Harvard University, is made to resemble a plastic cigarette case or notebook (Figure 4).[20] It consists of a black celluloid case $5\frac{1}{16} \times 2\frac{3}{4} \times \frac{3}{4}$ in., filled with 133 g of 8 per cent Napalm gasoline gel and fitted with a time-delay ignition mechanism. The gross weight is 189 g, the heat output is about 5,500 Btu, and the burning time is about 15 min.

The time-delay igniter on this unit had to be safe, reliable, silent, and waterproof. It consisted of a standard OSS time-delay pencil actuating a spring-loaded firing pin, which pierced a thin, 0.005-in., celluloid cylinder and fired an ordinary strike-anywhere match-head. The OSS time-delay pencil consisted of a metal wire holding a spring-loaded firing pin and a glass tube of corrosive liquid contained in a thin metal tube which could be pinched to break the glass tube and initiate the mechanism. The fire of the match-head was passed on to the main gasoline gel filling by a potassium chlorate booster charge.

The high Btu output of the H2 incendiary gives a high fire-starting power. On packing-case tests, piles of faggots and logs, a wooden attic, and stacks of packing cases, the H2 was demonstrated to be a potent fire starter. The H2 incendiary was produced in large quantities by the Office of Strategic Services and used abroad in sabotage operations.

FIGURE 4. H2 vest-pocket sabotage incendiary, assembly, and construction.

2.3.4 FM Sabotage Incendiary

This unit, developed by the Factory Mutual Research Corp., consists of a celluloid case, 5x2¾x¾ in., filled with cotton waste and paraffin wax in which are embedded two cores, 5x½ in., made of 45 per cent sodium nitrate, 35 per cent aluminum powder, 15 per cent SAE 40 motor oil, 5 per cent sulfur.[18, 21] The gross weight of the unit is 175 g. The units were ignited by means of a temporary first-fire charge, but a time-delay igniter could be fitted to it for actual use.

These units were tested by burning them between two packing case ends, 24x45 in., placed 3 in. apart, as representative of a sabotage location in a warehouse or supply dump (see Section 3.2 for further description and photographs of this test arrangement). The FM incendiary set fire to such a setup when dry, after being soaked in water, and after being soaked in water and covered with snow, although, of course, the speed of starting the fire varied with the conditions.

The FM incendiary was competitive with the H2 vest-pocket incendiary. The FM unit had the advantage that the filling was stable over a wide range of temperatures, it was not subject to leakage or evaporation, and it would stand very rough handling without malfunctioning. Its fire starting efficiency was comparable to the H2 unit. However, the H2 incendiary was selected for production and use in this class of incendiary.

2.3.5 Chicago Hand Incendiaries

These incendiaries, developed by the University of Chicago, were made in a variety of sizes and types of cases. All were filled with a mixture of polymerized divinylacetylene (SDO, synthetic drying oil, a du Pont product), sodium nitrate, and heavy petroleum oil (Figure 5).[17, 22, 23] The composition of the mixture was 30 per cent SDO, 60 per cent sodium nitrate, and 10 per cent oil. This project was originally started in the belief that SDO was an incendiary material of superior merit, because it ignited readily and had accidentally caused some bad fires in

FIGURE 5. Chicago hand incendiaries, external views and method of igniting.

laboratories. However, further investigation showed that the heat output of SDO was the same as that of other hydrocarbon materials, and that it really had no superior fire starting ability. This mixture was placed in tubes made of paper, cellulose acetate, or magnesium. The principal sizes used were approximately ⅞x7½ in., ⅞x4⅜ in., 1¼x7½ in., and 1¼x3 in. The units were fitted with a match-head and scratcher similar to that of the M1 fire starter.

The SDO-sodium nitrate mixture burned with a blowtorch flame which would melt and ignite a magnesium casing. The flame was impressive, but in comparative tests in packing cases these units were not as effective in starting fires as M1 fire starters which weighed less. Development was discontinued in 1942.

2.4 E16, ALL-WAYS FUZE FOR AN-M69 TYPE BOMBS

At one time the stability of AN-M69 bombs when dropped in aimable clusters was in doubt. Therefore development of an all-ways fuze for this bomb was initiated in the spring of 1944

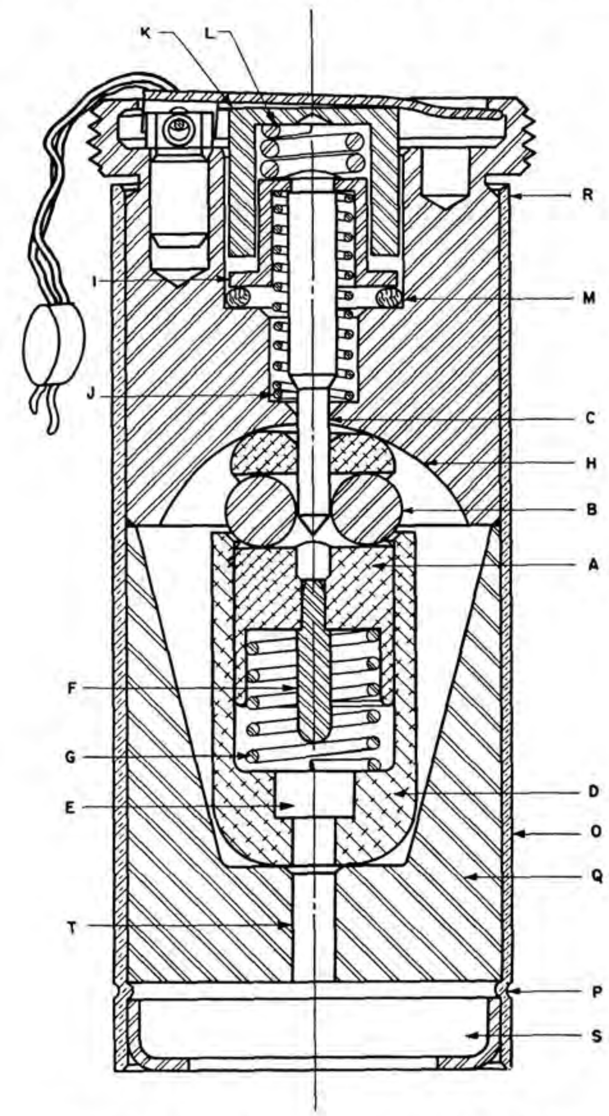


FIGURE 6. E16 all-ways fuze for AN-M69 type bombs.

by Arthur D. Little, Inc., under Contract OEMsr-242. This fuze was to be able to fire at all angles of impact with a sensitivity comparable with that of the M1 fuze, was to be waterproof and have a reliable safety device which would be operative up to the moment of stacking for clustering.

Figure 6 shows the design of the E16 fuze.[24] The firing-pin plunger *A* carries the two balls *B* which, when held apart by the safety pin *C*, prevent the firing-pin plunger from entering the primer holder *D*. Parts *A* and *D* are made of either brass or aluminum. The primer used is the M29 and is located in the cavity *E*. The firing pin *F* is of the type that has a rounded end with a radius of curvature of 0.046 in. The firing pin is normally kept away from the firing cap by the spring *G*. The assembly with the firing-pin plunger *A* is forced down onto the primer when the bomb lands because of inertia in either longitudinal direction, or by a squeezing action if it lands sidewise due to the curved surface *H*.

The safety and waterproofing features are contained in the top plug assembly. The safety-pin cap *I* is assembled to the safety pin *C* so that the joint is waterproof. This assembly is forced toward the top by the spring *J* so that the safety pin *C* is disengaged from the balls, unless a force is exerted on the top plunger. The top plunger *K* is separated from the safety cap by the spring *L*. The spring *L* has only a small normal extension with the result that the parts lie much as shown in the lower view on the subassembly drawing of the top plug when no force is applied to the top plunger. When the top plunger is pushed in, the safety pin *C* enters to spread the balls *B* apart and the safety-pin cap flange comes down on the Neoprene gasket *M* making a watertight joint. The spring *L* is necessary only to provide some tolerance for its position when held in place by the other bombs.

The tube *O* has a groove *P* against which the bottom plug *Q* seats. The top plug assembly is then held tightly against the bottom *Q* by crimping in the top of the tube, as indicated at *R*. The chamber *S* is provided to take the booster charge. Provision was made for a delay train to be put in the hole *T*. If no delay is wanted, this hole can be left empty. This fuze is of the same external dimensions as the present M1 fuze in the AN-M69 bomb, and can be substituted for it without any changes in the bomb.

Tests were made by dropping from small heights onto concrete at various angles. The limits found were 2 to 6 ft, none firing at less than 2 ft and all firing at 6 ft, with a large percentage firing at 5 ft. The sensitivity can be adjusted by varying the weights of parts *A* and *D*, the tension of spring *G*, and the clearance between the top of the primer and the end of the firing pin *F*. The shape of the contour *H* is not particularly important.

In the spring of 1945, 500 experimental models of the E16 fuze were turned over to the Chemical Warfare Service for final development and production if needed. However, the stability of the AN-M69 bomb in aimable clusters appeared to be satisfactory so that the E16 fuze would probably not have been needed.

2.5 M1 INCENDIARY LEAF

Development of this item was initiated in September 1940 by Brown University under Contract OEMsr-57. The objective was to develop an impact-sensitive ignition coating for incendiaries, especially celluloid incendiary leaves. The British had used incendiary leaves early in World War II using white phosphorus as a means of spontaneous ignition, and impact-sensitive ignition coating appeared to have possible merit.

The principal incendiaries for which this coating is intended are celluloid disks approximately 7.7-in. diameter by ¼ in. thick. The result is an incendiary leaf which fires on impact.[25, 26, 27] The steps in producing the impact-sensitive coating are as follows.

1. The disks are immersed in a solution composed of 5.0 per cent polyvinyl alcohol (du Pont RH-428), 47.5 per cent methyl alcohol, 45.5 per cent water, and then dried in air. The purpose of this coating is to protect the celluloid against the action of the storage liquid, which is principally carbon tetrachloride.

2. About ½ in. of the periphery of the disks is coated with red phosphorus by rotating the disks at a predetermined depth of immersion in either of two suspensions. Suspension *A* has the composition 17.4 per cent red phosphorus, 1.5 per cent calcium carbonate, 4.1 per cent celluloid, 77.0 per cent nitromethane. Suspension *B* has the composition 29.3 per cent red phosphorus, 2.4 per cent calcium carbonate, 6.8 per cent celluloid, 61.5 per cent acetone. This coating is then dried in air.

3. The phosphorus coating is then covered by a sensitizing coating by rotating through a solution composed of 17.6 per cent sodium perchlorate, 4.5 per cent pyroxylin, 23.4 per cent ethyl acetate, 54.5 per cent acetone. This coating is dried in air with a relative humidity of at least 60 per cent to prevent spontaneous ignition.

4. Final dehydration and drying is then accomplished by suspending the disks in boiling carbon tetrachloride, or its vapors, until they are sufficiently dried to become sensitive.

5. The sensitized disks are packed in a cylindrical metal container in which they are immersed in a storage solution composed of 80 to 85 per cent carbon tetrachloride and 15 to 20 per cent heptane.

This coating remained sensitive on storage for 155 days at 60 centigrade and for 230 days at room temperature. Surveillance was discontinued at these times so that the stability for longer times is not known. Coatings employing sodium chlorate or potassium chlorate did not remain sensitive for periods of more than a few weeks, and they were discarded for this reason.

These incendiary leaves were carried in airplanes in cylindrical metal bomb cases provided with a time fuze for opening and discharge of the leaves at a predetermined altitude. The disks were blown out of the tail end of the bomb case by an explosive charge in the nose, and after drying out in flight, the leaves would ignite on impact on the ground or a building. However, on flight tests it was found that many of the leaves were ignited in the air by the force of the ejection, while many would still not ignite on impact on the ground. This showed that the limits of allowable sensitivity were quite narrow and great uniformity of the sensitive coating would be necessary for satisfactory performance. The development was discontinued at this point, although some experiments indicated that several means might be used for preventing the ignition of leaves on discharge from the bomb case.

It should be mentioned that the M2 incendiary leaf, developed by Chemical Warfare Service in parallel with the M1 leaf, consisting of a celluloid disk with an insert of white phosphorus, similar to the original British leaves, looked considerably more promising than the M1 leaf. Development of both these items was discontinued because the requirement for this type of incendiary was dropped.

2.6 MODIFIED AN-M52 BOMB FOR LIGHT STRUCTURES

Ever since the tests at Dugway Proving Ground in June and July 1943, it had been apparent that the AN-M52, 2-lb magnesium bomb had definite possibilities for area incendiary attacks in Japanese cities (see Section 3.4). However, the AN-M52 had excessive penetrating power for one-story Japanese houses at its normal striking velocity of about 325 ft per sec, and the bomb was on the verge of being unstable because the center of gravity was about 5½ in. back from the nose. Therefore, the problem of correcting both these features was assigned to Harvard University under Contract OEMsr-179 and the Factory Mutual Research Corporation under Contract OEMsr-257.

The first step was to build some Japanese structures and determine the proper striking velocity of the AN-M52 bomb by shooting bombs down onto the structures at various velocities from an overhead mortar. Variables studied were one-story and two-story structures, tile and sheet-metal roofs, presence and absence of tatami mats on floors. It was found that the tatami mats offered the greatest resistance to passage of the bomb. On the basis of these tests it was concluded that the effective striking velocity of the AN-M52 could be anywhere between 200 and 300 ft per sec, with 225 ft per sec selected as the optimum value if the distribution of one-story and two-story houses was assumed to be 50-50.

The striking velocity of the bomb could be reduced and its stability improved by the simple expedient of adding some small cloth streamers to the metal tail assembly (Figure

7).[28] Three streamers, 3/4 x 36 in., gave the desired striking velocity of 225 ft per sec. Three streamers, 7/8 x 30 in., gave equivalent results. This minor change solved both difficulties of the AN-M52 bomb.

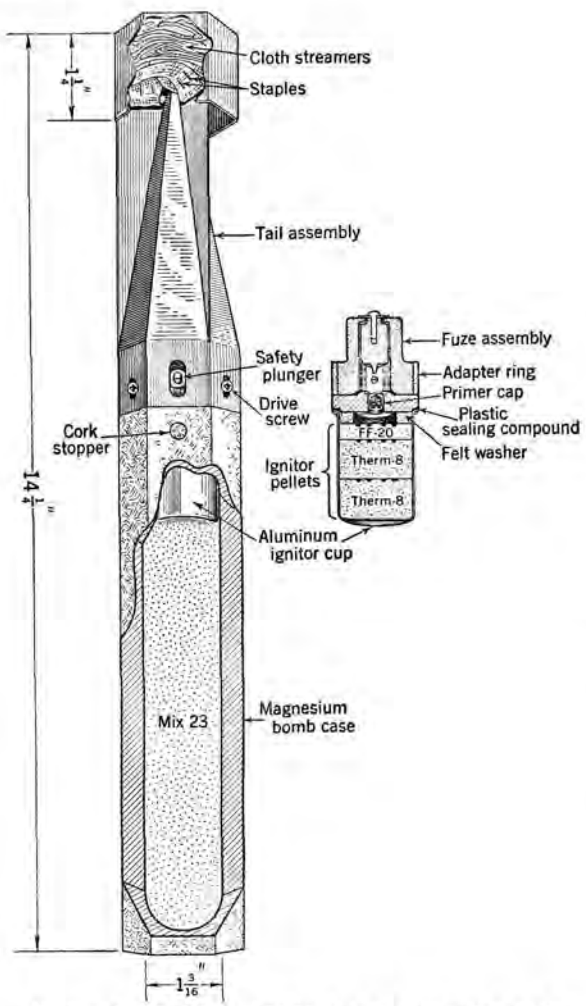


FIGURE 7. Modified AN-M52 incendiary bomb for use on light structures.

In addition to this improvement, the investigators made a further improvement in the incendiary composition of the bomb. The inside diameter of the magnesium body was increased from 1 to 1 3/16 in. and filled with the following mixture instead of the standard therm-8:

Flake aluminum	17.1%	SAE 40 motor oil	8.3%
Sodium nitrate	17.0%	Sulfur	1.9%
Barium nitrate	13.5%	Thermite	42.2%

This modified bomb showed some improvement in burning characteristics and fire-starting ability over the standard AN-M52 bomb. The oil gave a larger flame, the burning time was increased from 65 to 95 sec, the molten magnesium did not sputter, and the sulfur dioxide gas given off was a valuable fire-fighter deterrent. Comparative burning tests in attic structures consistently showed a slight advantage in favor of the modified bomb.

2.7 MODIFIED FILLING FOR AN-M50 BOMB

Investigations on various types of thermite mixtures at Factory Mutual Research Corporation under Contract OEMsr-257 had indicated that certain mixtures might be superior to ordinary thermite or therm-8 for filling magnesium incendiary bombs, especially the AN-M50 bomb. A mixture which showed great promise for this purpose was the following.[29]

Aluminum flake	24%
Sulfur	43%
Thermite	33%

This filling weighed 210 g, when pressed into the AN-M50 bomb body under 26,400 lb per sq in., compared to 276 g for the standard therm-8 filling. The heat content of the modified bomb is 16,000 Btu compared to 14,700 Btu for the standard AN-M50. This filling melts and ignites the magnesium bomb body just as well as the standard filling. In addition to a higher Btu content, the modified M50 burns with a larger flame than the standard bomb, the molten magnesium does not tend to sputter as much, and the sulfur dioxide generated acts as a valuable fire-fighter deterrent.

Comparative burning tests on attic structures showed the modified M50 to have a small but definite superiority in fire starting over the standard AN-M50. Considering all factors, it seems probable that use of this filling would have materially increased the effectiveness of the approximately 250,000,000 AN-M50 and British 4-lb bombs dropped in World War II. However, these results came too late to permit a change in production of the AN-M50 bomb.

Chapter 3

TESTING AND EVALUATION OF INCENDIARIES

3.1 INTRODUCTION

THE DEVELOPMENT AND application of testing methods were important parts of the program of all NDRC contractors in the field of incendiaries, but the most important contributions were made by the Standard Oil Development Co. under Contracts OEMsr-183 and 354, and the Factory Mutual Research Corporation under Contract OEMsr-257. In the latter phases of World War II also important was the Joint CWS-NDRC Incendiary Evaluation Project at Edgewood Arsenal, the personnel of which was drawn from Factory Mutual Research Corporation, Massachusetts Institute of Technology, under Contract OEMsr-21, Division 11 of NDRC, the Office of Field Service of OSRD, the Chemical Warfare Service Technical Command, and the British Ministry of Aircraft Production.

The ultimate objective of testing and evaluation is to ensure that the incendiary will be capable of starting fires when it is used in actual operations. Final tests should therefore approximate as closely as possible the conditions under which the incendiary will have to function in actual use. Testing and evaluation are necessary at every stage of development, to ascertain that the incendiary device and all of its components will finally perform in the desired manner.

The scope of the tests which must be applied in the development of incendiary bombs is indicated by the military and technical requirements to be met. First and most obvious is the requirement that the bomb must exhibit a high efficiency in starting fires. It must present no undue hazards in manufacture, handling, shipping, and loading into aircraft. It must withstand storage for extended periods of exposure to the extremes of climate and weather without impairing its capacity to function. It must have good ballistic properties so as to fall in true flight along a predictable path to the target. Its mechanical strength must be adequate to sustain the shock and stresses incident to penetrating roofs and impacting on hard surfaces, without mechanical failure or malfunctioning. The fuze must function reliably after penetration into the target, and bombs which contain an incendiary filling must distribute the filling in a manner conducive to effective incendiary action. Both the area over which fuel is dispersed and the size of the pieces of fuel are important in this connection.

Clusters of small incendiary bombs must similarly be tested for satisfactory ballistics and proper functioning of the fuze which causes disintegration of the cluster. It must be determined that the individual bombs will withstand the shock of being released from a cluster falling at high velocity, will not function prematurely in the air, will fall in true flight, and will be dispersed in a satisfactory pattern of impact on the target area.

The complete testing program, throughout development and manufacture, involves a host of tests which are applied to the various components of the bomb as well as to the complete munition. In this chapter the discussion will be chiefly concerned with tests that pertain to the penetration, functioning, and incendiary action of the bombs.

Simple Tests for Functioning and Penetration. Small incendiary bombs usually have an inertia type fuze, so that they will function when dropped from a specified minimum height, or when clamped in a pendulum and made to swing against a vertical surface. The former test is often used to determine the safe height from which a bomb may be dropped without functioning and the additional height from which functioning is certain to occur. The bombs may be dropped down a tube, or, if it is desired to test the functioning of an all-ways fuze, they may be dropped at random behind a safety barrier. The pendulum test is a safe and convenient method for tail-ejection bombs, since the bomb is securely held and pointed in a definite direction.

The ability of bombs to withstand impact on a hard surface and function reliably is often tested by dropping them singly from a small airplane onto a concrete slab from an altitude of 1,000 ft. If the bombs are thrown out at random, a good indication of their inherent flight stability can be obtained by noting whether they quickly assume a condition of true flight or whether they yaw, tumble, or spin.

The use of an air gun permits the horizontal projection of a bomb at any desired velocity, and has proved to be of great value in testing both the functioning of small bombs and their ability to penetrate various roof sections. Combined with high-speed movies, this technique was employed by the Chemical Warfare Service in the development of the M74 bomb, in which it was desired that the gel be ejected within 8 ft of the first surface penetrated by the bomb, so as to be deposited in the attic or upper story of a Japanese dwelling. The speed of action of the fuze and ejection charge were varied until the desired functioning was attained, as evidenced by the photographs of shots from the air gun.

The air gun also is admirably suited to penetration tests, because of the convenience with which the gun can be loaded and the various simulated roof slabs can be mounted, since the entire setup is on the ground and readily accessible. Similar penetration tests can be conducted with a vertical mortar mounted above the test slabs. Because of the importance of the vertical mortar its use will be discussed in the section which follows.

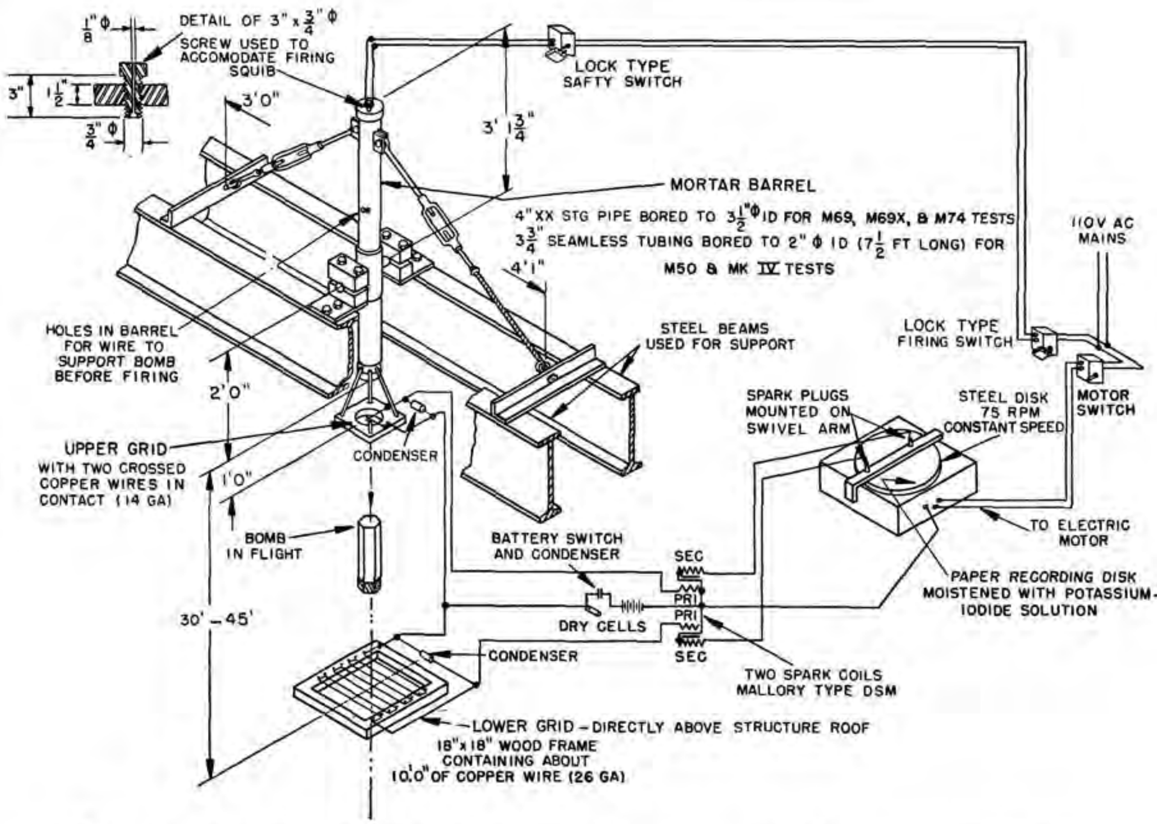


FIGURE 1. Diagram of mortar and chronograph arrangement for firing incendiary bombs.

Mortar Tests. A vertical mortar, mounted on a tower above a test building, has advantages which make it one of the most useful and versatile tools for the testing and evaluation of incendiary bombs. Figure 1 shows a schematic diagram of an early mortar; improved models were developed and used later. When employed in tests with full-scale rooms and buildings, the downward flight of the bomb is to be preferred;

it simulates the approach of a bomb released from high altitude, and gives data on penetration, functioning, and incendiary action which correlate well with data obtained in airborne tests and actual incendiary raids. With a mortar suitably mounted on a movable support, it is possible to fire bombs through every part of a roof and to repeat the shots until an adequate basis has been established for drawing firm conclusions from the data. No such control of the point of impact of the bomb is possible in airborne tests, in which conclusions must often be based on a limited number of hits on the target.

A mortar is equally suitable for tests with industrial targets. Bombs can be fired directly into such wooden targets as work benches, stacks of packing cases, bins, and can be fired into adjacent locations to determine the radius of action of a bomb that penetrates into a factory without scoring a direct hit on combustibles.

In the case of a bomb like the M74, which functions immediately after penetrating a light roof and ejects gel while the bomb is still in motion, mortar shots provide the only acceptable method of performing tests to determine the chance that the bomb will deposit gel in a location favorable for setting fire to combustible objects.

With a bomb like the M69, the terminal velocity of which in free fall can be measurably controlled by varying the length of the cloth tail streamers, mortar tests can indicate the velocity that will give a desired degree of penetration through roofs, and the length of the streamers can be adjusted accordingly.

Details such as the strength of the case and of the fuze to withstand impact on hard surfaces can be tested with the mortar, as also can the sensitivity of the fuze needed to give reliable functioning upon hitting a very light roof. From accumulated experience it appears that future testing of small incendiaries should concentrate on tests in which the bombs are fired from a movable mortar into full-scale rooms and buildings, both domestic and industrial, where type of roof, floor and occupancy could be varied to include all cases likely to be encountered in actual attacks. Airborne tests would be employed to determine satisfactory performances, aimability, dispersion patterns on the target area, and general ballistic properties, for which no incendiary targets would be required. A final airborne test employing full-scale target buildings would serve as an overall check on the readiness of the bomb for standardization and operational use.

Evaluation of Incendiary Effectiveness. First of all the necessary improvements were made in design, development, and manufacture to ensure satisfactory mechanical properties of the bomb, and when at last the bomb was dropped onto a combustible target, the sole utility of the incendiary lay in its ability to start a fire. It was natural therefore that much of the early experimental work was directed toward the inherent incendiary power of fuels. Small-scale laboratory tests sufficed to indicate a relative order of merit among the fuels whose availability and low cost made them otherwise attractive. As experience indicated the profound effect of the nature of the target on the incendiary results obtained in tests, larger and more elaborate targets were employed. Full-scale rooms and buildings were finally used, in order to obtain data directly applicable to the design and development of the kind of bombs that would be effective against enemy targets.

Because of the great number of factors that influence the results obtained in incendiary testing, it is of the highest importance that all conditions of the experimental work be controlled. This is true despite the lack of any such control over enemy targets; absence of such control can reverse the relative performance of two munitions differing enough in merit to make the right choice important. Adequate ventilation with exclusion of drafts, control of wood moisture content, and careful placement of the fuel in a definite position are among the factors that must be controlled. Static placement of fuel will often give results quite different from those obtained when fuel is ejected from a bomb. It is apparent that no single simple target is adequate for the purpose of determining the incendiary merit of bombs for all uses. Some targets are more responsive to heat transferred by convection from flame and hot gases, while others respond better to radiant heat. Only by use of a series of simple targets can the relative effectiveness of bombs be determined, and their absolute effectiveness can only be gauged by tests which involve full-scale target structures and which duplicate other conditions obtained in the enemy targets.

Even with the utmost care in performing controlled experiments there is enough variation in the results to require that tests be repeated until sufficient data are obtained to express the probability that a fire will be started under the given conditions.

3.2 SMALL-SCALE LABORATORY TESTS

3.2.1 Introduction

The burning trials classified as small-scale tests are those which employ small structures of major dimensions under 2 ft. These structures are usually arbitrary arrangements of pieces of wood, and do not necessarily imitate combustibles occurring in a dwelling or factory. The tests are of some value in determining the relative merits of various fuels, and were used in early work to select the most promising incendiary fuels from among those available.

In developing a target suitable for a relative evaluation of fuels, the combustibility of the structure is first adjusted so that it will react to reasonable amounts of the fuels to be compared. This is accomplished by using a quantity of fuel which can be weighed or measured with adequate precision and which will burn for a reasonable time, and by conducting preliminary trials in which the dimensions and arrangement of the wood are varied until it is found that the target is sufficiently vulnerable to attack. Targets which are so resistant that any of the fuels will only char the surface slightly, or targets which are so combustible that a very small amount of fuel will cause complete burning, are not useful.

Since various types of targets react differently to heat transferred by radiation or by convection, the disposition of the combustible surfaces with respect to the fuel warrants consideration in the choice of a target for small-scale tests. If a target consists of vertical surfaces placed near but not touching the fuel, it will be most susceptible to radiant heat, whereas a vertical target in contact with the fuel, or one constructed of horizontal surfaces supported at some distance above the fuel, will be attacked most effectively by flame and hot gases rising from the fuel. A reversal of the apparent relative effectiveness of two dissimilar fuels may

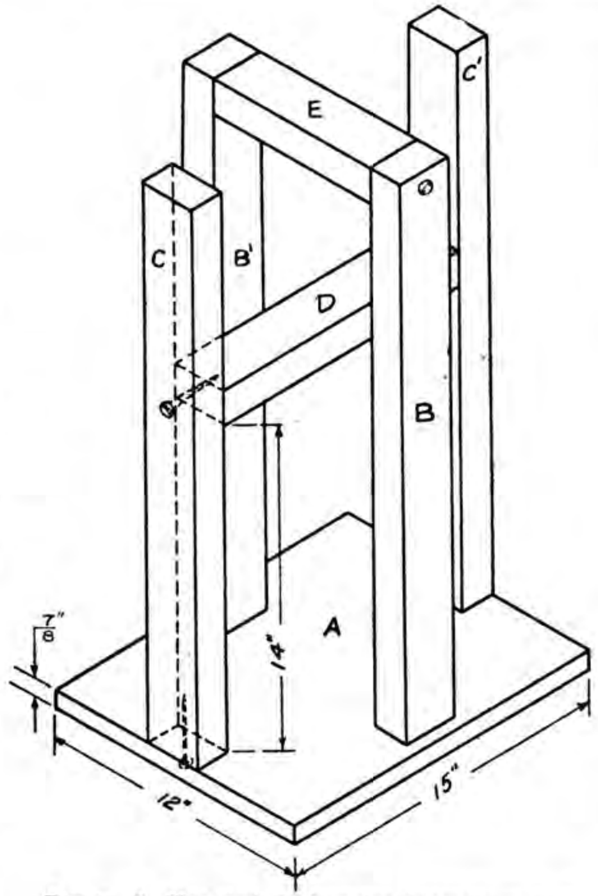


FIGURE 2. Harvard University incendiary test setup.

therefore take place if tests are carried out using two different types of targets. An adequate comparison of fuels may be made by employing a target embodying both horizontal and vertical surfaces, or by separate tests using each type of surface.

3.2.2 Description of Tests

Harvard University Test.[1, 2, 3, 4] This test arrangement, illustrated in Figure 2, was the

FIGURE 3. Factory Mutual packing case ends. Test shown used 0.14-lb gasoline soaked in cellucotton.

first incendiary test used in World War II. A 3-oz fuel sample was placed in the center of the base, and the following data were recorded: time of aggressive burning, loss of weight after buffing off charred wood, and surface area attacked. This type of test served for early rough comparisons of incendiary materials, but as a rough gauge was little used after early 1942.

Factory Mutual Vertical Strip Test.[5] This test arrangement was even simpler than the previous one. It consisted simply of two wooden strips 24x2x¾ in., nailed to a wooden base 8x8x¾ in., and spaced at the top by a narrow strip of transite. A 30-g fuel sample was placed in the center of the base, and the loss in weight of base and uprights determined after burning.

Factory Mutual Packing Case Ends.[5, 6, 7, 8] This test setup consisted of a pair of wooden structures representing the ends of two adjacent packing cases. Figure 3 shows the arrangement and a typical burning test. This test was used primarily for testing sabotage incendiaries for which packing cases represent logical targets.

University of Chicago Roof Section.[9] This setup illustrated in Figure 4 was the first of

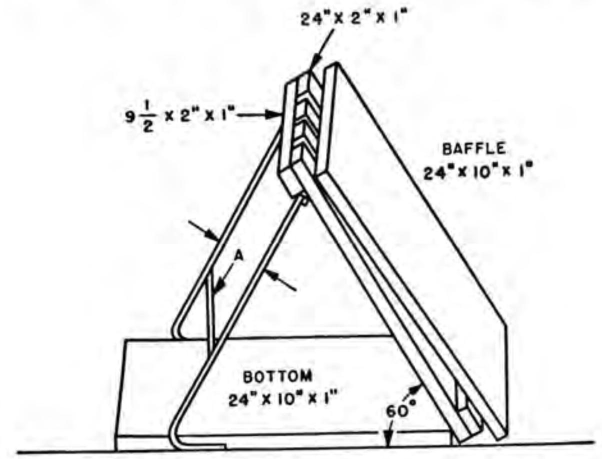


FIGURE 4. University of Chicago roof-section test setup. Baffle on back is transite.

the eaves, or half-attic type, although much smaller in size than those used extensively later on. The baffle shown was made of transite. Various incendiaries were placed in a standard position and comparative results observed qualitatively.

Standard Oil Development Co. Temperature Measurement.[10] This test consisted of a structure resembling the Harvard setup, but made of angle iron, supporting 8 thermocouples at various distances from a sample of fuel burning in a pan on the base. The test showed the superiority of gasoline gels to either liquid gasoline or to heavy oils in that they maintained the highest temperatures for the longest times. This test was useful in the early stages of development of the AN-M69 incendiary bomb.

Texas Company Corner-Burning Tests.[11] This test, illustrated in Figure 5, is simply a wooden corner, 8x8x8 in., in which a 100-g fuel sample is burned and temperatures recorded by a thermocouple placed 5 in. above the base and 1 in. from each vertical board. The time-temperature curves obtained were quite useful in a preliminary comparison of incendiary fuels, and they showed a worthwhile correlation with later larger-scale tests. Loss in weight of the structure also was determined. Some of the interesting conclusions indicated were (1) cellucotton-bodied fuels were superior to jellied fuels, (2) turpentine and toluene were superior to gasoline, (3) fortifying agents such as magnesium powder and ammonium nitrate were valuable additives.

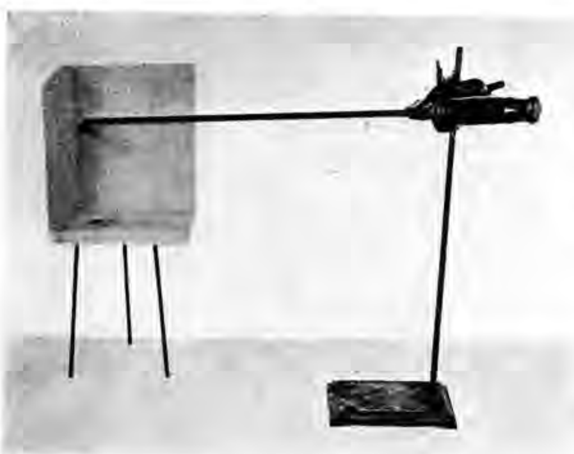


FIGURE 5. Texas Co. corner-test setup.

3.2.3 Discussion

The necessity of close control of all variables affecting burning became apparent in the small-scale evaluation tests. After the dimensions of the target had been fixed, such factors as the kind of wood, moisture content, draft, gel consistency, area of burning fuel, placement of fuel with respect to target, and the amount and particle size of additives in the fuel, were shown to have an influence on the burning of the target.

Small-scale tests proved useful in demonstrating the value of some oxidizing agents in improving the burning characteristics of the jellied fuels. Although oxygen is preferably drawn from the air rather than carried with the fuel, the time of aggressive burning of the fuels and their capacity for destroying the small targets was increased by addition of small quantities of oxidizing agents. The shortened total burning time still permitted destruction of the small-scale targets, but tests on larger and more difficult targets indicated the need for longer burning fuels.

The advantage of small-scale tests lies in their simplicity. Their value appears to be limited to selecting the more promising fuels for further study on a larger scale. Careful choice of the target and good control of all experimental variables must be exercised if the results of small-scale tests are to have any significance. Small differences among fuels subjected to small-scale tests should be disregarded, and more adequate test methods should be employed (see Sections 3.3 and 3.4).

3.3 LARGE-SCALE LABORATORY TESTS

3.3.1 Introduction

Since the results of incendiary tests are functions of the targets used as well as of the incendiaries tested, results are of doubtful value, unless a careful simulation of targets of practical interest is made. Accordingly, the small-scale tests used early in World War II were soon replaced by tests on structures simulating actual targets such as parts of houses and combustible contents of factories. These test targets usually had a minimum dimension of at least 4 ft. Vertical tongue-and-groove wooden partitions, whole or half-attics, factory work-

benches, stacks of packing cases, etc., were used as representative targets.

