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dear lynn:

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Sad to say they were declassified several years ago but some foia officer at nara screwed up and sent the decision letter to our old office on mass. avenue--the letter never got forwarded and the mistake went unnoticed... until i called to see what the heck was going on with this old request.

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Billy

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FIRE EFFECTS OF NUCLEAR WEAPONS: A SUMMARY OF CONTRIBUTING FACTORS (U)

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INSTITUTE FOR DEFENSE ANALYSES
RESEARCH AND ENGINEERING SUPPORT DIVISION

January 1964

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STUDY S-141

FIRE EFFECTS OF NUCLEAR WEAPONS: A SUMMARY OF CONTRIBUTING FACTORS (U)

F. A. Williams
F. B. Porzel
D. B. Olfe

INSTITUTE FOR DEFENSE ANALYSES
RESEARCH AND ENGINEERING SUPPORT DIVISION
Contract SD-50
Task 28

PREFACE

The thermal effects of multimegaton nuclear weapons can extend over significantly greater distances than their blast effects. Therefore, an enemy might be able to inflict severe fire damage on large areas of the United States with relative impunity by detonating such weapons beyond the range of the defensive systems that have so far been considered feasible.

Even a cursory examination of the literature discloses that (1) there are a great many reports on various aspects of thermal pulses and their effects, (2) much of the information is inconclusive or apparently contradictory, (3) much of the data are inapplicable in the "real-world" situation, and (4) limits of reliability of data are rarely given. With these limitations in mind, the members of the Fire Panel have attempted to distill the present state of knowledge with respect to thermal phenomena of nuclear weapons in an effort to predict those conditions which would be conducive to conflagrations or fire storms. In the process of making this evaluation, emphasis was given to setting limits of reliability on present knowledge of various aspects of the problem.

As a first step in the analysis, a symposium arranged by L.M. Sharpe was held at IDA on October 31 and November 1, 1963, on the subject of "Large-Scale Fires That Might be Initiated by Nuclear Weapons." A list of speakers, their affiliations, and the titles of their presentations appear as Appendix D.

The rest of the analysis involved the study of material contained in the talks and in reports, and an effort to arrange the material in a comprehensible fashion in order to extract high-confidence limits from the results. Some calculations of high-confidence limits on radii of ignition were also performed.

FOREWORD

IMPLICATION CONCERNING DEFENSIVE AND OFFENSIVE PLANNING

In Sec. 1.3, the large uncertainty in the fire effects of nuclear weapons is emphasized. In spite of this uncertainty, it is of interest to attempt to derive relatively confident conclusions concerning both the offensive and defensive strategies from the available data. In order to obtain such conclusions, we shall assume that the total area of severe fire damage is approximately equal to the area of ignition produced by the thermal pulse of a weapon. This basic assumption enables us to derive high-confidence statements from Figs. 1.1 and 1.2. The basic assumption appears to have a greater probability of being true than a hypothesis that fire spreads over additional areas comparable in size with the initial area ignited or that most of the fires in the area of initial ignitions go out, but it must be emphasized that a region of relatively large ignorance is overlooked in the following paragraphs.

First consider the viewpoint of an offensive planner. In order to obtain high-confidence conclusions concerning the minimum extent of fire destruction, the offense will use the dashed curves in Figs. 1.1 and 1.2.

According to the dashed curves in Fig. 1.1, weapons of 2.5 Mt or below would have to be burst below 10 km in order to provide a high degree of certainty of producing ignitions on an average clear day. Even then, the offense would be reasonably well assured of igniting an area of only a 10-km radius for 2.5 Mt weapons.

On the other hand, on a clear day, a 30-Mt weapon burst at 30 km (which is above the protection altitude of most AICBM systems) would ignite an area of 35-km radius, with a high degree of confidence. Employing this strategy, the offense is reasonably well assured of setting fire to all of New York or to all of Washington with a single bomb on an average clear day. On a day with medium cloud cover, such an explosion could not be counted upon to set any fires, but the offense would presumably have access to U.S. weather reports and could plan their attack accordingly.

With a 150-Mt weapon burst at 30 km, the offense is reasonably certain of igniting all of New York or Washington even through a medium cloud cover, and on a clear day would be reasonably certain of producing an ignition radius of 75 km. Thus, the offense could probably ignite both New York and Philadelphia with a single 150-Mt bomb on a clear day.

The large orbital bomb is not a very promising offensive weapon because even 1000 Mt burst at 80 km can be counted upon to ignite an area with a radius of only 40 km on an average clear day. However, the uncertainties become very large at these high altitudes, and the orbital bomb may well be a dangerous threat from a defensive viewpoint, since the high-confidence upper limit on the ignition radius of a 1000-Mt weapon burst at 400 km on a day with medium cloud cover (and also of a 100-Mt weapon burst at 150 km on an average clear day) is 150 km.

The present-day thermal threat that is most appealing to the offense appears to be a weapon in the 30 to 50 Mt range burst at an altitude of the order of 30 km. This is a very attractive offensive strategy.

Next, consider the viewpoint of the defensive planner. In order to obtain conclusions concerning the maximum extent of fire damage, the defense will use the solid lines in Figs. 1.1 and 1.2.

The defense must consider the thermal threats of all weapons of yields greater than about 100 kt, because a 100-kt weapon, airburst at sea level, may well ignite an area of 15-km radius if enhancement by a medium overcast occurs. This same high-confidence upper limit on the ignition radius drops only to about 10 km on a clear day (with no cloud enhancement).

If the defense develops an active system capable of preventing detonations below 30 km, then it must still be concerned with weapons in the 1-Mt range, since the high-confidence upper limit on the ignition radius is about 20 km for a 1-Mt burst at 30 km on an average clear day.

Against the threat that is most attractive to the offense (30 Mt at 30 km, average clear day), the defense can, with high confidence, conclude only that the radius of the area of ignition will not exceed 150 km for a single burst. (Medium cloud cover drops this radius only to 90 km.) Thus, for one such burst over Philadelphia, the defense would have to consider the possibility of ignitions in both New York and Baltimore on a clear day. The uncertainties concerning atmospheric transmission become very large at these large ignition radii. However, it does appear that the offensive planner's optimum thermal threat is one of the potentially most devastating threats from the defensive viewpoint.

It may be concluded that, for the defensive planner, the thermal threat of nuclear weapons is formidable.

ACKNOWLEDGMENT

The authors of this report are pleased to acknowledge the valuable assistance in the form of discussions and critiques by W.D. Barfield, J. Bengston, R.L. Brock, J.F. Coates, R.H. Fox, S. Rand, L.M. Sharpe, and B.L. Tucker.

Special thanks are due R.L. Brock for his detailed analytical review and L.M. Sharpe for arranging the two-day symposium on "Large-Scale Fires Initiated by Nuclear Weapons," held at IDA on October 31 and November 1, 1963. Thanks also are due to those who attended the IDA symposium, especially to Craig C. Chandler for his continued interest and advice.

Section 2, and most of Section 1.7, were written by F.B. Porzel; Sections 3 and 1.8 by D.B. Olfe; the remainder of the report was written by F.A. Williams. John M. Porter provided some of the material for Appendix C.

CONTENTS

3. ATMOSPHERIC TRANSMISSION

4. IGNITION

5. FIRE SPREAD

6. MASS FIRES AND THEIR EFFECTS

REFERENCES

FIGURES

TABLES

1. INTRODUCTION AND SUMMARY

1.1 Introduction

The potential military uses of nuclear weapons are often conceived primarily in terms of the destructive effects of blast and overpressure caused by nuclear explosions. Interest in radioactive fallout and thermal radiation effects, however, has increased as a consequence of advances in nuclear technology and in understanding the implications of thermonuclear war. If, for example, a ballistic missile defense system for cities precludes penetration of nuclear weapons to their optimum altitude for maximum blast destruction, then the attacker may still have the alternative of bursting his weapons on the surface upwind from the target, but beyond the range of the defensive system, so as to produce lethal radioactive fallout over the city. Alternatively, if the defense system were characterized by a limited-altitude zone within which interceptions were possible, attacking weapons could be detonated at altitudes above the maximum interception altitude and perhaps achieve disastrous thermal damage to the target, even if blast and radioactive effects were small. In fact, if mass fires engulfing large urban areas could be initiated readily by large weapons burst at high altitudes, such attacks might be preferred even though no defense were present. Therefore, it is of considerable importance to determine as accurately as possible the potential fire effects of nuclear explosions.

1.2 Objective of the Study

The purpose of this study is to review what is known about the fire effects of nuclear weapons. Special emphasis is placed upon large-scale fires that might result from nuclear explosions. Existing data are reviewed. However, the attribute that distinguishes this study from other reviews is the attempt made to place high confidence limits on existing data and to derive statements of high likelihood. Although, for reasons that appear in the report, this endeavor has not proved very successful, nevertheless, a number of areas in which major uncertainties exist have been identified. Views on the current overall status of the subject and on areas in which significant progress might be made through research are also given. Because of time limitations, certain important topics were only mentioned. These topics are identified in the text.

1.3 Principal Conclusion

If one main conclusion were to be drawn from this study, it would be the following: The mass fire effects of nuclear weapons are extremely difficult to predict with a high degree of reliability.

Although the qualitative influences of a multitude of factors upon mass fires are well known, we do not know the minimum requirements for initiation or maintenance of fire storms and conflagrations.* Furthermore, it is quite possible that, depending upon the values of many parameters, very large mass fires may be induced by a nuclear explosion, or all fires resulting from nuclear thermal ignitions may rapidly die out. The range of possible fire phenomena is so great that, except in a few specific areas, only rough qualitative statements can be made. These specific areas do not interlock sufficiently to enable one to reliably calculate the total extent of fire damage from a nuclear explosion, even under conditions specified as precisely as currently possible. Although very wide high-confidence limits on radii of ignition can be given, in the event of a full-scale nuclear exchange, one cannot say whether or not fire effects will be of significance.

In the following section, the broad topics that must be considered in studies of the process of mass fire development from nuclear explosions are identified, and the extent to which it is reasonable to attempt

*Nominally, "fire storm" refers to a large, intense, localized fire with high velocity winds, and "conflagration" refers to a large propagating fire.

to make quantitative calculations of high-confidence limits is indicated. Major areas of uncertainty are listed in Sec. 1.5. The individual steps involved in fire development from nuclear detonations are summarized at somewhat greater depth in Sec. 1.7 to 1.11, where the degree of uncertainty in each area is discussed.

1.4 Brief Summary of Results

Whenever mass fires occur, they must develop as a consequence of a substantial amount of fire spread following ignition. Nuclear weapons produce ignition by transmission through the atmosphere, from the fireball to the ground, of the electromagnetic ("thermal") energy--the thermal pulse--emitted by the fireball. Thus, five steps (underlined above) may be assumed to be involved in nuclear-induced large-scale fire phenomena. Each of these steps should be described quantitatively if a quantitative prediction of the extent of mass fire damage is to be made. These five steps are treated in chronological order (Thermal Pulse, Atmospheric Transmission, Ignition, Fire Spread, Mass Fires and Their Ecological Effects) in Secs. 2 to 6; they are summarized in the same order in Secs. 1.7 to 1.11.

In studying mass fires, we found that they have not been described quantitatively in sufficient detail to enable one to discover what are the important underlying parameters that govern their structure and their time development. Whether a propagating conflagration or a stationary fire storm would be observed in a given city, under given weather and climatic conditions, and with a specified initial fire distribution cannot be stated with a reasonable degree of certainty. Consequently, the total area burned by a mass fire and the extent of damage within the burned area cannot be predicted quantitatively. The qualitative effects of some parameters that appear to be relevant can be discussed (Sec. 6), but numerical estimates of damage in hypothetical mass fires constitute little more than guessing games.

The situation is not quite so poor in regard to the question of the spread of smaller fires. Here, most of the important parameters have been identified; some of these are the distances separating combustible structures, heights of structures, materials of construction, contents of buildings, the types of fire protection measures taken in designing buildings, moisture content of materials, surface wind speed, upper atmospheric conditions, and topography. The quantitative effects of many of these parameters have been assessed. However, so many parameters appear that, unless a great effort is expended in collecting and analyzing data, quantitative calculations cannot be completed on the extent of fire spread in a given city, under given conditions, and with a specified initial distribution of ignitions. Therefore, appraisals of the extent of fire spread following a hypothetical set of ignitions are generally qualitative.

Quantitative high-confidence limits* can be established for the processes of ignition, atmospheric transmission, and thermal emission by the fireball of a nuclear bomb. The radiant energy per unit surface area of the material, required to ignite the lightest of kindling materials, is known to lie between 2 and 20 cal/cm^2 for all thermal pulses of nuclear weapons. The transmissivity of the atmosphere to the thermal radiation of nuclear fireballs can be specified within the high-confidence limits indicated in Sec. 1.8. The amount of energy emitted as thermal radiation in a nuclear explosion can be bounded as stated in Sec. 1.7. Knowing quantitatively the uncertainties in each of these processes, we are able to compute high-confidence limits for the radius R of the ground circle within which ignitions would occur if a nuclear weapon of a given yield W were exploded at a given altitude h on a day with weather conditions specified as accurately as is usually done in meteorological reports. The results of such a calculation, which is carried in Appendix A, are shown in Figs. 1.1 and 1.2 for an average clear day and for medium cloud cover, respectively. We believe that the limits shown in these curves lie between 80 and 100 percent confidence limits; the difficulties in ascertaining the precise percentage are considered in Appendix B.

In Figs. 1.1 and 1.2, high-confidence limit curves of the ignition radius R as a function of weapon yield W at burst altitudes of 0 (sea level, airbursts), 10, 30, 50, 80, 100, 200, and 400 km are shown.

*These are not precise confidence limits in a statistical sense, but instead represent bounds within which the reasonable theoretical and experimental results appear to fall.

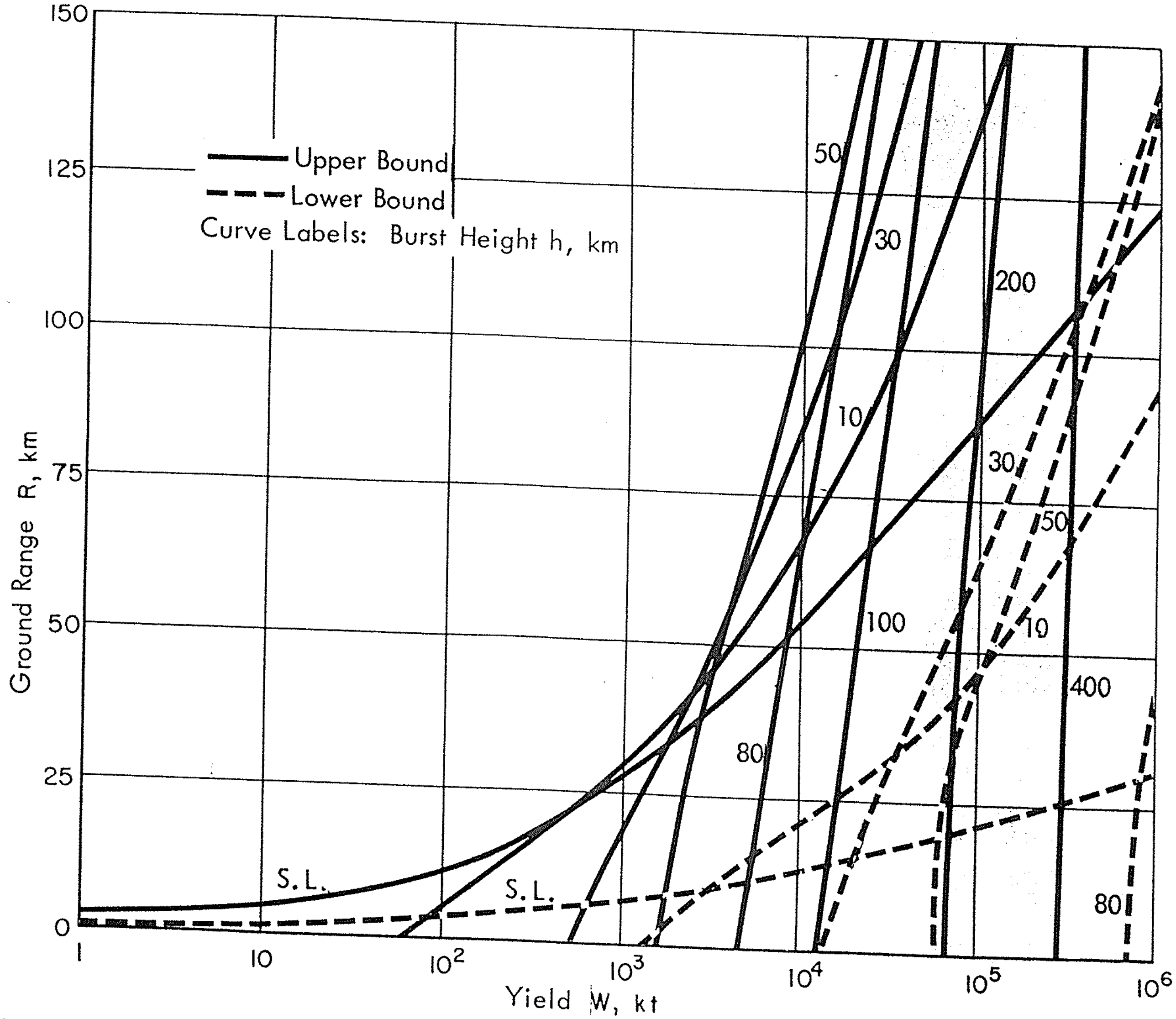

FIGURE 1.1a High Certainty Limits for the Thermal Ignition Radius as a Function of Weapon Yield, for Various Heights of Burst, on an Average Clear Day