Large-scale tests are useful for determining the relative incendiary values of fuels and for testing incendiary bombs. With proper design of targets and control of experimental conditions, large-scale laboratory tests can go a long way toward establishing the absolute incendiary effectiveness of a bomb or quantity of fuel on the structures tested. In such tests many factors that influence the burning of a target become less critical than they are in small-scale tests, and therefore the results are more consistent and give a reasonably good indication of the incendiary action that may be expected in actual attacks. Such large-scale tests, utilizing a mortar to shoot bombs downwards onto the targets, can give answers to all the variables of penetration, functioning, and fire starting, except the final answer involving the ballistic properties and flight stability of the bombs, for which airborne tests are required. However, intelligent application of the principles of large-scale laboratory testing can reduce the requirements for airborne testing to a minimum.

Tests may be conducted by placing bombs or weighed quantities of fuels in definite positions in relation to the test structures, by causing bombs to eject fuel against or into the test structures, or by shooting bombs down onto the test structures from a mortar. When such tests are carried out with a variety of structures which are faithful replicas of enemy targets, they serve to establish the optimum quantity of fuel and hence, the required size of bomb to destroy such targets. The following sections describe the principal test arrangements used, representing both domestic and industrial targets.

3.3.2 Standard Oil Development Co. Half-Attic Structures

The prototype of this category of test structure is the half-attic structures designed and used by the Standard Oil Development Co. in the winter of 1941-42. The design shown in Figure 6 had 2x4-in. joists on 16-in. centers with 1-in. boarding below the joists. Other designs used were similar to the one illustrated, but with 1-in. floor boards above the joists, or with a lath and plaster ceiling below the joists. Still others had 2x6-in. joists on 24-in. centers. The roof section of rafters, battens, and transite baffle was similar in all cases.

Fuel was placed statically at definite distances from the eaves line, or was ejected into the eaves. The principal data recorded were (1) whether a destructive fire was obtained or not, (2) the time taken by the structure to collapse, and (3) the time the fire reached the low point.

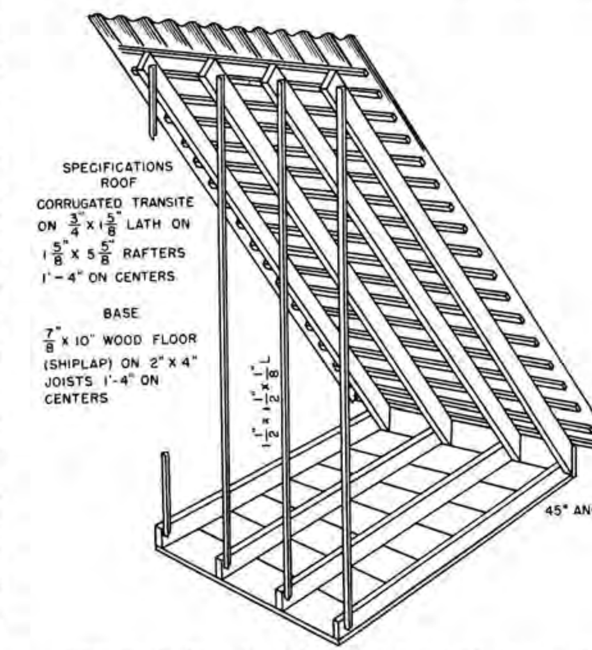


FIGURE 6. Standard Oil Development Co. half-attic test structure.

Tests in these structures showed clearly the advantage of gel fuels over liquid gasoline or heavy oils. The efficiency of the tail-ejection or target-seeking principle also was clearly demonstrated. A great deal of the mechanism of fire starting was learned in these tests; namely, the importance of reinforcing radiation from two burning surfaces or of two pieces of fuel. An important result observed was a quantitative relationship between the distance from eaves line and the weight of gel required to start a destructive fire. This relation is illustrated in Figure 7, which shows that for the structure used 10 lb of gel are required at 3 ft from the eaves, 20 lb at 4 ft, etc. The tests showed that for this type of structure, gasoline gel was slightly superior to magnesium and greatly superior to therm-8. Tests on these structures were remarkably reproducible, although con-

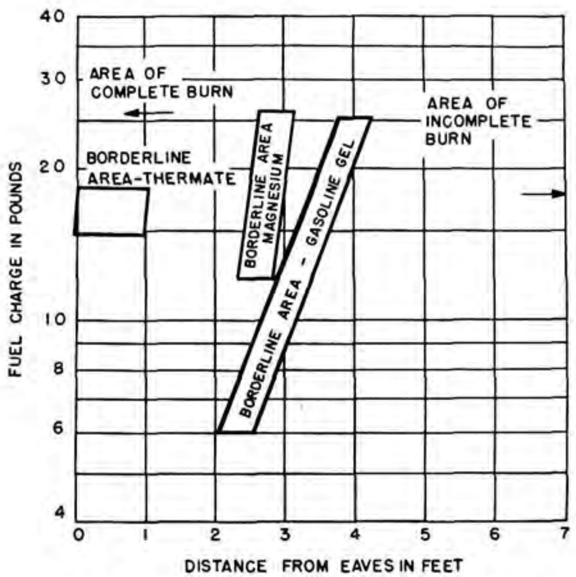


FIGURE 7. Relationship between fuel charge required to produce a destructive fire and the distance from the eaves.

sideration had to be given to wood species, wood moisture content, ambient temperature, and other factors.

Tests with the half-attic structures were of vital importance in the development of the AN-M69 incendiary bomb. The tests outlined above gave assurance that the bomb would contain enough fuel to be an effective incendiary.

3.3.3 Factory Mutual Half-Attic Test Structures[5, 12, 13]

The Factory Mutual group employed a structure which was quite similar to that used by Standard Oil Development Co., the main difference being that it was somewhat more difficult to ignite. It was set up inside a specially constructed wooden room, which in turn was enclosed by a noncombustible building. With these precautions there was relative freedom from drafts, and the confinement of heat and radiation from surrounding surfaces simulated the conditions that would normally be found in small rooms. This structure was primarily used in the early stage of development of the E19 bomb.

In an endeavor to develop a single target that would prove adequate for the evaluation of small bombs, about 10 small attic-type structures were devised and used in tests. It was concluded that no single target was entirely satisfactory, but for small magnesium bombs excellent results were obtained with a half-attic structure having a floor 2 ft sq and a sloping-roof section 2x4 ft set at an angle of 60 degrees to the horizontal (Figure 8). When made of 1-in. boards, it has a suitable response to the initial flame and residual radiant heat from small magnesium bombs having different incendiary fillings to reveal second-order differences.

3.3.4 Factory Mutual Industrial Type Targets[14, 15, 16, 17]

The Factory Mutual Research Corporation was the first NDRC contractor to become interested in fire starting in industrial rather than domestic occupancies. The principal targets

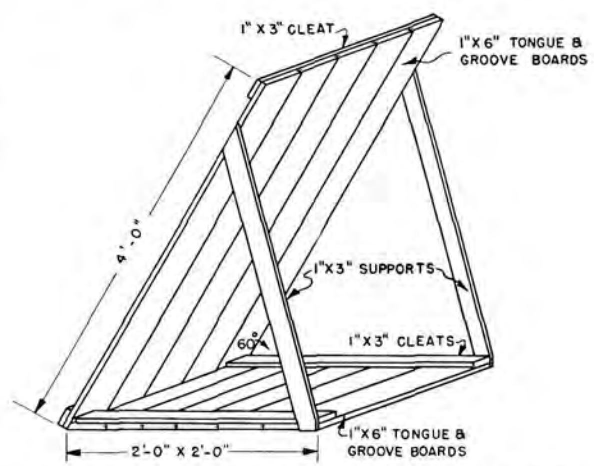


FIGURE 8. Factory Mutual small half-attic test structure.

with which they worked were a light workbench, a heavy workbench (Figure 9), a section of tongue-and-groove wooden partition (Figure 10), and pairs of packing case ends (see Sec-

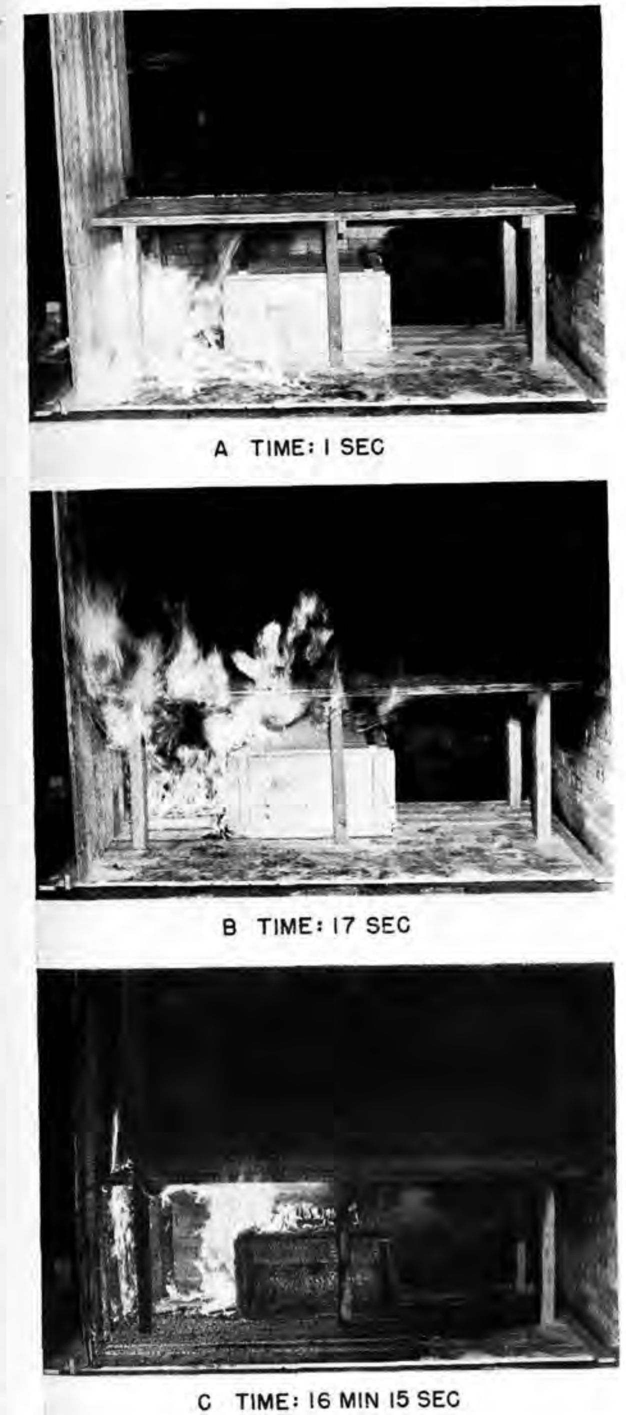


FIGURE 9. Heavy workbench-incendiary test structure. Test shown was made with gasoline soaked in cellucotton.

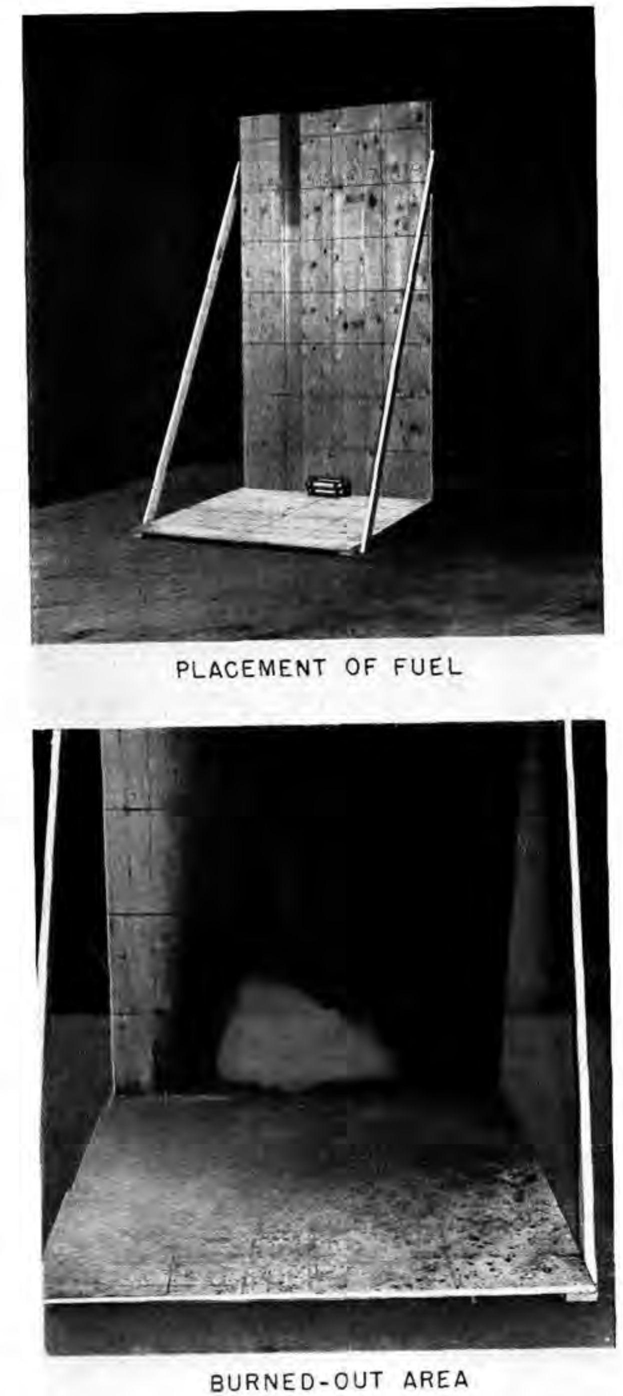


FIGURE 10. Tongue-and-groove wooden partition test structure, showing test with four M52 incendiary bombs.

FIGURE 11. Factory Mutual radial incendiary-test structure, closed-center, 8-panel type.

tion 3.2). Tests were made on these four targets with various fuels and bombs at different distances. The relative impotence of the 4-lb magnesium bomb against most of these targets and the equivalence of gelled and cellulose-bodied fuels were among the significant conclusions resulting from these studies.

In an attempt to develop a universal incendiary target, Factory Mutual designed some radial targets of the type shown in Figure 11. These did not represent any actual targets, but it was thought that they could be calibrated in terms of various actual targets, and thus be useful as a universal yardstick of incendiary merit. While the idea was interesting, it proved to be too awkward and too far from reality to be greatly useful.

3.3.5 Incendiary Evaluation Project Industrial Targets[18]

The Incendiary Evaluation Project group at Edgewood Arsenal extended the Factory Mutual work on industrial targets in an extensive series of tests on five typical combustible objects usually found in factories, viz., light workbenches with tote box underneath, vertical storage bins, vertical tongue-and-groove partitions, stacks of eight packing boxes, and corrugated cardboard cartons, all of which are illustrated in Figure 12. These targets were finally chosen as being representative after inspection of a number of industrial plants. The

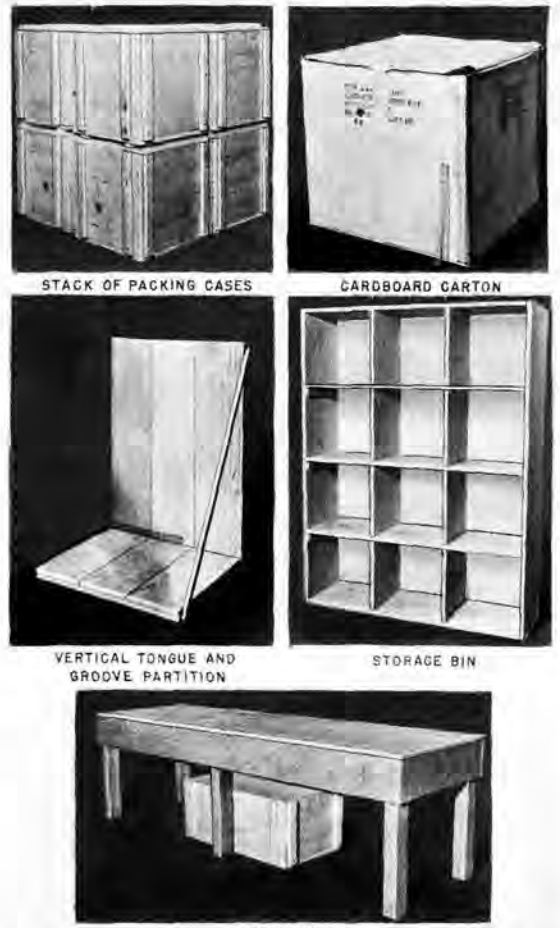


FIGURE 12. Industrial targets for incendiary testing used by the Incendiary Evaluation Project at Edgewood Arsenal.

targets were constructed of two kinds of wood, 1-in. Douglas fir for the workbenches, storage bins and partitions, and 1-in. Sitka spruce for the tote boxes and packing cases.

Tests were carried out with the AN-M69, AN-M50, and M74 bombs by firing the bombs from the mortar downwards onto or near the targets. It was possible to substitute statically placed bombs for part of the tests on the M50 and M69, but in the case of the M74 all tests had to be made with the mortar in order to simulate the true action of the M74. The results are described in the following sections.

AN-M69 Bomb. 1. The total length of travel of the gob of gel in an ejection along the floor (unobstructed) is 100 ft.

2. If the gob strikes normal to a smooth vertical surface, or within 30 degrees of the normal, the gob sticks against the surface.

3. If the gel strikes a smooth vertical surface at an angle greater than 30 degrees to the normal, it is deflected at an angle of approximately 5 degrees and then travels for an average distance of 15 ft.

4. When the bomb lands directly in a stack of cardboard cartons, wooden packing cases, or in a storage bin, a fire will always be started.

5. When the gel strikes the side of a stack of cardboard cartons at any angle, sufficient gel will remain on the cartons to cause a fire.

6. If the gel strikes the side of a stack of wooden packing cases at an angle within 60 degrees of the normal, a fire is started.

7. When the gel strikes the vertical tongue-and-groove partition at an angle of 30 degrees to the normal or less, the chance of starting a fire is 0.63 if some other combustible, such as cardboard cartons, boxes, etc., is present immediately behind the partition to provide reradiation for the flame on the back side. If the gel sticks at a point where no other members which will support fire are present, or if the gel rebounds from the surface, a negative result is obtained with the partition.

8. If the bomb lands directly in a tote box under a workbench, the ejection will blow the gel from the box without setting it afire, and the probability of a fire becomes the same as if the bomb hit on an open floor.

9. If the gel strikes the side of a tote box under a bench at an angle of 30 degrees to the normal or less, the gel sticks and a fire is started. When striking at angles over 30 degrees to the normal the gel rebounds and a negative result is obtained. (The legs of the benches are assumed not present.)

10. If the gel strikes the open side of a storage bin at any angle, a fire is started. When gel strikes the end of a bin at an angle of 30 degrees or less to the normal, the gel will stick. At greater angles it rebounds, but when it sticks, the chance of starting a fire is 0.63.

AN-M50 Bomb. 1. If the bomb lands directly in a stack of cardboard cartons, wooden packing case, storage bin, or tote box under a bench, a fire will always be started.

2. If the bomb lands within 9 in. of a stack of cardboard cartons, the radiation and glowing sparks will cause a fire. The distance of 9 in. is the maximum for 100 per cent probability of fire. At greater distances up to 4 ft, the bomb gives lower probabilities of destruction.

3. If a bomb lands outside of a stack of wooden packing cases, even if directly against the side, no fire results.

4. If the bomb lands outside of the tote box under a bench, even if against the side of the box, a negative result is obtained.

5. If the bomb lands within 2 in. of the vertical tongue-and-groove partition at a point where some other combustible is at the back side, a fire is started. If no other fire-supporting surface is present, or if the bomb is at a greater distance from the partition, no fire results.

6. If the bomb lands immediately in front of the open compartments of the storage bin, a fire is started, but at any greater distance, negative results are obtained. If the bomb is within 2 in. of the partition forming the end of the bin, a fire will result.

M74 Bomb. 1. If the gel from an M74 lands on top of a stack of cardboard cartons, or hits the side of the stack, or lands on the floor within 12 in. of the side of a stack, a fire is always started.

2. When the bomb is yawed and the gel lands on top of a stack of wooden packing cases, the chance of starting a fire is 0.93. If the gel strikes the side of the stack, the probability of starting a fire is 0.59. When gel lands on the floor within 5 in. of the side of the stack, a fire will always be started.

3. If the gel from an M74 bomb hits the side of a vertical tongue-and-groove partition at a point where some other combustible is at the back side, the chance of starting a fire is indicated to be approximately 0.60. When gel lands on the floor within 8 in. of the partition, a fire will always be started. If no other fire-supporting surface is present, or if the gel lands at a greater distance from the partition, no fire results.

4. When the gel from an M74 lands on top of a storage bin, the probability of starting a fire is 0.75. When the gel strikes the shelves on the open side of the bin, or on the floor within

6 in. of this side, a fire may always be expected. If the gel strikes the end of the bin, the chance of starting a fire is assumed to be the same as that for gel hitting the matched partition, or 0.60. Finally, when gel lands on the floor within 8 in. of the end of the bin, a fire will always be started.

5. If the gel from an M74 lands on top of a workbench, it burns harmlessly without effect other than to burn a hole through the bench top. When the gel strikes the side of the tote box under the bench, or on the floor within 6 in. of the side of the box, a fire is always started.

These conclusions do not cover all possibilities that could be envisioned, but they indicate the general order of fire-starting probabilities for each combination of bomb and target. In the next section these results will be combined into an analysis of the probability of starting a fire in a given factory.

3.3.6 Application of IEP Tests to a Model Factory Target

Incendiary tests of the kind described in the previous section answer the question whether a given incendiary will start a fire in a given position relative to a combustible object in a factory. In order to combine these isolated results into the overall probability of starting a fire in a factory, a model factory layout was made and calculations carried through for each type of bomb. The factory layout used contained the five combustible objects which have been used in the burning experiments: namely, workbenches, storage bins, wooden partitions, wooden packing cases, and cardboard cartons. Other combustibles such as trash, oil, and waste, may be present in an actual factory, but their quantities are unknown; therefore they were ignored in this calculation. Experimental work has dealt primarily with initiation of fires in targets without regard to the probability of spreading fires; hence the analysis given here indicates only the probability of starting a fire —not of its spreading or destroying the factory.

Description of Model Factory. The factory layout is shown in Figure 13. Stacks of cardboard cartons and wooden packing cases, each 15 ft high, are present in the receiving and shipping section. One workbench with tote box is also present in this section. In the main working section are 16 benches plus tote boxes, and 16 storage bins, each 10 ft high, placed back to back. A vertical tongue-and-groove partition, extending to the roof (20 ft), separates the two sections. The total combustible floor loading is 24.8 per cent, distributed as follows:

	Area, sq ft	% of total floor area
Cardboard cartons	136	4.9
Wooden packing cases	127	4.5
Workbenches	319	11.4
Storage bins	108	3.9
Vertical partitions	3	0.1
	693	24.8

The total area of the factory is 2,800 sq ft.

Analysis for M69 Bomb. The plant layout was first divided into 112 sections as shown in Figure 13. Each of these sections was then further divided into nine equal subsections, so that a total of 9x112 or 1,008 separate areas were created. In order to minimize the number of points required for analysis, one out of each group of nine subsections was chosen according to a table of random numbers, and the probability of starting a fire if a bomb came to rest in the center of each of these areas was determined. An earlier analysis of the factory layout using 1,681 separate points yielded the same overall probability of starting a fire as found by the random number method.

In order to find the probability of fire in each case, a measurement was made of the total angle within which a gob of gel ejected from an M69 would start a fire. The angle that was subtended by a surface from which the gel bounced to a combustible object was counted as part of the total angle in which a fire could be started. The probability of starting a fire was then determined by dividing the angle within which fires would be initiated by 360 degrees. In order to show the contribution of each target in the factory to the overall probability, separate totals were kept for each of the various combustibles.

A sample calculation is here given for point No. 58 (Figure 13) to illustrate the method used in obtaining the data. By use of a transparent overlay, the angles subtended by the

various combustible objects and within which gel will stick and cause a fire, are determined. The total effective angles subtended for each type of target within range of point No. 58 are as follows.

Tote boxes under benches	55°
Storage bins (open sides)	70°
Storage bins (ends)	55°
Wooden partitions (side)	25°
Cardboard cartons (side)	5°

The angles for all 112 points are averaged, and this average angle is divided by 360 degrees to obtain the probability of gel from an M69

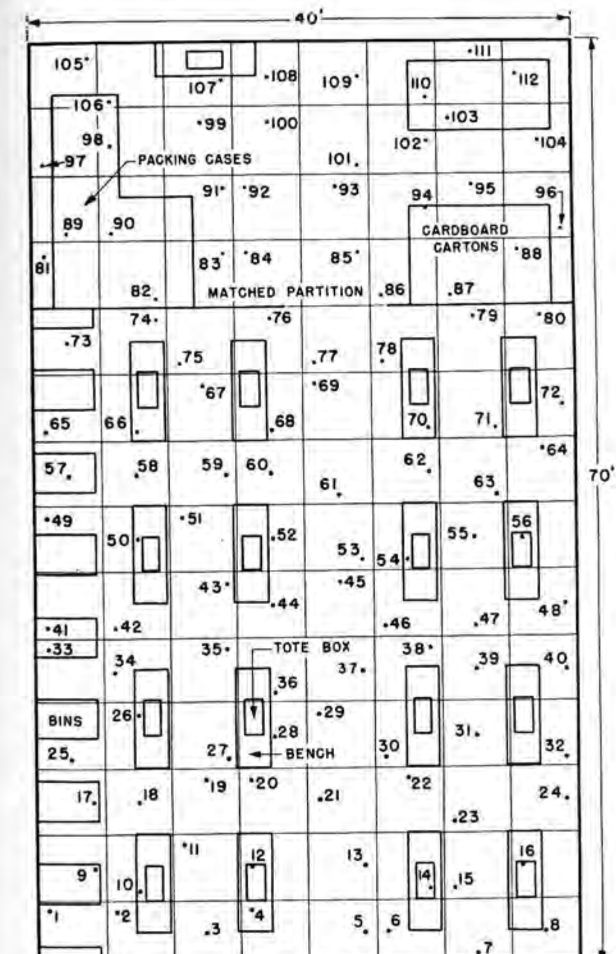


FIGURE 13. Plan view of model factory used for estimation of incendiary-bomb effectiveness.

bomb hitting a particular target. If this probability is then multiplied by the probability of starting a fire in the particular target under the conditions, the overall probability of starting fires in this target is obtained. The sum of these probabilities for all types of targets then gives the overall probability of starting fire in the factory. For the M69 bomb the final probabilities of fire starting were calculated to be as shown below.

Tote boxes under benches	0.126
Storage bins	0.141
Wooden partitions	0.018
Packing cases	0.086
Cardboard cartons	0.113
Total	0.484

Thus an M69 bomb dropped at random into this factory has a 0.484 probability of starting a fire.

Analysis for M50 Bomb. Since no complete data are as yet available on the nature of the bouncing which occurs when an M50 strikes the floor of a factory, the analysis has been carried out assuming that the bomb stays where it lands. The probability of starting a fire is then merely the ratio of the area within which the M50 is effective to the total area. The area within which the M50 is effective is made up of two parts: (1) The area of the combustibles within which the M50 will start a fire, and (2) a small strip of area around these combustibles wherein the bomb will cause a fire. If it is assumed that the bomb does bounce an appreciable distance, the probability of fire is increased somewhat over the values shown, although even if the bomb bounces against some of the targets (wooden packing cases and tote boxes under benches), no fire is obtained.

Applying the same approach as used for the M69 bomb, the final probabilities of fire starting for the M50 bomb were calculated to be the following:

Tote boxes under workbenches	0.023
Storage bins	0.040
Wooden partitions	0.001
Packing cases	0.045
Cardboard cartons	0.065
Total	0.174

Thus an M50 bomb dropped at random into this factory has a 0.174 probability of starting a fire.

Analysis for M74 Bombs. It is known that

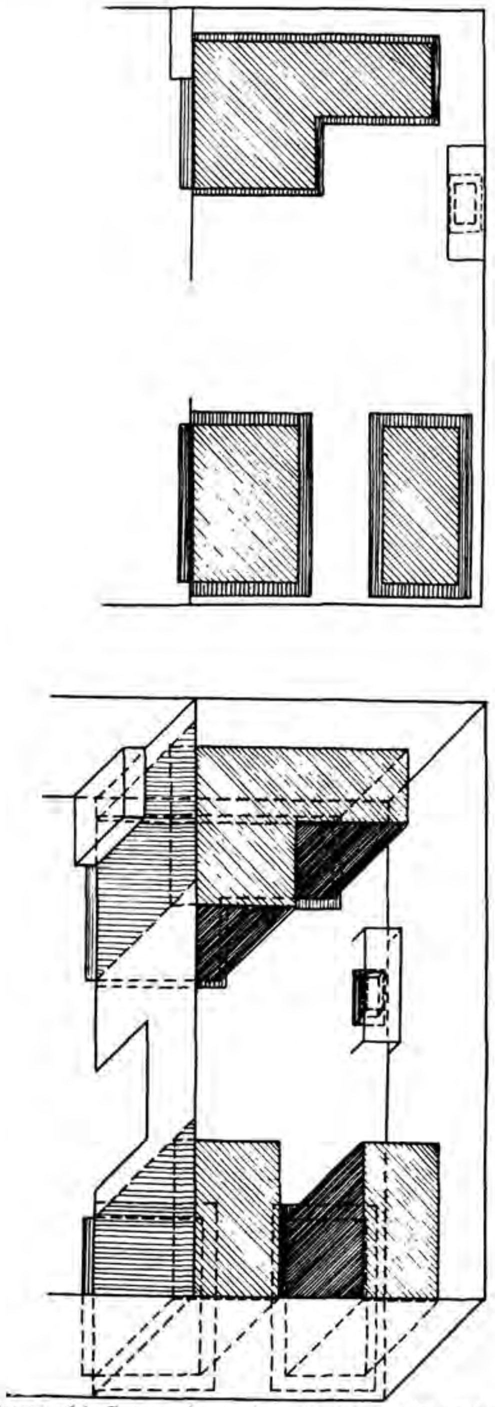


FIGURE 14. Comparison of vertical and 26° oblique views of storage section of model factory, for use in estimating hits by M76 incendiary bomb.

M74 bombs ordinarily yaw so that the gel charge descends at an angle, with the result that the gel and the case do not follow the same path. A study of the gel paths of M74 bombs dropped on the prototype factory building at Edgewood Arsenal led to the conclusion that 26 degrees from vertical was a good average angle of descent for the gel charge from M74 bombs.

The analysis for the M74 bomb is similar to that for the M69 bomb, except that the circular distribution of hits from a given point involves three dimensions instead of two dimensions, as with the M69. Since a complete integration around 360 degrees proved to be quite laborious, the problem was simplified by taking shots from 16 evenly spaced directions at intervals of 22½ degrees. Perspective drawings were made of the factory from 16 directions, all at an angle of descent for the gel charge of 26 degrees. As an example, Figure 14 shows the comparison of the plan view and 26 degrees perspective view of a section of the factory. The vulnerable exposed areas are shown shaded. The shaded areas of these views projected onto the horizontal plane are a measure of the probability of an M74 bomb projecting its gel charge against a combustible surface. The analysis for the M74 bomb was made in terms of 16 directions instead of 112 points, and the analysis was kept separate for each target type as before. If the vulnerable areas of each type of target are multiplied by the respective probabilities of starting a fire, the overall probability of starting a fire in this type of target is obtained.

The final probabilities of fire starting for the M74 bomb were calculated to be the following:

Tote boxes under workbenches	0.011
Storage bins	0.052
Wooden partitions	0.018
Packing cases	0.051
Cardboard cartons	0.070
Total	0.202

Thus an M74 bomb dropped at random into this factory has a 0.202 probability of starting a fire. The M74 loses efficiency by the nearly vertical descent of its gel and the inability of the gel to break through 1-in. board surfaces when it hits them.

Discussion of Results. Table 1 summarizes the results given in the above sections, with two additional variables, the length of time for fires to become self-sustaining and the number

TABLE 1. Probability of fire starting in model factory layout. Number given equals fractional number of functioning bombs penetrating to interior of factory building which start fires capable of consuming the local target; called probability of fire start, P_f.

	M50 Bomb Self-sustaining within*			M69 Bomb Self-sustaining within*			M74 Bomb Self-sustaining within*		
	3 min	10 min	40 min	3 min	10 min	40 min	3 min	10 min	40 min
Fires which extend to roof									
Packing cases	0.045	0.045	0.045	0.086	0.086	0.086	0.049	0.051	0.051
Cardboard cartons	0.065	0.065	0.065	0.113	0.113	0.113	0.070	0.070	0.070
Matched partition	....	0.001	0.001	....	....	0.018	....	0.018	0.018
Storage bins	0.039	0.039	0.030	0.111	0.111	0.141	0.021	0.034	0.052
Subtotal (fires to roof)	0.149	0.150	0.151	0.310	0.310	0.358	0.140	0.173	0.191
Fires which do not extend to roof									
Tote boxes under benches	0.023	0.023	0.023	0.126	0.126	0.126	0.011	0.011	0.011
Total	0.172	0.173	0.174	0.436	0.436	0.484	0.151	0.184	0.202

*Time limit given is time within which fire grows to such proportion that incendiary material may be removed without fire going out.

of fires which are likely to ignite the roof. This last point is important as analysis of attacks on German factories shows that a major damage is usually obtained if the roof is combustible and is ignited. All the targets are assumed to be capable of igniting a combustible roof, except workbenches, due to their low height.

In preparing Table 1, time intervals of 3, 10, and 40 min were selected as being of interest in indicating the relative effectiveness of the bombs in starting quick fires. In Table 1 the values given in each column include the values for lesser times. Thus, for the M74, the chance that a bomb will produce within 40 min a fire that will eventually involve the roof is 0.191. Of this total chance, 0.140 is the chance of such a fire being established within 3 min. On account of the probable importance of a quick-starting fire and the relatively great importance of starting a fire which ultimately reaches the roof, the chance of fire starting is so subdivided.

From Table 1, the following may be noted:

1. For every 100 functioning bombs entering a factory layout such as that shown in Figure 13, fires will be started as shown below.

	Total fires	Fires that can eventually reach the roof: Total	Self-sustaining within 10 min	Self-sustaining within 3 min
M50	17	15	15	15
M69	48	36	31	31
M74	20	19	17	14

2. For the number of bombs in a 500-lb aimable cluster, assuming penetration and 100 per cent functioning in the factory layout, fires will be started as shown in the chart below.

	Total fires	Fires that can eventually reach the roof: Total	Self-sustaining within 10 min	Self-sustaining within 3 min
M50	19	17	17	17
M69	18	14	12	12
M74	8	7	6	5

For full details on the calculations and more detailed data see reference 8.

3.3.7 Texas Company Panel Test[11]

This test arrangement consists of plywood panels supported on a cement block wall (Figure 15). The purpose of the test was to find the best incendiary filling for the E9 40-lb oil bomb. Accordingly, a mortar was built to hold the same volume of fuel as the bomb contained and to eject it in a manner that duplicated normal ejection from the bomb at rest. The ability of the various fuels tested to avoid excessive breakup and to adhere to the target was observed. The percentage of the wooden panel destroyed within 10 min was adopted as the basis for comparing the incendiary merit of different fuels.

Some conclusions reached in tests on this structure are as follows.

1. An incendiary filling made up of units of a predetermined size is better than one the unit size of which is dependent on the ejection forces.

2. The best filling is one which combines

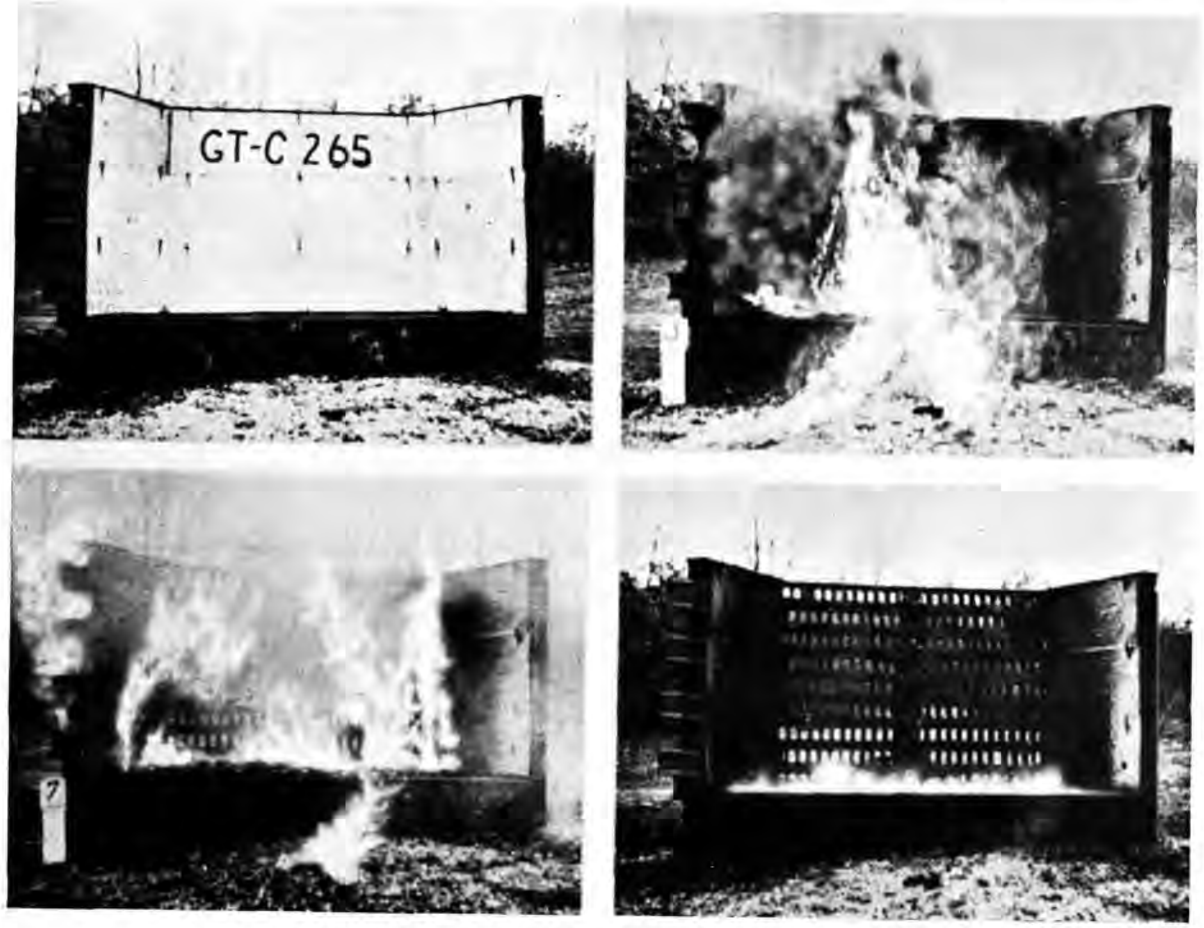


FIGURE 15. Texas Co. panel test setup. Fire was extinguished in 10 min.

TABLE 2. Penetrating power of small incendiary bombs.

Description of roof	Normal striking velocity ft/sec AN-M69 230	M69X 245	AN-M52 325	M74 420	AN-M50 420	E19 600
Metal sheeting, 20-26 gauge	P*	P	P	P	P	P
Asbestos sheeting, ¼ in. (6 mm)	P	P	P	P	P	P
Wood planking, 1 in. (2.5 cm)	P	P	P	P	P	P
Slate on wood sheathing	P	P	P	P	P	P
Tile on wood battens	P	P	P	P	P	P
Hollow tile slabs, 2½-3½ in. thick, with or without 2-5-in. cinder concrete for drainage	P	P	P	P	P	P
Lightweight reinforced concrete (1,000 psi), 2½-3½ in. thick, with or without 2-5-in. cinder concrete for drainage	P	P	P	P	P	P
Reinforced structural concrete (3,000-4,000 psi), 3 in. thick	NP†	NP	?	P	P	P
Heavy tile slab, 8 in. thick, with 2-5-in. cinder concrete for drainage	NP	NP	NP	P	P	P
Reinforced structural concrete (3,000-4,000 psi), 4 in. thick	NP	NP	NP	?	?	P
Reinforced structural concrete (3,000-4,000 psi), 5 in. thick	NP	NP	NP	NP	?	P
Heavy tile slab, 8 in. thick, with 2-in. reinforced concrete	NP	NP	NP	NP	NP	P
Reinforced structural concrete (3,000-4,000 psi), 6 in. thick	NP	NP	NP	NP	NP	P

*P = penetrates
†NP = does not penetrate

maximum heat of combustion with satisfactory burning characteristics.

3. Rolls of cellucotton saturated with turpentine gave the best results, originating from the combination of high heating value of fuel and retention in large masses.

4. Addition of furfural extract from lube oil refining to fuel mixture increases the heating value, while addition of powdered magnesium promotes more rapid burning. Both additions seem to be desirable.

3.3.8 Penetrating Power of Bombs

The vertical mortar setup at the Standard Oil Development Co. was utilized to make a systematic study of the penetration, or perforation, of domestic and industrial roof types by small incendiary bombs. Sections of various roof types were constructed and placed under the mortar in a horizontal or pitched position, depending on the roof type, and then subjected to test by bombs at their normal striking velocities. The bombs tested in this manner included the AN-M50, AN-M52, AN-M54, AN-M69, AN-M69X, and M74. The AN-M52 and E19 bombs were tested by similar technique at the Factory Mutual Research Corporation. The data obtained are summarized in Table 2.

3.4 TESTS IN FULL-SCALE ROOMS AND BUILDINGS

3.4.1 Introduction

Tests in full-scale rooms and buildings surpass all others in significance because the data can be applied directly in estimating the results to be expected in actual incendiary raids. Airborne tests permit an evaluation of the overall performance and incendiary effectiveness of the bomb, and are therefore to be conducted in the late stages of development and as service tests prior to standardization. However, all essential information regarding penetration, performance, and fire-starting ability can be obtained from mortar shots where bombs are fired downward into the structures. In such tests the bomb can be delivered through any desired part of the roof, and it is not necessary to employ the extensive array of targets that are needed to get a reasonable percentage of hits in airborne tests. It is believed that future test work should be concentrated on mortar shots into full-scale rooms and buildings, with a final minimum number of airborne tests as an ultimate check on overall performance.

3.4.2 Tests at Huntsville Arsenal

Among the earliest tests in full-scale buildings were those conducted by the Chemical Warfare Service at Huntsville Arsenal in April 1942. One- and two-story farm buildings of frame construction were used in static tests of the small magnesium and therm-8 bombs and the experimental 7-lb base-ejection oil bomb. It was reported that the AN-M54, AN-M50A1, and AN-M52 were of comparable effectiveness when fired statically in buildings of light construction. The small oil bomb was judged the most effective of the bombs tested, despite the observation that the burning fuel was easily extinguished.

In airborne tests very few hits were obtained so that no conclusions could be drawn regarding fire-starting efficiency, but it was noted that the M50 and M54 had excessive penetration for this type of structure.

3.4.3 Tests at Jefferson Proving Ground

In July 1942 tests were run by CWS and the Ordnance Department at Jefferson Proving Ground, with NDRC participation. Several groups of typical farm buildings were used as targets, and dropping tests were conducted with the M50 and M52 magnesium bombs, the M54 therm-8 bomb, a plastic incendiary bomb, the M47 oil bomb, and two sizes of small base-ejection oil bombs, weighing 4.8 and 6.2 lb, respectively. The objectives of the tests were to determine the relative merits of the various munitions. Data were obtained on stability in flight, penetration, functioning, incendiary effectiveness in structures, ability to set grass fires, number of duds and their cause, dispersion pattern of clustered bombs, and ignition and dispersion of gel from the M47 bomb. The majority of the tests were conducted from 2,500 ft altitude, with a few from 5,000, 10,000, and 20,000 ft.

The flight stability of the M50 was found good, and its functioning and incendiary effectiveness satisfactory. The M54 had good flight stability and reliable functioning, but was not as good an incendiary as the M50. The M52 showed marked instability in flight and poor functioning. However, it was considered to have promising incendiary properties for a bomb of its weight. The 6-lb oil bomb (M56, later M69)

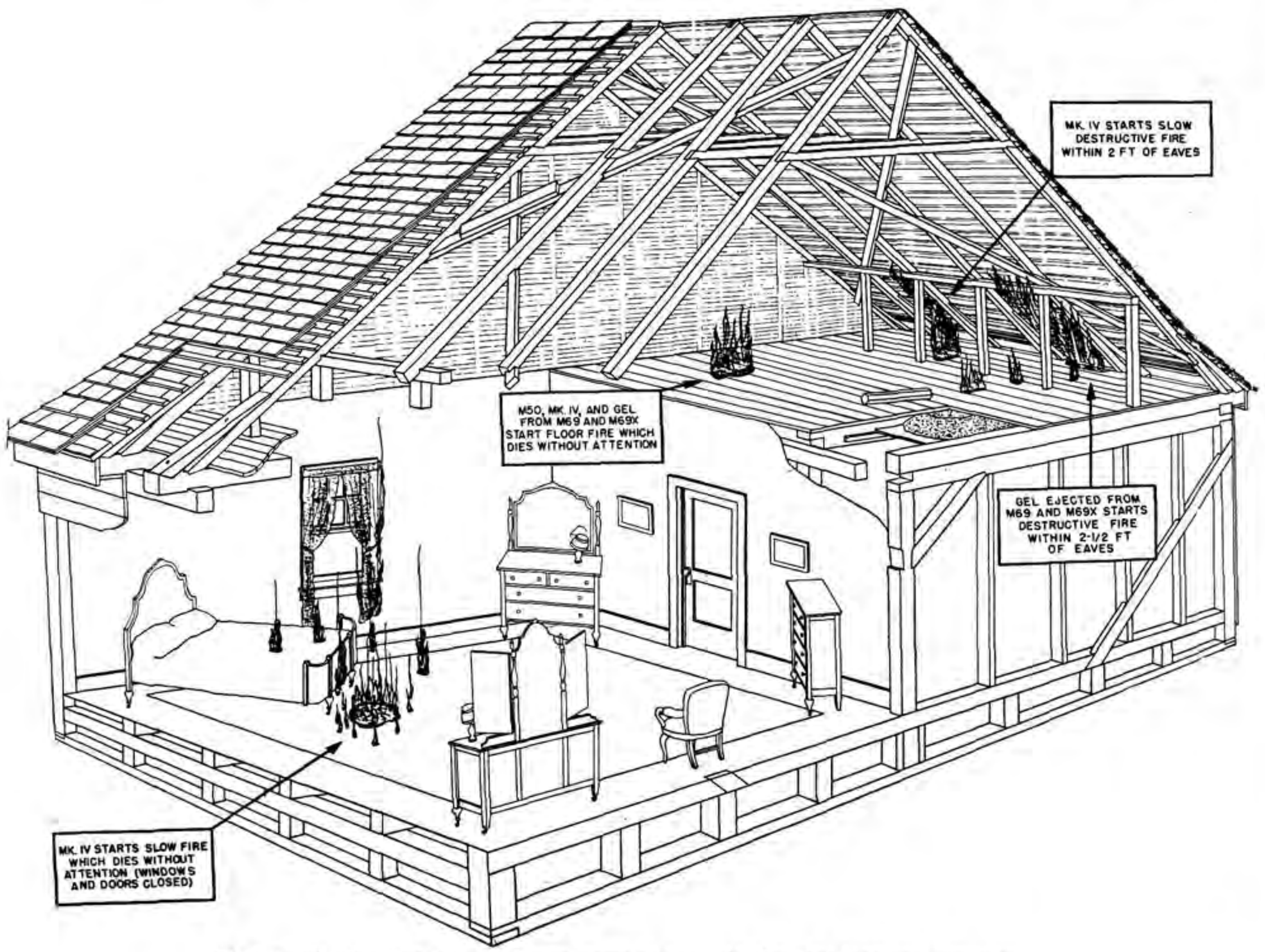


FIGURE 16. Construction and summary of tests in Central German structure.

was considered promising and superior to the 5-lb bomb. It was recommended by CWS that development work to improve the M47, M56, M50, and M54 bombs be undertaken and that these bombs should be manufactured in quantity. NDRC observers concluded that the principle of delayed ejection of gel had been shown to have considerable merit.

3.4.4 Tests by Standard Oil Development Co. [19, 20, 21]

The previous tests at Huntsville Arsenal and Jefferson Proving Ground had suffered from the usual difficulty of getting a desirable number of significant hits in airborne tests. Furthermore, the buildings used as targets served only to establish a relative order of effectiveness of the bombs. In order to obtain sufficient quantitative data on authentic structures, it was decided to conduct mortar tests on target buildings that would be exact reproductions of German houses. Three types of houses were designed and built, typical of Rhineland, Central German, and Eastern German construction. Tests with the Rhineland and Central German

structures were completed prior to construction of the target village at Dugway Proving Ground, and constitute an important record of large-scale tests and demonstrations. Figures 16, 17, 18 show the construction and typical tests in these structures.

FIGURE 17. Outside view of incendiary test in Central German structure.

Tests with Rhineland Structures.[19] The M50, M69, and M69X bombs were fired from a movable mortar, aimed at rafters and between rafters, and at points near the ridgepole and near the eaves. Inert bombs were used for penetration tests, and live M69 and M69X bombs were fired for performance. A limited number of fires were permitted to go to the point where the incendiary effectiveness of the bombs could be demonstrated.

It was found that the M50 frequently penetrated the roof and the attic floor when no rafter was encountered. The M69 did not penetrate through the attic floor when fired at its normal terminal velocity of 225 ft per sec. A substantial proportion of the M69X bombs, fired at 270 ft per sec velocity, penetrated through the roof and attic floor. Satisfactory performance of the M69 after penetrating the roof was demonstrated, and it was determined that if from one-third to one-half of the gel is ejected into the eaves the M69 will start a destructive fire in these structures. However, it was shown that neither the M50 nor the M69 will start destructive fires in a typical Rhineland attic if the incendiary contents are more than 4 to 5 ft from the eaves.

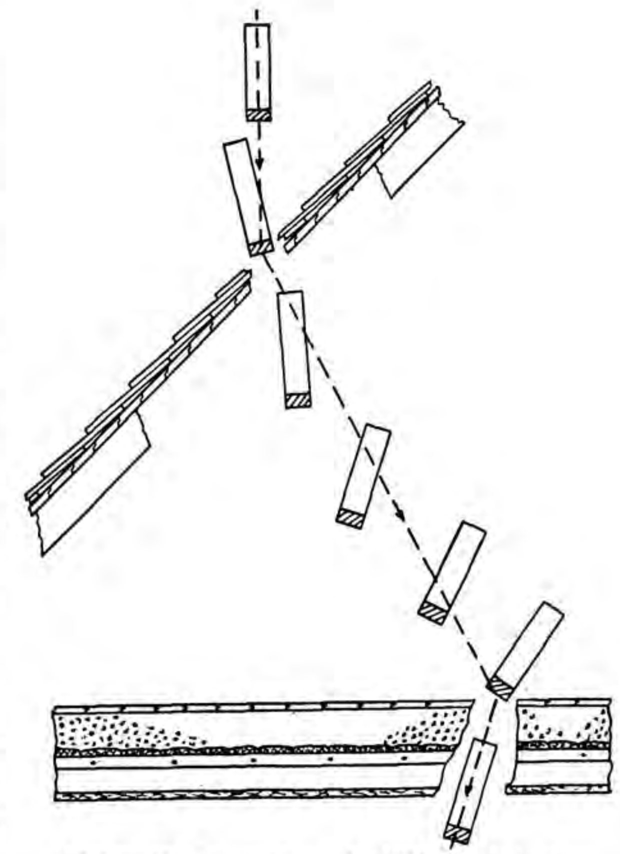


FIGURE 18. Penetration of M69X bomb in German structure.

Tests in Central German Structures.[20] The M50, M69, and M69X bombs were used in tests similar to those performed with the Rhineland structures. The Central German structure had a tile-on-batten roof instead of the slate-on-sheathing roof generally found in Rhineland structures. Data on penetration, functioning, and fire-raising power were obtained. Bedroom furnishings were placed in the room below the attic floor, to test the incendiary capacity of the M50, which often penetrates to that level. Particular attention was paid to the moisture content of the structures, tests for destruction being performed only when the moisture content was not lower than 10 to 12 per cent. A few tests were run with moisture content in the range of 20 to 25 per cent.

It was found that the tile roof offered the major resistance to the M69 bomb, little difference in ultimate penetration being found as the shots progressed towards the eaves line. Approximately 25 per cent of the M69 bombs remained sticking upright into the attic floor, none penetrating through the floor.

The penetration of the M50 was dependent on the position where the bomb came through the roof. When entering near the ridge, all M50's remained in the attic; in the middle of the roof from 21 to 40 per cent of the bombs penetrated through the attic floor, depending on the velocity at which they were fired. Near the eaves, all bombs penetrated the attic floor, 14 per cent of them at higher velocities penetrating two floors below the attic.

Tests with live bombs showed that the M69 and M69X started rapidly destructive fires when the fuel charge was ejected into the eaves of the attic. No bomb (M50, M69, or M69X) was effective when the fuel charge was more than 6 ft from the eaves. In a closed furnished bedroom, the M50 started slowly destructive fires.

Miscellaneous Tests in Attic and Sub-attic Structures.[21] An extensive series of tests was conducted to study the effect of fuel consistency, fuel distribution, burning rate of fuel, effect of ventilation and design of structure, on the initiation and propagation of fire. These tests were conducted with the M69 bomb, and employed a Rhineland type attic and a furnished bedroom representative of German practice.

The results of the investigation may be summarized as follows.

1. Ample ventilation must be provided in order for incendiary bombs to be effective in establishing destructive fires.

2. Napalm fuel having a consistency of 400 to 600 g Gardner, appears to give optimum breakup and optimum burning rate in furnished bedrooms, being superior to the 9 per cent Napalm gels and IM gels used in M69 production.

3. In attics, fuel consistency is not so critical, but again the 400 to 600 g consistency appears best.

4. The burning rates of thickened gasoline fuels depend on the surface exposed to the air. For equal surface areas the IM2, IM3, and Napalm fuels containing from 2 to 9 per cent thickener burned at the same rate as gasoline.

5. The surface area of the fuel exposed after ejection depends on the consistency of the fuel, the force of ejection, and impact against a target. These factors must be kept in mind in formulating the fuel for a particular bomb.

FIGURE 19. Views of Factory Mutual incendiary-test room (*upper*) from the door and (*lower*) from the window.

6. In furnished rooms, considerable breakup of fuel, with simultaneous ignition of several incendiary centers and a rapid build-up of temperature, appears desirable.

7. From a consideration of the geometry of

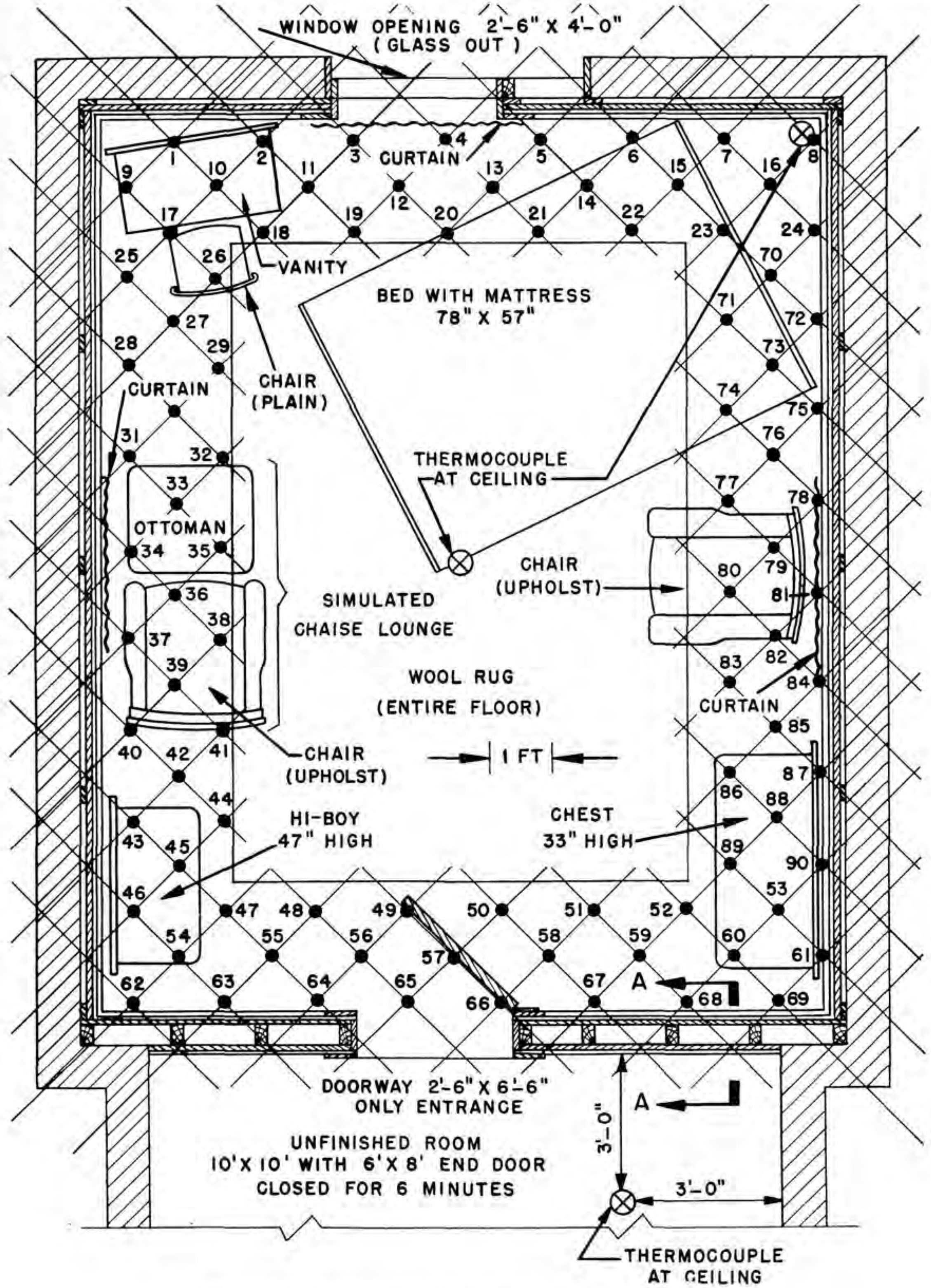


FIGURE 20. Layout and location of test points in Factory Mutual room.

the furnished bedroom, combined with all the test data, it was estimated that 20 per cent of all M69 bombs ejecting within the room would

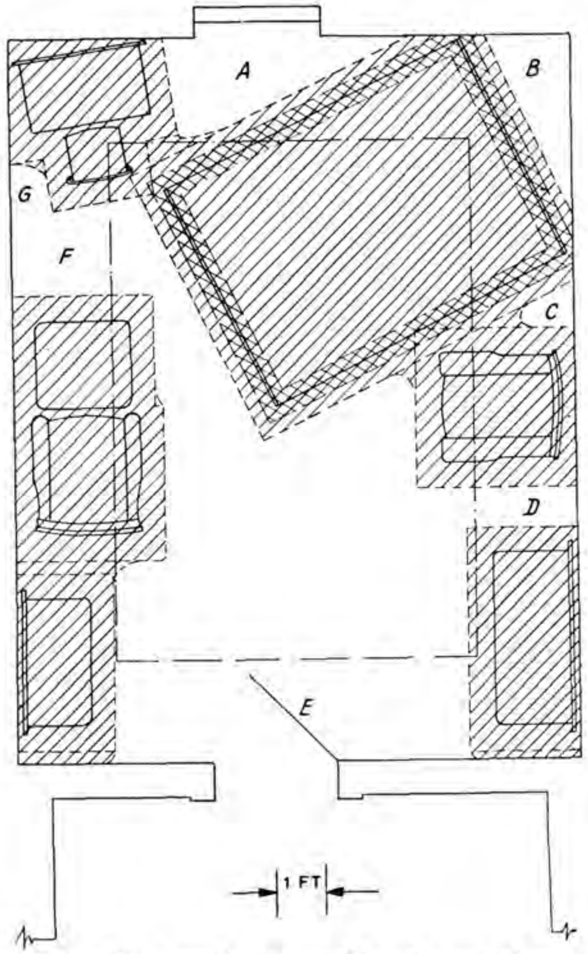


FIGURE 21. Areas in Factory Mutual room vulnerable to E19 bomb.

cause destructive fires if they contained gel of the optimum consistency.

3.4.5 Tests by Factory Mutual Research Corporation[17, 22]

Comparative evaluations of small incendiary bombs were made under controlled conditions in a furnished bedroom. The bombs were compared by determining the relative areas in which fires were started and went out of control by a stirrup pump after a waiting period of 6 min.

Description of Test Room. The test room measured approximately 12 ft by 15 ft, with a ceiling height of 7½ ft. Figures 19 and 20 show the layout of the room. The walls and ceiling were covered with gypsum board for easy replacement. The average weight of the furnishings was 3.2 lb per sq ft of floor area.

Test Procedure. The bombs were placed in locations shown in Figure 20, and fired statically. After 6 min elapsed, an experienced fire fighter and helper attacked the fire with a stirrup pump, approaching through the adjoining room, where he encountered heat and smoke from the bedroom. If he was unsuccessful in dealing with the fire it was judged out of control.

Results. The tests indicated that the E19 incendiary bomb would cause uncontrollable fires when burning within areas that amounted to 67 per cent of the floor area. In Figure 21 the crosshatching shows the vulnerable area for the E19 bomb. The M50 4-lb magnesium bomb was found to be effective in only 7.2 per cent of the total area in similar tests. It was found that the temperature reached within the room

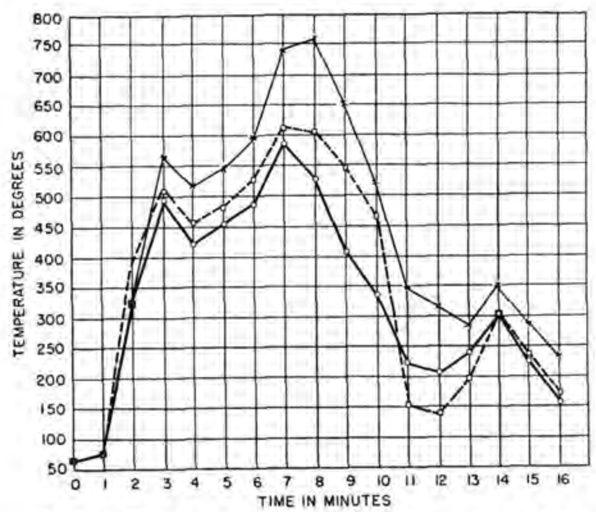


FIGURE 22. Typical time-temperature curves for incendiary test in Factory Mutual room. Three thermocouples were at ceiling in locations shown in Figure 20.

at the end of the 6-min waiting period was not a reliable index of the outcome of the test. In one test a temperature of 320 F at 6 min was recorded for a fire that could not be controlled,

whereas in another test a temperature of 620 F was reached in 6 min, but the fire was put out. These observations have been confirmed by later work which has shown that when furnished rooms attain a maximum intensity of burning the temperature may reach 1800 F. Figure 22 shows typical time-temperature curves during an incendiary test.

3.4.6 Tests at Dugway Proving Ground[23-27]

Although much valuable information regarding the penetration, proper functioning and incendiary effectiveness of small bombs had been obtained from mortar tests, it was recognized that airborne tests on full-scale target structures would be required in order to obtain a complete quantitative evaluation of the bombs. Such factors as the flight characteristics of the cluster, the functioning of the cluster fuze, the dispersion pattern of the individual bombs when released from a cluster, and the performance and functioning of the bombs could be evaluated by airborne tests without having an incendiary target, but it was felt that there might be factors the existence and importance of which would be revealed in full-scale airborne incendiary tests. Such an appraisal seemed necessary in order to be sure that the bombs would be effective when released upon enemy targets. A location suitable for these tests was found at Dugway Proving Ground of Chemical Warfare Service, situated some 70 miles southwest of Salt Lake City, Utah. Figure 23 shows some views of this project.

Description of Target Structures. 1. German structures. Six adjoining houses were built, three of the Rhineland type and three of the Central German type, similar to the Standard Oil Development Company structures, but much larger. Three had roofs of slate on sheathing, and three had tile on battens. The second-story rooms contained heavy furnishings characteristic of German custom.

2. Japanese structures. The Japanese dwellings were faithful reproductions of row houses occupied by factory workers. They were equipped with authentic straw floor mats and simulated furniture in an amount usually found in such dwellings. No trouble or expense was spared in making all details of these dwellings correspond with authentic Japanese practice.

Description of Tests. An elaborate program of tests included dropping the M50 and M52 magnesium bombs, the M54 therm-8 bomb, and the M69 6-lb oil bomb. Both live and inert bombs were released at altitudes of 3,500 ft and 10,000 ft, from quick-opening clusters. Extensive data were taken on every point of functioning and performance, in order to have a sound basis for establishing the relative merits of the bombs. When hits on the targets were obtained, a complete record of each bomb was made, including the point of entry, the path of the bomb through the structure until it came to rest, the location where the functioning and incendiary action occurred, and the incendiary result achieved. Fires were classified according to the time it took for them to reach various stages. Thus, the classifications A1, A2, and A3 were assigned to fires which were judged to be going out of control by stirrup pumps within 2, 4, and 6 min, respectively. Fires that did not develop rapidly, but which would eventually go out of control, were classified as B fires. Small fires which would go out even if unattended were called C fires. Dud bombs were designated D. In order to avoid excessive damage, the fires were attacked with garden hose or full-scale fire-fighting equipment as soon as the expert evaluators had established the classification of the fire. Data were likewise taken on fires caused by gel ejected by M69 bombs onto buildings (ejection hits). Figure 24 shows a typical destruction fire in progress in a Japanese structure.

Results. Early in the program the M54 therm-8 bomb proved to be such a poor incendiary that it was given no further consideration. The M50 bomb was found to have excessive penetration for the Japanese structures. In the German dwellings it penetrated to the attic or to the floor below, but caused no rapid fires, being effective only when it burned in a favorable location. The M52 magnesium bomb exhibited marked instability of flight, but showed that its penetrating characteristics and incendiary effectiveness were adequate for Japanese con-

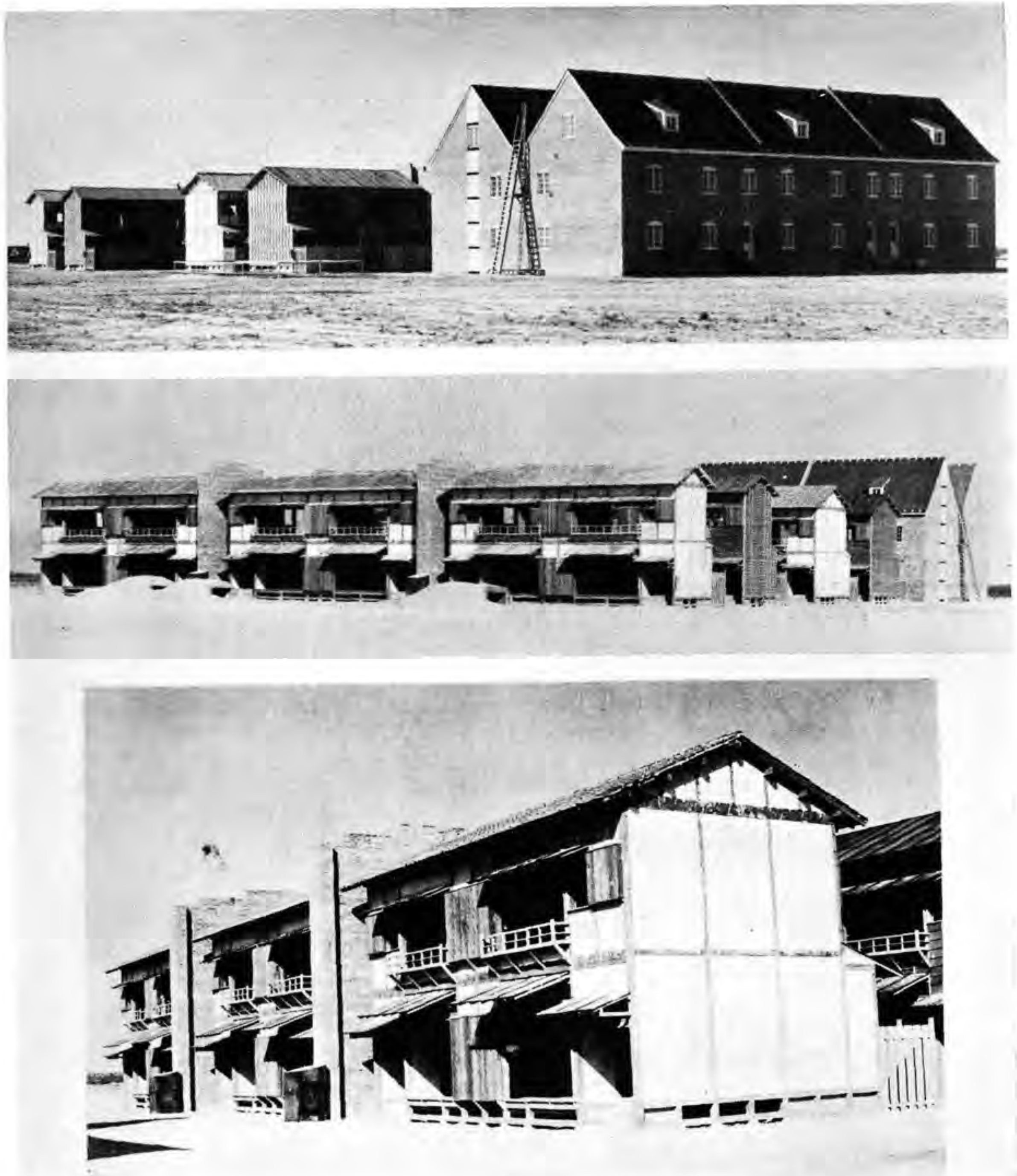


FIGURE 23. Views of Dugway incendiary-test "Village."

struction. The M69 bomb was the most effective of the bombs tested, and showed itself to be a potent weapon against Japanese construction. It also caused some good fires in the German buildings, and it was adjudged the best of the bombs tested on these structures. Table 3 summarizes very briefly the results of these incendiary tests; for more detailed data the reader is referred to the official report.

Fire-Fighting Tests with the M69. Because of

the belief that the Japanese are resourceful and determined fire fighters, it was decided to conduct a series of tests in which the fires would be attacked soon after the bomb had functioned. M69 bombs were placed so as to eject gel into predetermined locations, selected on the basis of earlier airborne tests. The bomb was fired electrically, and immediately thereafter a man equipped with stirrup pump or sand and shovel was permitted to enter the building, search for the fire and endeavor to put it out. An assistant was available to operate the pump. Tests were also made in which two bombs were fired simultaneously. The fire fighter and his assistant then attacked the most readily accessible fire until it was extinguished, and then proceeded to locate and attack the second fire. Both experienced and inexperienced personnel were used during the course of the tests.

Results. Of 36 bombs attacked by both experienced and inexperienced fire fighters using simple fire-fighting methods, 7 caused fires that went out of control. Of the single fires in readily accessible locations, 5 out of 37 went out of control; in locations difficult of access, 3 out of 6 went out of control. When two bombs were fired simultaneously and each caused an A or B fire, 8 out of 16 went out of control, despite attack by fire fighters. The general conclusion was reached that fires initiated by the AN-M69 bomb in Japanese houses could frequently be controlled by fire fighters, and that the important factors in such control were the method utilized, the experience of the individual, the accessibility of the fire, and, above all else, the time that elapsed before the fire was attacked. The results of these tests indicated that previous estimates of the effectiveness of the M69 for the bombing of Japan would need revision upward to allow for the defensive measures that would probably be taken by the enemy.

These tests led to the following conclusions.

1. Attack within 1 min would reduce potential fires per 100 AN-M69 bombs dropped from 46 to 10.5 as a minimum.

2. Previous estimates of 6 to 10 tons per sq mile were too low. Based on 50 per cent roof area, of which 50 per cent are multistoned structures, the bomb density should be about 40 tons per sq mile for reliable destruction.

In comparison with bomb densities used in the last six months of World War II, the above figure is quite low. However, it should be pointed out that the densities actually used may have been unnecessarily high, and that there probably was a big difference between density dropped and density on the target area.

TABLE 3. Results of incendiary bomb tests on Dugway structures.*

Fire classification	Japanese houses AN-M50	Japanese houses AN-M52	Japanese houses AN-M69	German houses AN-M50	German houses AN-M52	German houses AN-M69
A	22%	26%	68%	0%	0%	37%
B	20%	14%	13%	26%	18%	16%
C	58%	60%	19%	74%	82%	47%

*Dud bombs are excluded from the summary of bomb tests in this table.

3.4.7 Incendiary Tests in Experimental Japanese Room[28]

The tests at Dugway had shown that small incendiary bombs, particularly the AN-M69 and the M74, were effective in starting fires in Japanese dwellings, and that these dwellings were vulnerable to incendiary attack and easily destroyed by fire. Tests in England with the AN-M69 and other small incendiary bombs had indicated that small bombs were inadequate, seldom starting fires that would go out of control in a reasonable time, and then only when the bombs functioned in a few favorable locations. It was pointed out that the moisture content of the wood in the Dugway targets had averaged only 11 per cent in the first series of tests, and had been still drier in some later tests, moisture contents in the range of 3 to 6 per cent having been recorded for the hung

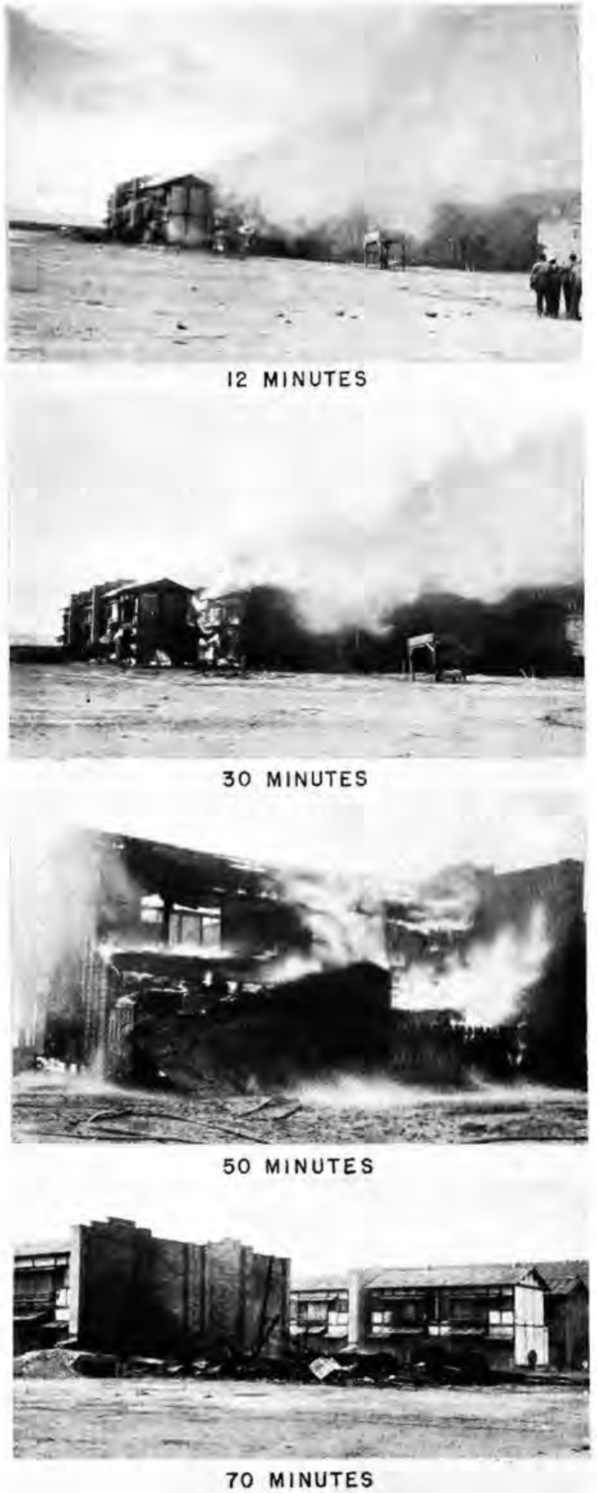


FIGURE 24. Destructive fire in progress in a Japanese structure at 12, 30, 50, and 70 min after impact.

ceilings. Serious doubt was expressed as to the validity of the conclusions drawn from the Dugway tests, in view of claims that the moisture content of wood in Japan might approach 20 per cent. The British urged that larger bombs, such as the jet bombs, J-30 and J-20, were needed for effective attack on Japan. The implications were so serious that a British mission visited the United States in November 1944, and held several discussions in an attempt to reconcile the differences that had been found in the results of tests in America and England.