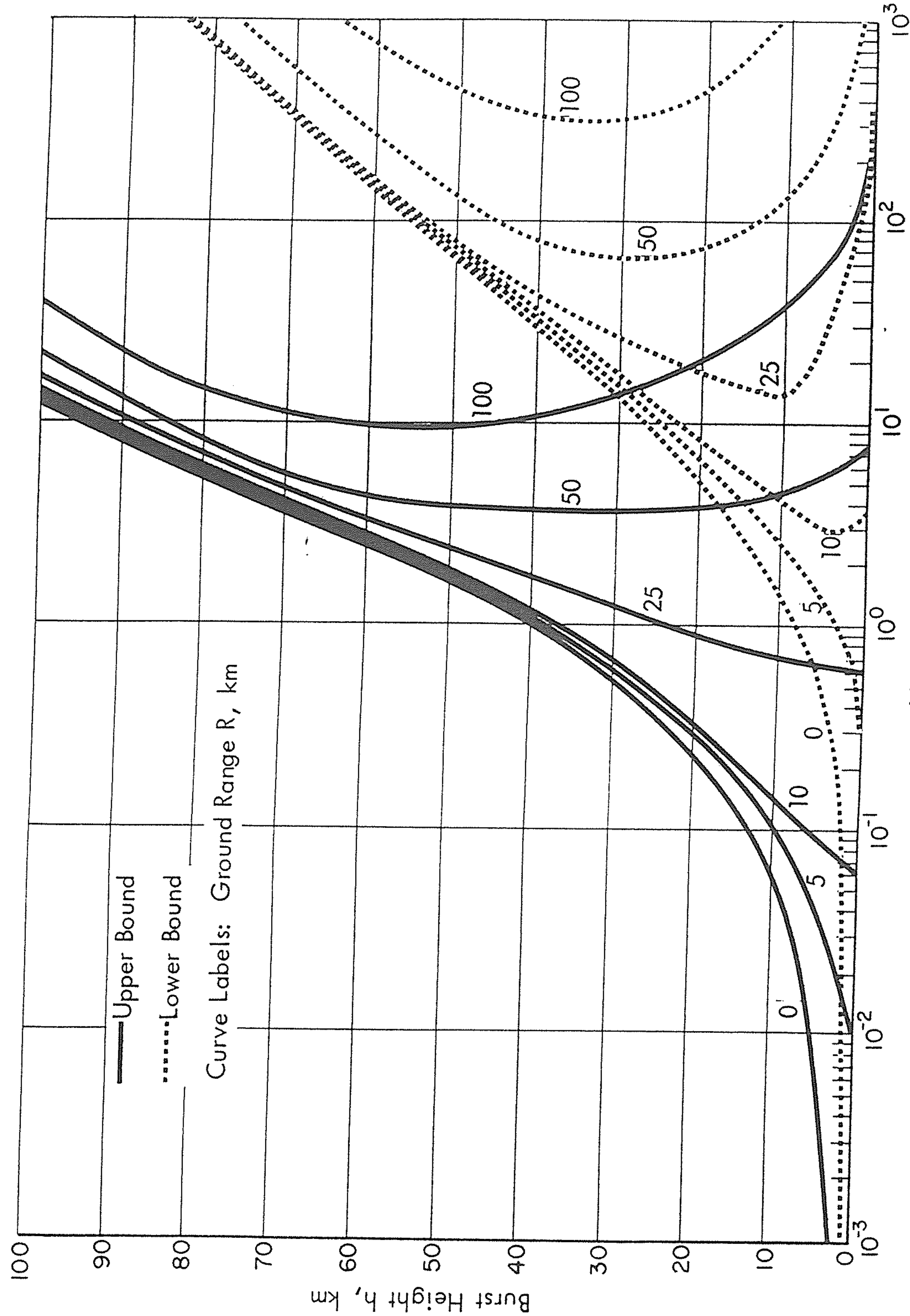

FIGURE 1.1b Cross Plot of Figure 1.1a Concerning High Certainty Limits for the Thermal Ignition Radius on an Average Clear Day

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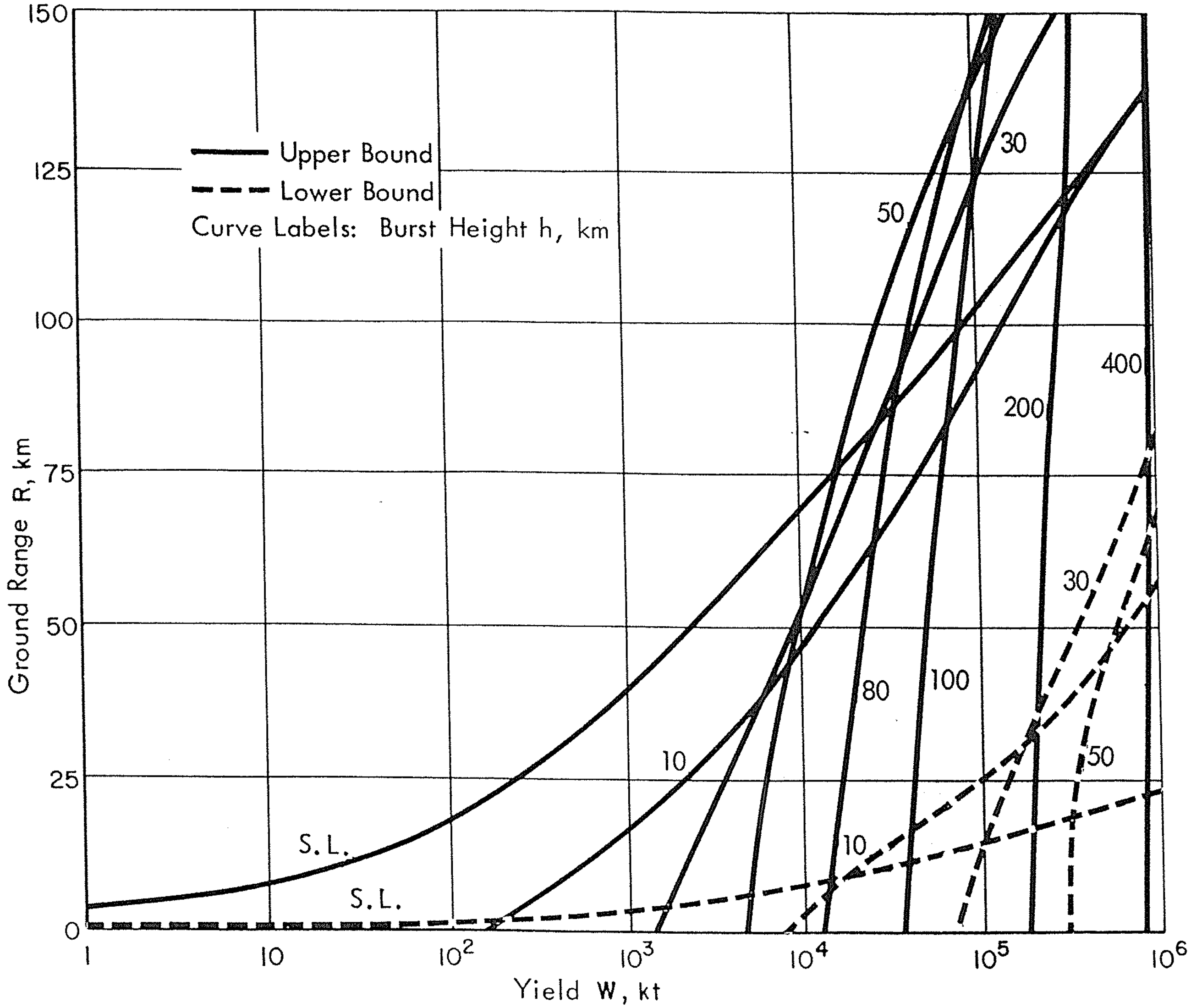

FIGURE 1.2a High Certainty Limits for the Thermal Ignition Radius as a Function of Weapon Yield, for Various Heights of Burst, on a Day with Medium Cloud Cover

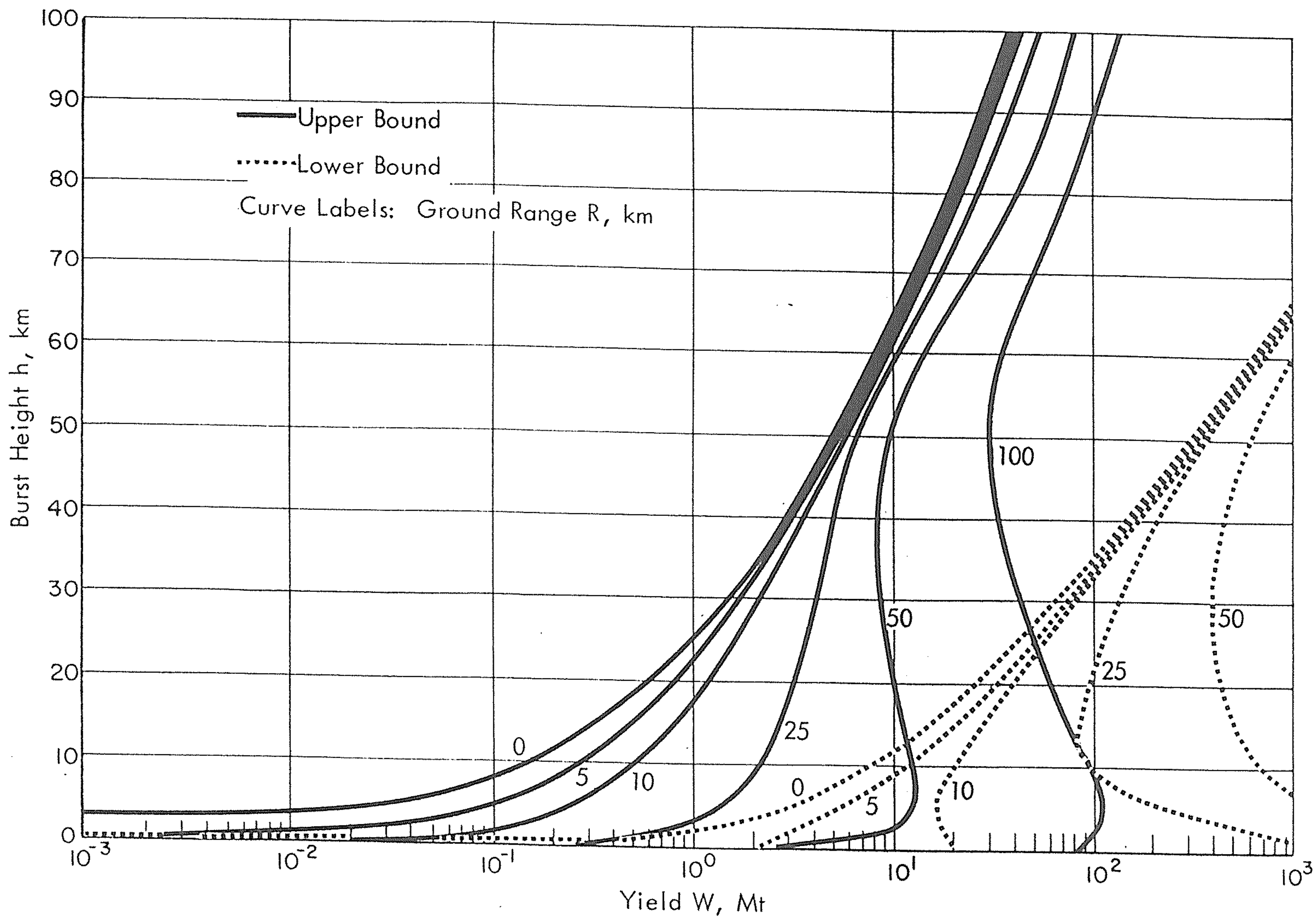

FIGURE 1.2b Cross Plot of Figure 1.2a Concerning High Certainty Limits for the Thermal Ignition Radius on a Day with Medium Cloudy Cover

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Curves showing the upper bound on the ignition radius appear for all of these altitudes; altitudes for which lower-bound curves do not appear have lower bounds that lie off the scale (i.e., at yields above 10^6 kt). The most striking feature of these ignition radius curves is the large distance between the high-confidence upper and lower bounds. The factors contributing most strongly to this difference are usually the uncertainty in the energy per unit area required for ignition, but the uncertainty in the energy emitted as thermal radiation by the fireball attains equal importance at higher altitudes (greater than about 40 km) and the uncertainty in the transmissivity of the atmosphere is of substantial significance at large values of the ignition radius R.

As an illustration of the wide separation of the high-confidence limits, one may observe in Fig. 1.1 that the sea-level bounds differ by as much as a factor of 5 in R, and that the upper bound at h = 80 km exceeds R = 150 km at a value of W more than a factor of 10 below that for which the lower bound reaches R = 0. When it is recalled that the ground ignition area is proportional to R^2, the extremely large difference between high-confidence upper and lower bounds on areas of ignition becomes apparent. One is able to support almost any desired conclusion concerning the severity of the threat of thermal ignitions by nuclear weapons through judicious selection of numbers that fall within the limits of high certainty of existing data. In view of this fact and of the uncertainties concerning fire spread and mass fires discussed above, the futility of attempting to obtain numerical predictions of the sizes of areas burned as a result of nuclear explosions, becomes eminently clear.

This conclusion should not be interpreted as implying that certain high-likelihood statements cannot be made through qualitative reasoning or that any statement that has been made in the past regarding the extent of fire damage from nuclear explosions may conceivably be correct. Our qualitative appraisal of the fire threat of nuclear weapons is as follows: The fire threat of nuclear weapons of 100 kt and above is significant in comparison with the blast and radioactivity threats. Many sets of conditions will permit nuclear-induced fires to severely damage the initial area of ignition. A few very rare sets of conditions permit the development of large conflagrations that might propagate tens of miles into initially unignited urban areas or consume hundreds or thousands of square miles of initially unignited wild-land areas. However, pictures of large propagating fires engulfing one city after another, and suggestions that a single 100 Mt nuclear detonation might sear five or ten large states, are overestimates by an order of magnitude.

1.5 Major Areas of Uncertainty

It is of interest to indicate, in somewhat greater detail than above, the major areas of uncertainty that contribute to the overall uncertainty emphasized in Sec. 1.3. In the following list of these areas, the degree of uncertainty and the problems involved in each area are not given; a proper presentation of this additional information entails some discussion and therefore is left to the main body of the report.

a. The thermal pulse of high-altitude nuclear explosions (above 40 km).

b. The accurate specification of atmospheric transmissivities for small elevation angles in a clear atmosphere.

c. The transmissivities of clouds.

d. The basic mechanism of the radiant ignition process.

e. The practical significance of the existing ignition energy data.

f. The probability of a small sustained fire developing at an ignition point.

g. The time required for an indoor ignition to produce violent flaming throughout a room.

h. The relative importance of thermal ignitions and of secondary blast ignitions* (only inside the 5 psi circle).

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*Secondary blast ignitions, ignitions resulting from destruction caused by the blast wave, are not studied in this report.

i. Precise conditions under which wild-land fires will develop.

j. Precise and simple criteria for "no fire spread" in urban and wild-land areas.

k. The essential ingredients of fire storms.

l. The long-term ecological effects of mass urban and wild-land fires.

Significant advances in knowledge in these areas are necessary before the fire effects of nuclear weapons can be discussed quantitatively.

1.6 Areas in Which Well-Defined Problems Exist

In many of the areas listed above, there are no study routes that will with a high degree of certainty lead to substantial progress. It is, therefore, of interest to point out the areas in which the road signs are relatively explicit. Well-defined problems are indicated in the following areas:

a. Measuring the thermal pulse of high altitude nuclear explosions.

b. The basic mechanism of the radiant ignition process.

c. Obtaining accurate ignition energy data for shorter pulse times and for larger irradiated areas than those of the current data.

d. The time required for an indoor ignition to produce violent flaming throughout a room.

e. Analytical studies of precise "no fire spread" criteria for building fires in urban areas.

f. Precise systematization in isolating and cataloging the effects of the various factors influencing fire spread in urban areas, untilizing existing field data.

g. The physical phenomena involved in fire storms.

Even if intensive research programs were to be encouraged in all of these areas, major advances in our ability to predict fire damage from nuclear explosions would not ensue for at least 5 to 10 years.

1.7 Thermal Pulse

The first chronological step in the initiation of fires by nuclear weapons is the emission of electromagnetic radiation by the fireball of the bomb. The "thermal pulse" of the weapon is conveniently defined as electromagnetic energy emitted by the weapon in the wavelength range between 0.3 and 3 microns. This wavelength restriction is imposed because the earth's atmosphere absorbs radiation very strongly outside of this wavelength band.* Therefore, in a good approximation, the only radiation that can be transmitted with sufficient intensity to exert a significant influence in igniting fires lies in this "atmospheric window" (0.3 to 3μ).**

For burst heights from sea level to about 40 km, the thermal radiation from nuclear detonations is approximately black-body radiation with a maximum temperature between 6000 and 8000°K (which approximates solar radiation). At these black-body temperatures, most of the radiation is emitted in the atmospheric window; about 5 to 15 percent of the radiant energy occurs at wavelengths below 0.3μ and only a few percent occurs at wavelengths above 3μ. As the fireball cools, the effective black-body temperature decreases and an increasing fraction of the energy is emitted at wavelengths above 3μ. Since the atmospheric absorbtivity is not 100 percent at all wavelengths above 3μ, to some extent a question remains as to whether radiation above 3μ, emitted

---

* The absorption below 0.3μ is practically 100 percent; that above 3μ occurs mainly in rather broad bands (in which the absorptivity is practically 100 percent).

** A number of other definitions of the "thermal pulse" have been employed in the literature. Some of these are based on considerations of ignition phenomena as well as atmospheric transmission. The more reasonable definitions appear to differ from ours, in total energy emitted, by less than 30 percent for most bomb pulses.

over relatively long times, might exert a measurable influence on thermal ignitions from very large weapons.

For burst heights above about 40 km, experimental measurements appear to indicate that the emitted thermal radiation begins to depart from black-body radiation, exhibiting a flatter power-wavelength curve, with enhanced ultraviolet and infrared emission. The enhanced ultraviolet is still absorbed practically completely by the atmosphere, but the enhanced infrared might conceivably exert measurable effects for large bombs at high altitudes.

The grossest property of the thermal pulse is the total amount of energy Q contained in it. This energy is conventionally related to the total yield of the weapon W by a thermal efficiency factor η, viz.,

$$\eta = Q/W \qquad (1)$$

The total energy in the thermal pulse can be computed from a knowledge of the yield and the thermal efficiency.

One principal objective of theoretical and experimental studies of nuclear explosions has been to determine the thermal efficiency as a function of burst height, yield, and weapon design. Bomb experts often disagree about the value of the thermal efficiency and its dependence upon burst height and weapon yield. (See Sec. 2.) For use in computing high-confidence limits on the ignition radius (Appendix A), we have established high-confidence limits on the thermal efficiency of nuclear weapons as a function of height of burst. These limits appear as the boundaries of the shaded region in Fig. 1.3 and are intended to be valid for <u>all weapon yields</u>. Had we introduced a yield dependence of η into Fig. 1.3, we would have been able to narrow the bounds somewhat, but not to a very great extent.*

*For sea-level bursts, it is implied in Sec. 2 that the thermal efficiency η is roughly proportional to $W^{-0.07}$, (W = weapon yield). This very weak dependence can lead to a significant difference between the values of η for megaton and kiloton weapons. As the burst altitude increases, the yield dependence of η becomes more and more highly controversial. In the altitude range of greatest interest, i.e., above 30 km, there is no reasonable basis for ascribing a yield dependence to the high-confidence limits.

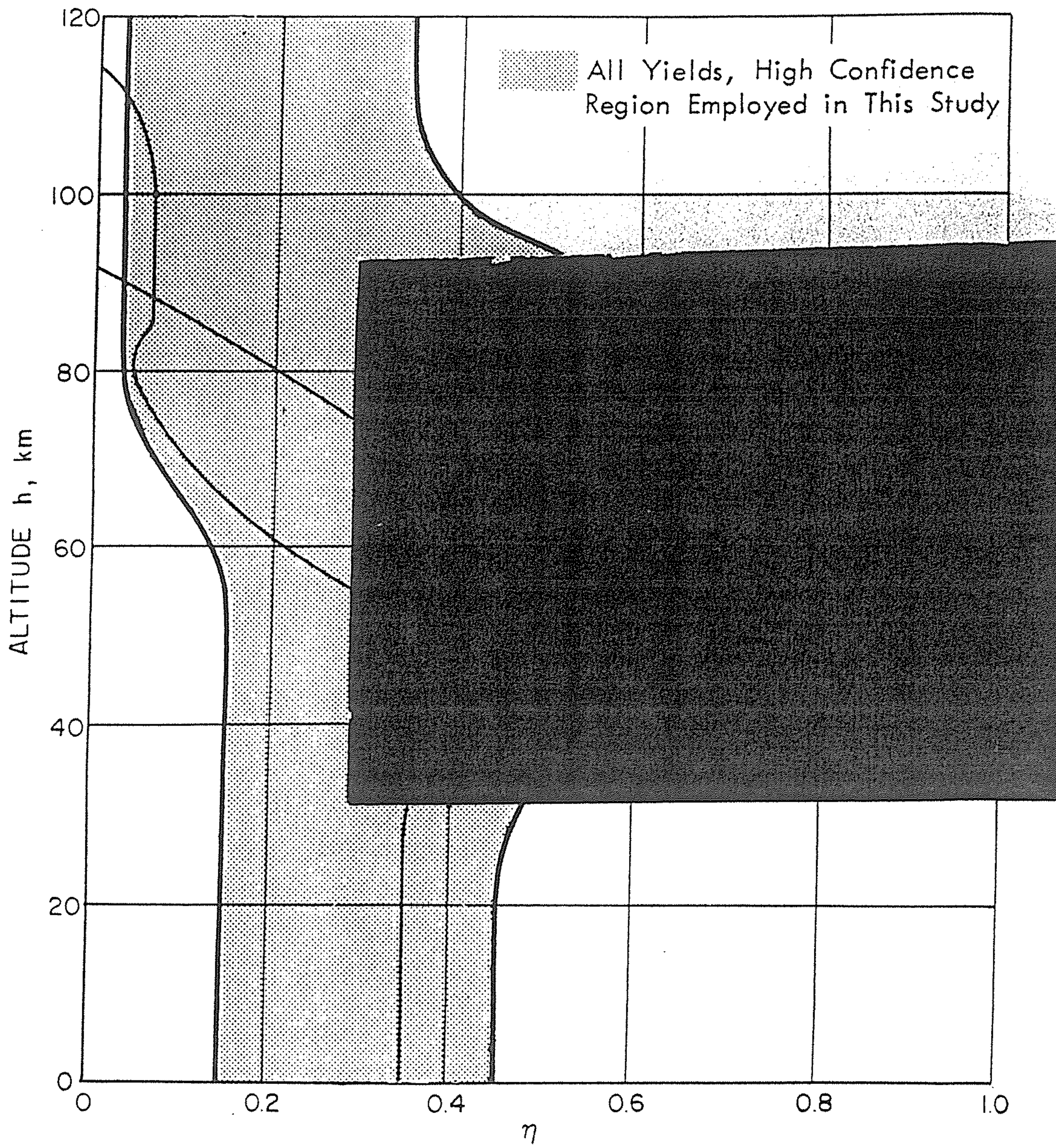

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FIGURE 1.3 Range of Predictions of the Thermal Efficiency of Nuclear Weapons as a Function of Altitude

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In order to illustrate that not all of the results reported by bomb empiricists and theoreticians fall within our "high-confidence limits," results of calculations by Rand* (Ref. 6 of Sec. 2), and a bolometer measurement by Gauvin et al., (Ref. 15 of Sec. 2) are also shown in Fig. 1.3. Rand's curves drop to zero at very high altitudes where our minimum efficiency remains at 3 percent. But Rand has not considered all of the emission processes that might occur at very high altitudes; he did not intend to study the very high-altitude regime specifically. [redacted] It was on the basis of rather rough considerations of this type that we felt justified in allowing a few results to fall outside our "high-confidence limits."

DOE (b)(3)

The total energy in the thermal pulse is not the only property of the thermal pulse that affects the ignition of fires. It will be seen in Sec. 1.9 that the energy per unit surface area required to ignite a given material depends upon the length of the time interval over which this energy is delivered. Therefore, the thermal pulse "length" is of importance in determining ignition radii. Since it is very difficult to ascribe a single characteristic "length" to bomb pulses, the required information on the time dependence of the thermal pulse is best presented in terms of the total radiant power, dQ/dt (cal/sec), emitted in the atmospheric window, as a function of time (t). Representative curves showing this information are given in Figs. 1.4 and 1.5. Two distinct thermal pulses appear in these figures (at least at moderate and low

---

*The curves shown are obtained from Rand's data by assuming that the X-ray yield is 70 percent of the total yield below 45 km and increases to 100 percent of the total yield at 80 km and above.

**This "measured" value of the efficiency was obtained by applying a variety of correction and extrapolation computations to the raw experimental data. According to A.T. Stair, it represents the least reliable of the AFCRL experimental measurements on TEAK.

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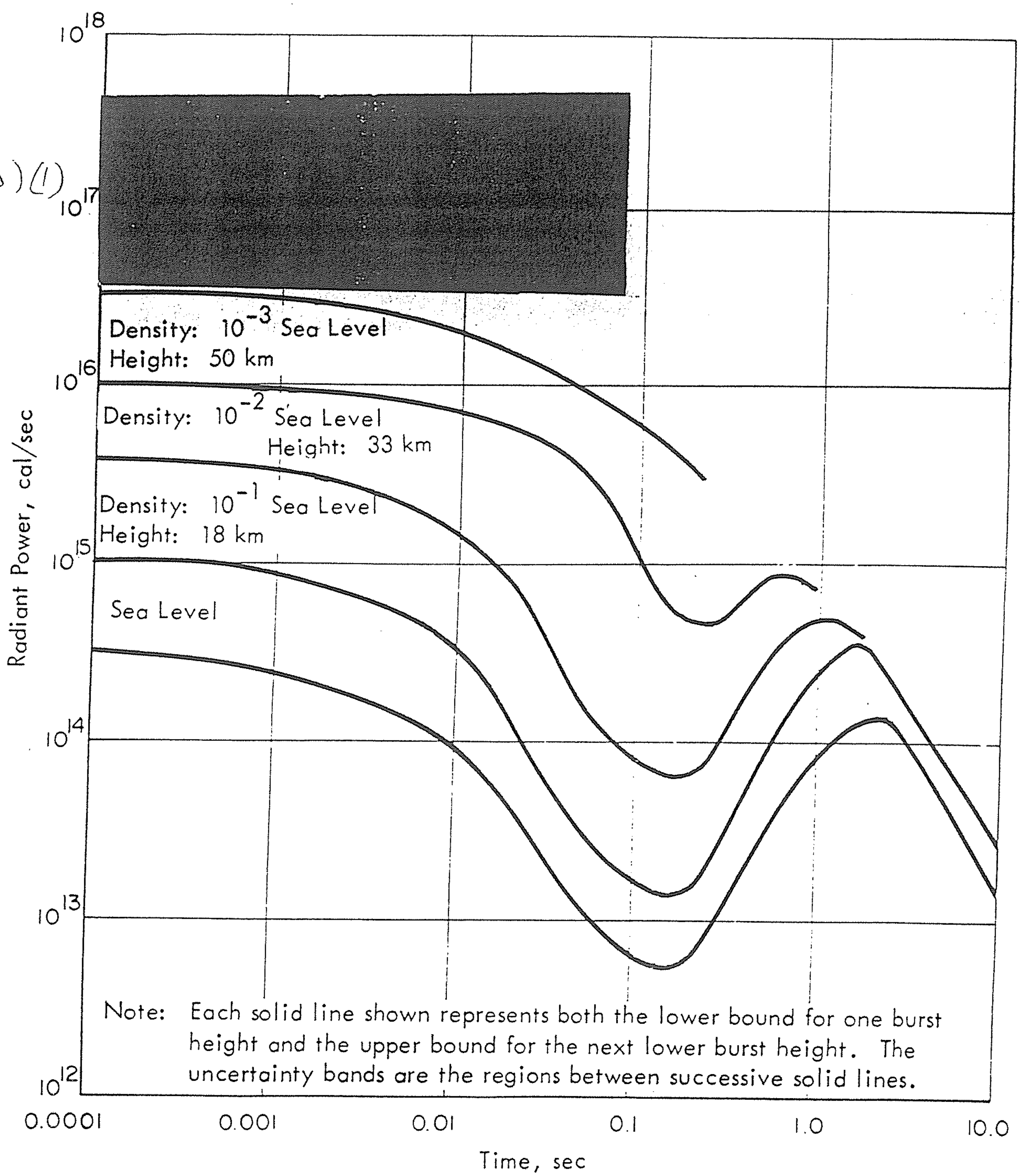

FIGURE 1.4 Radiant Power vs Time for 4 Mt in the Spectrum, 0.3 μ to $\cong$ 3.0 μ

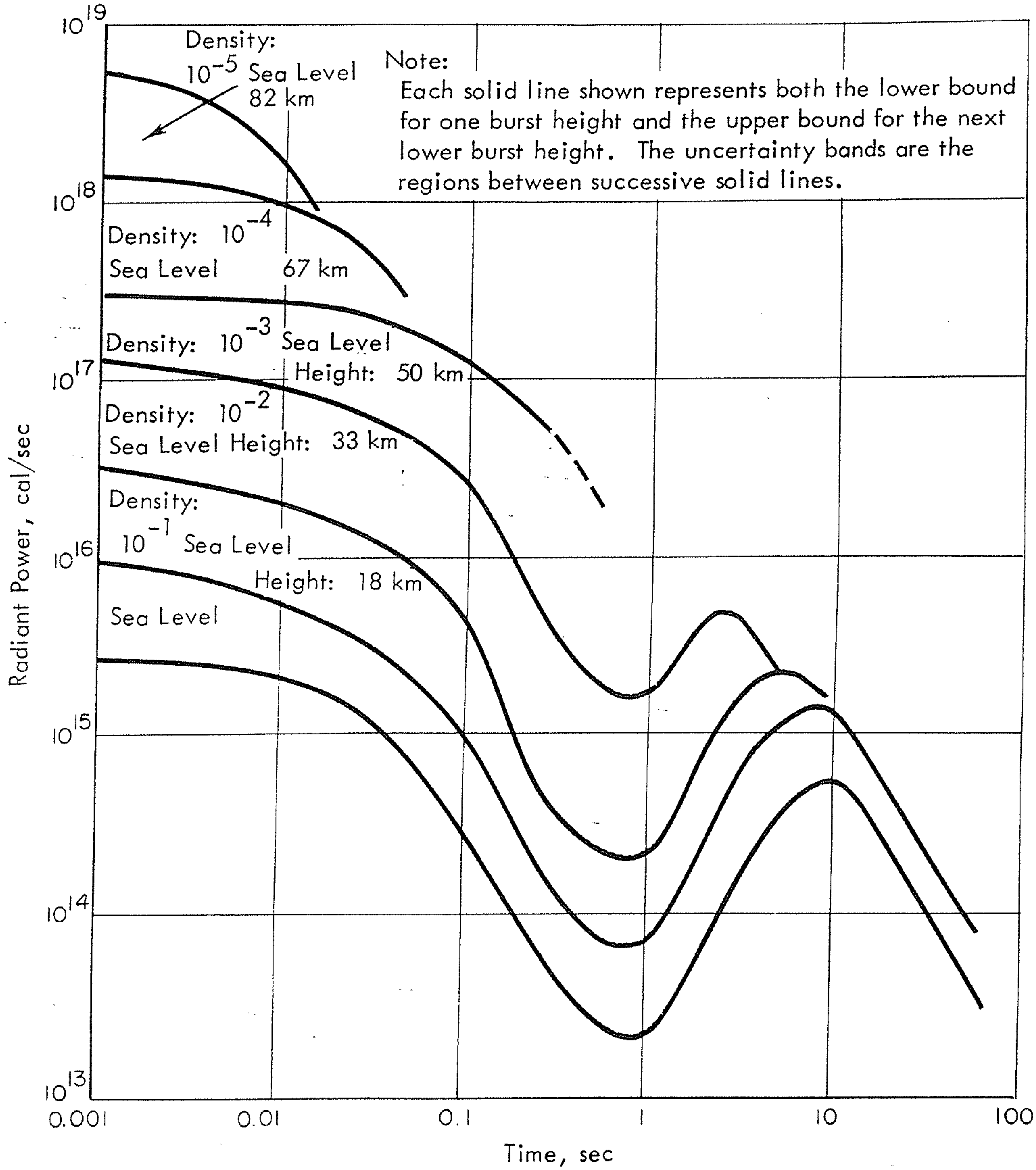

FIGURE 1.5 Radiant Power vs Time For 100 Mt in the Spectrum, 0.3 μ to ≅ 3.0 μ

altitudes); most of the energy is contained in the second pulse at low altitudes and in the first pulse at high altitudes. Figures 1.4 and 1.5 were constructed by Porzel from all available experimental data and from certain theoretical considerations. The current uncertainties are displayed by the bands whose limits at early times generally differ from the mean curve by a factor of two. The band width encompasses the reasonable difference between the theoretical prediction and the measurements, the difference being within their combined uncertainties.

Most of the experimental uncertainty in Figs. 1.4 and 1.5 arises because virtually no measurements of absolute total radiant power vs. time are available. Only relative power is usually reported, uncorrected for spectral reponse or field of view of the specific instrument or for the specific air path and weather conditions under which the data were observed. The HARDTACK report of 1958 does cite numbers for absolute maximum power. [redacted] OSD (b)

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They are the only first-pulse data meaningful enough to serve as a check against theory. Unfortunately, total-power-vs.-time measurements were not undertaken as a formal measurement on OPERATION FISHBOWL in 1962, a series involving burst altitudes up to 400 km. A concomitant measurement of total radiant flux could be used to calibrate a relative power curve, but this would not answer the transmission questions and would often introduce a new host of experimental questions such as the relative spectral response and field of view of each instrument, time duration of the integrated measurement, relative obscuration, etc. After nearly two decades of nuclear testing, the thermal efficiency of low altitude bursts is still cited as lying between 30 and 40 percent of the bombs' energy, within a spread of 30 percent.

Various scaling laws for the first and second thermal pulses have been proposed. These laws enable one to relate the power-time curves, for a range of values of the yield and of the burst height, to a single power-time curve (e.g., to that for a 1 Mt weapon burst at sea level). Scaling laws are useful in rough analytical calculations of thermal ignition radii. Within their specified ranges of validity, the laws are accurate to about 20 or 30 percent. The current scaling laws are stated (and are discussed critically) in Sec. 2.