It was finally agreed that tests would be conducted by both groups, employing an experimental Japanese room designed to embody essential elements of construction, and assembled entirely from panels preconditioned to a proper moisture content.

Description of Test Room. Figures 25 and 26

FIGURE 25. Interior of experimental Japanese room at Edgewood Arsenal.

show the interior and exterior of the unit built at Edgewood Arsenal. The design was agreed upon in conference with British experts, and represented a compromise between American and British test structures. The test room proper measured 9 by 12 ft and was supported by a massive external framework. At one end was a noncombustible enclosure to simulate a plastered hallway. This was furnished with combustible ceiling panels, which would normally be present above a hallway. The test room was assembled immediately before each test, panels being removed from the condition-

FIGURE 26. Exterior of experimental Japanese room, with fire in progress.

ing room and set in position in 15 to 20 min.

Since no reliable data were available on the moisture content of wood in Japan, it was decided to conduct wood-moisture equilibrium studies at a location where the climate corresponded closely to the summer climate of the Tokyo district. Key West, Florida, was a suitable place during the winter months, and samples of wood were there exposed out of doors and in several rooms in three different houses. Weights of samples, and determinations of relative humidity and temperature of air, were taken twice a day over a period of several weeks. It was concluded that a maximum wood-moisture content of 15 per cent was to be expected in houses in the Tokyo district. The panels for the experimental Japanese room were therefore conditioned to a moisture content in the range of 15 to 17 per cent.

Test Procedure. The AN-M69 bomb was chosen for the tests, because it was in large-scale production and scheduled for early use on Japan. The periphery of the room was divided into zones within which the combustibility was considered uniform. On the assumption that the angle subtended by a zone at the center of the room was a fair average of the angles subtended from points uniformly distributed over the floor, angles from the center to each zone were measured to determine the probability of ejection into that zone (see Figure 27). By combining these probabilities with results of incendiary tests on each zone, the fraction of the total ejection shots by AN-M69 bombs found to be effective was established at 77 per cent. Allowing for a decrease of one-half in effectiveness due to penetration of gel through the shutters to the exterior, one concludes that 38 per cent of the bombs penetrating into the room would yield fires that would become uncontrollable within 5 min. This last may be an overcorrection. A few M74 bombs were fired into the room from the vertical mortar, and the results indicated a degree of effectiveness similar to that obtained from the AN-M69.

Conclusions. From the results of these tests it was concluded that (1) Japanese domestic construction of the type occupied by factory workers, and conditioned to a moisture content of 15 to 17 per cent, is easily ignited and vul-

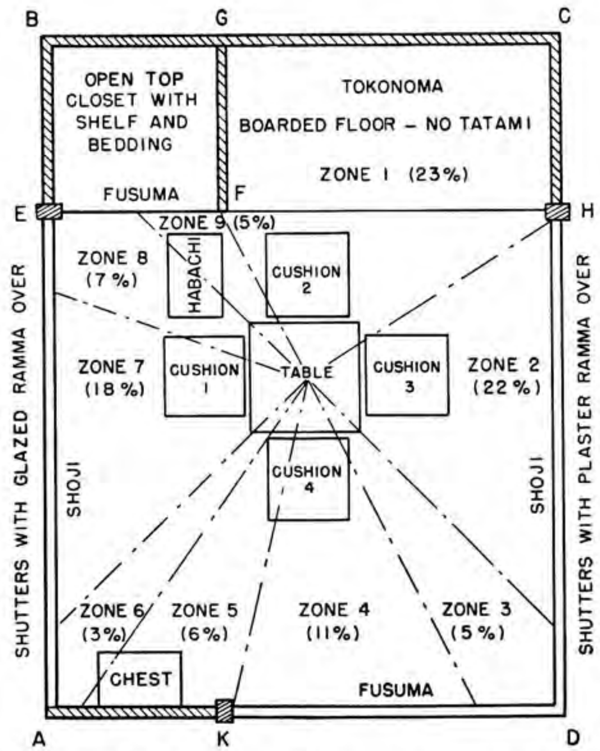


FIGURE 27. Layout and vulnerable zones in an experimental Japanese room.

nerable to fire; (2) the AN-M69 bomb is adequate for the purpose; and (3) the M74 bomb is also adequate for the purpose.

Before these results were published, the his-

FIGURE 28. View of an Eglin Field factory-type, incendiary test building.

toric raids of March 1945 on Tokyo with the M69 bomb had amply demonstrated the overall effectiveness of that bomb, particularly when dropped in such numbers as to overwhelm defensive measures which might have coped with smaller numbers of bombs. All tests revealed that small incendiary bombs are easily controlled in the early stage of their burning against a target, and that the indispensable condition for their success in starting fires is that they be undisturbed for periods of time up to 5 or 6 min.

3.4.8 Tests at Eglin Field

Because the policy of the American Air Forces in 1943 and 1944 was to concentrate on the precision bombing of industrial targets, a need was felt to evaluate incendiary bombs by airborne tests employing a full-scale factory structure. The only available structure was one situated on H field at Edgewood Arsenal, Maryland, and the heavy demands on its use by CWS and by Ordnance, combined with the frequent occurrence of weather that prevented bombing from high altitude, made it advisable to erect a new building in a more favorable location. Permission was obtained by NDRC to construct a target building at the AAF Proving Ground at Eglin Field, Florida. Here were available all types of airplanes, all necessary instruments, and a skilled personnel to operate them. Ground was broken for this structure in November 1943, and it was ready for use in March 1944.

Description of Target Structure. A major consideration in designing the building was to include those types of roof construction which would be representative of the roofs commonly found on enemy factories. The building would then not only serve for testing the penetration and functioning of all incendiary bombs being developed, but would yield data directly applicable to the planning of incendiary raids on enemy targets.

A side elevation of the target structure is shown in Figure 28. The structure was of steel-frame construction, with a concrete floor, except for one section measuring 140 by 68 ft which had wood-block flooring covered with tar. The width of the building was 140 ft, and the total length was 375 ft. There were three sections, the lengths of which were 100 ft, 125 ft, and 150 ft, respectively. The first section was three stories high, of reinforced concrete. The floors of intermediate stories were 8-in. reinforced concrete and the roof was 6-in. reinforced concrete. The second and third sections were laid out in bays measuring 25 by 20 ft, with a height of 20 ft between the floor and roof. In the second section, half the roof was made up of 2 to 5 in. of cinder concrete over 3-in. hollow tile, covered finally by two layers of asphalt felt. The other half was 3 in. of cinder concrete over 3½ in. of light concrete, covered by two layers of asphalt felt. The third section had a sawtooth roof consisting of light steel framing which supported glazed windows and 1-in. wooden sheathing covered with two layers of asphalt felt. The sides of the building were open and there was a concrete apron 50 ft wide surrounding the entire structure. Two hundred yards away was a bombproof shelter from which observers could view the length of the target building.

Use of the Eglin Field Structure. The principal data obtained in hits on the building were on penetration through the various types of roof and on the functioning of the bomb after penetration and subsequent impact on the floor. The AN-M69 bomb was tested on several occasions, being released in aimable clusters at altitudes up to 30,000 ft, with the cluster fuze set to open the cluster at any desired height above the target. It was found that a free fall of the individual AN-M69 bomb of approximately 5,000 ft was necessary to permit the bomb to decelerate to its normal terminal velocity of about 225 ft per sec.

The AN-M69 penetrated the sawtooth roof, and also the various light-weight roof slabs when no reinforcing members or supporting beams were encountered. It failed to penetrate the 6-in. reinforced concrete roof.

By an analysis of data on the prevalence of various roof types in Germany, and by comparison with previous test data, it was concluded that the common incendiary bombs would penetrate the following percentages of German industrial roof area: M50, 81 per cent; M47, 87 per cent; M69, 74 per cent; M69X, 75 per cent.

Subsequent photocover indicated that the AN-M69 and M69X would penetrate the roofs on over 90 per cent of the high-priority industrial targets in Japan.

In cooperation with Chemical Warfare Service, NDRC conducted a series of tests with the M47A2 70-lb oil bomb, to determine whether the M12 burster, black powder and magnesium, or the M13 burster, tetryl and white phosphorus, should be preferred for this munition.[20] The M12 burster is slower in its action and does not bring down as much roof material as the M13 when the bomb penetrates cinder concrete or tile roof slabs. The faster action of the M13 burster appears to cause more gel to lodge against sawtooth roofs, frequently causing roof fires. The general conclusion was reached that either burster gave satisfactory ignition of gel and that neither appeared to have any marked superiority over the other.

In the tests at Eglin Field no attempt was made to evaluate the incendiary effectiveness of the bombs. Circumstances were noted under which roof fires occurred, and in some tests rough wooden benches were placed about the floor.

As in other airborne tests, observations were made as to the ballistics and functioning of the cluster, the flight characteristics of the individual bombs, and the dispersion pattern around the center of impact. Recovery of bombs was frequently made, and causes of malfunctioning determined. The overall results of these tests contributed much valuable information that could be gotten in no other way, and provided a sound basis for predicting the results that might be expected from bombs dropped in actual attacks.

3.4.9 Tests at Edgewood Arsenal[18, 30]

The industrial target structure at Eglin Field proved to be so useful that the Chemical Warfare Service erected a similar structure at Edgewood Arsenal in the fall of 1944.

Minor changes over the Eglin Field structure were made, such as omitting the tar-covered wooden block flooring, and the substitution of metal or laminated plastic for most of the glass panes in the sawtooth section. An important change was the addition of hinged metal panels which enclosed the structure on all sides and minimized the effect of wind while still permitting adequate ventilation. The Incendiary Evaluation Project provided wooden benches, stacks of packing cases, storage bins, radial targets, and cardboard cartons, which were arranged in the two sections having light roofs. These covered approximately 5 per cent of the floor area, and permitted an evaluation of the incendiary effectiveness of the bombs. This particular floor loading was selected for tests with the

M47 bomb, which distributed gel over an area of about 3,000 sq ft, and provided a good chance that several different targets would receive gel when an M47 hit into the building.

In tests on this building with the M74 8-lb incendiary bomb, the angle of descent of the PT gel was determined by noting the hole in the roof and the position on the floor where the gel had struck. In 25 hits on the sawtooth section the angle between the vertical and the path followed by the gel varied from zero to 60 degrees, the average being 26 degrees. This important fact was combined with other data obtained in mortar tests to establish the probability of an M74 starting a fire in a factory setup which contained combustible targets covering 25 per cent of the floor area. (See Section 3.3.)

In tests with the AN-M50A2, it was found that a high percentage of bombs that penetrated the sawtooth roof failed to function upon reaching the floor. This was apparently caused by the failure of the fuze to be activated by the slight deceleration that accompanied penetration through such a light roof, which, however, rendered the fuze insensitive to the subsequent shock upon hitting the floor. These results indicated the need for a more sensitive fuze than the one that had been incorporated to meet safety requirements in handling the bomb, in order to insure a satisfactorily high percentage functioning on light roofs.

Tests were also run with the AN-M69, the E19, and several 500-lb incendiary bombs being developed by CWS.

An evaluation was also made of incendiary fillings for the 4.2-in. mortar shell, which was fired into the building containing the incendiary targets.

3.5 FUNDAMENTAL STUDIES ON THE IGNITION OF WOOD

Most of the combustible material used in building construction and furnishing is wood, and a knowledge of the factors which govern the burning of wood is fundamental to the development of a sound technique of incendiary bomb testing.

When wood is heated the first result is that some of the moisture it contains is vaporized and driven off. Decomposition of the wood substance also begins to take place with the evolution of heat, and the volatile products of this decomposition are also driven off. If the source of heat is large enough to raise the temperature of the wood continuously, a point is reached at which this endothermic decomposition proceeds with almost explosive violence if a pilot flame is applied. At higher temperatures ignition takes place spontaneously. The continuance of this burning, once it has been started at the surface, can only take place if the heat liberated at the surface, plus the heat from the initial source, are together sufficient to drive off the interior moisture, raise the temperature of successive layers of wood to the ignition point, and supply heat loss out through the wood to its unheated face. These various factors are considered in more detail under the following headings.

3.5.1 Radiation Density Required for Ignition

This factor in the problem was studied by exposing woodblocks of various species of wood to heat from a standard radiating source and measuring the time necessary for ignition. At average moisture contents it was found that a minimum value of about 18,000 Btu/hr/sq ft was necessary for self-ignition. At an intensity of 20,000 Btu/hr/sq ft ignition occurred in 25 sec; at 50,000, in 3 sec. These results correspond to total inputs of 125 and 40 Btu/sq ft, respectively, illustrating the decrease in total energy required as the rate of input increases. When a gas pilot flame is applied, instead of relying on spontaneous ignition, the intensity of irradiation required drops markedly, 12,000 Btu/sq ft per hr for ignition in 25 sec compared to 20,000 without a pilot flame. Although initiation of fire is accomplished with a minimum of total energy if its intensity is a maximum, persistence of the flame is very brief after removal of the heat source, because of the substantial absence of any stored heat in the wood layer behind the flame. A sustained intensity of irradiation of about 10,000 Btu/sq ft per hr was found necessary to maintain the flame on a

wood surface indefinitely, or until an edge or supporting member was involved.

Little difference in inflammability was found for a number of wood species tested.

3.5.2 Effect of Moisture Content[31-36]

In the tests just referred to blocks of different moisture content were used, but there was little effect on the time required for either pilot-ignition or self-ignition under the conditions of high irradiation density used, since only the surface of the wood was then involved. When, however, the continuance of burning was at stake, moisture content was found to have a material effect.

In another series of tests, sticks of Douglas fir 1x2x7½ in. of different moisture contents were located in such a way with respect to the burning fuel used as a heat source that the transference of heat was effected more by convection and conduction than by radiation. The samples were exposed to various input rates and the ignition times measured as well as the weight loss after 1 min burning. A marked difference in the behavior of 8 and 15 per cent wood moisture was found. Depending on the rate of heat input, the ignition time of the drier wood was from 43 to 58 per cent of that for the wetter wood when using a pilot flame, and from 60 to 80 per cent without a pilot. With pairs of samples spaced ½ in. apart and the 2x7-in. surface facing, those containing 8 per cent moisture continued to burn 3.7 times as long as the samples having 15 per cent moisture when the heat source was removed immediately after ignition.

This effect was strikingly demonstrated by using pairs of vertical planks spaced 2 in. apart, with a known amount of incendiary material burning between them at the base. In one test using 0.6 lb gasoline soaked in 0.1 lb cellucotton as the fuel, it was found that with 11 to 12 per cent wood moisture, flames reached the top of the planks (12 ft) after 3 min and the structure continued to burn to destruction, whereas, with 21 to 22 per cent wood moisture the flames took 5 min to reach 7 ft, after which they receded and the fire died out.

In all subsequent tests, therefore, the wood used was preconditioned to a known moisture content, and special rooms were built for this purpose for the Incendiary Evaluation Project at Edgewood Arsenal.

The actual value of moisture content to use for any set of tests involved a knowledge of (1) the relation between the relative humidity of the atmosphere and the equilibrium moisture content, and (2) the average relative humidity in the locality selected for incendiary bombing.

The generally accepted equilibrium relation between relative humidity and wood moisture content was found to be only approximately true. Since this relation was established as a result of tests carried out on wood shavings with a high specific surface, tests were therefore made in which wood slabs of different thicknesses were exposed to atmospheres of controlled temperature and relative humidity, and allowed to approach their equilibrium moisture content first from above and then from below.[36] The direction of approach, the species of the wood, and its previous heat treatment were all found to have a marked effect on the final moisture content established. Especially was this so in the case of Douglas fir, which is frequently kiln-dried at a higher temperature than other woods, a process which appears to lower its equilibrium moisture content by as much as 2 to 4 per cent.

Studies were made of existing climatic data for Germany and Japan, and estimates made of the probable effect of building construction and living conditions on the inside relative humidity in relation to the outside relative humidity, which is normally recorded by the Weather Bureaus.

For Germany it was predicted that the values for wood moisture content would be as follows:

Attic		Living quarters	
Summer	*Winter*	*Summer*	*Winter*
8-12	12-15	11-13	10-12

Information from German sources indicated that it would be more accurate to work at the higher ends of these ranges.

In the case of Japan, a detailed study was made in houses in Key West, Florida, where climatic conditions in winter are generally similar to those of Tokyo in the summer, and where living conditions and occupational densities could be found which were comparable with those known to exist in Japan.[36] As a result of this study, it was established that the most likely value for the moisture content of interior wood in Japan in the summer (the dampest period) was 15 per cent, a value which was used in all subsequent tests.[36]

3.5.3 Effect of Wood Thickness

In early experiments it was found that isolated wood panels over a certain thickness, about ¼-½ in., would not continue to burn after the igniting source had been removed. For example, two vertical planks spaced 2 in. apart, one ¼ in. and the other ¾ in. thick, were ignited on their inside faces with burning incendiary fuel at the base and allowed to burn until both surfaces were burning vigorously. The panels were then separated, and while the ¼-in. plank continued to burn to destruction, the fire on the ¾-in. plank died out. Measurements showed that only a small proportion of the heat produced at the burning surface was transmitted inwards, and in the case of the thick wood was conducted away from the surface too rapidly for the temperature of the next adjacent layer to reach the ignition point and thus allow burning to continue. Much of this heat lost from the surface could be saved, and the general level of temperature raised considerably, by placing the incendiary fuel in such a way that two or more adjacent surfaces were ignited simultaneously and could establish mutual interchange of heat. For example, it was shown that a 4-lb magnesium bomb burning on the floor outside, but close to an open-topped box made of 1 in. thick wood, did not start a continuing fire. When, however, the bomb was placed inside the box where mutual support was provided by all the interior faces, a rapidly destructive fire resulted.

In many instances (light paneled European furniture, Japanese screens, shutters, etc.) it was found that the wood could be fired directly, provided the burning time of the incendiary fuel was longer than the minimum necessary to ignite the surface. In other instances when the objects were heavy constructional members of German attics, heavy furniture and industrial furnishings, etc., it was found necessary to locate the fuel so that more than one surface could be ignited at a time. An interesting case in point was the adoption of the horizontal gel ejection principle in the AN-M69 bomb, which enables the gel, in a German attic, for example, to be thrown right into the eaves where the fires on the floor and the sloping boarded roof can reinforce one another and grow.

3.5.4 Effect of Wood Species[37]

The existing literature on the relation between the burning properties of wood and species was found to be somewhat conflicting, although there was general agreement on the fact that the higher the density of the wood the more difficult it was to ignite. The problem became acute when it was necessary to select an American wood that would be a satisfactory substitute for the mahogany and oak furniture which was stated to be prevalent in Germany. Two kinds of test samples were used: sticks 1x1x18 in. and boards 1x6x18 in. In both cases the ignition source was allowed to impinge at an angle on to the sample. As a result of a large number of tests, it was found that the average ignition time varied from 46 to 162 sec for the following species of wood in order: Eastern spruce, Mexican mahogany, white oak, Philippine mahogany, Douglas fir, rock maple, and West Virginia maple. From this it was concluded that standard American maple furniture would be as difficult to ignite as the wood of typical furniture in Germany.

For Japan the problem was different, since the Japanese house contains practically no furniture and reliance must be placed on ignition of the light wooden screens and shutters which take up most of the periphery of the room. The woods most frequently used for this purpose in Japan are hinoki and sugi, and experts advised that the closest available substitute for these woods from the point of view of density and essential oil content was Sitka spruce. In tests at Dugway a good deal of pine had been

used, and in England, Japanese type houses had been built of Douglas fir. It was therefore desirable to carry out a direct comparison of these three species under conditions simulating the burning of thin vertical surfaces. Vertical panels, 5 ft square, made of carefully selected ¼ in. thick, butt-jointed boards of each species, were preconditioned to the same moisture content and then ignited by burning a given amount of incendiary fuel at the base of one side. The progress of the burning was noted, and when the fires had died out the unburnt material was weighed. The results are shown in Table 4 and Figure 29. From these results it was concluded that these three species show appreciable differences in their burning characteristics, corresponding roughly with their differences in density.

TABLE 4. Comparative burning characteristics of wood.

	Douglas fir	Sitka spruce	Ponderosa pine
Density of wood	0.57	0.44	0.33
Time of maximum intensity of fire	4'30"	4'0"	3'20"
Time of marked diminution of fire	6'	6'	9'
Proportion burned	28%	30%	66%

Confirmatory evidence of the difficulty of starting fires with Douglas fir was obtained during the series of tests with the Jap structures at Edgewood. Sitka spruce was usually used, but on two occasions comparative tests were carried out with Douglas fir, and in both cases the fires were more sluggish. The particularly high-density Douglas fir used in England was considered to be an important contributory factor in the difficulty of starting fires there.

3.6 ANALYSIS OF ATTACKS ON ENEMY TARGETS

In the last analysis the evaluation of an incendiary is its effectiveness on enemy targets. Most of the analyses of air attacks on enemy targets were made by the Ministry of Home Security, RAF Air Intelligence, and U. S. AAF Air Intelligence, including the Joint Target

FIGURE 29. Comparative burning test of three wood species.

Group, but some analyses were made by NDRC groups. Below are summarized 2 of NDRC's contributions in this field: One covering the analysis of attacks on German targets by the group established under Service Project AN-23, and one giving an analysis of incendiary attacks on Japanese cities by W. T. Knox of the Standard Oil Development Co.

3.6.1 Analysis of Air Attacks by NDRC AN-23 Group

In August 1944, Divisions 2 and 11 and the Applied Mathematics Panel jointly accepted Service Project AN-23, the objectives of which were to gather data on the results of bomb attacks on European factory targets, analyze the results to establish the effectiveness of the various weapons used, and, if possible, evolve a technique of predicting the results of planned attacks, particularly on Japanese industry. Primary concern was the prediction of damage due to combined high-explosive and incendiary attack. The work of collecting data, described in detail in EWT-1d, was carried out in Europe. After elimination of all the American attacks on which data were incomplete or unsatisfactory, 38 remained. These yielded data on the physical character, before and after attack, of 1,276 separate building units, together with the probable density of attack on them. In addition, complete data were collected on one RAF attack, involving damage to 14 different industrial plants. The data have proved adequate in quantity and quality for establishing many illuminating generalizations concerning bombing operations, and have yielded vulnerability equations which should be useful in planning attacks. A summary of the results of the study appears below.

In the spring of 1945 a program of control attacks for the 20th Air Force was prepared. This was adopted in the field; the results were sent to Washington and were analyzed with a view to improving the effectiveness of attacks against Japanese industry.

Data Collection and Recording. For each of the attacks complete damage assessments were obtained from photo-interpretation carried out chiefly by DIDAS of the 8th Air Force and the Interpretation Unit of RE8 at Princes Risborough. The following additional data were collected at their source: the number of bombs aimed at the target, their type, size and fuzing, the identification number of the attacking groups, the number of planes and shape of formation flown, intervalometer setting used, bombing altitude, heading, track, time of bomb release. The study of a number of attacks had to be abandoned because the data were found at the source to be confusing, incomplete, or occasionally contradictory. Bomb plots were made of the locations of HE bombs within the site rectangle, based on pre- and post-attack photocover, for all the attacks studied.

To permit a quick and accurate examination of the data for indication of various suspected relationships among the variables, a punch-card system was adopted, with one card for each of the 1,276 building units (see EWT-1, 1). The punches on each card recorded the raid number, the building number, per cent of the floor covered by combustible material, roof classification as to combustibility, per cent of floor area subject to fire, building plan area to nearest 100 sq ft, number of floors, damage in hundreds of sq ft to structure and contents (separated into HE, fire, and mixed damage), superficial and contents damage (separated into fire and mixed damage), internal damage (separated into HE and fire), type of weapon used, approximate density of attack for each weapon (low, medium, or high).

Preliminary Tests on Validity of Data. Accurate estimation of the number of hits on a target is obviously a first requirement for assessing the performance of the various weapons. Determination of HE hits on a site rectangle was by actual plotting of bomb craters. To check the identification of bomb hits from photocover, the number of total photo-identified hits in a given target area was multiplied by the fractional built-up-ness of the target. The result was compared with the number of building hits identified. The agreement was from +6 per cent to −3 per cent (see EWT-1e).

Incendiary bomb density on a site rectangle was calculated by multiplying the actual density of HE bombs (determined as described above) by the ratio of incendiaries to HE bombs in the

plane loads. In EWT-5a, this method was checked by comparison with a few known-to-be-incomplete M47 IB plots, and a method was developed for correcting these plots to a completed basis for comparing densities in different parts of the target area. The results are in fair substantiation of the simpler procedure relied on exclusively in the weapon analysis studies.

The accuracy of roof classification is important in incendiary studies. Pre-attack photocover had been used at Princes Risborough to classify roofs. In EWT-1f this classification was compared with the better classification based on post-attack photocover. It was found that 80 per cent of the roofs had been classified correctly. Based on a classification of 1,233 roofs, 68.5 per cent of building units had combustible roofs, and 60 per cent had both combustible roofs and combustible floors.

A homogeneous target is one comprising building units in which all units are essentially equally responsive to attack by a particular bomb. A reasonable approximate vulnerability equation for such a target is $F = 1 - e^{(M_1D_1 - M_2D_2)}$. Let x = the fraction of the total density, $d = (D_1 + D_2)$ which is of type (2), i.e., $x = D_2/(D_1 + D_2)$. It is then easy to show that the gross MAE based on the total density varies from M_1 when $x = 0$ to M_2 when $x = 1$, and is linear in x. This provides a test for homogeneity of targets. When applied, the test indicates that noncombustible roof buildings are moderately homogeneous, but combustible ones are not (see EWT-1h).

Building Types. Classification of buildings by roof type has already been mentioned above. The spans of the principal structural members, the number and spacing of columns, the height of the structure, presence of traveling-crane runways are all features significantly affecting the resistance of a building to HE damage. Based on a classification of 1,276 building units, the dominant types were found to be industrial, single-story buildings of less than 10,000 sq ft floor area (38.4 per cent), multistory framed and wall-bearing buildings (9.6 and 11.6 per cent), and large single-story buildings without traveling cranes, of simple beam-and-column or truss construction (11.1 and 15.4 per cent).

Structural HE Damage. Based on 178 building units, the mean area of effectiveness of the 500-lb U. S. GP bomb was found to vary for 5 building types from 2,600 to 3,300 sq ft per bomb hit including no-damage hits, or from 3,100 to 4,100 sq ft excluding such hits. These are plan areas in multistory buildings. The floor damage is represented by the figures above, multiplied by the number of stories. For details see EWT-2f.

The near-miss effects of the 500-lb GP bomb were studied in EWT-1j. Based on 433 analyzable cases of misses within 45 ft of a building, it was concluded that a 500-lb GP bomb falling more than 15 ft from a European industrial building causes insignificant damage and that near-misses within 15 ft are but 10 per cent as effective as direct hits.

Fire Spread. The determination of the importance of fire spread in industrial buildings was essential to the development of a satisfactory quantitative relationship for predicting damage. Spread of fire damage was first studied in the case of pure HE attacks. Thirty-four analyzable incidents were available in which no incendiaries were used. It was found that HE fires starting in a single-story fire division with combustible roof usually spread through the fire division regardless of its size; in 10 to 14 combustible-roof cases the fire completely burned out the fire division, and in 3 of the remaining 4 the fire was stopped by interior partitions (the average plan area per fire division was 20,000 sq ft). By contrast, in fire divisions with noncombustible or fire-resistant roofs, the average spread was 33 per cent; the average plan area of single-story fire divisions in this category was 100,000 sq ft. Spread to an adjoining fire division occurred whenever the HE bomb fell within 40 ft of a fire division (see EWT-2g).

Mixed HE-IB attacks on single-story buildings were studied next. An analysis of 148 fire divisions with combustible roofs and 28 with noncombustible roofs led to the conclusion that combustible roof fire divisions burn out completely. Fire divisions with noncombustible roofs burn out completely if the plan area is up to 10,000 sq ft; for larger fire divisions, a limiting size of about 35,000 sq ft of burn-out is approached. A quantitative expression of this generalization is $E = 35{,}000(1 - e^{-A/35{,}000})$. It shows that the area of damage E approaches a limit of 35,000 as A increases (see EWT-3c).

If the buildings are multistory and the roofs and floors are combustible, a complete burn-out occurs due to fires from mixed attacks. If the roof is combustible and the floor noncombustible or resistive, 2- and 3-story buildings burn out about 1.5 floors (see EWT-3d).

Sometimes several building units are grouped by target analysis into a single composite fire division. An analysis of 94 building units comprising 36 composite fire divisions was made. Assuming that if a building unit in a composite fire division was not involved in a fire that destroyed the other buildings, then that building unit had been wrongly classified; it was found that at most 18 errors of assignment had been made on the 94 units.

From the above studies it appears that the concept of a fire division is essential in the estimation of damage to be expected by incendiary attack on industrial structures, and that knowledge of the areas of fire divisions in enemy targets is essential.

The Probability of Starting a Serious Fire. The method of analyzing data to determine p, the probability of starting a serious fire, is presented in EWT-3b for the 500-lb U. S. GP bomb, and in EWT-5b for incendiary bombs. These will be discussed separately.

Probability of Fire Starting by HE. Based on 440 fire divisions in 14 targets attacked by HE bombs alone, their probability of starting a fire was estimated in several ways. The values center around 0.17, the extremes found in reasonable samples being 0.15 and 0.19. This probability of one-sixth is independent of roof construction and height, but probably depends on building type and combustibility of contents. The probability of a 15-ft near-miss causing a fire is 0.05 ± 0.05.

From the above, it is concluded that when the area of a combustible-roof fire division is about 6 times the high-explosive mean area of effectiveness of the bomb, the bomb damage by fire will equal its HE damage. Since the MAE for a 500-lb HE bomb is around 3,000 sq ft, this calls for a fire-division area of around 18,000 sq ft to make the two effects equal. This is actually in the middle range of European industrial buildings. It follows that fire damage by HE bombs is not a minor correction factor in calculating total damage, but is rather of about the same magnitude as the HE damage.

Probability of Starting a Fire with an M47 IB (EWT-5c). Based on 560 fire divisions attacked with M47's, of which 186 were damaged by fire, the p for the M47 was found to depend on height and estimated occupancy[a] when the roof is combustible. A decrease of p with increase in height was observed in all but the highest occupancy class. Considering the facts that occupancy is an estimated quantity depending on available Intelligence and photo interpretation, and that true occupancy was for most cases unknown, deviations from a reasonable pattern of results are to be expected. It was concluded that p could be expressed[b] as the product of a roof-height factor, decreasing from unity for an 8-ft roof to 0 for a 55-ft roof, by an occupancy factor increasing from $\frac{1}{3}$ for 5 per cent occupancy to unity for 45 per cent occupancy. These functions are presented in Table 5.

TABLE 5. Probability of starting a serious fire with an M47 bomb.*

Height	Height factor	Occupancy per cent	Occupancy factor
8	1.0	5	0.33
15	1.0	15	0.66
25	0.5	25	0.78
35	0.2	35	0.89
45	0.1	45	1.00
55	0.0		

*Combustible-roof, European industrial buildings.

Table 6 presents a comparison of the observed and calculated number of fires found in each height-occupancy class.

The agreement is seen to be good. For noncombustible and fire-resistant roofs no dependence of p on height was found, but p does depend somewhat on occupancy. The value of p is around 0.05-0.06, varying from 0 for 15 per cent occupancy to 0.13 for 35 per cent occupancy.

Because there is generally a relation between

[a] Occupancy is numerically measured as the per cent of the floor area covered with combustible material.

[b] p = height factor × occupancy factor.

TABLE 6. Comparison of observed and calculated number of fires in each height and occupancy class.*

Occupancy (%)	5	15	25	35	45	Totals in height class
Height, ft 7 to 9			5 4.0 (22)	2 2.0 (7)	0 0.6 (2)	7 6.6 (31)
10 to 19		2 1.7 (5)	20 20.3 (54)	19 17.3 (46)	1 1.2 (2)	42 40.5 (107)
20 to 29		2 1.6 (3)	6 7.7 (19)	6 4.1 (10)	2 2.1 (6)	16 15.5 (38)
30 to 39		0 0.6 (1)	1 2.5 (9)	2 1.7 (4)		3 4.8 (14)
40 to 49	0 0.0 (1)	0 0.2 (1)	1 0.9 (4)	0 0.5 (2)		1 1.6 (8)
50 to 59		0 0.0 (1)	0 0.5 (2)	0 0.0 (1)		0 0.5 (4)
Totals in occupancy class	0 0.0 (1)	4 4.1 (11)	33 35.9 (110)	29 25.6 (70)	3 3.9 (10)	69 69.5 (202)

*Combustible-roof buildings, attack No. 10 excluded.
Upper left entry is observed number of fires.
Upper right entry is calculated number of fires.
Lower entry in parentheses is number of fire divisions in sample.

building type and roof height, one may expect p to vary with building type. This is borne out by the data. Small single-story buildings of less than 10,000 sq ft have a high p, near unity; when the area exceeds 10,000 ft but the span is less than 75 ft, p drops to 0.39; when the area exceeds 10,000 sq ft and the span exceeds 75 ft, $p = 0.02$.

Probability of Starting a Serious Fire with an M50 IB (EWT-5d). The available data were not sufficient to establish p with the same certainty as for the M47. 135 fire divisions, of which 51 were damaged, were analyzed. In addition to the inadequacy of the data, there is some doubt as to the right to determine number of hits on a fire division from the average density over the site rectangle, because of the non-random fall of bombs released in clusters. However, the same general trends in p were noted as for the M47; namely, the distinct difference between combustible and noncombustible roofs ($p_{avg} = 0.05$ and 0.01, respectively), and a strong effect of height and of occupancy. Smoothing the data leads to recommended values of p given in Table 7.

TABLE 7. Probability of starting a serious fire with an M50 IB.*

Height in ft	Occupancy in % 5	15	25	35	45
7 to 19	0	0.02	0.05	0.10	0.15
20 to 29	0	0.01	0.03	0.05	0.07
30 to 39	0	0	0.02	0.03	0.04

*Combustible-roof, European industrial buildings.

Similarly to the M47 study, the relation of p to structural class of building was determined (all combustible-roof structures). Single-story small buildings, larger buildings with small spans, and larger buildings with spans above 75 ft have p values of 0.07, 0.05, and 0, respectively.

Data on noncombustible roof buildings were not available to an extent permitting determination of p.

Overall Damage Prediction. An attempt to fit the data by a pair of simplified vulnerability equations, one for combustible-roof buildings and one for noncombustible buildings, was not successful (EWT-1i).

Direct-Hit Effects of 500-lb GP Bomb (EWT-3f and EWT-4). Calculation of expected total damage was carried out in each of two ways. In the first, the actual number of counted hits on the target was used to predict damage. In the second, actual observed number of hits was replaced by a probability of hitting using the average density of bombs over the site rectangle. The corresponding equations developed are:

$$g = A\,\{1-[1-(pE+qM)/A]^{h}\} \tag{1a}$$

and

$$g = A\,\{1-e^{-(pE+qM)D}\} \tag{1b}$$

in which g = total damage area,

A = plan area of target,

p = probability of HE bomb to start serious fire = 0.17 (See EWT-3b),

E = expected area of extent of an individual fire. Depends on roof type. For combustible-roof buildings, $E = A$.

For other buildings E (in 1,000's of sq ft) = $35 \times (1-e^{-A/35})$.

$q = 1 - p$,

M = HE structural MAE (See EWT-2f),

h = observed number of direct hits,

D = density of bombing, number of bombs per unit area.

Note that g, A, E, and M are to be expressed in the same units. The above equations apply only to single-story fire divisions consisting of one building unit. For modifications to allow for multiple-story buildings and composite fire divisions, see original report.

A comparison of observed and expected damage, based on structural class of buildings, indicates an overall average error of 6 per cent when equation (1a) is used. As expected, when actual counted number of hits is replaced by the use of an average attack density D, the average error in prediction of results increases. On 13 attacks it is 11 per cent.

Miscellaneous. In EWT-1k the requirements for adequate pre-attack, attack, and post-attack photographic cover are discussed.

The experience of the AN-23 group in obtaining suitable data and the conflicting views held in various circles on inadequate evidence, led to the outline of a program of control attacks (described in NDRC Memo. No. A109N, OSRD Report No. 5034) designed to settle some of the outstanding questions in choice of airborne weapons.

3.6.2 Analysis of Incendiary Attacks on Japanese Cities

The information on which this analysis is based was obtained from the Joint Target Group, Air Intelligence, Army Air Forces, and from the Operations Analysis Section, Twentieth Air Force. This information was preliminary in nature and subject to revision on the basis of ground observations.

The data cover the first 27 attacks on Japanese cities during the period from January 3 to June 19, 1945, which have already been summarized in Table 4 of Chapter 1.

Incendiaries Used. The total tonnage of bombs dropped on these cities was 48,000 tons, of which 47,000 (97.4 per cent) were incendiary bombs. Out of 281 sq mi of built-up area in these cities, 107 sq mile (38 per cent) were burned out completely. Seventy-five hundred B-29's attacked these targets in order to deliver the 48,000 tons of bombs; 2,500 B-29's bombed visually and 5,000 bombed using radar, mostly on night raids.