1.8 Atmospheric Transmission

Having determined the thermal pulse of a nuclear weapon as accurately as possible, one must next compute the fraction of the energy in the thermal pulse (i.e., in the atmospheric window) that is transmitted through the atmosphere in order to obtain the energy flux that is available at the ground for starting fires. This fraction is conveniently expressed in terms of the transmissivity T of the atmosphere, which is defined as the ratio of the energy per unit solid angle received at the ground to the energy per unit solid angle emitted in the thermal pulse.* The value of T differs from unity because of absorption and scattering in the atmosphere.

Atmospheric absorption in the atmospheric window is produced almost entirely by the infrared bands of H_2O and CO_2, which have well-known absorption characteristics. The absorption is only weakly dependent upon optical depth and is therefore relatively independent of atmospheric conditions (H_2O concentration) and slant-path length, the distance from the fireball to the point of reception on the ground. Absorption decreases T by 10 to 35 percent. (See Sec. 3.3).

The scattering by the atmosphere (Sec. 3.4) is much less accurately known and is much more variable than the absorption. On an average clear day scattering alone yields tranmissivities for direct plus diffuse visible solar radiation of 0.80 for an elevation angle of 90°, 0.55 for 20°, and 0.15 for 15°. Thus the scattering will have a

*In Sec. 3, a spectral transmissivity is introduced in order to account for the variation of transmission with wavelength. It is shown in Sec. 3 that, within the accuracy to which overall transmissivity calculations can be made (no better than 30 percent), variations in the spectral characteristics of thermal pulses with time of emission, altitude, and yield produce negligible variations in T. Therefore the overall transmissivity is used here and in Appendix A without introducing a weapon yield or burst height dependence.

strong dependence on slant-path length, as well as a strong dependence on atmospheric conditions. Use of visibility values quoted at weather stations to determine a scattering coefficient on the ground at a given time and location will produce a scattering coefficient uncertain to almost a factor of two, because of the imprecise manner in which visibilities are determined. Accordingly, the uncertainty in attenuation due to scattering, computed by current procedures, will be roughly a factor of two when attenuation is small;* the uncertainty in the transmission factor increases as the attenuation increases (due to the exponential character of the direct line transmission).**

A formula for T on cloudless days, obtained from the equations of Sec. 3 and accounting for both absorption and scattering, is

$$T \simeq T_A e^{-2D/V} (1 + 1.4D/V), \qquad (2)$$

where T_A (~ 0.65 to 0.90) is the transmissivity due to absorption, D is the slant-path length in the atmosphere (km), and V is the visibility (km).

Some measurements on certain clouds yield the following approximate cloud transmissivities: 0.75 for a light haze, 0.5 for a medium haze, 0.3 for a medium cloud cover, and 0.1 for a heavy cloud cover. These factors are multiplied by the value of T given in Eq. (2) in order to obtain the total transmissivity on cloudy days. Errors will occur in estimated transmissivities because data do not exist for different cloud types, and because of the operational fact that one will not know precisely how thick a cloud is along a particular slant path at a given time. Transmissivities on cloudy days can be computed at best to within a factor of about 2 or 3.

Our views on the utility of smoke screens for thermal protection during a nuclear attack are given in Sec. 3.6.

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*This produces a rather small uncertainty in the transmissivity, T, of the order of 10 or 20 percent.

**This leads to very large uncertainties in T (often more than an order of magnitude) in the regime that is usually most critical for computations of ignition radii.

1.9 Ignition

Knowing the characteristics of the thermal pulse and the transmissivity of the atmosphere, one can ompute the ground radius of the circle inside of which ignition of a given material is produced simply by specifying the integrated energy flux q (cal/cm^2) required for igniting the material. Many detailed investigations have been directed specifically toward determining q. (See Sec. 4.) In most of these, rectangular flux-time curves are employed (a constant normal flux (cal/cm^2 -sec) is applied over a specified time interval); the results for rectangular pulses have been related approximately to those for sea-level bomb pulses (Sec. 4.2.6), but apparently the applicability of the rectangular pulse data to high-altitude bomb pulses has not been considered.

The rectangular pulse studies revealed zones of transient flaming, glowing ignition, and flaming destruction, as illustrated and defined in Fig. 4.1. The boundaries of these zones have been delineated rather accurately (to within 20 or 30 percent) for α-cellulose sheets irradiated in circular spots 3/4 in. in diameter, and the influence of the thickness of the sheet, the moisture content of the material (relative humidity), and the absorbtivity of the surface upon the locations of these boundaries has been determined. Corresponding curves have been developed for representative kindling materials commonly found in the real environment. The two major criticisms of the existing data are that measurements have not been made for the short pulse times characteristic of high altitude bursts and that measurements have not been made on sufficiently large samples to be applicable for the long pulse lengths characteristic of high-yield weapons burst at low altitudes.*

The length of the rectangular pulse is generally related to weapon yield by very rough considerations, so that curves of q as a function of W can be drawn. (See Fig. 4.3.) Because of the uncertainties in relating rectangular pulses to bomb pulses, graphs of this type are valid at best to within 50 percent and probably only within

*S.B. Martin intends to study the impulse effects of very short pulses, and A. Hochstim is obtaining ignition data for short pulses. Measurements for larger irradiated areas are currently in progress at the Naval Munitions Laboratory.

type are valid at best to within 50 percent and probably only within a factor of 2. Added to this uncertainty is the problem of determining which, if any, of the boundaries shown in Figs. 4.1 and 4.3 (viz., transient flaming, glowing ignition, etc.) corresponds to ignition in the real environment. The ignition problem is intimately connected with the problems encountered in the initial stages of fire spread. The uncertainty in q for tactical situations is well above a factor of 2 and, therefore, the following rule, which seems reasonably certain, is suggested for high-confidence calculations: The integrated energy flux q must exceed 2 cal/cm^2 for the ignition of any kindling material, and q is always less than 20 cal/cm^2 for the ignition of some kindling material, for all existing weapons and all heights of burst.* This rule is applicable only to areas in which average light-kindling materials (e.g., newspapers), not saturated with water, are exposed to the thermal radiation.

1.10 Fire Spread

From the results summarized in Secs. 1.7 through 1.9, it is possible to set high-confidence limits on ignition radii of bombs of given yield and given height of burst. This is done in Appendix A, and the results are discussed in Sec. 1.4. Fire spread and the development of mass fires can be discussed only qualitatively at present because of the greater degree of uncertainty in these areas.

In discussing conditions under which fires will develop from thermal ignition points, inhabited and uninhabited regions must be treated separately. In uninhabited areas, fire development is governed by the same factors that influence the development of peacetime wild-land fires. These include humidity, wind, other weather

*It is generally agreed that q tends to increase with increasing weapon yield for large-yield weapons burst at sea level. By introducing a yield and burst-height dependence of q, one would therefore be able to state slightly narrower high-confidence limits. However, the yield dependence of q for burst heights above about 30 km is not known. Therefore, the slight improvement over a narrow regime, obtained by introducing a yield and burst-height dependence, does not appear to justify the additional complexity.

factors, fuel type, fuel loading (weight of combustible per unit surface area), and topography. The vulnerability of uninhabited areas to thermal attack depends so strongly upon these parameters (and probably also upon others not yet identified) that, depending on their values, large fires may develop from every ignition, or all fires may rapidly die out. (See Sec. 5.1.4.)

Experts seem to agree that, in most inhabited areas, nuclear weapons are more likely to induce indoor fires than outdoor fires. Conditions affecting the development of indoor fires are not as well known as those affecting the development of outdoor fires; for example, the occurrence of indoor fires is only weakly correlated with weather conditions. A deduction that appears to be of paramount importance is the following: A clean environment and a well-equipped populace knowledgeable in methods for rapidly extinguishing small fires are very effective assets (perhaps, the only effective assets) in the control of the growth of fires induced by the thermal pulses of nuclear weapons in inhabited areas. (See Sec. 5.1.2.)

Secondary blast ignitions may be of importance in inhabited areas. These are touched upon in Sec. 5.1.3, where blast-thermal interactions and fire-fallout interactions are also mentioned.

A question of obvious importance is whether the fires that do develop from nuclear thermal ignitions will spread to regions outside the initial area of ignition. Detailed criteria for "no fire spread" in urban and wild-land areas are discussed in Secs. 5.2 and 5.3. Factors influencing fire spread include building separation distances, building density (the ratio of the projected roof area to the total area), building heights, building construction, building contents, fuel loading, fuel type, moisture content of materials, humidity, precipitation, surface winds, upper atmospheric winds, lapse rate of the atmosphere, topography, and firebreaks. The relative importance of these factors is discussed in Secs. 5.2.2 and 5.3.2. Many sets of conditions permit little or no fire spread in either urban or wild-land areas. A few relatively rare sets of conditions permit the development of large conflagrations that might consume tens of square miles of initially unignited urban areas or hundreds or thousands of square miles of (initially unignited) wild-land areas. Fire propagation through areas larger than this is highly unlikely because the probability of dangerous fire spread conditions existing over large regions simultaneously is practically negligible.

Three recent studies on fire spread from nuclear detonations are appraised in Sec. 5.2.3.

1.11 Mass Fires and Their Effects

Mass fires, e.g., conflagrations and fire storms, are highly complex, and spacially and temporally nonuniform phenomena. Failure to recognize this fact has led in the past to proposals of over-simplified theories of fire storms that are incapable of describing all of their essential properties. (See Sec. 6.1.3.) In spite of a great deal of study, the essential ingredients of fire storms are not known today. Most experts appear to believe that fire storms resulting from simultaneous ignitions over very large areas will not differ greatly in intensity from the fire storms that have been observed in the past. But there is no firm logical basis for this view. Practically everything about fire storms will remain highly uncertain until a great deal of related basic research is completed. Some of the pertinent research problems are currently in progress and are defined and discussed in Sec. 6.1.3. Much more research will be necessary. Many of the pertinent problems cannot be foreseen at the present early stage. Practically the entire fields of subsonic fluid dynamics, radiative and convective heat transfer, chemical thermo-dynamics, and homogeneous and heterogeneous chemical kinetics are involved. Two specific related problems that are not currently under study are to determine the statistical character of very large scale turbulence in free convection and to determine to what extent various partial scaling procedures, keeping certain dimensionless parameters fixed but allowing others to vary, can be used to extract useful information from model studies. It is safe to predict that fire storms phenomena will not be understood well for at least 10 years.

The history of past urban and wild-land mass fires is summarized in Sec. 6.1.2, where special emphasis is placed upon the incendiary bombings and the two atomic bombings of World War II. The facts that past mass fires have not totally destroyed entire cities and have not annihilated a majority of the population in the fire area are emphasized. It is argued that the simultaneous ignitions over very large areas, that may be capable of being produced with the large nuclear weapons now available, will engender no qualitatively new fire phenomena.

Ecological effects of mass fires are considered briefly in Sec. 6.2. This may well be the area of greatest uncertainty.

The demonstrated effectiveness of certain underground shelters is indicated in Sec. 6.2.1.

1.12 Previous Related Studies

Various elements involved in the mass fire effects of nuclear weapons (e.g., the thermal pulse, ignition criteria, mass fires) have been reviewed periodically in the past. The only recent study that we found covering all of the essential elements is Ref. 1, which is barely six months old. It would be of little interest to merely reiterate the topics of Ref. 1 in a different format. Therefore, this report attempts to avoid repetition of the material. Work that has appeared within the last six months is discussed, and aspects of the subject not emphasized in Ref. 1 are considered.

Reference 1 is open to two criticisms: The material is arranged in a somewhat confusing manner and, therefore, is rather difficult to follow; the review is rather indiscriminate and therefore erroneous conclusions might be drawn from some sections. We have attempted, in the present report, to avoid both of these criticisms. The arrangement of material (Thermal Pulse, Atmospheric Transmission, Ignition, Fire Spread, Mass Fires and Their Ecological Effects) adheres strictly to the chronological sequence of events following a nuclear explosion. Our attempt to establish limits of validity of existing data tends to reduce the possibility of drawing erroneous conclusions.

The present report is somewhat more opinionated that Ref. 1. The existence of Ref. 1 partially justifies this. However, we also believe that, in expressing our reasoned judgment, we provide a greater degree of continuity in presentation and minimize the possibility of misinterpretation.

1.13 Action Recommendations

The list in Sec. 1.6 identifies only general problem areas in which progress can be made; detailed descriptions of promising approaches to specific problems of importance were not given. A few such approaches are identified and discussed in the text. A more complete list of problems and of possible useful approaches is given in Appendix C. Most of these topics are basic research studies, but a few are more operational in character. They are all directed toward gaining a better fundamental understanding of the fire effects of nuclear weapons. The list in Appendix C is not exhaustive; it represents only a fraction of the total number of investigations that would be needed before our ability to make *a priori* predictions of fire damage from nuclear explosions in the real environment could be improved significantly.

In this section, we discuss a few steps that would tend to improve our current defensive and offensive standing, in the event of a nuclear exchange insofar as fire effects are concerned.

1.13.1 Every effort should be made either to remove or shield from possible thermal pulses all kindling materials in urban areas. This is a many-faceted suggestion; it would involve disposing of waste paper, wood, etc., storing essential, easily ignitable materials in shielded areas, providing portable or readily deployable shields* for protecting paper, wool-upholstered furniture, etc. from thermal

*Light-sensitive glass that becomes opaque when exposed to high-intensity radiation may prove useful in this respect; see Chemical Week, Feb. 15, 1964, pp. 51-52.

pulses and initiating other steps of this nature. In principle, such a program could increase the minimum ignition energy by a factor of about 10, and thereby decrease the radius of ignition by roughly a factor of 3. In practice, however, such a program would be ineffective unless a very large percentage (at least 99 percent, and probably much more) of all kindling materials were so removed or shielded, because many more materials than would be needed to start uncontrollable fires are currently exposed. There is a very strong objection to this suggestion: it requires the cooperation of practically the entire population. Without a totalitarian type of control, it is highly unlikely that such a program would be effective.

1.13.2 The general populus should be educated and equipped to extinguish the small fires that would immediately follow a nuclear detonation. Approximately 30 min would elapse between the time of the blast and the time that the fires would become too large for small groups of nonprofessional fire fighters to handle. During this time, the public, acting cooperatively, could conceivably reduce the number of fires to such an extent that the existing professional fire departments could control the remaining fires. In order to implement this approach, it has been suggested that members of all households be given brief instructions and provided with hand extinguishers, and that small first-aid volunteer groups (consisting of 3 or 4 men per group for each urban block) be trained by the professional fire departments and equipped with hose apparatus with a capacity of ~30 gal/min. The principal objection to this proposal is the same as the objection in Sec. 1.13.1.

1.13.3 Official high-level government endorsement of a reasonable set of building codes (e.g., those of the National Fire Protection Association) should be obtained and all municipalities should be persuaded to adopt them and prohibit any exception to them. This measure would not have an immediate effect, but within a few years after its adoption, the susceptibility of many U.S. communities to extreme fire damage would be reduced substantially. Measures of this type are much more important in the U.S. than in the USSR or Europe because combustible materials of construction are much more prevalent in the U.S.

The principal objection to this proposal is practically the same as the objection to the suggestion in Sec. 1.13.1; municipalities exhibit long reaction times and seldom adopt consistent rules.

1.13.4 Detailed standardized specifications for urban fire-fighting apparatus should be prepared and all municipalities should be influenced (perhaps by subsidy) to install the standardized equipment. As an interim measure, adaption devices should be designed and supplied to local fire departments so their apparatus may be used in all surrounding communities where they would be needed in the event of nuclear war. The fire hoses of the New Brunswick, New Jersey, fire department cannot be connected to the hydrants in South Amboy, New Jersey, barely 10 miles away, because the outlets are of a different size. Although steps have been taken to remedy problems of this type in some areas, the New Brunswick-South Amboy situation is typical of problems existing throughout the country. Continual checks for standardization of installed equipment would have to be performed because once these systems are standardized, local inhomogeneities tend to develop (due to replacement, etc.) as time increases.

1.13.5 The current fallout shelter program should be replaced by a fire-and-fallout shelter program. For megaton weapons, estimated total areas threatened by fire from the thermal pulse are usually larger than estimated total areas threatened by hazardous fallout. Construction of effective fire shelters is generally somewhat more expensive than construction of effective fallout shelters, but it is less expensive than blast shelters. The two fire-shelter requirements that are not shared with fallout shelters are: (1) ventilation outlets located in an area free from combustible materials and (2) shelters located so that burning rubble will not fall on top of them. A fire-and-fallout shelter system capable of housing a reasonable percentage of the population would greatly enhance our ability to survive a nuclear exchange.

1.13.6 A system to continuously monitor weather forecasts in potential enemy countries should be instituted. The data to be collected would include radio and newspaper weather information, TIROS-type satellite cloud-cover photographs, etc. The data should be used on a real-time basis to obtain local weather predictions (cloud cover, fire hazard index, etc.) for potential targets. The information would be useful for attack or retaliation planning in order to make optimum use of the thermal pulses of available weapons.

2. THERMAL PULSE

2.1 Introduction

This chapter summarizes briefly our current ability to describe, on theoretical and experimental bases, the significant military features of the thermal pulse from the fireball of a high-yield nuclear detonation. Burst heights range from sea level up to high altitudes, above the sensible atmosphere.

To clarify the significance of the terms "high yield" and "high altitude" it is convenient to discuss nuclear attacks under three categories:

a. Section 2.2, "Low Altitude, All Yields," concerns multiple 100 Mt or even a gigaton (1000 Mt) explosions near sea level (< 20 kft), corresponding to a saturation attack. This domain of phenomenology is the best understood, and is also a convenient way to introduce the problems which arise at higher altitudes.

b. Section 2.3, "Moderate Altitudes, Moderate Yield," concerns 5 to 10 Mt at heights of ~ 20 to 60 kft, which correspond to "conventional warheads" that might be used to provide thermal effects in a conventional way. The first pulse is well understood theoretically but is not militarily important; study of this domain of altitudes focuses on an area of present uncertainty: scaling of the second thermal pulse to high altitude.

c. Section 2.4, "High Altitudes, High Yield," concerns 100 Mt weapons above 150 kft, which could conceivably be used to exploit novel thermal effects such as starting fires over large geographical areas or producing thermal shocks (Refs. 5,9). This domain also characterizes the principal area of present uncertainty about the first thermal pulse.

To separate the "knowns" from the "unknowns," it is convenient to further subdivide the phenomenology in each domain under three headings. Thus, the next three subsections have identical subtitles: Factual, Reasonably Certain, and Controversial.

a. "Factual" describes those features of the pulse in that domain which are established well enough by experiment and theory to qualify as fact.

b. "Reasonably Certain" outlines phenomena which are almost certainly true but do not enjoy the status of consensus by virtue of being well understood, well established, and widely recognized.

c. "Controversial" discusses the areas of incomplete, unverified, or controversial knowledge about the output of thermal radiation in each domain.

A final section, "Summary," is a way of appraising the present status of knowledge.

2.2 Sea-Level Burst, All Yields

2.2.1 Factual

As is well known, the important thermal pulse from a sea-level burst is the second of two pulses, such as shown in Fig. 2.122 of Ref. 1. The first pulse is due to black-body radiation from an incandescent (strong) shock front, and the time of "breakaway" (when the shock front is too weak to be incandescent) roughly separates the two pulses. The shape and amplitude of the second pulse are well established experimentally (Ref. 2), and the law of its decay with time can be explained theoretically (Ref. 4). The total "effective" fraction of radiation is around 0.35 of the total hydrodynamic energy release W, for weapons near nominal yields of 20kt.

2.2.2 Reasonably Certain

Scaling laws usually cite that the duration of the second pulse, the time of the minimum, and the time of second maximum all increase as $W^{1/2}$ (Ref. 1), but a $W^{.42}$ dependence falls within the scatter of the measurements (Ref. 11).

[redacted]

DOE (b)(1)

energy appears in a pulse of substantially longer duration; both effects reduce the thermal effectiveness somewhat. If we neglect stronger atmospheric absorption for longer distances, then the net result is that the peak surface temperatures of most surfaces exposed to the thermal radiation will scale roughly like a hydrodynamic variable, i.e., similar temperatures are produced at distances ($W^{1/3}$) where similar shock pressures are produced (Ref. 9). Thus, there would be little to gain or lose in thermal damage relative to blast for large-yield surface bursts.

Well established by measurement is the fact that about 99.7 percent of the thermal radiation appears in the second pulse and is engendered, not from bomb debris or X-radiation directly, but by air which was irreversibly heated by the shock. This air behind the shock front is incandescent even though it has expanded hydrodynamically down to ambient pressure by the time it radiates.

2.2.3 Controversial

Despite how well the second pulse of sea-level bursts is known, experimental absolute power vs. time measurements for the first pulse are virtually nonexistent. This is the root of the trouble in extrapolating to high-altitude bursts because, according to Ref. 3,

* A spectral band of 0.3 μ to 3.0 μ is used in this paper as the criterion for "effective" thermal radiation, but is somewhat arbitrary. Much of the true total thermal radiation from the bomb is emitted at late times, in the far infrared, and at rates which are too low to be of military consequence. It is not usually measured for it is beyond the spectral response of most instruments and subject to severe absorption. The criterion used here, 0.3 μ to 3.0 μ, does double duty by eliminating the tail fraction both because of late time and long wavelength.

all the familiar details of the early fireball history at sea level reappear as part of the main thermal pulse at the high altitudes.

Historically, the formal thermal radiation programs have emphasized spectroscopic diagnostics. References 3 and 4 appear to be among the few early systematic studies of the sea-level thermal pulse done from a point of view of their military effect. Among those results which may be regarded as novel or controversial are the following:

a. The first maximum is mostly due to the mass effect of the bomb. Hence, one expects the yield-to-mass ratio to be a controlling feature of the main thermal pulse at high altitude.

b. Radiation is initially transported outward with nearly the speed of light for about one free path. Beyond a mean free path, a random walk model of photons describes the radiative phase of a fireball growth. Subsequently, the photons cascade downward in energy as the fireball cools by hydrodynamic expansion until the bulk of the energy is at "visible" wavelengths, at which time the main thermal emission occurs.

c. The $W^{1/3}$ (hydrodynamic) time-scaling applies in the first pulse even though $W^{1/2}$ time-scaling applies successfully in the second pulse. Shock formation plays a controlling role in the thermal radiation rate for heights of burst up to roughly 200 kft.

d. The first minimum at sea level is not due to special absorption processes such as the formation of oxides of nitrogen but to an actual increase in transmission of radiation from the interior fireball as the fireball expands. An expanded transparent fireball radiates more quickly than a smaller black-body sphere with comparable energy in a dense atmosphere near sea level.

2.3 Moderate Altitudes, Moderate Yields

2.3.1 Factual

It is generally conceded that a black-body-fireball model applies in the atmosphere and that thermal radiation effects are much reduced above the atmosphere. The interesting questions are really how high and why. Owing to fireball observations on TEAK (3.8 Mt at 242 kft) and on ORANGE (3.8 Mt at 150 kft) most theoreticians would now agree that the fireball is a black body and is spherical at those altitudes, more certainly so at altitudes from 20 to 60 kft for yields from ~ 5 to 10 Mt.

2.3.2 Reasonably Certain

On the basis of preliminary studies by Porzel, direct hydrodynamic scaling of the fireball rate of growth curve (radius vs time) as observed at sea level has been found to apply for TIGHTROPE [redacted] Similar results for bursts at much higher altitudes leave little doubt that the fireball from 5 to 10 Mt at 20 to 60 kft would scale hydrodynamically from sea level, and hence calculations of radiation rates for the first pulse using a black-body model is a straightforward and appropriate procedure (Ref. 3). DOE (b)(3)

With such confidence about the phenomenology of the first impulse, it is only natural to seek some still higher altitudes at which the black-body model does fail. As a result, the domain 20 to 60 kft has often been dismissed as a transition region from interest in the second pulse at sea level to interest in the first pulse at high altitudes.

2.3.3 Controversial

Reasonable consensus ends with the first pulse [redacted]

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DOE (b)(1)

[redacted]

2.4 High Altitude, High Yield

2.4.1 Factual

OSD (b)(1)

DOE (b)(1)

In OPERATION HARDTACK in 1958, both [redacted]

Impressive auroral displays of very long duration were observed which were extensively measured on OPERATION FISHBOWL but they are not of military interest for thermal damage.

2.4.2 Reasonably Certain

Owing to the paucity of experiments at high altitudes, "reasonably certain" in this domain means within a factor of two with something like 80 or 90 percent probability.

DOE (b)(1)

[redacted]

[redacted] DOE (b)(1)

2.4.3 Controversial

Owing to the absence of a formal program to measure total radiant power versus time on OPERATION FISHBOWL, much of the high altitude thermal phenomenology remains controversial. Because of the current test ban it will probably remain so, but it is hoped that informal measurements of total radiant power made incidentally by Project 8A1 (Ref. 13) and Project 4.1 on FISHBOWL may provide some insight about the shots of the series. These shots were

STARFISH	1.45 Mt at 400 km
CHECKMATE	[redacted]
KINGFISH	
BLUEGILL	
TIGHTROPE	

DOE (b)(3)

Owing to TEAK at 80 km, "above the atmosphere" has come to mean "above 100 km" and the greatest controversy exists in that domain. The present uncertainties can be tabulated as follows:

[redacted] DOE (b)(3)

b. Existence of a "pancake" fireball of thickness ~10 km and height ~(h-80)km for bursts above 80 km. This effect was suggested in Ref. 3, and by most other investigators [redacted] DOE (b)(1)

c. Total thermal radiation above 80 km. Most thermal theories show a marked drop in thermal efficiency (down to a few

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*As recently derived by S. Rand (Fig. 1 of Ref. 6).

percent) above 80 km. Ref. 3 holds, however, that the problem is one of evaluating the indeterminant product arising from a near-infinite volume of air, even if at virtually zero emissivity, because of the density. So far as we are concerned with subsequent reradiation received at the ground surface, the albedo, due to the atmosphere, may never reduce the thermal efficiency by much more than a factor of two.

d. The effect of venting of X rays to outer space. This is a principal reason for the reduction in thermal efficiency in Ref. 6, [redacted] Success in predicting blast at the ground without a reduction for radiative depletion for bursts up to 400 km would discredit radiative venting, but there is a reduction in blast pressure at the ground due to hydrodynamic venting.

DOE (b)(1)

e. Fluorescence at high altitudes. Direct radiation in the visible spectrum by fluorescence has been variously conjectured from a few percent up to perhaps 10 percent thermal efficiency. There [redacted]

DOE (b)(1)

f. Spectral distribution. [redacted] This must almost be considered fine structure in phenomenology when the total radiation itself is not yet known.

DOE (b)(1)

g. The role of hydrodynamic motion at high altitude. Some high-altitude thermal analyses neglect hydrodynamic motion, but this is an assumption, tacit or explicit, [redacted]

DOE (b)(1)

2.5 <u>Summary</u>

The status of present knowledge about the thermal pulse can be summarized as follows:

a. The second pulse from bursts at heights less than 10 kft can be considered reasonably well known for all conceivable yields.

b. At moderate altitudes (20 to 60 kft) and moderate yields (5 to 10 Mt) the second pulse is still the more important. Theoretical and empirical estimates are available, [redacted] DOE (b)(1)

c. At high altitudes (150 to 250 kft) the first pulse is of primary military importance and is reasonably well predicted using a gray-body model for emissivity.

d. The phenomenology of the thermal pulse for burst above 300 kft is presently controversial [redacted] DOE (b)(1)

3. ATMOSPHERIC TRANSMISSION

3.1 Introduction

Starting with a model of the spectral, spatial, and temporal characteristics of the thermal radiation from a nuclear detonation (Sec. 3.2), the effects of atmospheric absorption (Sec. 3.3), and scattering (Sec. 3.4) can be estimated. Cloud cover studies (Sec. 3.5) provide probabilistic estimates for attenuation and reflection by clouds. The feasibility of using smoke screens for thermal protection has been investigated (Sec. 3.6).

3.2 Thermal Radiation from Nuclear Detonations

In order to compute atmospheric transmission, one must first determine the characteristics of the radiation source. A ground burst will be approximately hemispherical in shape, while an air burst will be spherical up to an 80-km-burst altitude. Above the 80-km-burst altitude, the effective reradiating fireball may change shape, as discussed in Sec. 2.4.3, paragraph 6. Ground-and low-altitude airbursts radiate essentially as black bodies with maximum temperatures of 6000 to 8000°K. The effective black-body temperature as a function of time can be given; e.g., in Ref. 1, the time dependence of the radiation is approximated by considering five different black-body temperatures. It should be noted that the spectral dependence of the radiation from low-altitude bursts is roughly the same as that from the sun, which allows one to approximate bomb transmissivities by solar transmissivities. To first approximation, high altitude detonations radiate as black bodies at about the same temperature as the low-altitude bursts. (The enhanced ultraviolet radiation cannot penetrate the atmosphere, while the increased infrared radiation probably occurs over too long a time period and at too low a power level to be important in ignition studies.)

3.3 Atmospheric Absorption

The spectral region of interest for transmission studies is $0.34\mu \leq \lambda \leq 3\mu$. The atmosphere is opaque to radiation of wavelengths less than 0.3μ primarily because of ozone absorption which produces absorbtivities of practically 100 percent for all heights of burst. If one assumes an effective black-body temperature of 6000 to 8000^{o}K, then about 5 to 15 percent of the radiant energy is in the spectrum for 0 to 0.3μ. The radiation output from a nuclear burst at wavelengths greater than 3μ is nearly zero (Ref. 1) (only a few percent of the total radiant energy output) when the fireball approximates a black body at temperatures of 6000 to 8000^{o}K. Large-yield weapons may emit a substantial fraction of their total energy at lower effective black-body temperatures for which most of the energy is in the infrared above 3μ. However, this emission usually occurs over time periods that are considered to be too long to be of importance in ignition. Also, H_2O absorption occurs above 3μ.

The spectral transmission may be approximated by

$$\tau_{\lambda} = \tau_{O_2} \cdot \tau_{H_2O} \cdot \tau_{CO_2} \cdot \tau_S (1+G) \qquad (1)$$

for a surface perpendicular to the direct beam. Here τ_{O_2}, τ_{H_2O} and τ_{CO_2} are the transmissivities through the atmospheric O_2, H_2O, and CO_2, respectively. τ_S is the transmissivity of the direct beam through a scattering atmosphere, and G is the enhancement term due to diffuse scattering by the atmosphere. Here, in Sec. 3.3, we shall briefly discuss the absorption terms; the scattering terms will be considered in the next section.

The O_2 absorption is unimportant compared to that by H_2O and CO_2. The absorption of H_2O and CO_2 bands can be determined from the empirical relations of Howard, Burch, and Williams (Ref. 2). The amount of water vapor in the atmosphere, of course, varies appreciably from day to day and from one location to another. However, calculations show that there is little change in transmissivity due to differences in the optical depth of the water vapor; (the differences in optical depth may arise from differences in the concentration or in the slant-path length). It is seen from the curves in the report of Cahill et al. (Ref. 1), that a change in H_2O concentration from 0.5 to 14 precipitable cm (a factor of 28) decreases the transmissivity to the ground by only approximately 0.10 for most path lengths. This very weak dependence emerges because water vapor (and carbon dioxide) are strong absorbers in the infrared, so that a small amount of either constituent brings the absorption in a particular band to nearly 100 percent. In the visible region of the specturm there is essentially no absorption by atmospheric constituents. Thus the atmospheric absorption, $(1 - \tau_{O_2} \ \tau_{H_2O} \ \tau_{CO_2})$ is relatively independent of the deviations from an average atmosphere. From the limited data given in the references, we estimate that the absorption by atmospheric constituents decreases the transmissivity of the burst radiation by 10 to 35 percent, depending on the type of burst, atmospheric conditions, and slant-path length.

3.4 Scattering

Condensed water vapor, dust, and other particles can appreciably reduce the transmitted radiation through scattering, especially in urban areas where such "haze" can be dense. One can relate the scattering to the size and density of scattering particles by means of the Mie theory (which assumes the particles to be spherical). However, particle sizes and densities are not accurately known, so the attenuation due to scattering is estimated from visibility measurements performed at weather stations.* As mentioned above, the transmitted radiation from a nuclear burst will be in approximately