The tonnage of bombs dropped through June 19 was less than one-half of the total incendiary tonnage dropped on Japanese urban areas until the cessation of hostilities. Detailed data regarding these latter raids are not yet available. Attacks made subsequent to June 19 were on cities of less than 200,000 population.

TABLE 8. Summary of munitions used in destroying Japanese city areas, January 3 to June 19, 1945.

Bomb	Cluster	Tons dropped	% of total
AN-M69	E28, E36, M19	25,000	53.0
AN-M47	...	12,000	25.4
AN-M50	M17	9,000	19.1
AN-M76	...	1,000	2.1
M74	M20	200	0.4

Table 8 is a summary of the munitions used in destroying these Japanese city areas up to June 19, 1945.

Strategy, Tactics, and Operational Results. A brief description of the general strategy and

operational results during this period of large-scale incendiary attacks follows.

1. During January and February 1945, three small, high-altitude precision, daylight attacks were made on Nagoya, Kobe, and Tokyo. 800 tons of AN-M69 incendiaries in E6R2 clusters were dropped on these three raids, resulting in a total damage of only 1 sq mile burned out. Post-raid photos of these raids indicated excessive scattering of the incendiary bombs on the target. This was probably due to the abnormally high winds prevailing from 20,000 to 30,000 ft over Japan and the relatively poor aimability of the E6R2 cluster. The low tonnage of bombs probably permitted effective fire fighting.

2. Following the small-scale incendiary raids, five big night raids were made during the period of March 9 to 18 on Tokyo, Kobe, Nagoya, and Osaka. These raids were made at low altitude, with each individual plane dropping its bombs on the target by radar. Ninety-five hundred tons of all types of incendiaries were dropped on these five raids, destroying a total of 26.4 sq miles (360 tons dropped per sq mi destroyed). These raids proved the vulnerability of the large Japanese cities to incendiary attack, and it was indicated that the raids would have to be made at low altitude in order to obtain a high degree of accuracy and with large tonnages of bombs in order to saturate the target and nullify fire-fighting efforts.

3. Following the five big night raids, there was a delay of 1 month before the next incendiary raid due to a lack of incendiary bombs at Guam.

4. On April 13 and 15 three large-scale night raids were made on the Tokyo area from low altitude employing saturation bombing tactics. Forty-two hundred tons of AN-M69 and AN-M47 incendiaries were used on these raids and destroyed 20.8 sq miles of the city area (200 tons dropped per sq mile destroyed). These raids were made possible by the arrival of a shipload of incendiaries at Guam consisting of approximately 80 per cent AN-M69 and 20 per cent AN-M47 bombs.

5. Following these 3 night raids, another delay of 1 month ensued, again caused by a shortage of incendiaries at Guam.

6. Beginning May 14, super raids, 500 planes each, were made on the 5 largest Japanese cities of Tokyo, Nagoya, Yokohama, Osaka, and Kobe. In an attempt to confuse the Japanese anti-aircraft defenses, these raids were made both during the day and night and varied from low to medium altitudes. It was the opinion of JTG that fire fighting was probably abandoned by the Japanese air-raid defenses during these raids. 27,500 tons of all types of incendiaries dropped on these raids resulted in 48.6 sq miles of damage (565 tons dropped per sq mile destroyed).

7. After June 15, the large cities of Japan were considered to be burned out and no further incendiary raids were conducted on them. The focus of attack was shifted to cities between 200,000 and 400,000 population. Between June 17 and 19, about 1,000 tons each of AN-M69 and AN-M47 incendiaries were dropped on Kagoshima, Omuta, Hamamatsu, Yokkaichi, Toyohashi, Fukuoka, and Shizuoka. These raids were all made at night from low altitude and employing saturation bombing tactics. Most of the built-up area of each city was burned out on the first raid, about 1½ to 2 sq miles in each city.

8. From June 19 until August 10, attacks were centered on cities under 200,000 population because of the burning out of the larger cities. These raids were made mainly at night and from low altitudes. Plane losses during this period were negligible.

Observations concerning the tactics and conditions surrounding the raids include the following.

1. The rapid development of smoke during daylight attacks made precision bombing even from medium altitudes most difficult. This smoke in some instances obscured the target in 5 min, indicating exceedingly rapid fire development. Since these raids were conducted over a period of 1 to 1¼ hr and used formation bombing, the formations following the lead planes frequently were forced off course in order to obtain a bearing on the target. This resulted in the bombs landing as much as 2 to 4 miles away from the target. For example, during the May 14 raid on North Nagoya, only 14 per cent of the bombs released fell within 4,000 ft of

the assigned aiming point. Of the total of 12,000 clusters dropped, 64 per cent fell within the city, 17 per cent fell outside the city, and 19 per cent were unaccounted for. In this particular raid the area which received the heaviest concentration of bombs was approximately 2,000 ft away from nearest aiming point and was relatively unsettled farming and manufacturing area.

2. The effect of rapid smoke obscuration of the target during daylight raids on formations following the lead plane at an average altitude of 18,000 ft is shown in Table 9.

TABLE 9. Accuracy of day incendiary missions.

Period of attack	% of bombs within ½ mile	1 mile	2 miles	Average distance of bombs from target*
First quarter	27	55	20	4,300 ft
Remaining quarters	13	35	38	5,300 ft
Whole	17	41	30	5,000 ft

*Excluding bombs falling more than 2 miles from target.

3. Data regarding the accuracy of night incendiary missions employing individual radar bombing are given in Tables 10, 11, and 12.

TABLE 10. Accuracy of night incendiary missions.

Location of cities	Radius of circle containing 50% of ident. patterns (CEP)	Per cent of identified patterns which fell within 2,000 ft	4,000 ft	6,000 ft
Inland	6,250 ft	8	24	50
Coastal	4,000 ft	18	50	75

It appears from the data in Table 10 that the accuracy achieved on coastal cities was substantially higher than that achieved on inland cities, probably because of the greater accuracy of radar in delineating between water and land, as compared to areas completely surrounded by land.

TABLE 11. Accuracy of night incendiary missions.

	Per cent of identified patterns which fell within 4,000 ft AP		
Altitude in feet	7,500-8,500	9,500-11,000	15,000
Coastal cities	58%	50%	33%
Inland cities	....	26%	16%

The data in Table 11 indicate that the accuracy of bombing on night incendiary missions decreased significantly with an increase in altitude.

The data given in Table 12 confirm that the first quarter of the attack achieved a significantly higher accuracy than succeeding quarters, which phenomenon was first noticed in the precision daylight missions. The severe thermals encountered by the planes over the target after fires have been set may offer an explanation.

TABLE 12. Accuracy of night incendiary missions.

Period of attack	Radius of circle which contained 50% of the ident. patterns (CEP)	Per cent of identified patterns which fell within 2,000 ft	4,000 ft	6,000 ft
First quarter	4,200 ft	23	49	72
Remaining quarters	5,500 ft	8	33	60

It is generally believed that the effect of natural ground wind on fire propagation during these attacks was negligible in comparison with the tremendous draft created by the fires. For instance, on one raid in Tokyo there was reported a 70 mph ground wind in the city. Never in the history of the Tokyo weather observatory had there been a wind over 55 mph during that month. In general, the average wind over most of these Japanese urban areas varies from 10 to 15 mph.

Efficiency of AN-M69 Bomb. The most reliable estimate of the minimum bomb load required to accomplish substantially complete (80 per cent) destruction of typical Japanese dwelling areas is about 125 tons per sq mi, as shown in the table following below. These raids are discussed in greater detail in the following sections. The minimum bomb load was determined by excluding those areas which were supersaturated with bombs and excluding that part of the bomb load which was dropped on supersaturated and unsettled areas. Areas chosen for analysis were residential in which between 50 and 100 per cent destruction occurred, in order that a threshold value of bomb load required for 80 per cent destruction of residential areas (20 to 80 per cent roof coverage) could be determined.

City	Raid date	Tons of incendiary dropped AN-M69	AN-M47	Total area destroyed sq mi	Minimum tons incendiaries per sq mi of residential area required for 80% damage
Nagoya	5/14	2,679	0	3.1	160
Osaka	3/13	1,782	56	6.6	125
Kagoshima	6/17	476	360	2.0	
Toyohashi	6/19	558	426	1.7	120 avg
Shizuoka	6/19	531	375	2.3	

North Nagoya Raid, May 14, 100 Per Cent AN-M69. This raid was the only large-scale, daylight, 100 per cent AN-M69 attack on a Japanese city. Strike photos were available to permit a reasonably good analysis of the bomb-fall location[38] and pre-raid and post-raid damage photos have been analyzed for the extent of damage to various areas. Since most of the other large incendiary raids were either made at night with few strike photos or else employed a mixture of incendiary bombs, it is believed that this raid is probably the best source of data for a direct analysis of the efficiency of the AN-M69 bomb.

Possible errors in this analysis, however, limit its accuracy to about ± 50 tons per sq mile. These errors include (1) only 80 per cent of the bomb falls were able to be plotted, (2) the plotted location of a given bomb fall is estimated as varying up to 2,500 ft from the true location, and (3) this raid was conducted using formation bombing at five different aiming points located between previously burnt-out areas and farmland which resulted in numerous bomb falls landing in these waste areas. Also, in view of the relatively poor bombing accuracy on this mission (only 6 out of 42 plotted formation bomb falls fell within 4,000 ft of the assigned aiming point), it is probable that the concentration of bombs within the target areas was not uniform but spotty, thus leading to bomb requirement values in excess of the true tonnage required.

In summary, the conditions under which the Nagoya raid was carried out and the analysis made, make the 160 tons per sq mile value more likely to be higher than the true value. The subsequent analyses tend to confirm this statement.

Osaka Raid, March 13, 97 Per Cent AN-M69. This raid was the first large-scale raid on Osaka, and thus has the advantage over the Nagoya raid of striking virgin target areas. The raid analysis made by JTG[39] which led to the bomb requirement value of about 125 tons per sq mile may be summarized as follows: This raid was made at night, with all planes bombing individually using radar, a condition which should result in a normal distribution of bombs about the aiming point. With no strike photos available, a computation of the density of damage in circular areas about the mean center of damage was made. The values obtained indicated a good correlation with the normal distribution curve. Then, assuming that the density of bomb fall paralleled the density of damage, and that the center of damage coincided with the center of bomb fall, it was found that 125 tons per sq mile of M19 clusters (of AN-M69 bombs) was adequate to insure over 80 per cent destruction of Japanese city dwelling areas, about 40 to 80 per cent roof coverage.

This indirect analysis of AN-M69 fire-raising efficiency appears sound in principle, and may offer a more accurate solution than the direct analysis of the Nagoya raid, considering all the errors possible in trying to locate each bomb fall precisely. The values of 160 and 125 tons per sq mile obtained by the two methods are not, however, significantly different, and may be considered confirmatory.

Kagoshima, Toyohashi, and Shizuoka Raids, June 17, 19, 57 Per Cent AN-M69, 43 Per Cent AN-M47. As a further check on AN-M69 fire-raising efficiency, an attempt was made to analyze raid results on smaller cities. Most of these raids involved the use of several types of incendiaries, and thus are not strictly comparable with the Osaka and Nagoya raids. This analysis was undertaken for the raids on Kagoshima, Toyohashi, and Shizuoka using data on bombing accuracy from the Operations Analysis Section, XXI Bomber Command.[40, 41] The method of analysis employed was similar to that used for the Osaka raid: Bomb distribution was assumed to follow the normal distribution curve, since these raids were made at night using radar individual bombing. Exact values for the density of bombs were obtained from OAS, e.g., the circular probable error for this type of bombing has been found to be 6,250 ft.[c] The aiming points for these raids fortunately coincided with the centers of damage; thus it could be assumed that the aiming points coincided with the center of bomb density. Damage to various areas around the aiming points was estimated from post-raid photos. Calculations for the three raids have been averaged in the following table.

Radius of annulus about aiming point, ft	Annulus area, sq mi	Area burned out in annulus, sq mi	Bombs striking annulus area, tons (clustered)	Tons of bombs per sq mi damaged
0–2000	0.45	0.43	146	340
2000–4000	1.35	0.95	146	169
4000–5000	1.02	0.40	74	185

Since large areas in the outer annuli were not built-up but comprised mountainous and farming areas, a further series of calculations were made to limit the bomb requirement to residential areas which showed more than 20 per cent roof coverage.

Radius of annulus about aiming point, ft	Built-up annulus area, sq mi	Built-up area burned out, sq mi, %		Bombs striking built-up area, tons (clustered)	Tons of bombs per sq mi damaged
0–2000	0.44	0.43	98	143	330
2000–4000	1.08	0.92	85	117	123
4000–5000	0.51	0.35	69	37	106

The bomb-requirement value of about 120 tons per sq mile for 80 per cent destruction of residential areas is, of course, based on the mixed bomb load of 57 per cent AN-M69's and 43 per cent AN-M47's, and as such is not strictly comparable with the Osaka and Nagoya values. However, this analysis tends to confirm the order of magnitude of the previous values.

[c] Unpublished data from Joint Target Group (JTG).

Chapter 4

PORTABLE FLAME THROWERS

4.1 INTRODUCTION

THE USE OF PORTABLE flame throwers as they are thought of today dates back to World War I. These early models used a fuel mixture of a heavy and volatile oil which was propelled by compressed gas. At the start of World War II, few experiments had been made on the weapon, but the German army used them successfully against strongly held positions in the 1940 invasion of the Lowlands. With the United States entry in the war and the beginning of close jungle warfare, interest in flame throwers increased. A report of the Ad Hoc Committee on Flame Throwers in June 1942 showed that a limited interest in portable flame throwers existed and that development should be undertaken.

In this chapter, the NDRC contribution to the Portable Flame Thrower Program is summarized. As an expedient, the initial step consisted of redesigning the inefficient M1 portable flame thrower in order that thickened fuel as well as unthickened fuel could be used.

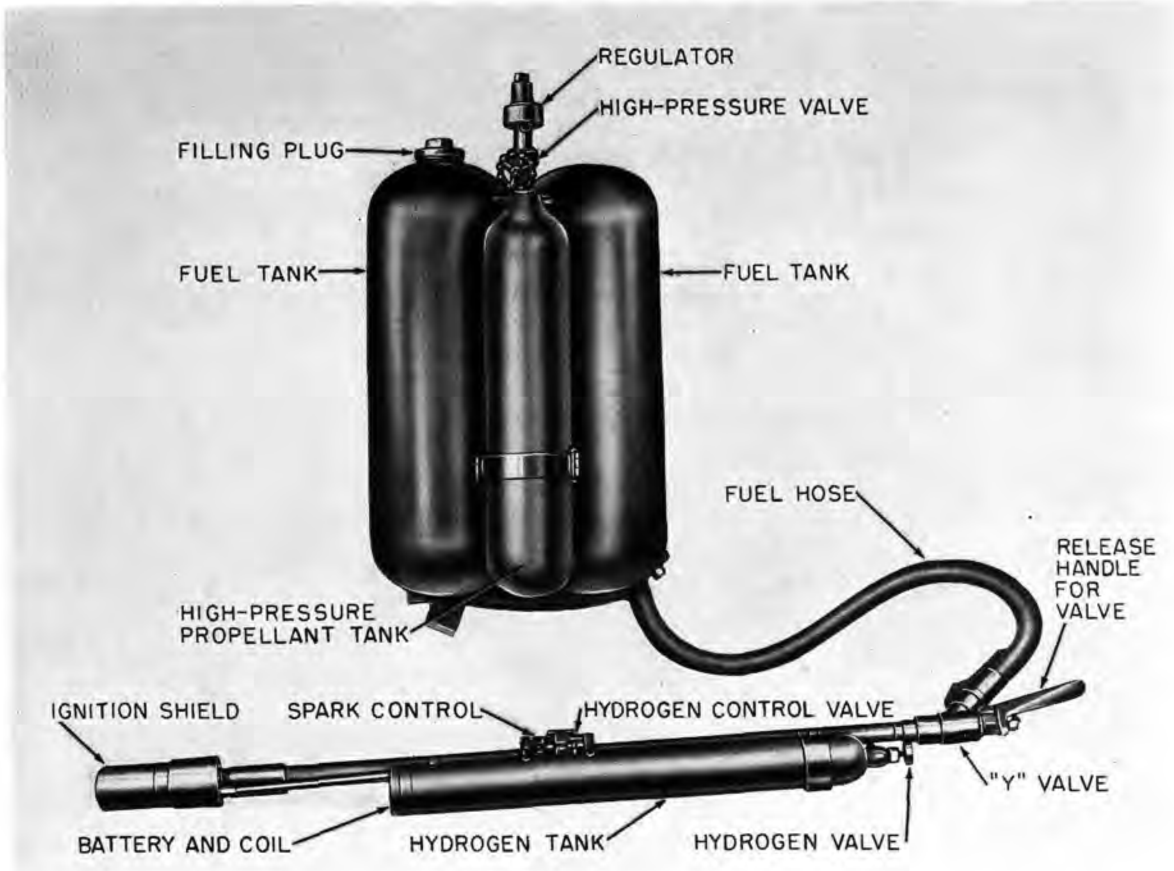


FIGURE 1. M1A1 portable flame thrower.

Realizing the limitations of the M1 model, or any improved model designed in the same manner, a development program was begun on an entirely different design. From this development work emerged the E2 flame thrower of Standard Oil Development, and E3 flame thrower of the Chemical Warfare Service. Comparative tests of the E2 and E3 by the using

Chapter 8

FUELS FOR INCENDIARIES AND FLAME THROWERS

8.1

INTRODUCTION

Fuels used in incendiary bombs and flame throwers played an important part in World War II. In fact, the contribution of these fuels resulted in using fire as a weapon to a far greater extent in this war than in any previous war in history. Of the fuels used, by far the most important was gasoline gel thickened with Napalm. This fuel, in varying consistencies, was used in the following important weapons in World War II:

AN-M47, 100-lb incendiary bomb, AN-M69, 6-lb incendiary bomb, portable flame throwers, flame throwers mounted in tanks, and jettisonable gasoline tanks, dropped from fighter airplanes.

This type of fuel was developed by NDRC. During 1942 and 1943 some AN-M47 and AN-M69 bombs were filled with gasoline gel thickened with isobutyl methacrylate polymer (IM). This material was developed by the duPont Co. under the joint sponsorship of NDRC and the Chemical Warfare Service.

The only other fuels actually used in the war were some fortified or pyrotechnic fuels (PT) consisting of mixtures of hydrocarbons, metals, and oxidizing agents which were used in the M74 and AN-M76 incendiary bombs. These fuels were developed by the Chemical Warfare Service.

The other types of fuels described in this chapter were experimental attempting to correct one drawback or another of Napalm-thickened gasoline fuels, or which were developed for some special use. In Section 8.3 are described liquid thickening agents, which arose from the desirability of mixing fuels in the field or on an aircraft carrier by simply mixing two liquids rather than a solid and a liquid. Section 8.4 describes methacrylate thickening agents, which were a valuable substitute until Napalm was fully developed. Sections 8.5 and 8.6 describe two possible substitutes for Napalm or methacrylate thickening agents in case both of these became in short supply. Section 8.7 describes fortified fuels which were more fiercely burning and less easily extinguished by water than ordinary gasoline gels. Section 8.8 describes self-igniting fuels which have an obvious interest both in flame throwers and in incendiary bombs. Sections 8.8, 8.9, and 8.10 describe fundamental studies which were undertaken better to understand the nature and modus operandi of thickened fuels.

8.2

NAPALM[1-54]

8.2.1

Introduction

The gasoline thickening agent called Napalm is an aluminum soap of naphthenic, oleic, and coconut oil acids, of which the most common formula uses 50 per cent coconut oil acids, 25 per cent naphthenic acid, 25 per cent oleic acid. The development of a new thickening agent for gasoline made from readily available materials was dictated by the unavailability of rubber for this purpose after December 1941. The development of Napalm was initiated by Harvard University in December 1941 under Contract OEMsr-179. In March 1942 Nuodex Products Co. came into the picture and made major contributions to the early development of Napalm, although their work was not formalized by Contract OEMsr-677 until August 1942. Other contributors to the development and improvement of Napalm were Arthur D. Little, Inc., working under Contract OEMsr-242, Standard Oil Development Co. under Contracts OEMsr-183, 354 and 390, Eastman Kodak Co. under Contract OEMsr-538, Harshaw Chemical Co. under Contract OEMsr-847, and Ferro-Drier and Chemical Co. under Contract OEMsr-882.

By February 1942 three types of soap thickening agents which showed considerable promise had been developed by Harvard University.[1] These were designated as (1) Palmene, aluminum palmitate and neo-fat 3R (40 per cent oleic, 60 per cent linoleic acid), (2) oleopalm, aluminum oleate and aluminum palmitate, and (3) Napalm, aluminum naphthenate and aluminum palmitate.

The first Napalm was made by putting aluminum naphthenate through a meat grinder with wood flour and milling aluminum palmitate into the mixture. A dry powder resulted which could be dispersed in gasoline at ordinary temperatures. A subsequent mixture of one part aluminum palmitate, one part aluminum naphthenate, and two parts of kerosene agitated in a dough mixer at 100 F was found to be greatly superior in toughness and stability. This tough, gummy mixture was incorporated into gasoline by passing it through a meat grinder and agitating the disintegrated material in the gasoline with a stirrer, or by circulation through a gear pump. Later, half the naphthenic acid was replaced with oleic because of the reported shortage of the former. Nuodex Products Co. found that this modified Napalm could be produced by means of a coprecipitation process as a dry granular solid readily dispersible in gasoline at ordinary temperature. Because of the ease of manufacture and of mixing with gasoline, this material was standardized, and manufacture was begun in December 1942. A total of about 80,000,000 lb was produced before the end of World War II.

Although practically all Napalm has been manufactured according to the standard formula (25 per cent oleic, 25 per cent naphthenic, 50 per cent coconut oil acids), additional research, both in this country and in England, has shown that the aluminum soaps of practically all combinations of these acids, including 100 per cent oleic or 100 per cent naphthenic, are moderately satisfactory gasoline thickeners, although varying considerably in specific physical properties. However, if more than about 80 per cent coconut acids are used, the resulting soap cannot be dispersed in gasoline at room temperature. The British used aluminum stearate-thickened fuels exclusively. These fuels were factory-mixed at 120 to 130 F.

8.2.2

Manufacture

General. At various times during the period 1943-1945 the following nine companies were engaged in large-scale production of Napalm: Nuodex Products Co., Imperial Paper and Color Corp., Ferro Enamel Corp., McGean Chemical Company, Pfister Chemical Co., J. S. and W. R. Eakins Co., California Ink Co., Oronite Chemical Co., and Harmon Color Works. In addition, a few batches were manufactured by Colgate-Palmolive-Peet Corp. All manufacturers used some variation of a process in which the water-insoluble, basic aluminum soaps of the mixed acids were coprecipitated from aqueous solution. Variations in precipitation and drying methods were largely attributable to differences in the equipment which was available to the individual manufacturers.

The most commonly used precipitation process is a batch process in which the total amount of caustic required, about 60 per cent in excess of the amount necessary to neutralize the acids, is added to the mixed acids, the alum then being added gradually until the precipitation is complete. In one variation of this method only enough caustic is added to the mixed acids to produce the stoichiometric soap solution, the balance being added with the alum solution. In this second method the precipitation is begun at a lower pH and the separation of aluminum soap is more gradual than in the standard batch method. In addition to the batch methods, a continuous two-stream precipitation technique was developed by one manufacturer, Eakins. This involves the addition of controlled streams of the alum and sodium soap solutions to a vessel supplied with vigorous agitation. The alum added in the first stage is insufficient to cause coagulation of the soap, and the resultant milky solution overflows into a second vessel along with another stream of alum to form an excess of this reagent. The suspended precipitate then flows to a washing and draining device. The first-mentioned batch method has been most generally used and was early recommended as a standard process.[10] The two-stream method requires less space for the equipment used, and in addition, yields a particularly fast setting variety of Napalm which is desirable in certain applications.

Raw Materials.[51] Variations in acid quality may be responsible for considerable differences in the character of the soap produced. Regular laboratory testing of new shipments of acid is a necessity for satisfactory Napalm production. The following specifications have been found suitable.

	Coconut oil acids	Naphthenic acid	Oleic acid
Acid number	260-270	230-245	190-200
Iodine number	Below 15	Below 10	85-90
Iron	Below 0.01%	Below 0.01%	Below 0.01%
Unsaponifiable	2% maximum	Below 8%	Below 2%
Titer, F.	75-77	......	46-54

At first it was considered necessary to use only rectified naphthenic acids, but as supply became critical, crude naphthenic was used with entirely satisfactory results. The use of high acid-value coconut oil acids results in Napalms of exceptionally high thickening power; hence this variable should be carefully controlled.

Some difficulty was encountered at first with war-grade alums made from clay; this was on account of their high iron content. If possible, the iron content should be below 0.03 per cent and manganese below 0.01 per cent. These materials are deleterious because of their action as oxidation catalysts; hence somewhat larger percentages can be tolerated if an oxidation inhibitor such as alpha-naphthol is incorporated in the Napalm.[51] It is recommended, however, that metallic impurities be kept at a minimum even if an inhibitor is used.

Dewatering and Drying. The type of dewatering used prior to drying has little effect on the product. However, there is some evidence that if the wet pump is allowed to stand overnight or longer before drying, the thickening power of the Napalm is increased. Tray and continuous belt drying have been successfully used, the first being the most common. In tray drying, an air temperature of 160 F is optimum and a drying time of 15 to 20 hr is common for cake depths of approximately 2 in. In general, it is advantageous to use as high a drying temperature as possible without causing undue oxidation or fusion. With belt driers and thin layers of material the drying temperature may be as high as 200 F and the drying time reduced to about 1 hr. At the end of World War II some contractors were beginning to install infrared drying equipment.

Packaging. Napalm is packed in hermetically sealed containers. Package sizes for regular Napalm are 5¼ lb, 15¾ lb, and 100 lb; the first two were primarily for overseas shipment for field mixing of flame throwers and blaze bombs, and the last for shipment to arsenals and factories filling incendiary bombs. Ground Napalm for the Navy is packed in 60-lb containers. Because of the moisture susceptibility of Napalm it is necessary that care be exercised in handling the Napalm between drying and packaging. Containers used for overseas shipment have been quite successful in preventing contamination of the soap by moisture, as evidenced by testing of numerous samples returned from the various war theaters.

Specifications.[11] The most important Napalm specification is the one regarding thickening power, which is evaluated by the Gardner mobilometer. Gardner consistency is the weight in grams required to force the plunger through the material in the tube at a rate of 0.1 cm per sec. Originally, consistency was specified only for 8 per cent gasoline gels, the allowable range being 500 to 800 g after storage for one day at 77 F and at 150 F. Later special consistency tests were instituted for 6.2 per cent and 11.5 per cent gels. The test gasoline used after about February 1944 was a high-boiling fraction (naphtha) supplied by the Continental Oil Co., Baltimore, Maryland. This gave, in general, higher consistencies than the Standard Oil Development Co. test gasoline used previously; the change was made because the naphtha, being low in unsaturates, was less likely to oxidize on long storage, and having a high boiling point lost less weight on handling and testing of the Napalm gels made from it.

Additional specifications include moisture, 0.4 to 0.8 per cent by CWS benzene distillation method, oxidation-inhibitor content, and general gel characteristics, stringiness, healing, etc. Gelation rate in gasoline was originally specified, but this specification was not in force during most of the period of production.

Variability. Although comparatively little difficulty was encountered by most manufacturers in producing Napalm which would pass specifications, the resulting products were quite different in some respects. In general, however, each manufacturer's product was quite uniform from batch to batch. The most important differences were in setting rate, variation of consistency with concentration, and susceptibility to water and other additives. In general, Eakins Co., Pfister Chemical Co., and California Ink Co. produced fast setting Napalms, Nuodex Products Co. slow setting, and the Napalms produced by others were intermediate. Setting times (6.5 per cent gels in test naphtha, 77 F) of ten samples from each manufacturer, produced in the period June 1944 to January 1945, were determined by the Chemical Warfare Service Technical Command[40] by using the disap-

TABLE 1. Consistency, stability, and moisture susceptibility of representative Napalms (1943).

Manufacturer	Condition % of relative humidity	Moisture CWS benzene distillation	Gardner consistency, grams 4% gel 1 day	4% gel 32 days	8% gel 1 day	8% gel 32 days
McGean 462	As received	0.75	195	130	770	730
	90 F–20	0.85	245	90	720	660
	90 F–50	1.45	85	46	550	440
	90 F–70	2.2	22	8	280	220
Ferro 184	As received	0.65	258	140	770	760
	90 F–20	0.55	255	130	770	660
	90 F–50	1.0	170	55	670	515
	90 F–70	1.45	72	27	445	295
Pfister N3-2432-94	As received	0.7	145	88	645	625
	90 F–20	0.7	145	84	675	640
	90 F–50	1.05	90	54	575	490
	90 F–70	1.30	57	33	490	390
Harmon R 11285	As received	0.7	160	80	660	600
	90 F–20	0.75	170	80	690	610
	90 F–50	1.0	84	42	610	410
	90 F–70	1.2	32	21	310	215
Oronite J-33-C	As received	0.5	250	100	960	805
	90 F–20	0.45	290	115	990	840
	90 F–50	0.7	175	54	900	680
	90 F–70	0.95	133	27	760	460
California Ink 98	As received	0.7	160	72	620	520
	90 F–20	0.85	138	74	560	480
	90 F–50	1.1	66	34	390	320
	90 F–70	1.55	24	17	235	225
Imperial NR-232	As received	0.7	110	60	640	575
	90 F–20	0.7	74	64	830	590
	90 F–50	0.95	60	37	510	410
	90 F–70	1.45	51	24	330	305
Nuodex 19889	As received	0.7	200	125	760	690
	90 F–20	0.95	150	120	670	650
	90 F–50	1.2	104	69	550	500
	90 F–70	1.7	50	43	370	360
Colgate-Palmolive-Peet N3-2854-56	As received	0.4	190	90	790	630
	90 F–20	0.5	150	72	710	570
	90 F–50	0.75	91	51	610	435
	90 F–70	0.95	62	36	470	325
Eakins N3-2981-431	As received	0.65	90	50	570	430
	90 F–20	0.45	102	66	590	515
	90 F–50	0.7	82	51	550	380
	90 F–70	1.05	62	42	355	310

pearing vortex method. The average values for the different manufacturers are: Eakins 1.4 min, Pfister 1.5 min, California Ink Co. 2.2 min, Imperial 4.9 min, Ferro 5.2 min, McGean 5.8 min, Oronite 6.7 min. The fast setting of the Eakins soap appeared to be a result of the two-stream precipitation process. Ferro Enamel Corp. later changed to the two-stream method in order to produce fast setting Napalm for the Navy. Nuodex Products Co., which was no longer producing Napalm when the tests mentioned above were carried out, obtained slow setting by wet densification and controlled comminution. It is known that the setting rate can be controlled to some extent by means of the excess caustic ratio during precipitation.

Table 1 gives data on variation in consistency, stability, and susceptibility to water for ten representative Napalms manufactured in 1943.[21] Table 2 gives fragmentary data on samples received from six manufacturers early in 1945.

The differences in concentration–consistency relationships were quite pronounced for Nuodex and Imperial Napalms. This was especially important because for a time in 1943-1944 these two varieties were packaged for field mixing of flame-thrower fuels (5¼-lb packages). Although both passed specifications and had similar consistencies at 8 per cent, they were quite different at 4.2 per cent, the concentration commonly used in the portable flame thrower. Comparison of ten Imperial and ten Nuodex soaps showed a consistency range for 4.2 per cent gel of 52 to 96 for the former and 117 to 250 for the latter.[28] Differences in setting rate were just as pronounced, the average for Nuodex samples being 25 min, for Imperial 13 min (4.2 per cent gels in motor gasoline). Because of probable confusion to men in the field, who might obtain either of these varieties from time to time, the Imperial product was in late 1944 standardized as the Napalm for flame throwers. Thereafter it was the only variety packaged in the 5¼-lb container.

As a result of the above mentioned variability in the soaps from different manufacturers, Napalm was placed on cooperative procurement in August 1944. During this period no specifications were in force, and attempts were made by

TABLE 2. Consistency and stability of representative Napalm gels (1945).

Manufacturer	%	Xylenol, %	Gardner consistency grams 1 day	Gardner consistency grams 2 weeks
Imperial NR-1764	3	....	16	
	4	....	48	
	5	....	135	127
	6	....	250	210
	7	....	390	350
	8	....	505	540
	6	1.25	34	
	9	1.5	173	185
McGean 4778	2	....	15	
	3	....	40	
	4	....	151	< 84
	5	....	270	167
	6	....	410	260
	7	....	500	425
	8	....	680	555
	6	1.25	24	
	9	1.5	240	250
Eakins 480	2	....	7	
	3	....	64	
	4	....	171	129
	5	....	295	260
	6	....	410	385
	7	....	575	565
	8	....	740	
	6	1.25	80	
	9	1.5	470	405
Pfister N5-157-702	2	....	26	
	3	....	78	
	4	....	164	124
	5	....	245	215
	6	....	375	385
	7	....	490	560
	8	....	660	
	6	1.25	97	
	9	1.5	565	465
Ferro	3	....	32	
	4	....	89	
	5	....	200	9
	6	....	305	210
	7	....	485	370
	8	....	670	540
	6	1.25	41	
	9	1.5	295	305
Harmon N5-139-78	2	....	10	
	3	....	42	
	4	....	138	
	5	....	260	230
	6	....	380	370
	7	....	515	560
	8	....	750	750
	6	1.25	90	
	9	1.5	460	600

Chemical Warfare Service in cooperation with the manufacturers to modify their various procedures so as to produce more nearly identical soaps. These investigations resulted in special specification tests concerning inhibitor content of the finished soap, and consistency of 6.2 per cent and 11.5 per cent gels were instituted.[45] The inhibitor-content specification was a result of tests indicating that susceptibility to peptizers was a function of the alpha- or beta-naphthol concentration in the finished soap. Another specification change was reduction of the consistency range for the 150 degree test (8 per cent gels) to 550 to 750 g Gardner. The effect of these changes on Napalm uniformity has not been fully evaluated because World War II ended soon after Napalm went off cooperative procurement. Consistencies of 6.2 per cent gels of some of the last batches which were manufactured are: Eakins 120, 140, 123; Imperial 157, 190, 175, 148, 133; Ferro Enamel 172, 138; McGean 160, 235, 192, California Ink 107, 210; McGean 160, 235, 192, 260; Oronite 157, 156; and Pfister 250, 260.

The success of most of the manufacturers in producing a uniform type of Napalm over long periods indicates that the best means of improving uniformity is production of all the material in a single plant under identical conditions.

8.2.3 Thickened Fuels from Napalm

General. Thickened fuels may be prepared with Napalm by adding the soap to the gasoline and stirring with a paddle, or mechanical stirrer, until the Napalm particles swell to the point that settling does not occur. This point has been termed the stir time, or set time, of the fuel. With 6 per cent Napalm at a temperature of 70 to 80 F the required time of stirring may vary from 0.5 to 10 min with different Napalms. At 4.2 per cent the stir time is somewhat longer, the average for Imperial Napalms being 13 min, as noted above. At temperatures below 60 F the stir time becomes very much longer, and it is almost impossible to mix fuels below 50 F without incorporating a low-temperature peptizer. At temperatures above 90 F the stir time is quite short, particularly at the high concentrations used in incendiary bombs. In fact, under these conditions it may be impossible to obtain a homogeneous fuel because of the mixture "setting up" before all the Napalm can be incorporated. For this reason incendiary bomb filling plants require refrigeration facilities for cooling the gasoline in the summer months.

In all applications in which thickened hydrocarbon fuels are used, such as flame throwers, blaze bombs, and incendiaries, ordinary Napalm-gasoline mixtures, prepared as described above, give satisfactory performance. However, numerous experiments have shown that Gardner consistency, irrespective of Napalm concentration, is a reliable guide to the performance of these weapons with Napalm fuels. Thus additives which impart properties desirable in the preparation, handling, or storage of Napalm fuels may be incorporated even though they raise or lower the consistency, as long as the Napalm concentration is adjusted to give the desired consistency. Most additives which have been used lower the fuel consistency. These additives, commonly designated as peptizers, will be discussed in the section on *"Peptized Fuels,"* p. 199.

Thickened Fuels for Portable Flame Throwers. The recommended mix for the portable flame thrower is 4.2 per cent Napalm in ordinary motor gasoline (one 5¼-lb can in 20 gal). With most Imperial Napalms this produces a consistency of 75 to 100 g, and tests by various groups engaged in research on flame-thrower fuels indicate that this is about the consistency which gives optimum long-range performance in the portable flame thrower. Variations resulting directly from gasoline quality,[35] the use of a different Napalm, or accidental introduction of water or other peptizers during mixing might easily result in 4.2 per cent fuels of consistencies anywhere in the range 25 to 250 g Gardner. Although, generally speaking, no instruments for measuring consistencies were available in the field, men in charge of mixing became capable of estimating consistency of fuels from their handling characteristics, pourability, etc., and reports from the field indicate that numerous alterations in the basic formula were made in order to obtain the desired mixing and firing characteristics. In addition to the change of Napalm concentration, these variations included incorporation of water, xylenol, silica gel, diesel oil, and motor oil. Some of these formulations will be discussed in separate sections below.

Thickened Fuels for Mechanized Flame Throwers. Mechanized flame throwers are those which are mounted on a vehicle, as opposed to portables which are carried on a man's back. Mechanized models which have a small, 5/16-in., nozzle use about the same fuel as portables, but models with larger nozzles, ½ to 1 in., can profitably employ a fuel of somewhat higher consistency.

Mechanized flame throwers with large nozzles have been used very little by the U.S. Forces. The Navy Mark I flame thrower (E7 gun), developed by Standard Oil Development Co., saw action in the Peleliu invasion. As a result of tests which had been carried out at SOD the fuel recommended for this gun was 7 per cent Napalm, approximately 400 to 500 Gardner. It was found that fuels of this concentration mixed on Peleliu gave a somewhat more bushy flame than desired and the concentration was increased. However, Lt. Williams of the Navy, who was in charge of the mixing operations, stated that the fuels mixed on Peleliu appeared to be considerably below normal in consistency. According to the statements of Lt. Williams, a rod-like flame was desired for ease of aiming, with a burning time sufficient to set off the ammunition stored inside pillboxes.

A critical study of the effect of fuel consistency on mechanized flame-thrower performance has been carried out by CWS-NDRC Flame Thrower Evaluation Group and the Flame Attack Section of the Medical Division, CWS, at Edgewood Arsenal. The bulk of the tests dealt with the lethal effects of thickened fuel shot into a pillbox, live goats being used as subjects. The tests showed that the fuel consistency for the best compromise among lethality, effective range, ease of handling, and aimability is 200 to 250 g Gardner.

The tests further show that for fuels varying from unthickened to 200 g consistency, roughly 1 gal per 1,000 cu ft of volume is required to kill the occupants. The required quantity of fuel increases with increasing fuel thickness up to approximately 2 gal per 1,000 cu ft for fuels of 700 g consistency. Maximum effective range was construed to be the maximum range at which all goats in the bunker were killed. No increase in maximum effective range, above 80 yd, was observed on increasing the consistency above 200 g. It is possible to refuel flame throwers from light drums with 20 psi pressure with fuels of 200 g consistency, but it is impossible for fuels higher than 400 g consistency. Interference to visibility due to bushy flame is slight for fuels of 200 g consistency, though somewhat greater than for fuels of 400 to 700 g consistency.

Ranges in excess of 200 yd (center of deposit) can be attained with large nozzles if fuel consistency is increased to 1,000 g Gardner.[54] A gun elevation of 15 degrees or more is required, and the fuel falls at a very steep angle at extreme range. Hence, aimability is greatly reduced, and the usefulness of such a weapon is limited to area firing, as in landing operations and river crossings.

Thickened Fuels for Blaze Bombs. A considerable amount of Napalm was used by both the Army and the Navy for thickening gasoline used in filling the droppable fuel tanks known as blaze bombs. The optimum consistency for this application was 200 to 400 g Gardner. Lower consistencies resulted in too much flash burn, higher consistencies in incomplete ignition of the fuel. Some of the fuel used by the Army in the European theater was mixed by National Oil Refineries Ltd. in England, the remainder, by chemical companies behind the lines. Eakins, Ferro, Imperial, and McGean Napalms were used at Llandarcy. Concentrations of 5.7 to 6.7 per cent were required to obtain the desired consistency. Parts of each batch were retained, and stability was generally satisfactory over a five-month surveillance period.[47]

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 the take-off. An injector-type mixer, similar to that used in producing foams for fire fighting, was developed by National Foam Systems, Inc., in conjunction with the Navy. The need for an especially rapid-setting Napalm for use in this

equipment led to the development of ground Napalm containing finely divided magnesium carbonate which served as a grinding aid and anti-agglomerant. Practically all this material was produced by Ferro Enamel Co. which converted its plant to use the two-stream precipitation process in order to obtain as fast setting a soap as possible. Laboratory tests have shown that the magnesium carbonate is not entirely satisfactory as an anti-agglomerant, since the ground Napalm is compacted into a solid mass after several days at 150 F. A few drums of the ground soap from regular production have been found to be agglomerated after storage at ambient temperature in the United States. However, since no complaints were received from the war theaters, the use of the ground soap can probably be considered a success.

Thickened Fuels for Incendiaries. Napalm has been used extensively as a thickening agent for gasoline fillings for AN-M69 and AN-M47 bombs. M69 bombs used 9 per cent Napalm, with a specification consistency range of 700 to 1,100 g Gardner. Tests carried out by CWS Technical Command[8] showed that consistencies of 500 to 1,100 gave satisfactory performance; the lower limit of 700 was set to allow for decrease of consistency on aging. The commonly used performance test for M69 bombs consisted in firing against a vertical plywood target and observing adhesion and scatter of the fuel. The peptized types of Napalm (those on the low side of the specification range) were found to give superior performance in this test, and at one time the use of peptized fuels in the M69 was considered. This was abandoned because of the difficulty of setting up specifications and mixing such fuels reproducibly.

The concentration of Napalm used in the M47 bomb was 11.5 per cent, the higher consistency being required because of the greater shearing force applied to the fuel on the bursting of this bomb.

Peptized Fuels. One of the earliest peptizers to be found useful was xylenol (and other phenolic compounds). With the use of this additive, it is possible to compound Napalm fuels at temperatures as low as zero F, whereas ordinary Napalm cannot be dispersed in gasoline in a reasonable time at temperatures lower than 55 F. In addition, the incorporation of peptizers renders Napalm fuels less rigid and elastic, and more like ordinary liquids. Hence, at equal Gardner consistencies peptized fuel can be more readily poured into a flame-thrower fuel than regular Napalm and is less susceptible to channelling in the tank. Peptized fuels are more stable than regular Napalm, especially at low consistencies. Hence, if storage of the fuel for a long time were required, a 6 per cent fuel reduced in consistency to 100 g Gardner with alcohol, xylenol, etc., would be superior to a 4 per cent Napalm without peptizer. For example, the consistency of a 4.5 per cent Napalm fell from 120 to 75 g Gardner in two months in a steel drum, and that of a 6 per cent Napalm containing 0.1 per cent ethyl alcohol, from 125 to 105.

At the request of the Infantry Board, a flame-thrower fuel was developed in an attempt to combine the principal advantages of unthickened and thickened fuels, i.e., fierceness of burning and long range, respectively.[26, 27] Flame-thrower shots with peptized and unpeptized fuels of various consistencies showed that the desired characteristics were most nearly attained at about 25 g Gardner. Ordinary 2.5 to 3 per cent Napalm fuels have about this consistency, but such fuels were considered undesirable because of long mixing time and poor keeping characteristics. After a series of tests with peptized fuels of 4 to 8 per cent Napalm, it was decided that a 4.2 per cent Napalm reduced to 25 g Gardner with either 0.5 per cent xylenol or 0.05 per cent water should be satisfactory if long-time keeping were not required. These fuels were tested by the Infantry Board, and the one prepared with water (one 5¼-lb can Napalm, two tablespoons water, 20 gal gasoline) was adopted for uses for which a "brush flame" was desired.

One important disadvantage of peptized fuels compounded with xylenol is their large increase in consistency with decrease in temperature. This is in contrast to regular Napalm gels, the consistency of which is relatively independent of temperature. Fuels peptized with water, on the other hand, decrease in consistency with decrease in temperature, and it has been found possible, by using a mixture of xylenol and water, to obtain a peptized fuel the consistency of which is essentially independent of temperature.[33] Very little work has been done on this, however, and it is probable that the proportions of xylenol and water required by different Napalms would vary considerably. The best single peptizers for low temperature coefficient of consistency are the alcohols.[49] If base mixing of flame-thrower fuels for shipping abroad should be undertaken, alcohol-peptized fuels would probably be most satisfactory from the standpoint of stability over the range of time and temperature which might be encountered.

Super-Peptized Fuels. When the amount of water in a Napalm fuel is increased beyond approximately one-tenth of the soap content, no appreciable further decrease in consistency takes place. Fuels compounded with excess water have been termed "minimum consistency" or "super-peptized" fuels. The obvious advantage for such fuels, particularly in a humid climate, is that they are not affected by small additional quantities of water, as are regular Napalm fuels. One such fuel used fairly extensively in the Pacific theater consisted of 13 gal of gasoline, one 5¼-lb can of Napalm, and 1½ qt of water, which corresponds to about 6.3 per cent Napalm and 3.5 per cent water. A number of such fuels prepared from representative Napalms were found to have consistencies of 15 to 20 g[40] and were quite stable at temperatures of 80 to 120 F. When these fuels are prepared and stored at 55 F, however, the one-day consistencies are very much higher, 200 to 400 g, since the peptizing effect of water is retarded at low temperature. After one month storage at 55 F, the consistencies are lower than at room temperature, on account of the inverse temperature coefficient of consistency of water-peptized fuels. Hence, their use should not be recommended at low temperatures.

Performance of the super-peptized fuels described above (15 to 20 g Gardner) in portable flame throwers is similar to that of other Napalm fuels of the same consistency, for example, the brush-flame fuel developed for the Infantry Board. Range in the air was 35 to 40 yd, center of deposit on the ground, 40 to 50 yd. However, very little fuel reached the ground.

In compounding these fuels in the field, particularly if the drum and paddle method of mixing is used, it is essential that the water be first mixed with the dry Napalm before adding to the gasoline. If the water is first added to the gasoline and agitation is not violent, most of the water remains as a separate layer on the bottom, and the consistency of the resulting fuel may be two to four times what it would be if the water were evenly dispersed.

Fuels Containing Dehydrating Agents. Incorporation of moderately strong dehydrating agents such as silica gel, calcium chloride, and magnesium sulfate in Napalm fuels increases their consistency and stability. Fairly extensive tests have shown that silica gel is the most efficient agent in this respect.[16] Magnesium sulfate is also quite satisfactory, but in most instances it does not produce so great an increase in consistency, and fuels compounded with it are not so stable as those containing silica gel. However, the total moisture capacity of the magnesium sulfate is greater than that of silica gel, making it somewhat superior in cases where water corresponding to more than about 20 per cent of the weight of the dehydrating agent is introduced either during compounding or subsequently.

Comprehensive tests with Napalm samples from a number of manufacturers have shown that incorporation of silica gel does not appreciably increase uniformity of consistency among the various Napalms, and that the increase in stability is not greater than would result from increasing Napalm concentration to give the same consistency.[48] However, fuels compounded with silica gel (3 per cent Napalm + 2 to 4 per cent silica gel) showed considerably greater resistance to the effect of such peptizers as xylenol, alcohol, acid soldering flux, amines, and potassium acetate. This is in keeping with previous experiments which had shown that certain Napalms could not be increased in thickening power by prolonged drying in a vacuum oven at 160 F, even though the incorporation of silica gel resulted in a large increase in consistency. This phenomenon may be accounted for by the adsorption of uncombined acid from the Napalm by the silica gel. It is this adsorption of other polar compounds, in addition to water, which makes silica gel superior to magnesium sulfate as an additive to Napalm fuels.

One possible drawback to the use of silica gel in Napalm fuels is the abrasive effect of the material on pumps which might be used in mixing, transferring or firing the fuel. In one case a high-speed Blackmer vane pump was ruined by 15 min recirculation of a fuel containing "thru 80" (actually, approximately 28 to 200 mesh) silica gel. Another possible difficulty is that of uniformly dispersing the silica gel in the fuel by paddle mixing. This is somewhat easier if the silica gel is added at about the stir time rather than at the beginning of mixing.

Base mixing of flame-thrower fuels stabilized with silica gel has been recommended by the 43rd Chemical Laboratory Company in Hawaii.[41, 43] Considerable quantities of such premixed fuels were prepared by the 43rd Chemical Laboratory Company, but World War II ended before these fuels could be given a thorough trial in the field. The Company reported that the abrasive effect of the silica gel is negligible if the material is ground to 200 mesh. This has been tentatively confirmed in unreported experiments at the Eastman Kodak Co.

Fuels Containing Heavy Oils. Numerous reports of the incorporation of diesel oil, bunker C oil, or motor oil in Napalm fuels to retard the setting rate at elevated temperatures have come from the field. Because the specifications for diesel oil are less rigid than for gasoline, considerable variation in consistency can result from its incorporation in thickened fuels. Incorporation of as little as 25 per cent of eleven representative diesel oils supplied by the Navy in 4 per cent Napalm fuels resulted in a consistency variation of 26 to 64 g, compared to a consistency of 61 for the fuel prepared with 100 per cent motor gasoline. It was observed that diesel oils which were darkest in color had the greatest deleterious effect.

Experiments conducted by CWS Technical Command showed that homogeneous fuels could be prepared with the fastest setting type of Napalm (Navy ground) at 100 F by first preparing a slurry of the Napalm in motor oil. The slurry is added through a coarse screen to the gasoline in the mixing drum, the volume of gasoline being reduced by the volume of oil added with the Napalm. Some motor oils contain additives which peptize Napalm, rendering the fuel too thin for use. Representative oils containing no such additives are Navy Symbol 2190, 2250, 3050, 3065, and 3080. These oils have been checked in the laboratory and found not to affect the consistency of Napalm fuel. It is understood that one or more of them are available in large quantity on practically any ship. The effect on Napalm consistency of motor oil available to Army personnel is not known. However, motor oil has been used in the field to retard the setting of Napalm, its peptizing action probably having been compensated by increasing the Napalm concentration.

Field Viscosimeters. As noted above, the Gardner consistencies of Napalm fuels serve as satisfactory guides to their performance in flame throwers, blaze bombs, and incendiaries. Since all fuels for incendiary bombs are mixed in the United States, the Gardner mobilometer is used for measuring their consistency. However, fuels for flame throwers and blaze bombs are usually mixed in forward areas where mobilometers are not available, and probably could not be conveniently used if available. For this reason, considerable research has been carried out in an attempt to develop a simple viscosimeter for field evaluation of thickened fuels.

An early attempt along these lines was a ball viscosimeter developed by Standard Oil Development Co. and the Chemical Warfare Service. The ball viscosimeter consists of a transparent plastic tube, about 2 in. in diameter, and steel balls of six sizes, $\frac{2}{32}$ in., $\frac{3}{32}$ in., $\frac{4}{32}$ in., $\frac{6}{32}$ in., $\frac{8}{32}$ in., and $\frac{10}{32}$ in. in diameter. The diameter of the ball which falls through 10 cm of fuel in 30 sec is the measure of the viscosity of the fuel. Although it does not give perfect agreement with Gardner values, the instrument is quite useful in evaluating fuels between 20 and 200 Gardner, these consistencies corresponding to the $\frac{2}{32}$-in. and the $\frac{10}{32}$-in. balls, respectively. Further study showed that somewhat better correlation with Gardner consistency is obtained if a fall time of 100 sec is used, and the usable range of the instrument can be increased to 600 g Gardner by using balls up to 1 in. in diameter.[38]

A simple viscosimeter which can be fabricated from materials available in the field has also been developed.[33, 36, 38] This consists of a C-ration can with a 1/4- or 1/2-in. circular opening in the bottom and an additional C-ration can for catching the fuel passing through the opening. In operation, the viscosimeter can is filled with the fuel to be tested and placed not over 1 in. above the receiving can. The viscosimeter can is kept full during the test by gradual addition of fuel from another container. The time required to fill the bottom can is a measure of the viscosity of the fuel.

The 100 Gardner fuel commonly used in the portable flame thrower corresponds to about a 4/32-in. ball (100 sec fall time), or an efflux time of 15 min with the 1/4-in. orifice (1.5 min with the 1/2-in. orifice). The 25-g consistency, which gives a brush flame, corresponds to a 2/32-in. ball, or an efflux time of 1 min with the 1/4-in. orifice. The 200 to 250 g Gardner consistency considered optimum in the mechanized flame thrower corresponds to 8/32-to-10/32-in. ball and an efflux time of 4 min with the 1/2-in. orifice. The 200 to 400 g consistency used in blaze bombs corresponds to 8/32-to-16/32-in. ball. The upper limit, 400 g, cannot be satisfactorily evaluated with the efflux viscosimeter, but the minimum efflux time should be about 5 min with a 1/2-in. orifice. If this is not attained with 6 per cent Napalm, 6.5 or 7 per cent should be tried. The probability of 6 to 7 per cent Napalm gel having a consistency greater than 400 g Gardner is very slight.

Temperature Effects. The temperature coefficient of viscosity of unpeptized Napalm fuels is small compared with that of ordinary Newtonian liquids. Fuels containing xylenol, however, have much higher consistencies at low temperatures than at high; those containing water have lower consistencies at low temperatures. In each case the change is reversible, the fuel regaining its normal consistency on being returned to the higher temperature. There is no good evidence of any Napalm fuel having broken down, either by syneresis or by abnormal reduction in consistency, on storage at low temperatures (down to −40 F). The normal decrease in consistency, which occurs on aging at ordinary temperatures, is accelerated at elevated temperatures, and the consistency after one day at 150 F is ordinarily considered to be the minimum consistency which will be attained on aging at ordinary temperatures. This is not necessarily true, however, since several 4 per cent Napalms, which had higher consistencies after one day at 150 F than after one day at 77 F, showed the normal decrease in consistency on aging at ambient temperature. The explanation for the increase in consistency at elevated temperature is given by a Napalm substitute containing 80 per cent coconut oil acids and 20 per cent oleic acid which had a consistency of 1,100 after storage at 150 F, as compared to 430 at 77 F.[51] Aluminum soaps of coconut oil acids cannot be dispersed in gasoline at 77 F, and the proportion of oleic acid used in this mixture was not enough to cause total dispersion. Thus, storage at 150 F has two opposite effects, one tending to increase consistency, the other to decrease it, and in certain cases the net effect may be an increase.

The effect of storage of Napalm gels at 120 F for one day to thirty-two days is shown in reference 12. In general, most of the decrease in consistency occurs in one day or two days at this temperature, in contrast with a more gradual decrease over the entire 32-day period at 70 F. The final, 32-day, consistency of 4 per cent gels was lower at 120 degrees than at 70 degrees, which indicates that the aging effect is predominant over the dispersion effect at 120 degrees.

An interesting phenomenon occurs when regular Napalm fuels are mixed and stored at 50 to 60 F, approximately the minimum temperature at which Napalm can be dispersed without a peptizer. Setting rate of the Napalm is greatly retarded and maximum consistency is not attained until two to four days after mixing. This maximum consistency, however, is very much higher than that attained at 80 F. For example, a 2 per cent gel may have a consistency of 80 g instead of 10 g, a 4 per cent may have a consistency of 250 instead of 100. On continued storage at 55 F, the consistency is still higher than normal after two months, although

it begins to decrease after a week.[44] This abnormal consistency is a result of retarded peptizing action of the water and uncombined acids in the Napalm at low temperature. If one of these fuels is brought to 80 F for only an hour, its consistency is found to be normal, even after being returned to the lower temperature.

The difference in flame-thrower performance between these abnormal fuels and ordinary fuels of the same Napalm concentrations is not so great as would be expected on the basis of consistency. In fact, the concentration seems to be a more reliable guide to performance than the consistency, this being the most striking exception to the rule that consistency, irrespective of concentration, determines performance. Gardner consistencies of these fuels, determined immediately after unignited firing from a flame thrower, show that their poor performance is due to mechanical breakdown of consistency in the gun. The "healing rate" at this low temperature is greatly retarded, but the material gradually returns to its abnormal consistency over a period of hours.

Examination of the data for the blaze-bomb fuels mixed at Llandarcy[47] shows that most of the fuels were mixed in the winter and that the gasoline temperature was generally in the range of 50 to 60 F. This accounts for the initial high consistency of these fuels, many being 500 to 600 g Gardner, and for the decrease in consistency which occurred on aging, the normal consistencies of 200 to 400 being attained in 2 to 3 months.

Another interesting temperature effect is observed on storing Napalm soaps at 150 to 160 F in hermetically sealed containers. Thickening power of representative Imperial Napalms increases from approximately 75 Gardner, for 4 per cent gels, to 150 to 200 in two weeks at the elevated temperature. This increase in consistency is accompanied by an increase in moisture content and a decrease in extractable acid. This indicates that some of the uncombined acid combines with alumina or mono-soap, water being produced by the reaction. Decrease in extractable acid is of the order of 2 to 3 per cent on the basis of total soap. Why this should result in such a large increase in thickening power is not clear. On continued storage at 160 F, the thickening power begins to decrease but is still above normal at sixteen weeks.

Storage at 120 F has comparatively little effect on the thickening power of Napalm in twelve weeks, which indicates that exposure to temperatures which will ordinarily be encountered should not be expected to materially change the thickening properties of the soap.

8.2.4 Substitute Napalm Formulas

As a result of what appeared to be an imminent shortage of naphthenic acids,[32] work was undertaken to develop a Napalm formula in which the naphthenic acid would be eliminated or its percentage materially reduced. After soaps of various acid ratios and excess caustic content were made up and tested, it appeared that the optimum composition, in the absence of naphthenic acid, was 80 per cent oleic and 20 per cent coconut oil acids precipitated at an excess caustic ratio of 30 per cent.[51] High ratios of coconut oil acids produce soaps which are not completely dispersible in gasoline at room temperature and gasoline gels which tend to be short and crumbly. Low ratios of coconut oil acid produce soaps which become gummy on drying. In addition, soaps of over 80 per cent oleic acid tend to form thick, clear jellies on cooling, which makes the precipitation of straight aluminum oleates from concentrated soap solution unsatisfactory. However, this tendency is eliminated for all practical purposes by 10 to 20 per cent coconut acid. High basicity (60 per cent excess caustic) produces soaps which are too high in thickening power (greater than 800 g Gardner).

The setting rate of the substitute containing 80 per cent oleic acid is somewhat faster than regular Napalm for corresponding particle sizes. In addition, the average particle size of the substitute is smaller than that of the regular Napalm; hence the overall tendency is for considerably faster setting. The length and healing rate are comparable to regular Napalm. The amount of alpha-naphthol required to prevent oxidation is directly proportional to the oleic acid content.

Several formulations containing reduced

quantities of naphthenic acid were also made up and tested. With respect to gel strength, crumbliness, and setting rate these formulations are all between regular Napalm and the aluminum oleates. It was decided to retain 5 per cent naphthenic acid in order to utilize the available supply of the three acids, and several full-scale batches containing 65 per cent oleic, 30 per cent coconut, and 5 per cent naphthenic acids were prepared by the manufacturers. No serious difficulties were experienced in any of the plant operations. The substitute material was tested by CWS Technical Command in M69 and M47 incendiary bombs and was reported to be completely satisfactory. Because of the fast setting of the material, it is felt that additional refrigerating capacity for cooling the gasoline might be required in some of the filling plants. However, before production could be shifted to the substitute formula, the naphthenic acid supply situation eased, and shortly thereafter World War II ended.

8.2.5 Other Aluminum Soap Thickeners

While research in the United States has been concentrated on improving Napalm with respect to uniformity, reliability, etc., numerous other aluminum soap thickeners have been developed in Great Britain.[54] These include (1) Brascon, a preformed concentrate of aluminum stearate peptized with cellosolve; (2) chan and chol, aluminum naphthenate and aluminum oleate, respectively, prepared by a direct reaction process; and (3) Camgel, consisting of two liquids; namely, aluminum cresylate solution and oleic acid, or a fatty acid solution. When mixed in gasoline these form the aluminum soap of the fatty acid.

Research in the United States has shown that chan and Camgel could be produced here if desired. The former is of little interest because of the naphthenic acid supply situation, but the latter is especially attractive because of the ease of mixing liquid components (see Section 8.3).

Other aluminum soap thickeners which have been produced in quantity are: (1) Metalex, an aluminum soap of stearic and naphthenic acids peptized with cresylic acid, produced in New Zealand, and (2) geletrol, an aluminum soap of oleic acid, produced in Australia.

8.3 LIQUID THICKENING AGENTS[51-55]

8.3.1 Aluminum Cresylate

This two-liquid thickening agent, known as Camgel in England, was developed as a result of a suggestion of A. E. Alexander of Cambridge University. The aluminum soaps are formed in situ by metathesis between aluminum cresylate solution and oleic acid (or a solution of a fatty acid) when the two are mixed in the gasoline. The aluminum cresylate is prepared by heating cresol with aluminum foil in a suitable solvent such as coal tar naphtha or kerosene, etc. Properties of the fuel are dependent on the ratio of aluminum cresylate to fatty acid, and are improved by the inclusion of such additives as methyl alcohol, cresol, water, and acetone. These peptizers are commonly incorporated in the fatty acid solution, thus limiting the number of liquid additives to two.

Because of the attractiveness of liquid thickeners for the continuous mixing of thickened fuels, particularly for blaze bombs, considerable work has been done in the United States on aluminum cresylate.[51, 55] It was shown that a satisfactory thickener could be manufactured from petroleum cresylic acids, the largest available source, and that refined lubricating oil could be used as the solvent, in order to reduce the fire hazard for storage on aircraft carriers. Some excess cresol must be incorporated in the lubricating oil solution for the sake of fluidity.

Tests of aluminum cresylate solutions from two NDRC laboratories and from PWD in Great Britain confirmed their essential equivalence, when the same amounts of aluminum cresylate and fatty acid are used. Optimum fuel characteristics are obtained with mixtures corresponding to 1.7 to 2.2 molecules of fatty acid per molecule of aluminum cresylate. Setting rate can be accelerated with water, or decelerated with cellosolve, the latter additive greatly in-

creasing the stability of the fuels. When the cresylate solution contains about 0.5 g aluminum cresylate per cu cm, the total additives required to produce a blaze-bomb fuel are 10 to 12 per cent by volume.

Because of the satisfactory performance of the Navy mixer with ground Napalm, aluminum cresylate was never produced in quantity. It was considered that this could be done if required.

8.3.2 Aluminum Alcoholates

Numerous alcohols and phenols, in addition to cresol, can be used in the preparation of liquid thickeners.[51] A very satisfactory thickener has been made by Harshaw Chemical Co. with mixtures of *sec*-butyl and isopropyl alcohol. An 80 per cent solution of this alcoholate in lubricating oil is fluid. The alcoholate is superior to cresylate in that the total additives required to produce a blaze-bomb fuel are only 5 to 6 per cent by volume (approximately 1.5 per cent alcoholate solution) 4 per cent acid mixture.

8.3.3 Sodium Aluminate

This thickener was developed at Harshaw Chemical Co. by Capt. John A. Southern of CWS.[51] One solution consists of sodium aluminate, sodium hydroxide, and water. The other is a special acid mixture of the following composition: 3 parts coconut fatty acids, 1.5 parts oleic acid, 1.5 parts naphthenic acid, 2 parts ricinoleic acid, and 0.25 part triethanolamine. The aluminate solution is prepared by suspending 200 g sodium aluminate and 500 g sodium hydroxide in enough water to make 1,000 cc and drawing off the clear solution after standing. Eight per cent of the acid mixture and 3.25 per cent sodium aluminate solution stirred briefly in gasoline produces a gel of the desired consistency. Prolonged stirring reduces consistency, and the gel does not tend to heal. It is much less stringy than Napalm, but it might be satisfactory in blaze bombs. The ease of manufacture and freedom from fire hazard of the aluminate solution make it particularly attractive.

8.3.4 Valone

Equimolecular quantities of 2-valeryl-1,3-indandione (Valone) and *n*-monododecylamine produce a gel when mixed in gasoline. Solutions of the individual components in gasoline may be used, but a more interesting application is the solution of the two in tetrachloroethane. A 50 per cent solution (25 per cent Valone, 25 per cent amine) is a mobile liquid, and 10 per cent of the solution forms a thick gel in gasoline. This gel, like that from sodium aluminate, is lacking in stringiness, but is of particular interest because of the single-liquid additive. All the two-liquid thickeners must be mixed in the correct proportions in order to be effective, thus requiring rather complicated mixing equipment. With a one-liquid thickener this problem is greatly simplified, the present Navy (injector) mixer, or a similar device, being adequate. In addition, the tetrachloroethane solution is noninflammable.

It has been found that amines of coconut fatty acids, available commercially, and crude Valone, which can be produced in large quantities, thicken gasoline as satisfactorily as the pure substances.

8.4 METHACRYLATE THICKENING AGENTS[7, 56-64]

8.4.1 Introduction

A number of synthetic and natural polymers were investigated as possible thickening agents for gasoline for use in various incendiary bombs and flame throwers. Rubber had been investigated for this purpose in 1941 and had proved quite good, but after Pearl Harbor there was no rubber available for these uses. By the time synthetic rubber was available in sufficient quantities, other thickening agents had been developed which were entirely satisfactory for these uses. Among the synthetic polymers investigated, the most successful was isobutyl methacrylate polymer fortified with certain sodium soaps. Thickening agents of this type were used extensively during 1942 and 1943 for filling AN-M47 and AN-M69 incendiary bombs, and they could have been used for flame-thrower fuels if Napalm had not been available and more convenient for field mixing.

The E. I. duPont de Nemours & Co., Ammonia Department, had cooperated with the Chemical Warfare Service during January to April 1942, in the development of a synthetic polymer thickening formula for filling the AN-M47 100-lb oil incendiary bomb. The result was the following formula.[59]

IM Type I

Isobutyl methacrylate polymer AE	5%
Stearic acid	3%
Calcium oxide	2%
Water	1.25%
Gasoline	88.75%

This filling was used extensively for filling AN-M47 bombs during 1942 and part of 1943 when it was replaced by IM Type IV (see page 207).

In May 1942 duPont was invited to cooperate on an informal basis with the NDRC-Standard Oil Development Co. group in developing an isobutyl methacrylate polymer formula for filling the new AN-M69 bomb. The result was the following formula.[57]

IM Type II

Isobutyl methacrylate polymer NR	5%
Hydrofol 51 (stearic acid)	2.5%
Naphthenic acid	2.5%
Aqueous solution of caustic soda (40%)	3%
Gasoline	87%

The filling was compared with other competitive gasoline gels in a series of tests in May 1942 with the result that IM Type II was adopted for use in the initial production of AN-M69 bombs. IM Type II was replaced by IM Type III in March 1943 (see page 207).

The code letters AE and NR stand for Arsenal Edgewood and National Research, respectively. Polymer AE was a much higher average molecular weight than polymer NR, although the actual molecular weight was not known for either one.

After the above developments a formal contract was made with E. I. duPont de Nemours & Co., Ammonia Department (OEMsr-744), beginning August 1, 1942, for the purpose of studying the several variables involved in these formulas and of developing either better formulas, or satisfactory formulas requiring less of critical materials such as isobutyl methacrylate and naphthenic acid. The remainder of this section describes the results obtained under this contract.

8.4.2 Laboratory Studies

The study of gasoline gels thickened by polymers is reviewed by summarizing the effect on gel properties of varying, in turn, the nature and concentration of each of the basic gel components.

Conclusions.[62] Gel preparation usually involves preparation of a low-viscosity gasoline solution containing isobutyl methacrylate polymer and soap-forming acids which are gelled or thickened by the addition of a small amount of aqueous alkali. In general, the polymer determines strength characteristics, while the soap ingredients contribute body to these mixtures.

1. The range of strengths required of gels for the various incendiary munitions was covered by using NR or AE grade isobutyl methacrylate polymer for the weaker gels, and one of a series of interpolymers of isobutyl methacrylate and methacrylic acid for the strongest gels. Polymer content of soap-fortified gels varied from 1 to 10 per cent. The minimum polymer contents consistent with stability and the desired gel strengths were determined.

2. A large number of soap-forming acids were assessed as gel bodying agents. Formulation of the six most effective acids was intensively studied in gels containing various combinations of two or three acids. Of these six acids, stearic and oleic acids impart stiffness, body, and high-temperature stability to all types of methacrylate gels. Naphthenic acid and dimerized soybean oil acids act as gel plasticizers, while rosin and Turkey-red oil normally function as plasticizing agents but occasionally fulfill both of the above-described functions. The most effective acid combinations are stearic acid-naphthenic acid; stearic acid-naphthenic acid-wood rosin; stearic acid-dimerized soybean oil acid; and stearic or naphthenic acids alone.

3. To study the effect of the gelation agent, strong and weak bases were tested at various ratios of acids to base to water. Only strong bases caused effective gelation. The use of aqueous sodium hydroxide, ground lime, and calcium hydroxide was studied in detail. Unsuccessful attempts were made to prepare stable gels with ammonia or amines.

4. Stiffness and a reduction in resilience were imparted to strong, fluid gels containing isobutyl methacrylate-methacrylic acid interpolymers by the addition of inert solid materials. Ground alpha-cellulose was the most effective filler tested.

5. Other NDRC research groups studied the gasoline requirements of methacrylate gels and concluded that an aniline point below 105 F was required to obtain gel stability.

Physical Measurements.[62] The physical properties of various gels were compared with the results of field evaluations, and the sensitivity of various tests to minor changes in composition of a given gel formula were determined. To obtain significant characterization of methacrylate gels, it was necessary to modify existing methods and to develop new techniques. New physical measurements developed under this contract include the impact strength, parallel plate, and burning rate tests. The impact strength, a measurement of consistency at a high shearing force, was useful in gel research to predict behavior of diverse gel formulas in static firing tests of incendiary bombs. The parallel plate test, a measurement of body under a low shearing force, was adapted to plant control on specific gel formulas, where it showed excellent sensitivity to quality of ingredients and method of compounding. The burning rate test gave a comparative measure of the incendiary characteristics of diverse gels.

The stability to exposure to both high and low temperatures of gels prepared during the formulation study was determined and has been correlated with gel composition.

New Gel Formulas.[60, 62] As a result of the studies made by duPont under Contract OEMsr-744, the following formula was selected to replace IM Type II for filling AN-M69 bombs.

IM Type III

Isobutyl methacrylate polymer AE	2%
Hydrofol 51 (stearic acid)	3%
Naphthenic acid	3%
Aqueous solution of caustic soda (40%)	4.5%
Gasoline	87.5%

This formula went into production in March 1943, replacing IM Type II for filling AN-M69 bombs, and still later it was replaced by Napalm for this purpose.

The following formula was selected to replace IM Type I for filling AN-M47 bombs.[60, 62]

IM Type IV

Isobutyl methacrylate polymer AE	3%
Stearic acid	4%
Calcium oxide	4%
Water	2.5%
Gasoline	86.5%

In this formula 3 per cent additional calcium stearate replaces 2 per cent of isobutyl methacrylate polymer in IM Type I, giving an equivalent gel. IM Type IV was later replaced by Napalm for filling AN-M47 bombs.

Isobutyl Methacrylate Interpolymer Formulas.[61, 62] An interesting series of gels were developed containing both isobutyl methacrylate polymer and free methacrylic acid, but no stearic or naphthenic acids. A typical formula would be:

Isobutyl methacrylate polymer AE	3 to 6%
Methacrylic acid	0.1 to 0.3%
Aqueous solution of caustic soda (40%)	1%
Gasoline	93 to 96%

Such gels gave strengths equal to IM Types I to IV, and contained materially higher percentages of gasoline, the primary incendiary material. Apparently, the free methacrylic acid, which contains a double bond, forms cross linkages similar to those in vulcanized rubber, thereby imparting high gel strength with a relatively small percentage of gelling agent. At first these gels were not sufficiently stable at low temperatures, but this was later corrected by good control of compounding. Although this type of gel looked attractive it was never used, since in the meantime Napalm had been perfected and dominated the field of thickening agents. Methacrylate interpolymer gels were particularly good when made with a fuel containing around 20 per cent of toluene.

Other Polymers. In a search for isobutyl methacrylate substitutes, a study of other commercial resins was undertaken. A search for gasoline-soluble polymers other than methacrylates revealed only the polyvinyl ethers, Vistanex (polyisobutylene) and the rubber substitutes derived from vegetable oils. Satisfactory strength in gels containing the latter two materials was obtained only when the polymer content exceeded 10 per cent. The polyvinyl ether procured from the General Aniline & Film Corp. was tested as a direct substitute for polyisobutyl methacrylate and as a constituent of soap-free gels. The properties of polyvinyl ether gels are comparable to those prepared from methacrylate polymers. Evaluation of these mixtures as flame-thrower fuels has been undertaken by other NDRC groups. Gel preparation was attempted with other commercial resins, especially ethyl cellulose, by adding an auxiliary solvent to the gasoline. It was concluded that without further modification such polymers do not impart sufficient strength to gasoline-soap gels and that the use of a water-miscible auxiliary solvent results in poor gel stability at high temperatures.

Modification of existing commercial resins and the synthesis of new polymeric gasoline thickening agents was "high-spotted." While several gasoline-soluble cellulose and vinyl resins were prepared, degradation occurred during the introduction of functional groups so that only low molecular weight materials were obtained.

8.4.3 Preparation of Gels

Batch Preparation.[62] The basic method of preparing methacrylate gels involves adding an aqueous solution of a base, such as sodium hydroxide, to a stock solution consisting of polymer and soap-forming acids dissolved in gasoline. The stock solution is prepared by dissolving first the acids, then the polymer, with strong agitation in the gasoline. To insure solubility of stearic acid, the gasoline temperature must exceed 12 C. When mixtures of acids were used it was found convenient to weigh the acids into a container heated on a steam bath or, when rosin was present, on an electric heater, and to add the molten mixture to the gasoline while stirring. Solution of polymer was most readily obtained by adding the entire amount required at one time. Stirring was continued until solution was complete. Fillers were sometimes added to this stock solution. Gelation was obtained by pouring the aqueous basic solution rapidly into this stock solution while stirring with an electrically driven stirrer. Agitation was continued for 1 min or until the mixture had sufficiently gelled to climb the shaft of the stirrer. The usual size of a laboratory batch was 400 g prepared in a wide mouth, 1-qt bottle. The gels were allowed to set in the closed container at least 24 hr before examination.

When lime was used as the gelling agent, the powdered dry lime was dispersed in the stock solution and water was then added to effect gelation. These mixtures were stirred at least 2 min after the addition of water. Since the particle size of the lime affected the rate of gelation and the final properties of the gel, a standard mixture was obtained by crushing USP lime, screening, and compositing the fractions to give a mixture with the following screen analysis.

35 to 60 mesh	22%
60 to 80 mesh	22%
80 to 100 mesh	22%
100 to 120 mesh	22%
Through 200 mesh	12%
	100%

This synthetic mixture has a screen analysis which is the average of several analyses on limes ground to pass 40 mesh.