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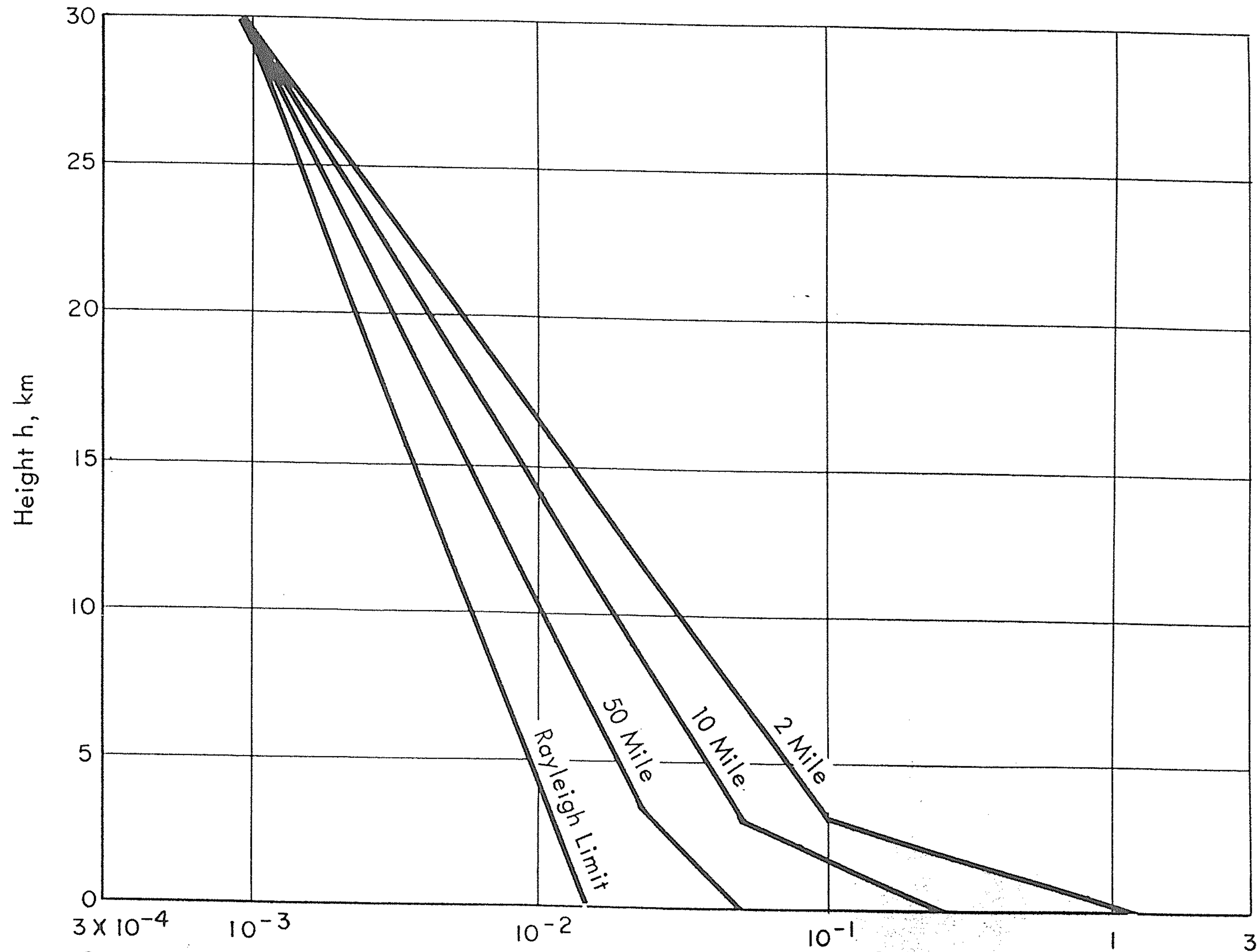
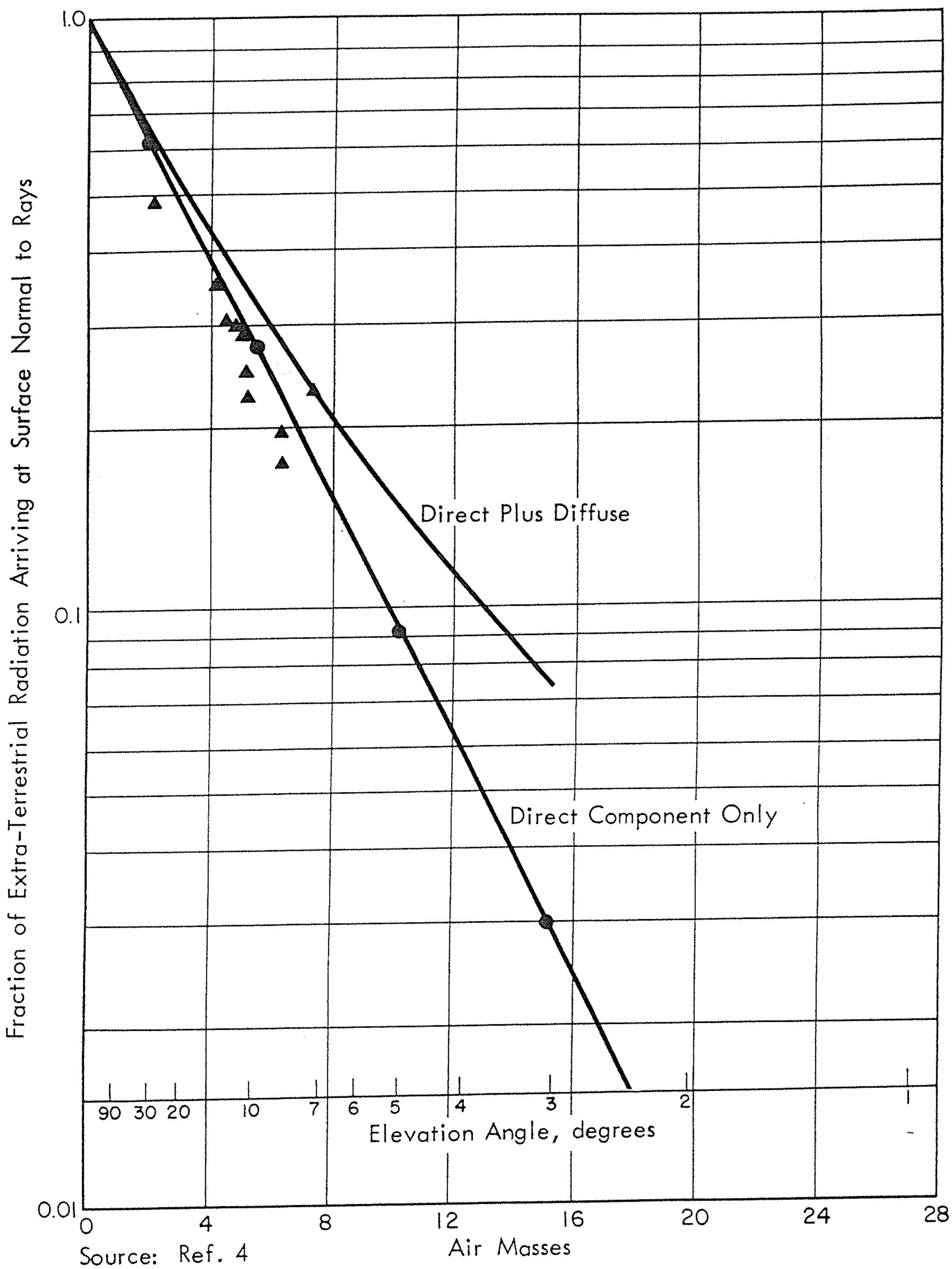
*Turbidity and radiosonde measurements have been suggested as possible sources of more accurate data (Ref. 4).



Source: Ref. 1

FIGURE 3.1 Variation of Scattering Coefficient $\sigma(h)$ with Height



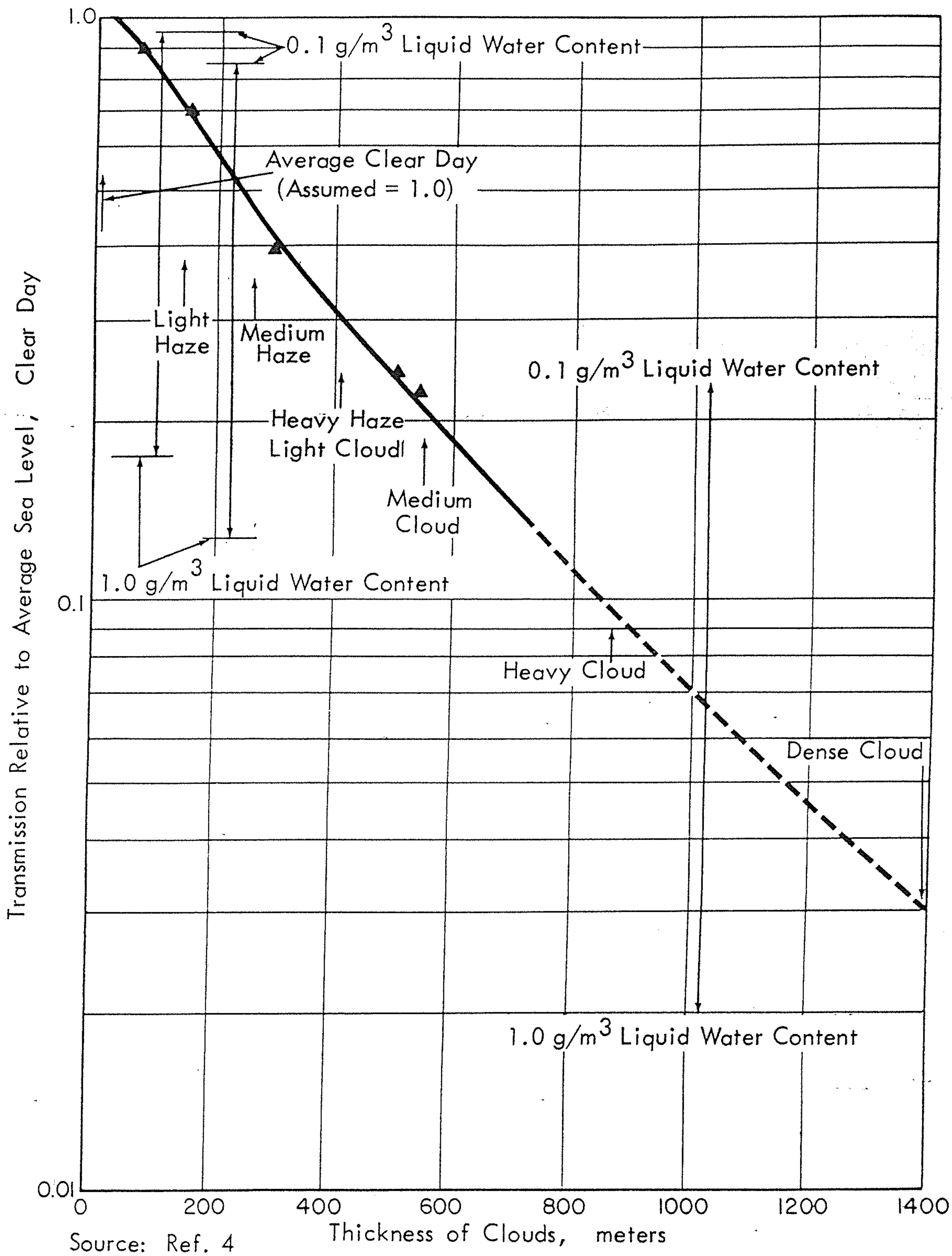
Source: Ref. 4

FIGURE 3.2 Atmospheric Attenuation Factors for High-Altitude Nuclear Detonations as a Function of Elevation Angle of the Ray above the Horizontal for the Average Clear Day at Sea Level plus diffuse solar radiation are 0.80 for a 90°-elevation angle, 0.55 for 20°, 0.33 for 10°, 0.15 for 5°, and 0.07 for 3°.* It should be noted that a large percent of the area which receives radiation from a nuclear burst will be at small elevation angles with respect to the burst, so small angles will be important for high-yield bursts occurring at relatively low altitudes. When the transmissivity is small, it is observed from the above scattering formula that changes in the visibility V, or scattering path length D, will produce large changes in the transmissivity. Thus the transmissivities at small elevation angles will be strongly dependent on meteorological conditions. This result can be contrasted with that in the preceding section, where absorption was found to be nearly independent of meteorological conditions and slant-path length (elevation angle).

3.5 Cloud Cover

The problem of cloud cover divides into two parts: (1) determination of transmissivities through various could types and depths, and (2) determination of the probabilities for the occurrence of the various cloud conditions. Theoretical and experimental studies of cloud transmissivities for solar radiation are surveyed in Ref. 4. There have been only a limited number of measurements, and the theoretical studies have not been refined enough to yield close agreement with the measurements. In Fig. 3.3, abstracted from Ref. 4, a plot of transmissivity vs thickness of clouds is presented. The cloud transmissivity must be multiplied by clear-day transmissivity to give the total transmissivity. Typical values for cloud transmissivities are 0.75 for a light haze, 0.5 for a medium haze, 0.3 for a medium cloud cover, and 0.1 for a heavy cloud cover. Errors will occur in estimated transmissivities because Fig. 3.3 does not distinguish between different cloud types, and because of the operational fact that we will not know precisely how thick a cloud is along a

*It might be pointed out that the transmitted fraction of the diffuse component of the burst radiation will be somewhat less than that of the sun.



Source: Ref. 4

FIGURE 3.3 Atmospheric Attenuation Factors for High-Altitude Nuclear Detonations as a Function of Cloud Thickness and/or Cloud Density as Visually Judged

RI-9-64-14

particular slant path at a given time. For a rough estimate of the effects of these limitations, we note that the transmissivity through the cloud cover changes by 0.2, from 0.1 to 0.3, as we go from a heavy to a medium cloud cover.

An initial study of the probabilities of various cloud covers has been carried out in Ref. 5 for Washington, D.C. The Weather Bureau has records of cloud covers over major U.S. cities. These records have been used in some studies to obtain rough curves of thermal ignition radii as functions of time for various cities. The most probable cloud covers for the U.S. are 0 to 1/10, and 9/10 to 10/10; it is rarely half cloudy. There is also less than 1 percent probability that the whole country will be completely clear or completely cloudy. The U.S.S.R. has much more cloud cover than the U.S.

If a nuclear burst occurs between the ground and a cloud layer, radiation reflected from the cloud layer will enhance the radiation reaching the ground. In such a case, the effects can be calculated by assuming the cloud layer to act as a diffusely reflecting plane. Cloud reflectivities can be as high as 80 percent. The effect of the earth's reflectivity is small since we are concerned with the radiation at the earth's surface.*

3.6 Smoke Screens

Estimates of the feasibility of using a smoke screen for thermal protection during a nuclear attack have been made by Willoughby in Ref. 6.** He uses the Mie theory to estimate the number of smoke particles required (a screen of two radiation mean free paths thickness will absorb 90 percent of the incident radiation). Calculations show that the smoke must be dispersed in a 100-meter thickness of air to keep the temperature down to an easily tolerable level; (1 and 20-Mt bursts were considered). Estimates yield a 10 x 10-mile protection cost (wind dispersed smoke) of about $200,000 per sq. mi. for certain

*The amount of radiation at high altitudes above the earth's surface, on the other hand, is strongly dependent on the earth's albedo (Ref. 1).

**Another recent study of the use of fog or smoke screens is: R.A. Atlas, A.C. Behrenhoff, and B.N. Charles, "Thermal Protection of Cities by Artificial Smokes or Fogs," Report No. D2-22494, The Boeing Co., Seattle, Jan. 1964 (Confidential).

asumptions. The screen would have only ten times the concentration of impurities already present in some cities. However, deployment is contingent upon at least 20- to 30-min advance warning of attack, and prevailing wind velocities of 5 to 10 mph or more. We believe that smoke screens do not afford a promising countermeasure.

4. IGNITION

4.1 Introduction

Precise solutions to the following problems would yield the rate of delivery of energy as a function of time to any object on the ground:

a. Determining the (electromagnetic) energy output of the bomb as a function of time, and

b. Finding the fraction of the energy output that is transmitted through the atmosphere from the burst point to any point on the ground.

The many uncertainties in these problems have been indicated previously. Next, we shall assume that they have been solved precisely, and we shall consider the remaining processes involved in the development of large-scale fires from nuclear explosions. Thus, this section begins with a specified irradiation rate-time curve and investigates ignition. Section 5 discusses the various subsequent stages of fire growth.

4.2 Well-Defined Ignition Problems

4.2.1 Scientific Ignition Problem

One obviously pertinent problem has been studied at great length. This problem, which will be seen to involve a number of subtleties, can be defined as follows: Assume a slab of a specified solid material with a given dimension, suspended vertically in atmospheric air, is irradiated normally with a rectangular energy pulse of a specified magnitude and duration. What integrated energy flux (cal/cm^2) is required for ignition?

4.2.2 The Character of the Ignition Problem

A few rough minimal estimates of the required radiant energy are given without explanation in Ref. 1. Although some data are available from weapon tests, the most extensive sets of experimental results have been obtained at the Naval Munitions Laboratory (Ref. 2) and at the Naval Radiological Defense Laboratory (Refs. 3 to 7). In a series of careful studies on α - cellulose sheets, Martin in Refs. 3 to 7 discovered a number of different ignition regimes, as illustrated in Fig. 4.1. Therefore, before accurate numbers for the integrated energy flux required for ignition can be obtained, one must decide which (if any) of the regime boundaries identified in Fig. 1 corresponds to ignition in a practical sense. This requires a deeper understanding of the character of the ignition process.

Presumably, most organic solids exhibit the qualitative behavior indicated in Fig. 4.1 and, therefore, the superficial nature of the direct ignition process appears to be reasonably well known. However, this does not mean that the basic nature of the process is understood.