Pilot Plant Continuous Preparation. For larger than laboratory scale preparation of methacrylate gels it seemed desirable to develop a continuous rather than a batchwise process. Gelation involves rapid intimate mixing of a gasoline stock solution containing polymer and soap-forming acids with the aqueous caustic solution. In preliminary tests the mixing obtained by injecting the two streams into a centrifugal pump seemed more controllable than the mixing obtained by passing the two solutions under pressure simultaneously through an orifice. The small-scale unit shown diagrammatically in Figure 1 was therefore assembled. The stock solution is prepared batchwise in holdup tank T-1 while the 40 per cent caustic solution is stored in tank T-2. These solutions are drawn from the tanks at calibrated rates by

metering gear pumps. The two metered streams join in a tee or Y which immediately precedes the inlet to the centrifugal mixing pumps. Shutoff and sampling valves are so located that the rate of flow of each stream can be calibrated

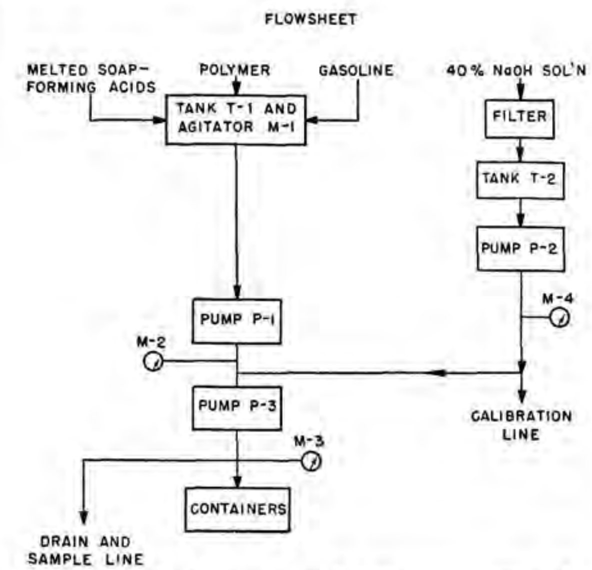


FIGURE 1. Continuous unit for the preparation of methacrylate gels.

separately. The gel produced in the mixing pump is forced through the discharge line and loaded directly into a bomb or container. The maximum production of the experimental unit, limited by pump capacity, was 10 lb of IM-II gel per min. At this rate the back pressure developed in the discharge line, which was 15 ft of standard 1-in. black iron pipe, including two 90-degree bends, was 5 psi.

To obtain the flexibility required for experimental studies, all three pumps were operated by variable speed drives. In the unit producing IM-II and IM-III gel at the Kilgore Manufacturing Co., it was found advantageous to operate both metering gear pumps from the same driveshaft, and to predetermine the ratio of the two streams by the proper choice of gears coupling the pumps to the shaft.

8.5 SODIUM SOAP THICKENING AGENTS[65, 66]

Before the advent of Napalm and isobutyl methacrylate thickening agents for gasoline, a considerable amount of work was carried out on formulas using various sodium soaps as the principal gelling agent.[65, 66] These formulas contained the following compounds: (1) a fatty acid which may be stearic acid, hydrogenated fish oil acid, tallow acid, oleic acid, or cottonseed oil acid; (2) resin; (3) a plasticizer which may be isopropyl alcohol, cottonseed oil, castor oil, fish oil, rapeseed oil, stearine, or glycerine; (4) sodium hydroxide solution; and (5) gasoline, kerosene, or both.

Hundreds of different formulas were tried. On the basis of burning rate, stability, availability of materials, and ease of preparation, the following formulas were considered to be fairly good, although even better formulas might have been worked out:

	SOD formula 122	SOD formula 392	SOD formula 433
Stearic acid	3.5%	4.5%	3.5%
Resin	1.75%	2.25%	1.75%
Castor oil	3.0%	...	...
Sulfonated cottonseed oil	...	0.2%	0.2%
Stearine	...	...	3.0%
Sodium hydroxide	2.0%	0.8%	2.0%
Water	2.0%	0.8%	2.0%
Gasoline	81.25%	83.2%	81.05%
Kerosene	6.5%	...	6.5%

These formulas were found to perform quite well in the AN-M69 bomb, although they were not suitable for the AN-M47 or other bursting type bombs on account of their low cohesiveness, compared to the NP and IM types of gels. Burning tests in incendiary-test structures showed that the sodium soap gels were not quite as good as NP and IM gels even in the AN-M69 bomb because of their greater breakup on ejection. Therefore the sodium soap gels were discarded and were never used in production of AN-M69 bombs. They were sufficiently satisfactory, however, and might have been used if a serious shortage of NP and IM had developed during World War II.

8.6 CELLULOSE-BODIED FUELS[8, 23, 67-73]

In addition to gasoline gel fuels, fuels bodied with cellulose wadding (cellucotton) appeared quite promising for use in incendiary bombs. They might also possibly have been used in some types of flame throwers, but could obviously not be used in conventional types. A fuel consisting of 13 per cent cellucotton and 87 per cent gasoline gave very good results in the AN-M69 bomb. The cellucotton simply soaks up the gasoline even though the gasoline weighs almost seven times the cellucotton.

Cellucotton-gasoline fuels have the following advantages over gelled fuels:

1. *Stability.* There is no question of the short or long term stability of this fuel, whereas stability was a major difficulty in the early development and production of Napalm.
2. *Simplicity of production.* This applies particularly to the factory filling of incendiary bombs.
3. *Ignition.* Ignition would be no problem with this fuel, whereas low-temperature ignition was always a problem with gelled fuels.
4. *Temperature effect.* Cellucotton-gasoline fuels would have nearly the same performance at all temperatures, whereas the performance of gelled fuels varied with temperature.
5. *Fuel distribution.* With cellucotton-bodied fuels it is possible to have a uniform, predetermined size of fuel chunks, whereas with gelled fuels the chunks varied very greatly in size, and shattering was always more or less a problem.
6. *Availability.* There would be no supply problem in the case of cellucotton, whereas constituents of both Napalm and methacrylate were in short supply throughout World War II.
7. *Cost.* Cost of filling bombs with these fuels would be much less than for gelled fuels.

Comparative burning tests of cellucotton-gasoline fuels in AN-M69 bombs against various incendiary-test structures indicated these fuels to be approximately equivalent to the same weights of gelled fuels. One disadvantage was the greater tendency of cellucotton fuels to bounce off target surfaces and lack of tendency to adhere. However, gelled fuels also bounce off surfaces in striking at small angles, and a thoroughgoing comparison was never made on this point.

The controlled size of fuel chunks would be a matter of minor importance in the AN-M69 bomb, but it might have been very important for bursting-type bombs, such as the AN-M47 and AN-M76. The E22, 500-lb tail ejection bomb, developed by Factory Mutual Research Corp., used a cellucotton-bodied fuel with very promising results.

In spite of the attractive features of the cellucotton-bodied fuels, they were never used in World War II primarily because the gelled fuels got started first. Cellucotton fuels were never tested for use in flame throwers primarily because the whole emphasis was on conventional nozzle-type flame throwers.

8.7 FORTIFIED FUELS[23, 72, 74-82]

8.7.1 Introduction

Numerous fuels in which hydrocarbons were fortified by the addition of combustible metals and oxidizing agents, or by the addition of either one, were investigated during World War II and proposed for use in incendiary bombs and flame throwers. The heat outputs of the standard gasoline gel fuels were quite satisfactory for use in incendiary bombs and flame throwers, but they had the drawbacks of burning at comparatively low temperatures and of being easily extinguished by water. It was to correct these two drawbacks that fortified fuels were investigated by NDRC, the Chemical Warfare Service, and by the British Petroleum Warfare Department. However, their use in the war was very limited, largely in the M74 and AN-M76 incendiary bombs, which were developed by the Chemical Warfare Service. NDRC work on fortified fuels was principally in connection with the development of the E9 and E19 incendiary bombs.

The principal advantages to be expected from fortified fuels are outlined below.

1. Higher temperature and greater fierceness of burning. This property is of interest in both incendiary and anti-personnel applications.
2. Less easily extinguished by water. This property is primarily of interest in incendiary-bomb applications.

Other less important advantages of fortified fuels are (1) greater range in flame throwers resulting from higher densities, and (2) production of irritant gases such as sulfur dioxide.

Since all fortifying additives have higher

densities than hydrocarbons, the densities of fortified fuels are always higher than gasoline gels. The heat outputs per unit weight of fortified fuels are lower than gasoline gels, but the higher density offsets this, so that the heat outputs per unit volume are usually about the same as gasoline gels. These facts constitute a net disadvantage for fortified fuels when weight is a critical factor as it sometimes is both in incendiaries and in flame throwers. Another disadvantage of fortified fuels is their generally lower degree of cohesiveness (greater shortness).

The following sections describe only NDRC work in this field. The formulas given are representative of a much larger number described in the original references.

8.7.2 Hydrocarbon-Metal-Oxidizing Agent Mixtures[72, 75, 77-79, 81, 82]

Mixtures under this heading constitute the most important fortified fuels investigated by NDRC. Most of these were investigated by Factory Mutual Research Corp. in connection with the E19 incendiary bomb, or by the Texas Co. in connection with the E9 incendiary bomb. Following are some representative formulas.

1. 25% Motor oil (SAE40)
   35% Aluminum powder
   40% Sodium nitrate

This mixture has a heat output of 8,930 Btu per lb and a density of 1.50, which puts it on a par on a volume basis with gasoline gel which has a heat output of about 17,500 Btu per lb and a density of 0.78.

2. 20% Motor oil (SAE40)
   10% Asphalt
   15% Aluminum powder
   55% Sodium nitrate
3. 35% Lubricating grease
   15% Aluminum powder
   5% Sulfur
   45% Sodium nitrate

This mixture has a heat output of 7,800 Btu per lb and a density of 1.54.

4. 7.1% Motor oil (SAE40)
   14.8% Aluminum flake
   1.6% Sulfur
   14.8% Sodium nitrate
   11.7% Barium nitrate
   50.0% Thermite

Mixtures 1, 2, and 3 were preliminary formulas developed for the E19 incendiary bomb, and 4 was the final formula for the principal filling for this bomb.

5. 30% Gasoline-rubber gel (7% rubber)
   11% Aluminum powder
   14% Sulfur
   45% Sodium nitrate with or without 2½% cotton or other vegetable fiber for strengthening.

This mixture was investigated as a possible flame-thrower fuel. It showed promise except for the unavailability of rubber.

Nuodex Products Co.[77] experimented with a variety of mixtures of gasoline gel, oxidizing agents, such as lead nitrate, barium nitrate, and lead oxides, and metals or other reducing agents, such as lead, iron, lead sulfide, and iron sulfide, in an attempt to find a satisfactory high density flame-thrower fuel. Densities in the range 1.3 to 1.6 were achieved. The principal requirements were high cohesiveness, reliable burning, and stability. No mixtures of practical value resulted from this work.

8.7.3 Hydrocarbon-Oxidizing Agent Mixtures[23, 74, 76]

1. 58.5% Turpentine
   19.5% Furfural extract, from lube-oil refining
   10% Ammonium nitrate
   12% Cellucotton

This mixture was developed for the E9 bomb and was highly recommended for that purpose, except that the final design of the E9 bomb was not adapted to the use of cellucotton-bodied fuels.

2. 30% Polymerized divinyl acetylene (DVA)
   10% Motor oil
   60% Sodium nitrate

This mixture was developed at the University of Chicago for use in sabotage incendiaries. The test results showed that divinyl acetylene had no greater fire-starting capacity than other hydrocarbons.

8.7.4 Hydrocarbon-Metal Mixtures[23, 80]

1. 58.5% Turpentine
   19.5% Furfural extract, from lube-oil refining
   10% Magnesium powder
   12% Cellucotton

This mixture was developed for the E9 bomb. The comparatively high burning temperatures of the hydrocarbons present were sufficient to ignite the magnesium, and it gave a very effective incendiary fuel.

2. 98% Gasoline gel (Napalm)
   2% Sodium or potassium

Finely divided sodium or potassium was made by melting the metals under a high-boiling hydrocarbon such as xylene, and then shaking the molten mixture, reducing the metal to fine droplets. The dispersed metal was then suspended in gasoline and the gasoline gelled with Napalm. These mixtures had the interesting property of bursting into flame when water was applied to them.

8.8 SELF-IGNITING FUELS[83-90]

8.8.1 Introduction

Substances which ignite more or less spontaneously upon contact with the atmosphere have been known and studied for a long time. Among those considered at one time or another as potentially suitable for use as primary or auxiliary fuels in flame throwers or incendiaries, two groups of substances stand out: organometallic compounds and liquefied white phosphorus compositions, although a variety of other substances has been contemplated as chemical igniters for flame throwers.[86]

Investigations of organometallic compounds within NDRC were initiated in 1940 under Contract NDCrc-61, later changed to Contract OEMsr-97.[83, 84] Ignition of flame throwers by introducing zinc diethyl as a secondary fuel also received brief study under OSRD Contract OEMsr-21 early in 1944. Liquefied phosphorus compositions were taken up by NDRC as possible flame-thrower fuels in April 1944 under Contract OEMsr-242, and this work resulted in an intensive study of the preparation, properties, applications, and physiological effects of liquefied phosphorus, as well as in design of instruments for its military use.[87-90]

8.8.2 Organometallic Compounds

Nitrated Lead Derivatives.[83] A number of these compounds decompose vigorously or explosively when heated, to give fine lead oxide smokes. The ballistic properties of these substances, however, are too low to warrant their consideration as explosives, although some of them suggest approaches to possible primers. The toxicity of these lead and lead oxide smokes has received only scant investigation.

Nitrated Arsenic Derivatives.[83] Some of these compounds decompose explosively when heated, to give fine arsenic oxide smokes; this is particularly the case with nitro-aryl arsenic acids and their lead salts. The presence of lead generally increases the explosive properties of nitrated arsenic acids.

Bismuth Compounds.[83] Organobismuth compounds containing two or more nitro groups in the molecule give off a bismuth oxide smoke upon ignition. However, self-igniting properties are low.

Aluminum Compounds.[83] Methylaluminum sesquichloride, $(CH_3)_3Al_2Cl_3$, a compound readily prepared by direct interaction of aluminum and methyl chloride, appears to possess some interest as a flame-thrower igniter or primary fuel.

Diethyl Zinc. This compound, although not as yet readily available, appears to possess some interest as a flame-thrower igniter. A disadvantage is the high proportion of zinc diethyl required as a flame-thrower rod coating, especially in cold weather.

Triethyl Boron.[84] In the course of the examination of a number of spontaneously inflammable substances for possible use as incendiary agents, triethyl boron was found to possess certain advantages, such as moderate thermal stability and high stability toward water, which were not exhibited by any other of the possible liquid substances.

The ordinary laboratory procedures for the preparation of this compound are, unfortunately, not satisfactory for large-scale industrial use. It was, therefore, the object of the research to develop a simple method for the synthesis of the compound from readily available materials and in conventional equipment used by the chemical industries.

In all, forty-three experiments were carried out, using all reasonably available starting materials and a great variety of conditions. Of these, only eight gave any trace of the desired product, and only two were sufficiently convenient and economical of material to merit consideration. These two methods involve the reaction of ethylaluminum sesquibromide (1) with triethyl borate and (2) with gaseous boron trifluoride. Of these two, the procedure employing ethylaluminum sesquibromide and triethyl borate appears to be most satisfactory on the basis of both yield and economy. No solvent is needed, the only starting materials being aluminum turnings, ethyl bromide, and triethyl borate. Scrap aluminum may be employed in place of the pure metal if the latter is not available. The first of the two steps in the reaction may be operated as a continuous process. The conversion of the aluminum compound to triethyl boron is quantitative, and it is conceivable that the aluminum residues could be returned to a refining plant and converted to the metal.

8.8.3 Phosphorus-Phosphorus Sesquisulfide Eutectic (EWP)

Liquid EWP.[87-90] The phosphorus-phosphorus sesquisulfide eutectic consists of 55 per cent by weight of white phosphorus and 45 per cent by weight of phosphorus sesquisulfide. The composition by elements is 80 per cent phosphorus and 20 per cent sulfur. The composition of the fuel is not critical, and a reasonable amount of deviation is allowable from the true eutectic proportions.

The fuel, when settled free from water, is a clear, yellow, heavy liquid of low surface tension, moderate viscosity, and oily appearance.

The specific gravity of the phosphorus-phosphorus sesquisulfide eutectic at 20 C is 1.840, as determined with a pycnometer.

Mixtures containing 40 per cent phosphorus sesquisulfide and 60 per cent white phosphorus possess a viscosity 5 to 6 times that of water at temperatures from 10 to 60 C.

The surface tension of the eutectic fuel has not been measured, but is believed to be much lower than that of water.

The eutectic fuel freezes at approximately −42 C. A tendency toward supercooling has been noted. However, samples of fuel maintained at −40 C for a period of several weeks, with periodic agitation, have remained consistently liquid. Samples solidified at lower temperatures and remelted several times continued to show consistent freezing between −40 C and −45 C.

Upon exposure to light for several days, the eutectic fuel gradually deteriorates and becomes turbid. It is believed that the change is due to the conversion of white phosphorus into the red modification. When the liquid is stored in the dark, or in opaque containers, no deterioration takes place.

When the phosphorus-phosphorus sesquisulfide eutectic is agitated with water, there is a tendency toward some dispersion of water in the eutectic, the clear fuel settling out completely only after several hours. Storage of the eutectic under a layer of water for several weeks at ambient temperature indicates no appreciable reaction beyond the formation of a slight yellow scum at the interface and the gradual acidification of the aqueous phase. Tests to determine stability in contact with water at −40 (ice) and 55 C failed to show any deterioration.

Samples of the eutectic fuel contained in light-proof vessels were placed in a freezing mixture at −40 C and in an oven maintained at 55 C. Another sample was alternately exposed to these temperature conditions for two-hour intervals, with intermediate one-hour intervals at room temperature. The tests, after proceeding for 60 days, disclosed no apparent deterioration of the phosphorus-phosphorus sesquisulfide solution.

A sample of the fuel was placed in a light-proof flask filled with CO_2 and exposed to a temperature of 212 F for 10 hr a day for 30 days. The pressure in the system as measured by an attached mercury manometer showed no appreciable change. The appearance of the fuel was unchanged.

Strips of different materials were immersed in vessels containing the eutectic fuel under a layer of water, and were allowed to remain in contact with the liquid for 24 days. Inspection of the specimens showed the following results:

Material	Condition after test
Steel	Somewhat corroded
Lead	Slightly tarnished
Tin	Slightly tarnished
Copper	Blackened
Aluminum	Unaffected
Rubber	Unaffected
Neoprene	Unaffected
Polystyrene	Unaffected
Ethyl cellulose	Unaffected

A 2-gal sample of eutectic fuel was stored under water in a tightly sealed steel container, at prevailing outdoor temperatures, from January until June 1945. Upon opening the steel drum it was found that only very slight pressure had developed, probably largely attributable to the change in ambient temperature; the eutectic was clear yellow in color; and when poured from the container, the fuel ignited instantaneously.

Self-ignition of the phosphorus-phosphorus sesquisulfide eutectic is a function of temperature and agitation of the fuel. For instantaneous self-ignition in a completely undisturbed state as, for example, when exposed to still air in a flat dish, the temperature of the fuel must be at least approximately 20 C. Any movement of the liquid, however, against the walls of the containing vessels, air currents against the surface of the liquid, exposure to sunlight, etc., tend to lower the self-ignition temperature, so that the exact ignition temperature in a state of rest is difficult to determine without elaborate precautions.

As the eutectic fuel is subjected to more violent mechanical disturbance, its self-ignition temperature drops sharply. To test ignition quality under conditions of violent impact, bottles filled with eutectic fuel were cooled in a dry ice mixture to a temperature of −50 C, at which the fuel was solid. Upon being flung against a wall, the fuel ignited violently immediately upon bursting of the bottle. This test was repeated many times with identical results.

When the eutectic fuel is ejected from an experimental flame thrower at temperatures above approximately 15 C, spontaneous ignition takes place at the nozzle. At lower temperatures, ignition is more likely to occur in flight or upon impact. While impact ignition is likely to decrease somewhat the range of the fuel, it is believed that, in the case of a fuel of the high specific gravity of the eutectic, the difference between ignited and unignited range would not be very significant. On the other hand, the delivery of an increased amount of fuel on the target, without loss by combustion during flight, has obvious advantages. For description and illustrations of devices using EWP fuels see Sections 4.4 and 6.7.

The phosphorus-phosphorus sesquisulfide eutectic burns largely to P_2O_5 and SO_2, resulting in the production of extraordinary quantities of very dense, white smoke; this smoke is very persistent and highly irritating. Appreciable amounts of sticky residue are also formed during combustion. It is believed that this residue consists largely of syrupy oxides of phosphorus, phosphoric acids (formed by hydration upon contact with atmospheric moisture), some elementary sulfur, and minor amounts of occluded elementary phosphorus. This residue is highly hygroscopic. Combustion of the fuel always results in a strong odor of phosphine in the vicinity; this odor tends to persist for days.

Thickened EWP.[89] When the phosphorus-phosphorus sesquisulfide eutectic (EWP) described above is ejected from a nozzle and ignites upon ejection, the flaming liquid tends to spray out into the air in a bushy pattern somewhat resembling that obtained when using unthickened hydrocarbon fuels in a conventional portable flame thrower. Although the high specific gravity of EWP and its somewhat slower burning rate, as compared with gasoline, permit it to attain an appreciably greater range than the latter under analogous conditions of ejection, much of the thickened EWP tends to burn in the air, the ballistic characteristics of the fuel are mediocre, and not enough of it is deposited on the ground or on a target.

It was therefore desirable to modify the EWP fuel in such a manner as to obtain it in thickened, preferably gel form, to make possible improved ballistic characteristics and increased range.

To date, no completely satisfactory thickened EWP fuel has as yet been produced; and much work still remains to be done on the formulation, stabilization, and use of thickened EWP fuels, as well as on the design of appropriate instrumentation for their use.

Attempts to produce an EWP gel analogous to Napalm-thickened gasoline have met with no success to date. Unlike petroleum products, the phosphorus-phosphorus sesquisulfide eutectic appears incapable of forming a gel structure with any known agent. It is immiscible with Napalm or any similar metal soaps; and while mixing with a gasoline-rubber cement results in a fairly stable mixture, the latter is definitely a mechanical suspension, which remains stable merely as a result of the high viscosity of the medium.

A stable mixture has been prepared by incorporating in the liquid EWP 0.75 to 1.00 lb carbon black per gal EWP. The product is a short, thick paste, which has been kept stable under ambient conditions for as long as two months, and which has shown good ignition, range, and burning characteristics. However, not much is known about the stability and viscosity characteristics of this mixture under widely different temperature conditions.

A modification of the above formulation contains 1 gal of liquid EWP, 2 lb carbon black, and 1 gal of a varnish consisting of 200 lb rosin, 15 lb fuel oil No. 2, and 1 qt gasoline. This mixture has been found to result in a stringier fuel than the straight EWP-carbon black formulation, but it suffers the disadvantage of retarded ignition.

In addition to carbon black, the following substances have also been used as thickeners for EWP: baking soda, borax, boric acid, powdered lime rosin, and fuller's earth. As the addition of carbon black considerably increased the range of EWP, and as the effect of this added agent appeared to be caused not so much by the mechanical raising of the viscosity as by delaying the burning rate, baking soda was incorporated in EWP, with the idea of producing an envelope of carbon dioxide to offset too rapid burning. Borax and boric acid were added to form crusts for the protection of the fuel in transit against excessively rapid burning. These agents gave increased range, but were most helpful in emulsions.

In an attempt to retard the burning speed of emulsions, carbon tetrachloride and water were tried, both without success. The carbon tetrachloride reacted in the flame, merely cutting down on total heat, and the water, probably through rapid volatilization, actually increased the burning rate.

Up to this point in the work the most successful mixture found was an emulsion of about equal parts by weight of rubber cement and EWP, preferably with the addition of bicarbonate of soda. With this mixture, a range of 80 yd could be obtained with good delivery of fuel on the far end of the range, which was always well covered with lumps of the burning mixtures. Rubber cement also has the advantage of being inert to acid and water. While natural rubber was used, oil-soluble synthetics might be of value here.

8.9 FUNDAMENTAL STUDY OF ALUMINUM SOAPS[29, 34]

In the early development work on Napalm and related thickening agents there were no reliable basic data on the chemistry of aluminum soaps. Even their existence as definite compounds was problematical. Much more knowledge of pure aluminum soaps was needed before applications could be made to the complex mixtures forming Napalm soaps and Napalm-thickened fuels.

The methods used in this study cannot be summarized here because of their highly technical and involved character, and must be found in the pertinent references.[29, 34] Only the most important conclusions reached by these methods can be summarized here.

The most important aluminum soaps are disoaps, corresponding to the formula $Al(OH)R_2$ where R is an acid radical. They form the bulk of Napalm soaps.

The properties of these soaps depend, of course, on the nature of the acid involved, its molecular weight, whether fatty or naphthenic, etc. In addition, a surprisingly large influence upon both its chemical and physical properties is exercised by the physical state of the soap, the degree of crystallinity of its structure.

For instance, aluminum dilaurate, an important constituent of Napalm, has been prepared in a high degree of purity in forms having the same composition but ranging from a highly crystalline and brittle, to an almost amorphous and fluffy solid. The former is inert to hydrocarbons at room temperature; the latter dissolves readily.

In contradistinction to di-soaps $Al(OH)R_2$, neither the mono-soaps AlOR nor the tri-soaps AlR_3 play an important role in Napalms. The former exist and can be prepared under special conditions, and the latter have probably never yet been prepared.

Fatty acids, although not combining with di-soap to form tri-soap, are readily sorbed by them and may be held quite tenaciously. Thus the small proportion of acids present in Napalm in excess of that forming di-soaps is neither combined nor truly free. It is held sorbed by surface forces.

In the presence of gasoline and other hydrocarbons aluminum soaps may show the full range of behavior from complete inertness, through swelling and thickening, to complete solution. What occurs in each particular case depends on the physical state of the soap, as mentioned above, as well as the nature of the acid forming the soap and that of the hydrocarbon, the temperature, and the presence of additives. It appears that any typical behavior may be produced, within reason, by varying any of these factors.

At low temperature a distinct gel phase is formed in general, in which the soap imbibes a certain amount of hydrocarbon, sometimes 50 volumes or more, but its particles remain separate and an excess of hydrocarbon will not be taken up. This is an opalescent, noncoherent, nonstringy, "applesaucy," or even syneretic, mass such as formed by Napalm soap at low temperatures and with high aniline-point gasolines.

The *jelly-sol* phase is formed at higher temperatures. Here the discrete particles have disappeared and a coherent, elastic, rigid jelly or a thin, easily flowing sol exists, such as formed by Napalm under ordinary conditions. Excess solvent is taken up spontaneously, and in the case of pure soap a clear system is formed.

The transition from jelly to sol and vice versa is gradual, depending on temperature and concentration without any definite boundary between them.

The transition from gel to jelly or sol, on the other hand, is sharp and may be rather easily observed.

Each of these forms is truly stable over certain ranges of conditions, but the jelly in particular may exist, without being stable, over a much wider range. Changes in viscosity corresponding to changes from jelly to sol may be very slow but start readily. This is the well-known aging of Napalm fuels. The onset of a change from a jelly to gel, on the other hand, does not occur readily in the absence of adequate seeding. The loss of coherence and possible syneresis may therefore be suspended for long periods of time running into years, even under conditions where it is finally bound to occur.

The transition temperature between gel and jelly depends on many factors, but for any given system the jelly cannot be indefinitely stable below this temperature. This fact suggests special problems connected with long-range storage of thickened fuels, particularly at low or cycling temperatures.

The properties of a mixture of aluminum soap with hydrocarbons, such as Napalm and gasoline, can be deeply influenced by the presence of many other substances, sometimes even of small amounts. The additive may accelerate or retard the interaction of the two, increase or decrease the final viscosity, change it toward dilatancy or towards plasticity (thixotropy). Each of the pairs of influences is independent and may be in either direction. The effect of a given additive may depend greatly on temperature, concentration, and even on the particular sample of Napalm studied.

Various samples of Napalm, although satisfying the requirements of the specification, differ when tested by other methods or under other conditions, to the point where the name Napalm appears almost to be their only common characteristic. These differences between Napalms manufactured under slightly varying conditions are not surprising. As mentioned above, both the physical state and small amounts of extraneous substances greatly influence the properties of all aluminum soaps. This emphasizes the need for more thorough characterization of Napalm from the point of view of physical state and impurities, and the study of the influence of manufacturing methods upon both.

Only a beginning could be made in the study of physical states of Napalms by various extraction and X-ray methods. Considerable progress was made in identifying in Napalm small amounts of several constituents absent from pure soap. Some of these were quite unexpected. Napalm may contain small amounts of inorganic substances, largely basic aluminum salts; hydrocarbon soluble sodium soaps; nitrogen (may be from proteins); partially volatile uncombined acids and unsaponifiables, and, of course, water. The bulk of Napalms, as already stated, consists of di-soaps.

8.10 FUNDAMENTAL STUDIES ON RHEOLOGICAL PROPERTIES[a]

The superior performance of thickened or gelled hydrocarbon fuels as contrasted to unthickened fuels was early recognized to be due, in large part, to their unusual flow characteristics.

Gels are dispersions which, when slightly stressed, exhibit elastic deformation, or strain, followed by a return to the original position upon removal of the stress. Gels exhibiting only elastic deformation until a definite shearing stress is exceeded may be thought to possess an elastic limit or "yield value," below which no real or permanent flow occurs. Napalm gels containing milled paper pulp and the IM-II gel behave in this manner (see Table 3).

[a] See references 14, 16, 18, 19, 21, 22, 25-28, 30, 31, 33, 36, 38, 40, 42, 44, 46, 48, 49, 52, 53, 91-102.

TABLE 3. Elastic properties of incendiary gels.

Incendiary fuel*	Shear† modulus dynes/cm²	Relaxation‡ time sec	Extensibility in.	Healing time sec	Healing rate constant	Notes
4% Napalm+10% MPP	21,000	Does not relax	....	....	....	Yield value
6% Napalm	300–550	17–20	....	10	0.20	....
8% Napalm	700–1450	....	....	....	0.12	....
9% Napalm	1400–2800	10–16	$1\frac{3}{8}$	35	0.10	Equal range
10% Napalm	1700	...	3	....	....	
8% Napalm+0.25% PPR	2800	...	$\frac{1}{4}$	....	....	
8% Napalm+2.0% PPR	4100	....	0	....	....	25% less range Yield value
12% Napalm	3400–4250	6–18	....	90	0.06	....
13.5% Napalm	2500–5300	6–30	....	....	0.04	....
IM-II	2600	Does not relax	....	8 hr	....	Yield value
2% IM+0.3% IP	24–97	5–10	....	....	....	Work harden
5% IM+0.3% IP	1020–1250	40	....	....	....	Work harden
3% IM+0.1% IP	3	....	....	75	....	Work harden
5% IM+0.1% IP	185–700	16–30	....	130	....	Work harden
MI Gel	1100–2700	....	....	....	....	....

*MI Gel = Gel described in CWS Spec. 196-131-102.
PPR = Poly pale resin (Hercules).
MPP = Milled paper pulp.
IM = Isobutyl methacrylate.
IP = Interpolymer.
†Measured in Clark-Hodsman viscosimeter, or Jeweler's lathe viscosimeter, or in the Sandvik-Goldberg resonance elastometer. For description of the latter, see Appendix II, Rheological Properties of Thickened Fluids, Eastman Kodak Co., May 7, 1943.[3]
‡Time for stress needed to maintain constant strain to fall to $1/e$ its initial value.

Other incendiary fuels possess such low strength that they are unable to support themselves when deprived of the support offered by the walls of their container and possess little, if any, yield value. These gels, after being slightly stressed, momentarily will return to their original position upon removal of the stress, but upon prolonged application of stress fail to do so, the gel accommodating itself to the stress, or relaxing by a slow flow or creep process. Such a process is referred to as relaxation, a gradually smaller force or stress, ultimately approaching zero, being required to maintain the material in the stretched or strained condition. The relaxation experimentally observed in such incendiary fuels accounts for the impossibility of measuring yield value in long-time static tests. Relaxation is a manifestation of imperfect elastic nature and not true flow in the ordinary sense of the word. It may be considered as microflow in contrast to true, real or macroflow.

With gradually increasing stress a point is ultimately reached where gel flow proceeds no longer by the relatively slow creep or relaxation process, but by a process of actual shear or sliding of one complete layer of gel along its neighboring layer. This point may be called the shear initiation point, and the shearing stress required, the shear initiation stress. In actual measurement, such flow transition may appear gradual rather than abrupt, on account of a changing amount of relaxation.

Beyond the shear initiation point, gels flow somewhat as ordinary liquids do. The resistance of an ordinary (or Newtonian) liquid to flow is called its viscosity. The coefficient of viscosity (μ) is defined as the shearing stress (F) divided by the rate of shear or shear gradient (S), and at constant temperature its value is independent of shear rate ($\mu = F/S$).

Incendiary gels are, however, non-Newtonian materials, the viscosity of which varies with the shearing stress to which they are subjected. The viscosimeters which have been employed to measure viscosity of gels are listed in Table 4 in order of shear range. The first four are rotational instruments which measure the viscosity of a confined sample. In the last four instruments a continuously fresh supply of material is forced into the capillary, pipe, or perforated disk. The latter do not attain steady-

TABLE 4. Viscosimeters employed for incendiary gels.

Name	Type	Shear range sec^{-1}	Steady state	Material renewed	Uniform stress
Clark-Hodsman	Concentric cylinder, hand-operated. $D_1=2.3$ cm $D_2=2.58$ cm.	0.01–1.0	No	No	Yes
Stormer (modified)	Paddle rotated in cup by falling weights.	0.05–1.0	Yes	No	No
MacMichael	Concentric cylinder in motor-driven cup. Inner cylinder suspended from torsion wire.	3–100	No	No	No
Jeweler's lathe	Concentric cylinder in motor-driven cup $D_1=2.30$ $D_2=2.58$. Inner cylinder suspended from drill rod. Mirror used as optical lever.	10–300	No	No	Yes
High-pressure capillary	Glass capillary tubes $2\frac{1}{2}''$ long. $r=0.0097$ & 0.021 cm. Nitrogen gas pressure to 2,000 psi as force.	1000–100,000	No	Yes	No
Grease gun	Hand-driven screw feed. Pressure drop along length of $\frac{1}{8}''$ pipe measured by gauge.	0.2–120	Yes	Yes	No
Pipe flow	Use of variable speed positive-displacement pump to measure pressure loss over length of $\frac{1}{2}''$, $\frac{3}{4}''$, $1\frac{1}{4}''$, and $1\frac{1}{2}''$ std. pipe.	0.3–11,000	Yes	Yes	No
Gardner mobilometer	Perforated disk pushed into sample in vertical cylinder.		No	Yes	No

state flow conditions, except in case of grease-gun and pipe-flow measurements where pressure loss is measured over a length at some distance from the point of entry. The Clark-Hodsman and Jeweler's lathe instruments confine the sample to a narrow annular ring at some distance from the axis so that the entire sample is subjected to nearly the same shearing stress. All other instruments impose a wide range of stresses on different parts of the sample. Thus inflow of gel through a capillary tube or pipe to the central parts may be stressed only elastically and the resulting flow, if any, will be of the creep or relaxation type, while the outer parts may possess actual shear between adjacent layers. Layers being sheared are under a wide range of stresses, with consequent variation in viscosity from one layer to the next. Under these circumstances, one measures only an apparent viscosity, that is, the sample ap-

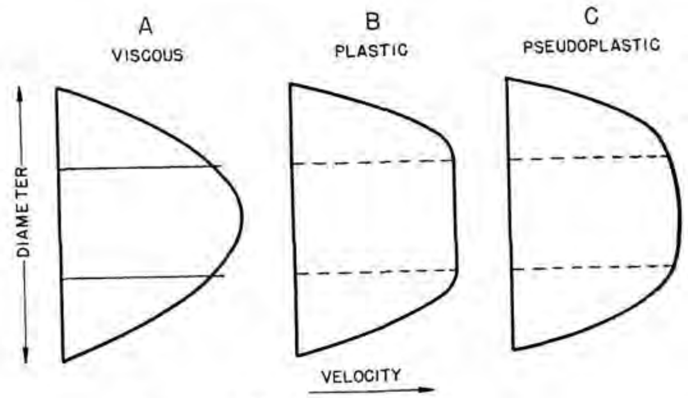


FIGURE 2. Various types of flow.

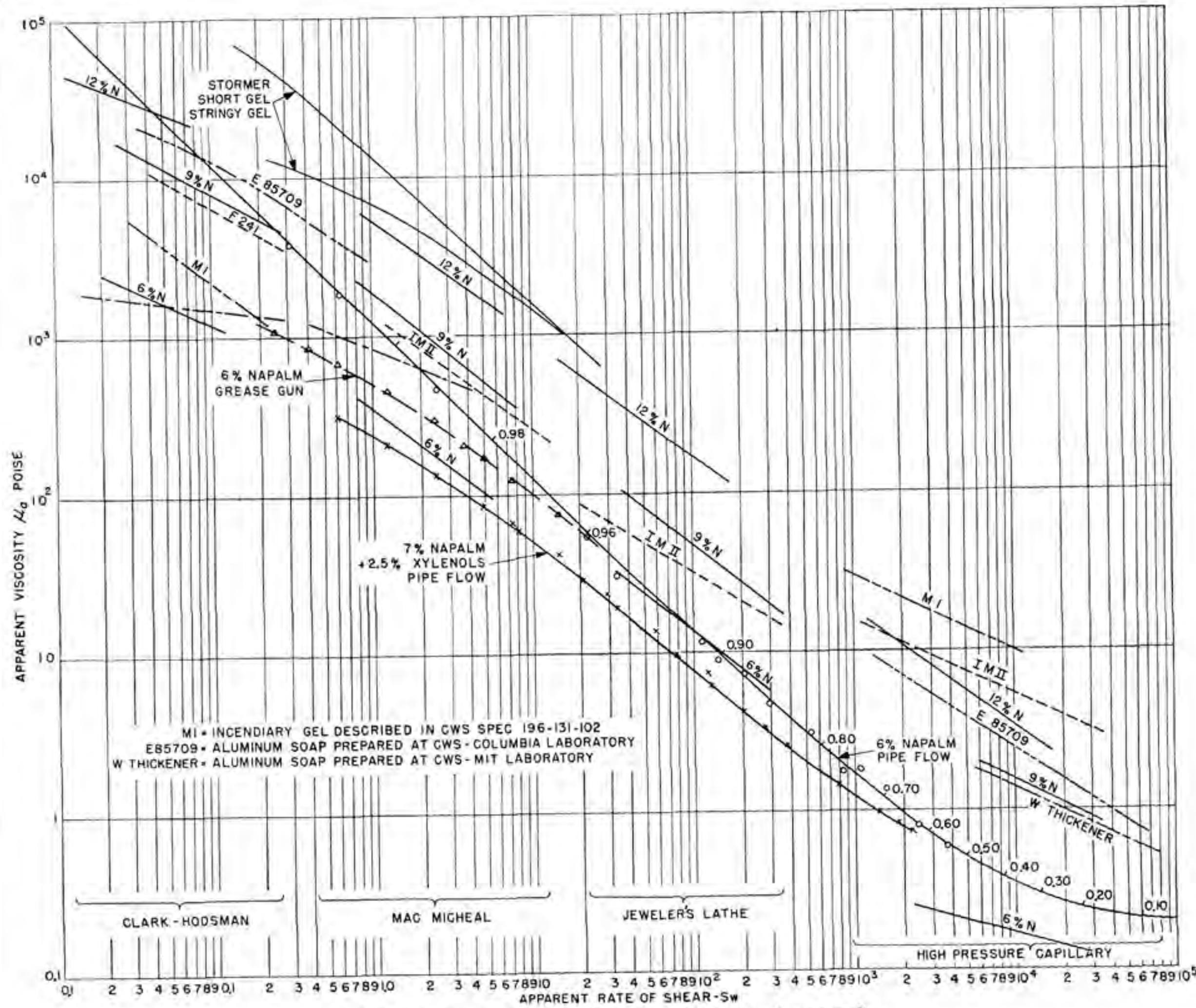


FIGURE 3. Apparent viscosity of incendiary gels.

pears to have the same resistance to flow as a normal liquid of the stated viscosity. The shearing stress due to the pressure imposed is zero at the axis and $PR/2L$ at the periphery.