4.2.3 Present State of Understanding of the Ignition Process

Let us consider briefly the factors involved in analyzing the underlying physics of the process of radiant ignition of solid combustibles. Heat conduction normal to the surface of the sheet is obviously of some importance. Martin in Ref. 5 was able to correlate (scale) some of his experimental results on α - cellulose sheets of different thicknesses in terms of the Fourier modulus $\alpha t/L^2$ (α = thermal diffusivity, t = pulse duration, L = thickness). Heat conduction concepts also provide some qualitative insight into the character of the transient flaming and glowing ignition regimes illustrated in Fig. 4.1. Transient flaming occurs only when the Fourier modulus is less than about 0.3 so the entire energy input is initially confined to a small layer of the material near the irradiated surface. Glowing ignition was observed to occur when the Fourier modulus exceeds 4. In heat conduction theory, this implies that the material

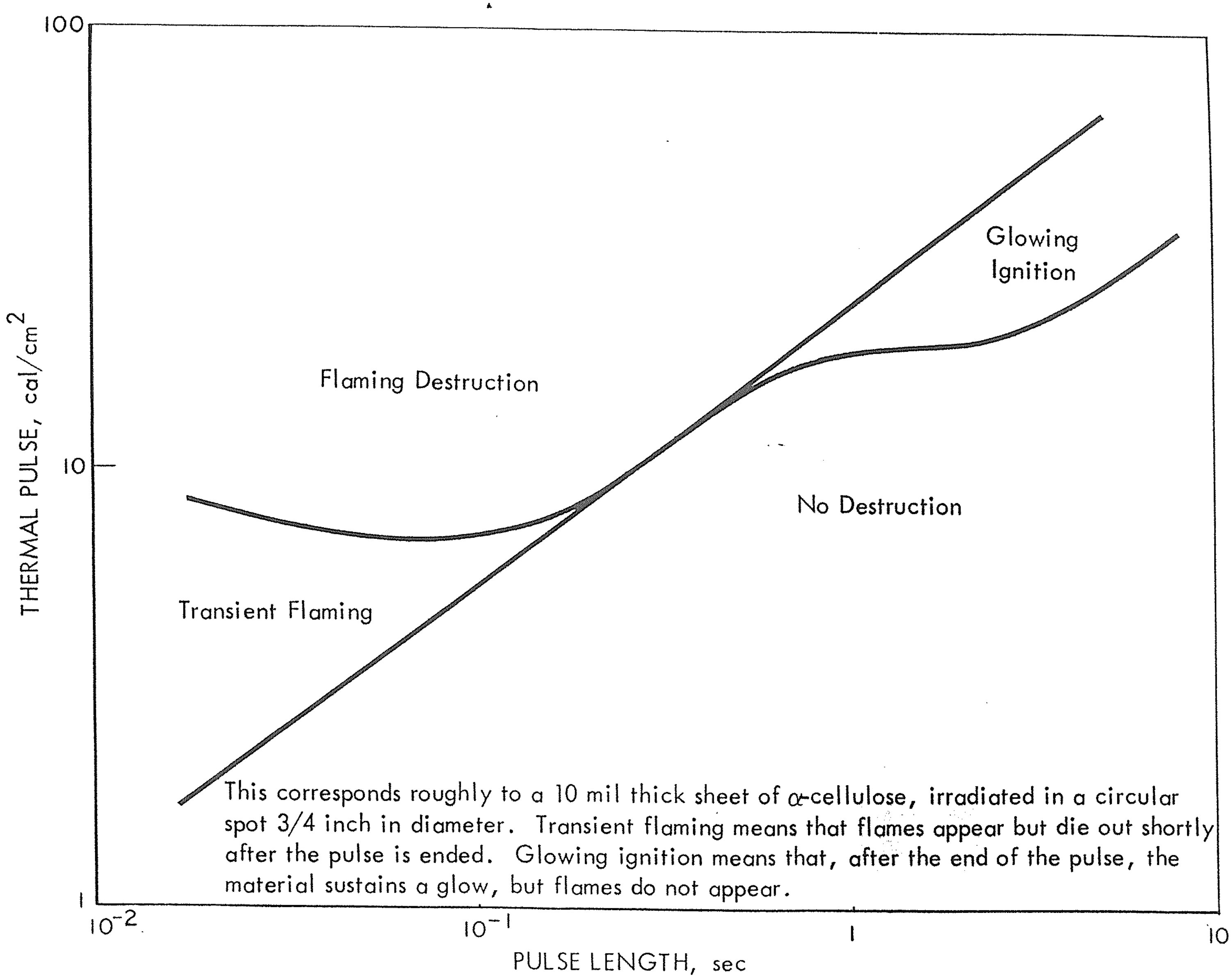


FIGURE 4.1 Illustrative Graph of Ignition Regimes

approximately maintains a uniform temperature.*

A few theoretical analyses of the ignition process have been presented. These all consider the one-dimensional, unsteady heat conduction problem, including radiative losses and convective losses (expressed in terms of a heat transfer coefficient) from the surfaces of the sheet. Most such treatments (e.g., Ref. 8) avoid considering any chemical kinetics by assuming that ignition occurs when an ignition temperature, which must be determined empirically, is achieved. Reference 9 included rudimentary chemical kinetic concepts by employing a one-step, overall rate formula for the potential volatile content and by assuming that damage occurs when the potential volatile content at the back face of the sheet is decreased by a factor of e^{-2}. All such analyses provide rough empirical correlations at best;** they are extremely primitive by current standards in combustion research.

The existing studies are all based on concepts developed in studies of combustible systems involving premixed reactants (fuel and oxidizer intimately mixed at a molecular level before the process begins). The one-step overall rate process approximation is very useful for studies of ignition and combustion in premixed systems; the ignition temperature approximation is less precise and is very difficult to apply accurately. Ignition in premixed systems is relatively well understood (Ref. 10). However, few if any solid combustible materials contain enough oxidizer to support a flame in the absence of ambient oxygen; ignition of wood, paper, etc., is essentially a non-premixed unsteady process (fuel and oxidizer are initially separated). Such processes are extremely complex, necessarily involving gas and/or liquid motion (neglected in all previous studies), gas-phase reactions, etc.

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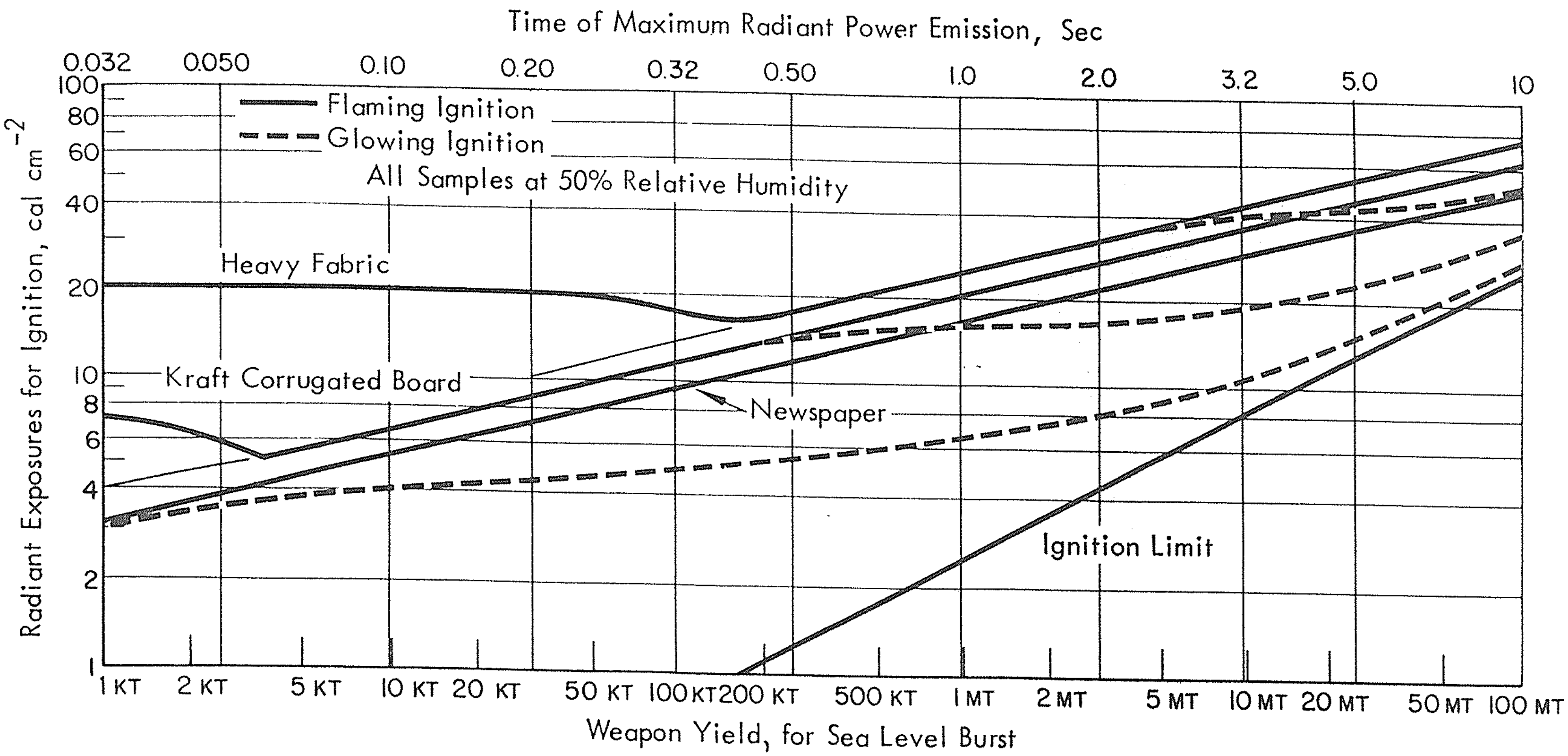
*The temperature for glowing ignition of α-cellulose was found to be about 300°C.

**As an illustration of the fact that the "ignition temperature" is not a fundamental molecular parameter, we may cite Hottel's finding (Ref. 8) that the empirical ignition temperature depends upon the size of the irradiated sample.



Source: A. Broido, using measurements by S. B. Martin

Note: These curves are derived from laboratory exposure of materials in a plane, normal configuration using a small (maximum diameter, 3/4 in.) apertured spot of uniform irradiation. They therefore ignore any possible influence of sample geometry and area. Some of these data have been confirmed for larger area samples exposed to low yield weapons during weapons tests. However, for the longer pulses of high yield weapons, materials exposed under less ideal conditions exhibit an increased susceptibility to flaming ignition. For this and other reasons, the curves for glowing ignition are believed by Broido to be of greater significance in estimating weapon effects.

FIGURE 4.3 Integrated Flux for Ignition as a Function of Weapon Yield

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Hardinggrass
Pine needles
Walnut leaves; wool serge, olive drab
Window shade material, cream color

Items appearing in the above list may be termed "kindling materials;" thick, sound, wooden construction materials, well-painted wood, etc., will sustain ignition only at much higher integrated energy fluxes than kindling materials.* Figure 4.3 presents ignition curves for dark newspaper, kraft corrugated board, and heavy fabric. Since newspapers are abundant in urban areas, many investigators have agreed to adopt newspaper as a representative, easily ignitable material for future ignition studies.

4.2.9 The Effect of Moisture Content of the Material

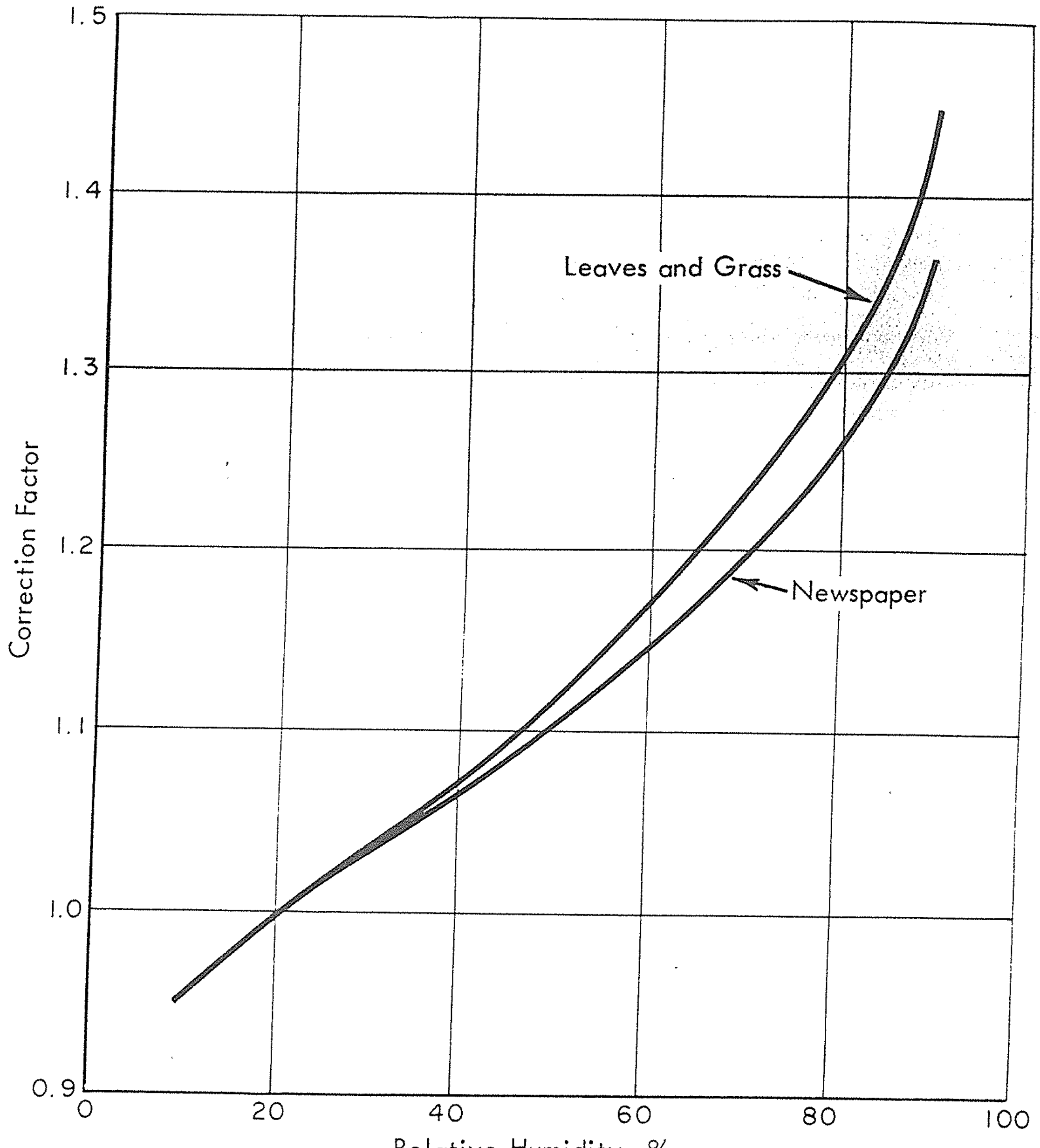
The moisture content of the material has a significant effect upon ignitability. Some information on this effect is available (Refs. 14 and 15). The integrated energy flux for ignition at a relative humidity of 20 percent must be multiplied by the factor shown in Fig. 4.4 to obtain approximately the required flux at other values of the relative humidity (Ref. 16). Here it is assumed that the material has been exposed to air with the given relative humidity long enough for the moisture content of the material to reach equilibrium.** For kindling materials this time is very short (much less than a day). Some heavier construction materials may exhibit ignition energies as low as 25 cal/cm^2 after a few weeks exposure to hot, dry conditions (Ref. 14).

4.2.10 Uncertaincies in Existing Results on Ignition

The existing data on minimum ignition energies is subject to two important criticisms. First, no data have been obtained for pulse lengths below 20 ms, and the experimental uncertainties are very large at pulse lengths below 50 ms. Since high-altitude

*Accurate values of minimum ignition energies for heavy materials, for pulse durations comparable to those of bomb pulses, do not appear to be available. Minimum energies for sustained ignition in excess of 100 cal/cm^2 appear to be reasonable.

**The moisture content of newspaper is 7 percent by weight at normal relative humidity (42 percent).



Source: Ref. 16

FIGURE 4.4 Factor Correcting Ignition Energy for Relative Humidity

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nuclear explosions have been observed to reach peak energy output at 0.5 ms and to emit half their total radiant energy yield in about 20 ms (Sec. 2.4.2), data are needed for shorter pulse lengths. If the short bomb pulses cannot be simulated accurately in the laboratory, then rectangular pulses as short as the time to peak energy output would be needed to enable one to deduce necessary ignition energy information for high-altitude explosions.* Martin's scaling criterion enabled him to infer some characteristics of the behavior of thin materials at short time scales from his experiments on thicker materials at longer time scales. However, direct experimental justification for this extrapolation is desirable. Preliminary experimental results at short time scales have been obtained by Hochstim (Ref. 17). Hochstim's work is continuing and may provide the required results. Also, Martin is searching for new physical phenomena that may occur for very short pulses.

The second criticism of the existing results applies to the experiments for long pulse times, ≥ 1 sec. In the laboratory tests, spots no greater than 3/4 in. in diameter were irradiated. For the longer 1 to 10 sec pulses characteristic of large-yield weapons burst at sea level, these spots are so small that convective fluid motion will have time to remove the heated gases from the irradiated region. Convective heat losses, therefore, may yield higher ignition energies in the laboratory than would be obtained in a typical tactical event for which large areas are usually irradiated. In Ref. 8, Hottel has emphasized this point and has performed very rough experiments in a furnace, where large areas of the sample are irradiated, in an effort to determine the magnitude of this effect. Conclusive evidence that the accepted minimum ignition energies are too large in this regime has been obtained, but accurate corrected values have not yet been presented. From theoretical considerations, Hottel recommends irradiating spots at least 6 in. in diameter to obtain reliable results for pulse lengths greater than 1 sec. In

*Since heat conduction theory implies that the peak temperature is reached very shortly after the time of peak irradiance, the ignition temperature hypothesis, in its strictest interpretation, implies that the first part of the pulse is of greatest importance in producing ignition.

Ref. 18, Broido has suggested that the existence of the glowing ignition regime in Fig. 4.1 may be attributable to the small-spot size, and that glowing may result in flaming for sufficiently large samples. The influence of convective heat losses for long pulses requires further study, some of which is in progress at the Naval Munitions Laboratory.

4.3 Ill-Defined Ignition Problems

4.3.1 The Practical Ignition Problem

It will be noted that Figs. 4.1, 4.2, and 4.3 do not provide unique ignition criterion. One must decide whether transient flaming, sustained flaming, or glowing ignition constitute ignition in a practical sense. The earliest inclinations favored sustained flaming as the ignition criterion. The convective heat loss question indicates that glowing ignition may be a better criterion than sustained flaming, where these two differ. However, all of these arguments presuppose an isolated vertical sheet of material. Environmental materials are not so arranged. Combustible sheets may be lying horizontally, materials may be wrinkled or crumpled, other objects may be located in the vicinity of the material so as to modify the convection currents or radiative heat losses, etc. Perhaps materials surrounding the kindling can be so located that heat losses are reduced to a point where transient flaming always develops into sustained flaming. More probably, the ignition criteria in complex environments cannot be represented well by any of the curves in Fig. 4.1. The possible variations are so numerous that one cannot state a well-defined problem that will cover all contingencies. Ignition is inextricably connected with the initial stages of fire spread, and the number of variables influencing the minimum ignition energy is therefore large.