For a normal liquid, the rate of shear is zero at the axis and $4V/R$ at the periphery, velocity distribution being as shown in Figure 2A. Viscosity (μ) thus becomes

$$\mu = \frac{F}{S} = \frac{PR/2L}{4V/R} = \frac{PR^2}{8VL}.$$

For a non-Newtonian material the shearing stress at the tube wall, or elsewhere, can still be computed accurately, but the rate of shear at any layer is uncertain. This is caused by the presence of a central region surrounding the axis in which shearing stress is too low to cause shear or flow to occur. A gel which possesses a definite yield value will not shear at all in those regions where shearing stress (F) is less than the yield value (f). Shear will commence at that radius where shearing stress ($PR/2L$) just equals yield value (f), and the velocity distribution across such a stream of gel will be as in Figure 2B. Such a gel is said

TABLE 5. Steady-state flow of gels in pipe.

6% Napalm					7% Napalm+2.5% Xylenols			
Flow rate gal/min	Pressure loss/ft lb/in.^{2}	App. rate of shear at wall sec^{-1}	Apparent viscosity poises	Std. pipe size	Flow rate gal/min	Pressure loss/ft lb/in.^{2}	App. rate of shear at wall sec^{-1}	Apparent viscosity poises
0.033	0.51	0.31	3800	1½″	0.866	0.21	8.11	60
0.067	0.51	0.63	1870		3.58	0.28	33.7	19.2
0.267	0.50	2.50	462		8.33	0.33	78.0	9.8
2.33	0.51	21.8	54		14.00	0.35	131	6.18
8.75	0.58	82	16.4		21.70	0.37	203	4.22
15.00	0.54	140	8.98		29.20	0.40	274	3.38
16.00	0.63	150	9.72					
21.80	0.64	204	7.36					
31.30	0.60	293	4.74					
1.58	1.10	111	11.72	¾″	1.80	0.65	126	6.12
7.58	1.36	530	3.04		5.36	0.82	375	2.58
15.25	1.63	1070	1.80		11.20	0.98	784	1.48
22.00	1.75	1540	1.34		20.00	1.16	1400	0.98
					26.3	1.30	1840	0.84
					32.3	1.41	2260	0.74
0.0165	2.60	33.2	30.4	⅛″	0.01	1.50	20.1	29.00
0.416	3.87	837	1.74		0.43	2.82	864	1.31
1.21	5.04	2435	0.80		0.56	3.87	1125	1.33
1.83	5.60	3680	0.59					
Results below from grease gun viscosimeter								
0.00012	0.675	0.242	1085	⅛″	0.0003	0.49	0.605	314
	0.88	0.400	854			0.65	1.21	206
	1.06	0.605	684			0.83	2.42	132
	1.41	1.21	453			1.08	4.84	86.8
	1.76	2.42	282			1.26	7.26	67.5
	1.94	3.63	208			1.55	14.50	41.4
	2.06	4.84	166			1.78	29.00	23.8
	2.19	7.26	117			2.06	58.00	13.8
	2.58	14.50	69		0.060	2.32	121.00	7.44
0.0144	3.00	29.00	40.4					
	1.86	2.42	299					
	2.13	4.84	171					
	2.31	7.26	123					
	2.83	14.50	75.5					
0.0144	3.85	29.00	51.5					

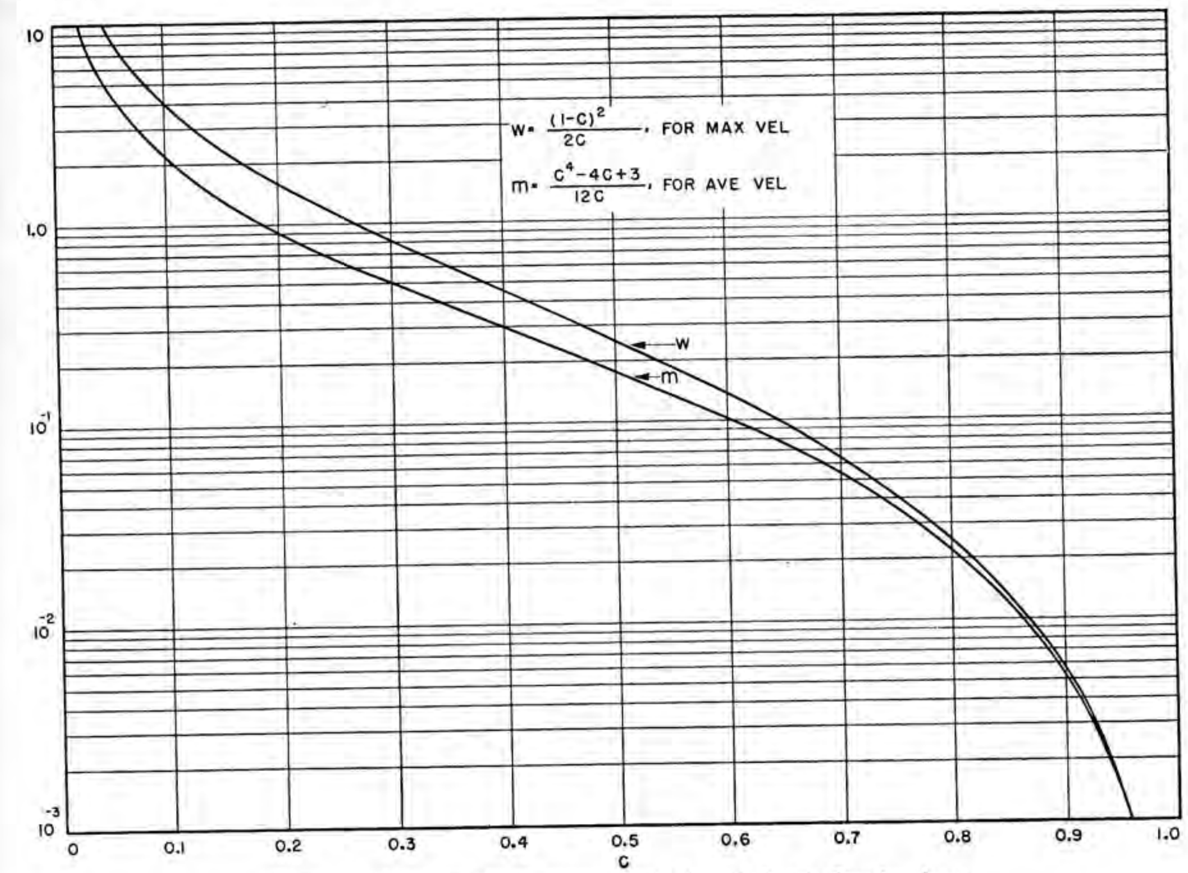


FIGURE 4. Factors for computing velocity of plastic flow in pipes.

to be plastic. If the gel possesses no measurable static yield value, but flows by a creep or relaxation process until a certain shear initiation stress is exceeded, then its flow in capillaries or pipes will resemble Figure 2C with a central region in which stress ($F = PR/2L$) is below the shear initiation stress and flow by the relatively slow creep process only occurs, surrounded by a region in which actual shear or macroflow takes place. Such a gel is called a pseudoplastic gel. Rates of shear at the tube wall are much greater for plastic and pseudoplastic materials, Figure 2B and C, than for a normal liquid (2A) at the same total flow rate. Experimentally, it is practically impossible to isolate a small sample of gel and test it under such conditions that the entire sample is subjected to the same shearing stress. The Clark-Hodsman and Jeweler's lathe instruments approximate this condition, both shearing a narrow layer between 1.15 and 1.29 cm radii, all the sample being stressed between 89 and 100 per cent of the stress at surface of the inner cylinder. This is equivalent to isolating the 20 per cent of material flowing adjacent to the wall of a tube or pipe. Unfortunately, the Clark-Hodsman instrument usually was not operated under conditions assuring steady-state flow. Consequently, apparent viscosities measured by the Jeweler's lathe instrument more closely approach the true viscosity of the gel than the measurements made with other instruments. The five viscosimeters available for the early work covered various ranges of shear rate, each having an approximately tenfold variation in range. This resulted in discontinuities and uncertainties in the resultant flow curves.

In spite of these uncertainties concerning viscosity measurements on gels, it is possible to show conclusively (Figure 3) that satisfactory incendiary gels possess very high viscosities (1,000 to 100,000 poises) at low rates of shear which gradually decrease as the rate of shear is increased until, at the highest shear rates attainable in the high-pressure capillary (approximately 100,000 sec^{-1}), the viscosities are of the order of 0.1 to 3 poises. According to this picture, flow of these gels in pipes should require considerable applied pressure at low flow rates, but very little additional pressure for much higher flow rates. That this is so is shown in Table 5, where data for flow of regular and peptized Napalm gels in pipes of three different sizes are given. A thousandfold increase of flow

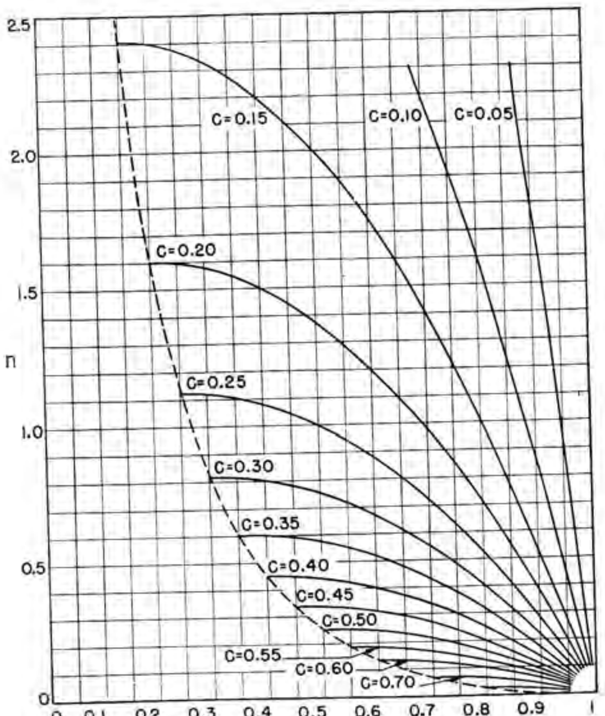


FIGURE 5. Values of $n = \dfrac{1 - 2c + 2cx - x^2}{2c}$.

rate of the 6 per cent gel in the 1½-in. pipe required only a 25 per cent increase of pressure. Such pipe-flow data actually constitute viscometric data covering a much wider range of shear rates than is possible with any single one of the instruments previously used (see Figure 3). These data are secured under steady-state flow conditions, and are free from the uncertain inlet loss and kinetic energy corrections associated with the use of ordinary capillary viscosimeters for gel measurements. Any single point of Figure 3 represents a composite or average for the stream as a whole. Actual rate of shear varies from zero at the tube axis to some value higher than the plotted point at the wall, and viscosity varies from some enormously high value, approaching infinity, in the central portion of the tube to a value lower than the plotted point at the tube wall. When very high rates of shear are produced at the tube wall, the viscosity approaches a minimum value somewhat higher than the constant viscosity of the dispersion medium, usually gasoline. The equations given below have been derived for computing the flow of plastic gels in pipes based upon a knowledge of the yield value

Equations for Plastic Flow in Round Pipes

f = yield value of gel in dynes/cm².
μ_∞ = minimum gel viscosity at infinite shear rate.
a = radius of tube or pipe.
c = ratio of central unsheared plug radius to tube radius.
x = ratio of any layer's radius to tube radius $x = r/a$.

Equation 1. Viscosity at radius x

$$\mu = \frac{\mu_\infty}{y} \qquad y = 1 - \frac{c}{x}$$

Equation 2. Velocity of central plug (maximum velocity)

$$U_p = U_m = \frac{afw}{\mu_\infty} \qquad w = \frac{(1-c)^2}{2c}$$

Equation 3. Velocity at radius x

$$U = \frac{afn}{\mu_\infty} \qquad n = \frac{1 - 2c + 2cx - x^2}{2c}$$

Equation 4. Average velocity in the tube

$$U_a = \frac{afm}{\mu_\infty} \qquad m = \frac{c^4 - 4c + 3}{12c}$$

Equation 5. Total volume rate of flow

$$Q = \frac{\pi a^3 fm}{\mu_\infty}$$

Equation 6. Apparent rate of shear at tube wall

$$S_w = \frac{4fm}{\mu_\infty}$$

Equation 7. Shearing stress at tube wall

$$F_w = \frac{f}{c}$$

Equation 8. Apparent viscosity for entire cross section of gel

$$\mu_a = \frac{F_w}{S_w} = \frac{\mu_\infty}{4cm}$$

Equation 9. Pressure drop along pipe

$$\frac{\Delta P}{\Delta L} = \frac{2f}{ac}$$

(f) of the gel, and this limiting viscosity μ_∞ approached at infinite shear rate.[b]

The quantities n, m, w, and y are dimensionless quantities dependent only on the geometry of the circular path of flow, and are entirely accurate for the flow of any real plastic in a circular pipe. Values of m and w are given in Figure 4, values of n in Figure 5, and values of y in Figure 6. Figure 5 actually shows relative velocity variation along the tube radius for a

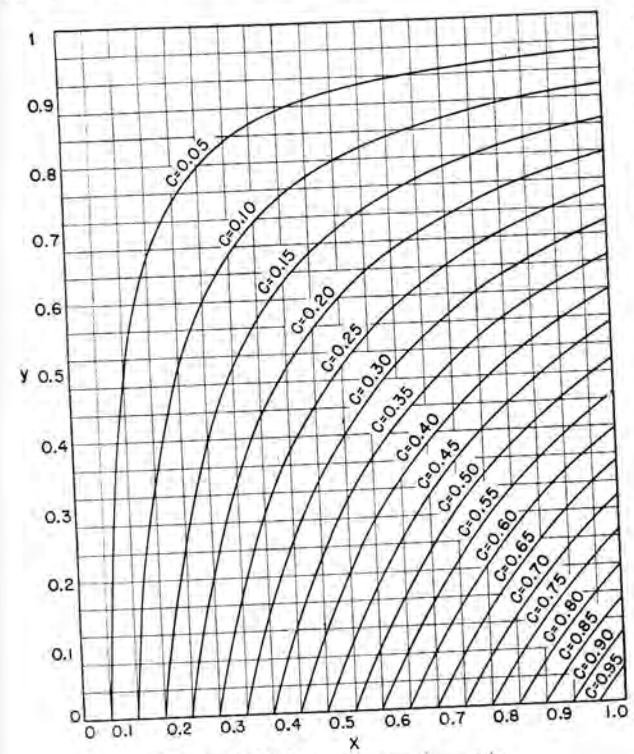


FIGURE 6. Values of $y = 1 - c/x$.

range of c values or central plug ratios. The y values given in Figure 6 allow computation of viscosity of the gel as it varies with radial distance from the tube axis. The quantities f and μ_∞ are characteristics of the plastic gel; their measurement is at present quite difficult.

These equations apply to plastic flow only; no satisfactory adaptation or correction to make them applicable to pseudoplastic flow has as yet been evolved.

The extent to which a 6 per cent Napalm gel agrees with these flow equations is shown in Figure 3, where the plotted points represent actual data secured in the order shown in Table 3, and the solid curve is a plot of apparent viscosity from equation (8) against apparent shear rate from equation (6) (see above) for various assumed values of c which are shown alongside the curve. The curve is based upon values of $f = 1{,}200$ dynes/cm² and $\mu_\infty = 0.18$ poise for the gel. Agreement of the flow data secured in the pump tests with the line representing the equation is excellent. The grease gun viscometric data secured later indicated the gel to be more mobile at the lower rates of shear; however, if we think in terms of a shear initiation stress, rather than yield value, of 1,200 dynes/cm² which must be exceeded before real flow or shear occurs, then even these data begin to conform to the curve, when 96 per cent of the tube is occupied by the central plug. At $c = 0.98$, creep flow within the plug appears to amount to 50 per cent of the shear flow in the outer 2 per cent. When $c = 0.99$, creep flow in the central plug equals shear flow in the outer 1 per cent. One might say that this gel appeared plastic in the first tests in the 1½-in. pipe and pseudoplastic in the later grease gun tests in ⅛-in. pipe. It is not known whether a yield value and, hence plastic nature of the gel, is actually easier to demonstrate in a larger pipe, or whether the change noted is entirely an aging effect. It is known that Napalm gels are more plastic or short when first prepared, becoming pseudoplastic and stringy upon aging. Pseudo-

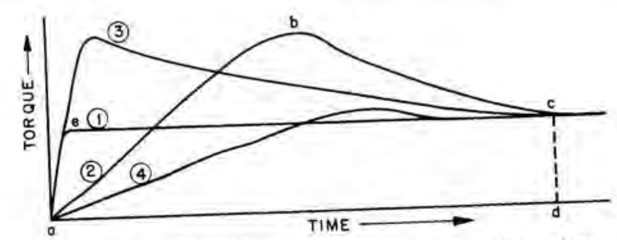


FIGURE 7. Variation of torque on torsion wire with time: (1) ordinary viscous liquid, (2) Napalm incendiary gel, (3) incendiary gels IM-Type II, (4) incendiary gels IM-Type I.

plasticity can also be induced by peptizing Napalm gels with various organic acids, alcohols, and water. The effect of such peptization is shown in Figure 3 for a 7 per cent Napalm, 2.5 per cent xylenol gel. The viscosity at low rates of shear is considerably reduced by the use of these peptizers.

[b] A more empirical but more readily used treatment of pressure drop in piping carrying Napalm gels appears in Chapter 7, Section 7.4.

In dealing with viscosity of gels, the steady state of equilibrium flow conditions has been stressed. The unsteady flow of gels or time effects in gel behavior are also of interest and may be of great importance in the flame thrower. We have already considered relaxation, a time effect in connection with elastic deformation. When stresses above the shear initiation stress are applied to a gel, flow does not immediately commence against a constant viscosity as in the case of ordinary liquids. Upon starting the Jeweler's lathe viscosimeter instantaneously, the force upon the torsion wire varies with time and the type of gel, as shown in Figure 7. The ordinary viscous liquid (1) develops a constant torque almost immediately, the rate of the initial steep climb being determined by the speed of rotation and the stiffness of the torsion rod, in other words, the response of the system. Napalm gels (2) produce a trace which usually shows a slight rapid rise at the start similar to the normal liquid. Then the force gradually climbs. This may be interpreted as an elastic stretching of the gel which may be accompanied by relaxation, although the time available for relaxation to occur is limited to from 0.05 to 1 sec depending upon the speed of rotation. The slope of the climbing trace is really a measure of the elasticity or shear modulus of the gel, the fact that a curving line results indicating deviation from Hooke's law. A steep slope indicates high shear modulus or a short gel, while a gradual slope indicates low shear modulus and a stringy gel. Both slope and shear modulus increase with increasing soap concentration in the gel. The faster the rotation the sooner peak or maximum force occurs, but for a single gel the peak always occurs after approximately the same number of rotations. For a typical 9 per cent Napalm gel this may be at one-third of a revolution, at which point the gel originally lying along a radius between the cylinders (0.14 in.) may be thought of as stretched over a curving arc of about 1-in. length; hence it has suffered a sevenfold stretch before real shear has occurred.

Slower speeds of rotation cause the maximum force at the hump to be less, an indication that relaxation or creep during the elastic stretch has, because of the longer time, played a more important role. Following the maximum, there is a gradual decrease until a constant force or torque is measured at ½ to 2 sec following the start of rotation. The Jeweler's lathe viscosity data of Figure 3 are based upon this part of the trace. This final force increases only slightly with great increase of rotational speed, producing lines on Figure 3 which approach the limiting slope of 45 degrees. Another point of interest in these traces is the excess of area *abcd* over *aecd*, which may be thought of as the additional work that must be done to the gel to start it flowing above that needed for a normal liquid of the same final viscosity. This additional work is greater the faster the rotation, again indicating less relaxation to be possible under such conditions.

When such Jeweler's lathe experiments are repeated upon the same gel after increasing time intervals, it is found that the maximum force developed is less than the original value, until a certain time has elapsed which may be referred to as the healing time of the gel (see Table 3). A 9 per cent Napalm gel shows a healing time of approximately 10 sec after being sheared at a rate of 211 reciprocal sec. The bulk of healing may be completed in half of this time. This means that such a gel possesses the property of thixotropy, that is, a time lag in regain of initial strength following the cessation of the shearing action.

In Figure 7 curves (3) and (4) illustrate traces made by incendiary gels IM-Type II and incendiary gels IM-Type I respectively. Most of the useful incendiary gels investigated are, to some degree, thixotropic. A healing rate constant (similar to a first-order chemical reaction) better characterizes the healing process than the rather uncertain use of the term healing time. Healing rate increases rapidly with increase of temperature. From the temperature dependence of this rate constant, the activation energy associated with this healing process was found to be 9 ± 1 kcal. This suggests that the linking may occur by means of hydrogen bonds.

Incendiary gels are imperfect elastic solids which suffer relaxation when stressed below the shear initiation stress. When stressed more than this, they become liquefied with an apparent viscosity which decreases with increasing severity of stressing, finally approaching a minimum limiting viscosity somewhat higher than that of the dispersing liquid or fuel. Incendiary gels are thixotropic, since upon cessation of stressing, time is required before they regain their initial elastic condition. To completely describe such gels it would be necessary to secure the following data.

- Modulus of rigidity
- Relaxation time
- Extensibility
- Apparent viscosity
  - Variation with shear rate
  - Shear initiation stress
  - Ultimate minimum viscosity
- Thixotropy
  - Healing time
  - Healing rate constant

All the above quantities have been investigated on various gels at various times. To attempt to measure all these quantities in a routine testing of incendiary fuels would be unwise and time consuming. The one property that appeared to be of greatest importance in incendiary fuels was the extreme variation of apparent viscosity with shear rate.

The Gardner mobilometer was finally chosen to serve as a routine testing instrument to determine gel quality. As used, it provides a measure of gel viscosity reported as grams weight necessary to cause a rate of shear corresponding to 10 cm disk travel in 100 sec. In arriving at this point, several weights are employed and a plot of weight versus time obtained. In addition to the 100-sec Gardner consistency,[c] the slope of such a plot furnishes a rough measure of the degree of pseudoplasticity (relaxation or stringiness) of the gel. Napalm supplied by different sources varies only to a limited degree in this property.

When ordinary liquids of low viscosity issue at high velocity from small nozzles, they tend to atomize immediately into very fine droplets. Liquids of moderate viscosity produce jets which, at some distance from the nozzle, break up into somewhat larger droplets. Very viscous liquids emerge as a smooth stream or rod that does not break up during the trajectory, which is, however, of limited length due to the high viscosity imposing a low initial velocity at the pressures available. Jet breakup is caused by surface tension of the liquid, frictional drag due to the surrounding air and to some extent aided by turbulent conditions in low viscosity liquids as they issue from nozzles. A very viscous liquid is able to resist the forces tending to cause jet breakup but, on account of the viscous parabolic velocity distribution, requires nearly twice the energy or pressure for a given average jet velocity that a more limpid liquid in turbulent flow does. It is also subject to much higher pressure losses in pipe and nozzle.

To secure maximum jet velocity, jet cohesion, and range, a type of liquid is required which has a sufficiently low apparent viscosity at high rates of shear to flow readily through pipes and nozzles, and a sufficiently high velocity, at the low rates of shear induced by friction with the air, after leaving the nozzle to cohere well in flight. The speed of the change from liquid condition adjacent to the nozzle wall to viscous condition in the emerging jet, apparently plays a significant role. Napalm gels which show much faster healing than, for example, the IM-II gel, have found more favor as a flame-thrower fuel. The IM-II and the Edgewood MI gel have, on the other hand, proved satisfactory for incendiary bomb use where fast healing is not of such great importance.

Another factor of great importance is the extensibility, or stringiness, of the gel which has been experimentally observed by measuring the length to which a given gel can be stretched or extended at a fixed constant rate before rupture occurs. Some data of this nature are included in Table 3. Napalm gels can be made short (lack of stringiness) by addition of poly pale resin or milled wood pulp. These very short gels are quite plastic, showing a definite yield value. The IM-II gel also possesses a definite yield value. Such short gels do not behave well in flame throwers. The jet of gel issuing from the flame-thrower nozzles consists of an elastic core surrounded by layers of gel which have been sheared. This elastic core is stretched and compressed in the nozzle. If this strain is too great, as in the short gels, the rod of fuel issuing

[c] The term commonly used in referring to these values, since the shear rate cannot be precisely determined.

from the nozzle pulls apart into separate small chunks which offer so great a surface that drag, due to air resistance, reduces the range. A less plastic or pseudoplastic gel which is capable of relaxing or creeping in the central elastic core accommodates itself to the elastic strains set up in going through the nozzle so that it holds together as a continuous rod upon issuing from the nozzle, contracting only sufficiently to offset the decreasing jet velocity. If the stringiness is too great so that practically no elastic recovery occurs as the jet or rod slows down, then looping into folds may occur. However, there is no definite evidence that excess stringiness, relaxation, or pseudoplasticity exerts a harmful influence on the range.

GLOSSARY

EWP. Phosphorus-phosphorus sesquisulfide eutectic.
FRAS. Aluminum stearate-thickened fuel.
IM. Gasoline gel of the isobutyl methacrylate type.
NP. Gasoline gel of Napalm type.
PT. Pyrotechnic mix.
SCFH. Standard cubic foot per hour.
SDO. Synthetic drying oil.
WP. White phosphorus.

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OSRD APPOINTEES

DIVISION 11

Division 11 was organized on December 9, 1942 when former Division B of the NDRC was broken up into four new Divisions, 8, 9, 10 and 11, known as the Chemical Divisions. Former Division B was under the Chairmanship of Roger Adams and had ten sections, each of which had one or more subsections. Division 11 was made up of Sections B-7, B-8, part of B-9 and B-10 (together with subsections B-7-b, B-7-d, B-7-e, B-8-a, B-8-b, B-8-c, B-8-d, B-8-e, B-8-f, B-9-a and B-9-d) of former Division B. Subsections B-9-b and B-9-c of Section B-9 were later incorporated in a new Division 19.

The list which appears below therefore shows essentially the organization since December 9, 1942. Although many changes were made during the years 1943-1945, the names of all appointees who held appointments to Division 11 at any time during this period have been included. In addition, the names of men who held appointments in the sections and subsections of former Division B, but who did not have appointments to Division 11 following the reorganization, have been included so as to give a complete picture of the organization since the beginning of the work under NDRC.

Section 11.3 comprises Subsections B-7-d and B-7-e and Section B-10 of former Division B.

Chiefs

R. P. Russell
H. M. Chadwell
E. P. Stevenson

Technical Aide

D. Churchill, Jr.

Members

D. Churchill, Jr.
E. R. Gilliland
H. C. Hottel
H. F. Johnstone
E. P. Stevenson
W. K. Lewis
J. H. Rushton
R. P. Russell
T. K. Sherwood

SECTION 3

Chiefs

N. F. Myers
H. C. Hottel

Technical Aides

R. H. Ewell
C. C. Furnas
S. M. Jones
C. E. Reed
C. S. Keevil
R. E. Loop
R. M. Newhall

Members

H. J. Billings
E. K. Carver
L. F. Fieser
H. O. Forrest
C. R. Hoover
H. C. Hottel
H. F. Johnstone
C. A. Kraus
W. E. Kuhn
T. V. Moore
J. D. Murch
N. F. Myers
J. K. Roberts
R. P. Russell
E. P. Stevenson
N. J. Thompson

Contract Numbers	*Name and Address of Contractor*	*Subject*
OEMsr-21 (11-109)	Massachusetts Institute of Technology Cambridge, Massachusetts	Design of Flame Thrower Nozzles; Applications of Thickened Fuels; Miscellaneous Problems Relating to Incendiaries and Flame Throwers; Design and Construction and Installation of a Large Flame Thrower in an M-4 Tank, Maintenance and Operation of Facilities for Testing of Incendiaries at Edgewood Arsenal, Md.
OEMsr-25 (11-117) (Superseded by OEMsr-179)	Harvard University Cambridge, Massachusetts	Preparation and Properties of DVA as an Incendiary and the Development of Containers for this Material.
OEMsr-57 (11-146)	Brown University Providence, Rhode Island	Development of Incendiary Devices.
OEMsr-113 (11-157)	University of Chicago Chicago, Illinois	Development of the "Chicago Incendiary" and Possible Use of the Material Developed as a U.P. Propellant.
OEMsr-167 (11-110) (Superseded by OEMsr-661)	Associated Factory Mutual Fire Insurance Companies Boston, Massachusetts	Development of nozzles for the projection of jets of combustible liquids, including nozzles approximately one-half inch in diameter suitable for use on portable flame throwers; studies of the general design of such equipment.
OEMsr-179 (11-186) (Replacing OEMsr-25)	Harvard University Cambridge, Massachusetts	Study of organic incendiary materials and organic materials of possible use as U. P. propellants; development of new types of incendiary bombs; determination of the ballistic characteristics of such munitions by means of wind tunnel tests.
OEMsr-179; Subcontract No. 1	Morgan Construction Company Worcester, Massachusetts	Fabrication of test samples of E-1 incendiary bomb casings and of E-1 500-lb. incendiary bomb assemblies.
OEMsr-183 (11-204) (Superseded by OEMsr-354)	Standard Oil Development Company New York, New York	Development of oil incendiaries.
OEMsr-198 (11-202)	Monsanto Chemical Company Springfield, Massachusetts	Development of a nitrocellulose container for incendiary materials; development of a nitrocellulose incendiary.
OEMsr-234 (11-205)	Massachusetts Institute of Technology Cambridge, Massachusetts	Studies of the kindling characteristics of wood.
OEMsr-242 (11-203)	Arthur D. Little, Inc. Cambridge, Massachusetts	Development of weapons and munitions relating to chemical warfare including incendiaries, flame throwers and organic and inorganic incendiary mixtures for use therein; development of countermeasures against flame throwers; study of combined HE-IB attack on precision targets.
OEMsr-242; Subcontract No. 1	William L. Gilbert Clock Corporation Winsted, Connecticut	Production of 600 special fuze units in accordance with Arthur D. Little, Inc., Assembly Drawing No. B1005; development of any modification that may become necessary as a result of the construction of these units.

Contract Numbers	Name and Address of Contractor	Subject
OEMsr-257 (11-231)	Factory Mutual Research Corporation Boston, Massachusetts	Development and testing of incendiary materials and incendiary bombs; selection and provision of certain instruments required for testing of incendiaries by the National Defense Research Committee at Edgewood Arsenal, Maryland.
OEMsr-296 (11-246)	Victor Chemical Works Chicago, Illinois	Development of processes for the utilization of phosphorus incendiaries.
OEMsr-354 (11-204) (Replaced OEMsr-183)	Standard Oil Development Company New York, New York	Development and production of oil incendiaries.
OEMsr-390 (11-270)	Standard Oil Development Company New York, New York	Development of flame throwers, especially the development of thickened fuels.
OEMsr-470 (11-279)	Gilbert and Barker Manufacturing Company Springfield, Massachusetts	Development of nozzles and ignition mechanisms to be used on flame throwers.
OEMsr-538 (11-300)	Eastman Kodak Company Rochester, New York	Study of the properties of thixotropic, dilatant, and other fluids applicable to flame throwers, incendiaries and vesicants.
OEMsr-538; Subcontract No. 1. (Replaced OEMsr-1281)	Ferro Drier and Chemical Company Cleveland, Ohio	Development, design and construction of equipment for the continuous mixing of dry Napalm and other thickening agents with hydrocarbon fuels to produce uniform gels.
OEMsr-538; Subcontract No. 2	Cleaver-Brooks Company Milwaukee, Wisconsin	Design and development of apparatus for the continuous mixing of Napalm and hydrocarbon fuels.
OEMsr-661 (11-367) (Replaced OEMsr-167)	Factory Mutual Research Corporation Boston, Massachusetts	Development of flame throwers, and, more particularly, attempt to improve the present portable flame thrower.
OEMsr-677 (11-368)	Nuodex Products Company, Inc. Elizabeth, N. J.	Development of methods and agents for thickening fuels for use in incendiary bombs and flame throwers and for thickening vesicants, with particular emphasis on the application of naphthenate soaps.
OEMsr-744 (11-364)	E. I. duPont de Nemours and Company, Ammonia Department Wilmington, Delaware	Development of agents and methods for thickening fuels for use in incendiary bombs and flame throwers and for thickening vesicants, with particular emphasis on the application of synthetic polymers.
OEMsr-847 (11-412)	Harshaw Chemical Company Cleveland, Ohio	Formulation of aluminum soap thickening agents and practical methods for their manufacture.
OEMsr-882 (11-416)	Ferro Drier and Chemical Company Cleveland, Ohio	Study of aluminum soap thickening agents.
OEMsr-898 (11-422)	The Texas Company 135 East 42nd Street New York, New York	Design, development and test of a medium-sized incendiary bomb, suitable for precision aiming and adapted to efficient loading on American aircraft.
OEMsr-898; Subcontract No. 1	Foster-Wheeler Corporation New York, New York	Design, development and test of medium-sized incendiary bomb, suitable for precision aiming and adapted to efficient loading on American aircraft.
OEMsr-898; Subcontract No. 2	Standard Products Company Detroit, Michigan (Port Clinton, Ohio)	Design, development and test of a medium-sized incendiary bomb, suitable for precision aiming and adapted to efficient loading on American aircraft.
OEMsr-916 (11-394)	Shell Development Company 400 Bush Street San Francisco, California	Development and production of improved fuels for flame throwers; development of flame throwers; design and development of mobile flame throwers.
OEMsr-943 (11-413)	C. F. Braun and Company Alhambra, California	Design, development, construction, and demonstration of mobile flame throwers.
OEMsr-1011 (11-447)	Standard Oil Company (Indiana) 910 S. Michigan Avenue Chicago, Illinois	Design and development of mobile flame throwers; development of fuels for flame throwers; development of a field unit for servicing flame throwers.
OEMsr-1011; Subcontract No. 1	Merz Engineering Company Indianapolis, Indiana	Design and development of mobile flame throwers.
OEMsr-1057 (11-455)	Stanford University Stanford University, California	Studies of structure and characteristics of soap-thickened fuels.
OEMsr-1170 (11-470)	Ford, Bacon and Davis, Inc. New York, New York	Design and construction of test structure and bomb-proof shelter at Eglin Field, Florida.
OEMsr-1266 (11-483)	Davey Compressor Company Kent, Ohio	Design, construction and the furnishing of necessary shop drawings and layouts of two (2) servicing units for flame throwers.
OEMsr-1281 (11-488) (Superseded by OEMsr-538, subcontract No. 1)	Ferro Drier and Chemical Company Cleveland, Ohio	Studies of methods of field mixing of flame thrower fuels.
OEMsr-1364 (11-498)	Morgan Construction Company Worcester, Massachusetts	Design of several different types of tank-mounted flame throwers; construction and installation in a M4A1 tank of an experimental flame thrower; construction of twenty (20) special flame guns.
OEMsr-1386 (11-499)	Consolidated Engineering Company Baltimore, Maryland	Construction of three buildings in accordance with certain drawings, entitled "Preliminary Layout-Test Laboratory for NDRC at Edgewood Arsenal."
OEMsr-1468 (11-512)	California Research Corporation 200 Bush Street San Francisco, California	Development of methods (1) for preparing aluminum cresylate from cresylic acids derived from petroleum and (2) for preparing satisfactory gels by the addition of such aluminum cresylate and fatty acids to hydrocarbon fuels.
OEMsr-1480 (11-514)	University of Iowa Iowa City, Iowa	Studies and experimental investigations in connection with (a) the design and construction of a flame thrower kit and the installation of such kit in a medium tank which will retain the main armament and (b) the construction of several additional flame thrower kits for installation in the field; engineering and consulting services for the construction of additional kits by Chemical Warfare Service contractors.

CONTRACT NUMBERS, CONTRACTORS AND SUBJECT OF CONTRACTS

SERVICE PROJECTS

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Office for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Title*
	Army Projects
CWS-10	Flame Thrower: (a) fuel composition (b) nozzle design.
CWS-12	Materials for Thickening and Increasing the Viscosity of Vesicants.
CWS-21	Study of Incendiary Materials.
	Navy Projects
NO-164	Rockets and Rocket Projectors.
NS-317	The Development of Countermeasures Against Flame-Throwing Equipment.
	Army-Navy Projects
AN-23	Studies of Combined HE-IB Attack on Precision Targets.

INDEX

The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy Agency listed on the reverse of the half-title page.