In view of these difficulties, a statistical approach to the ignition problem may be desirable. One may ask: Given representative urban, suburban, rural, and wild-land areas, what integrated energy flux is required to start a specified average number of fires per unit area? Although this is an ill-defined question, it is the kind of question to which very approximate answers have been given by bomb tests (Ref. 1). A large number of laboratory tests might provide a somewhat more accurate answer to this question.* Incontrovertible answers can never be obtained because of the ambiguity of the problem.

4.3.2 High-Confidence Limits on Critical Ignition Energies

Having recorded these uncertainties, we shall quote limits for the ignition energy that, as yet, have never been found to be violated. Ignition of kindling materials has never been obtained in accurate experiments at integrated energy fluxes below 2 cal/cm^2. For ignition pulses not exceeding 10 sec in duration,** 50 cal/cm^2 is sufficient to ignite all kindling materials and 20 cal/cm^2 will always ignite some kindling materials. With a high degree of certainty, the critical ignition pulse for typical light kindling materials, therefore, may be taken to lie between 2 and 20 cal/cm^2. Consequently, it may be reasonable to use 4 cal/cm^2 and 10 cal/cm^2 as working numbers for estimates for "bad" and "good" conditions, when viewed defensively.

*Some such laboratory tests, e.g., irradiating the edge of a folded newspaper, are currently planned at the Naval Munitions Laboratory.
**All pulses of existing weapons fall within this limitation.

5. FIRE SPREAD

5.1 Development of Fires that Amateurs Cannot Extinguish

5.1.1 Relationship between Ignition and the Development of Small Fires

After the critical ignition energy of the various kindling materials has been determined, one is tempted to infer that the number of serious fires produced by the thermal pulse of a nuclear weapon can be calculated simply by counting (from geometrical considerations) the number of kindling groups exposed to a pulse energy exceeding the critical value. Such an inference, however, is manifestly false. Clearly, an isolated newspaper on a paved road can burn completely without producing a serious fire. Anyone who has lit a campfire knows that favorable arrangements of kindling and of heavier combustibles are necessary for producing a sustained fire. One should count, therefore, only the ignition of kindling materials which by themselves or in combination with other combustibles can result in a sustained fire.

Although the conditions for the development of small sustained fires are known qualitatively to nearly everyone, quantitative data is practically nonexistent. Various basic physical processes governing small-fire development (radiative, convective and conductive heat transfer, heat-liberation rates, etc.), for the most part, are reasonably well understood, but the number of parameters needed to specify the relative geometrical locations of the various combustibles is so great that comprehensive deductive scientific analysis is impossible. Instead, a statistical analysis of experimental data is required. In spite of a number of attempts to determine the distribution of potential fire sources (Refs. 1 to 7), apparently few, if any, reliable statistics on the number of very small fires that might develop are available. It is usually assumed that, in areas where ignition occurs, there will be enough combustible arrangements conducive to fire development to insure that a large number of small fires will be produced, but this assumption may not always be valid.

The observation that the development of small fires is an essential step in severe fire damage immediately suggests one means of minimizing the hazard of fire from nuclear explosions: either eliminate or shield from the thermal pulse all kindling materials that can produce sustained fires (Refs. 8 and 9). At least to a certain extent, this measure is more reliable, less expensive, logistically simpler (in some respects) and less objectionable than the "smoke screen" measures that have been proposed (Ref. 9).

The process of the development of fires that amateurs cannot extinguish tends to differ considerably in inhabited and in uninhabited areas. Therefore we shall consider each of these regions separately.

5.1.2 Inhabited Areas

There seems at present to be a general consensus among experts that, in inhabited areas, nuclear thermal pulses are much more likely to produce small indoor fires than small outdoor fires (Refs. 7 and 10). The number of kindling piles per unit area is commonly much larger indoors, and indoor kindling is more likely to be favorably arranged with respect to heavier combustibles. (See Ref. 3 for an opposing view).

It has been found experimentally that about 4 lb of newspaper must be burned at the base of an external wooden wall to ignite the wall (Ref. 7). This much newspaper is seldom found outside, next to a wall, and exposed to possible nuclear thermal radiation. The structural fires from outside ignitions appear most likely to develop in rotting (punky), unpainted wood and, therefore, are expected to occur principally where wooden structures are in very poor repair.

It has been estimated that one or two ignitions of kindling materials of substantial magnitude inside a room of a typical house are sufficient to destroy the room if left unattended (Ref. 7). The probability of ignition is proportional to the exposed area of the room and depends upon the distribution of kindling materials. Perhaps 100 ignitions may be produced in a cluttered room with many windows, but many representative exposed rooms would experience no ignitions at all because of a greater degree of shielding and/or the absence of sufficient kindling materials.

The dependence of ignition probability upon weather conditions is very different for indoor and outdoor fires. Hot, dry, summer weather favors outdoor and wild-land fires; forest fires seldom occur in winter. On the other hand, inside many heated buildings in winter, the humidity and, therefore, the moisture content of kindling materials is very low, and the critical ignition energy is correspondingly reduced. Indoor fire susceptibility appears to be less strongly correlated with weather than does outdoor fire susceptibility.*

There appears to be little reliable quantitative data on the length of time required for indoor ignition to produce a fire that envelopes a whole room in flame ("flashover"), thus preventing nonprofessional fire-fighting. Rough estimates indicate that 5 to 20 min might be necessary.** This observation points up a second promising method for reducing fire damage from nuclear attack: Rapidly extinguish as many of the initial small fires as possible (Refs. 8 and 9). Many of the initial fires will be small enough to stamp out, others will require water, sand, or portable fire extinguishers. Although quantitative information on the amount of water, equipment, etc., required to suppress small fires has not been available, it has been estimated in Ref. 7 (and also by Lawson** below) on the basis

*Note, for example, that during World War II, incendiary bombing attacks in the rain were observed to produce only roughly 20 percent less damage, on the average, than corresponding attacks in clear weather (Ref. 11). Incendiaries produce mainly indoor ignitions.

**See D.I. Lawson and P.H. Thomas, "The Growth of a Fire," Chantry Publications Ltd., London, 1956. More accurate information is being obtained; see F. Salzberg, "Approach to Post-Attack Fire Suppression in Urban Areas," OCD Contract No. OCD-OS-62-210, 1964.

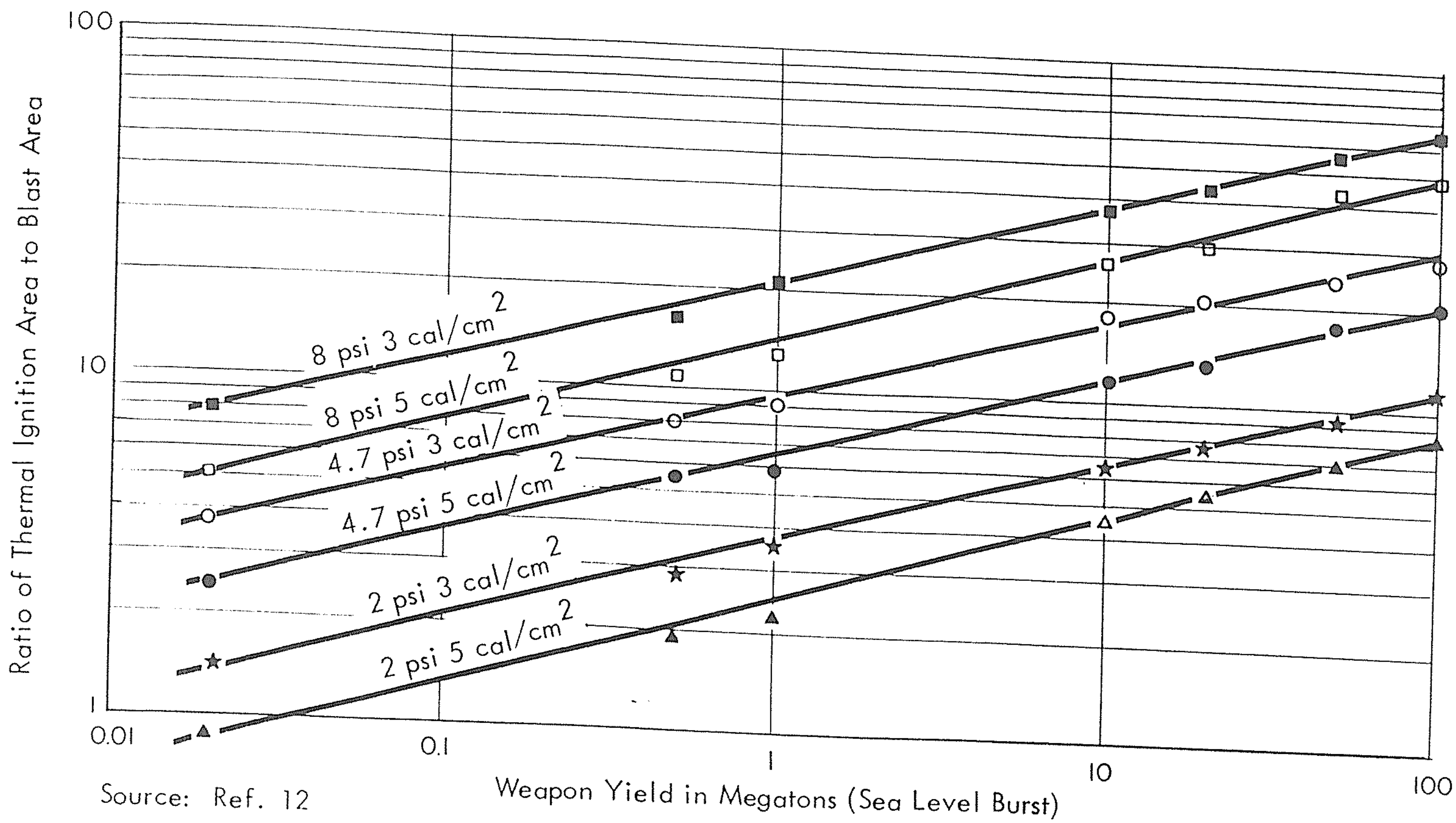
of recent experimental results that by commencing the suppression activities within five minutes after the thermal pulse, perhaps 90 percent of the indoor fires could be suppressed by individuals with hand extinguishers, provided these people were trained in the use of fire extinguishers, to overcome fear of entering a smoke-filled room, etc. Centralized fore departments by themselves would be completely inadequate for suppressing the large number of initial ignitions;* volunteer fire brigades (composed of perhaps 5 percent of the total able population) well trained (e.g., by the organized fire departments) in the use of water booster lines and equipped with water pumps of about 30 gal/min capacity, would be needed to suppress the 10 percent of the fires not controlled by individuals. Quick action by these "first aid" brigades could reduce the number of fires requiring the attention of an organized fore department to a point where fire control would be feasible. Clearly, establishing these "first aid" groups and training the general populace represents a very large program, but this may be the only effective means of controlling fires produced by a nuclear thermal pulse in urban areas.

5.1.3 Secondary Blast Ignitions

We have been considering only fires produce by the thermal pulse of the weapon. In inhabited areas (but not in uninhabited areas), fires may begin as secondary effects of the blast wave (e.g., turning over a stove, breaking a gas main, short-circuiting electrical wiring). Secondary blast ignitions are very likely to occur at 5 psi blast overpressures or above. Where severe blast damage occurs, the significance of the additional fire damage is not clear. Although the importance of secondary blast ignition merits study, we have not considered this topic.

Other blast effects can have an important influence on fire development from the thermal pulse. For example, if the blast breaks water mains, it may be difficult to obtain water for fighting fires. In atomic bombing of Hiroshima, water pressure in the center of the city dropped to zero because of an estimated 70,000 breaks in water pipes (Ref. 8). These blast-thermal interactions are difficult to analyze and are not considered in this report.

*It has been estimated roughly that, on the average, 10,000 ignitions/sq. mi. would be produced by a 5 cal/cm^2 pulse.



Source: Ref. 12

FIGURE 5.1 Ratio of Area Affected by Fire on a Clear Day to Area Affected by Blast for Several Values of Overpressure and Irradiance

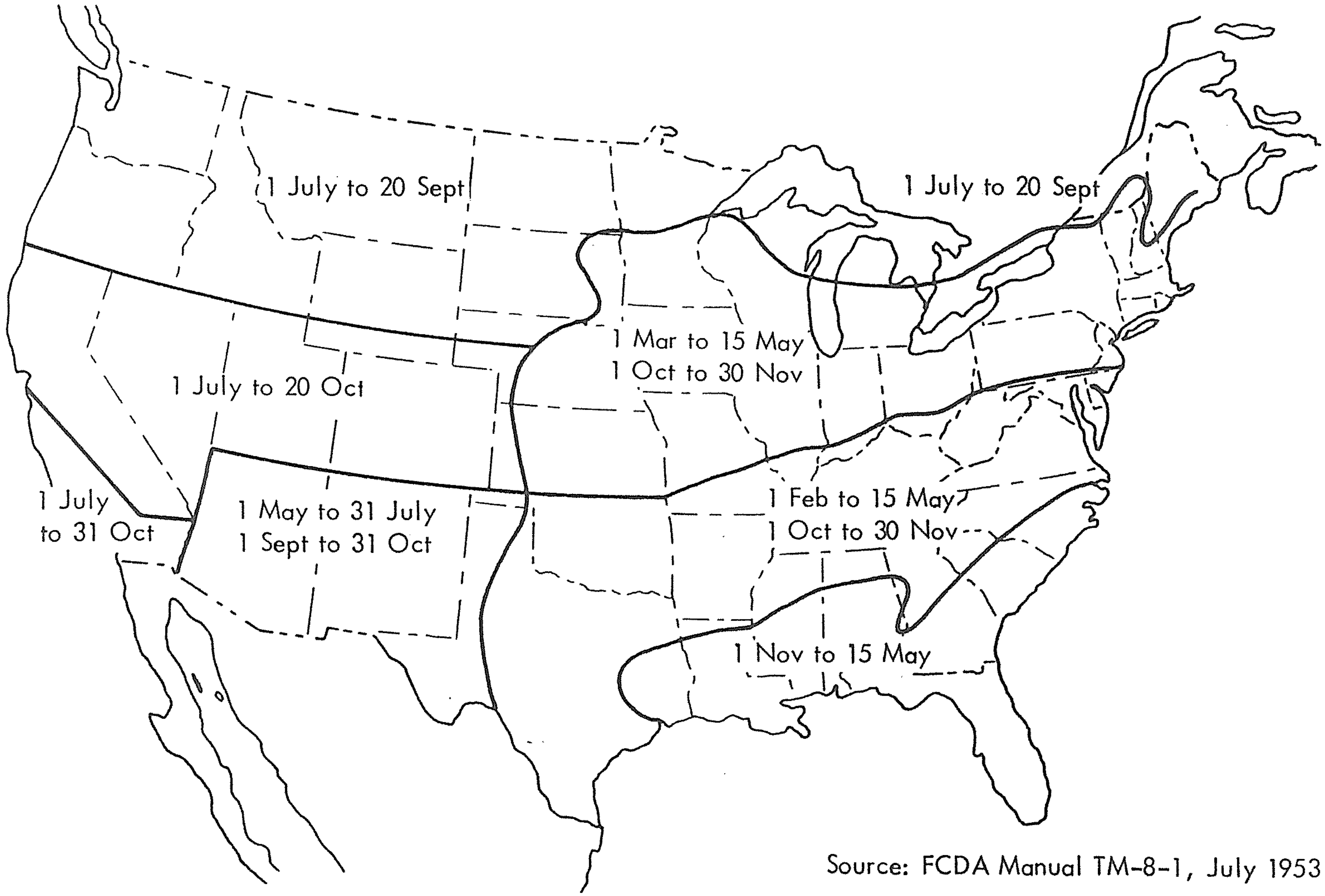
Figure 5.1, based on data from ENW, shows the ratio of the area affected by the thermal pulse to the area affected by blast. It can be seen from this figure that fires may occur in large areas in which blast damage is negligible. This, however, does not necessarily mean that blast-thermal interactions are negligible in these regions; a broken water main or destroyed fire-fighting apparatus many miles away from a burning area may seriously affect fire control efforts in that area under certain circumstances.*

5.1.4 Uninhabited Areas

Fires in uninhabited areas can probably be due only to the thermal pulse. It is difficult to predict where ignitions will occur; for example, green leaves on trees may shield dry kindling beneath, thus preventing ignition. Fire development after ignition will be affected by the same factors that influence the development of peacetime wild-land fires; humidity, wind, other weather factors, fuel density (weight of combustible/unit surface area), fuel type and topography (Ref. 12). Depending upon these conditions, fires may spring up at every ignition site, or all of the ignited spots may rapidly be extinguished. Early human fire-fighting efforts would not be feasible in large areas of exposed wild lands; nautral phenomena would determine the fire development and growth.

Figure 5.2 shows the fire seasons in various sections of the United States. Figure 5.2 is applicable only in a statistical sense. Not all days in the indicated interval will favor fires, and on some days outside the interval fire hazard may be extreme. Empirically, the wild-land fire hazard is dependent upon at least a 5-day weather history (Ref. 14). In good fire weather, the humidity is below 40 percent, the wind velocity exceeds 13 mph and there has been less than a trace of precipitation in the past 5 days. In poor

*Another interaction effect worth mentioning is that between a mass fire and fallout. A well-developed fire convection column modifies air flow patterns and thereby affects fallout. Laboratory experiments seem to imply that the fire will spread the fallout pattern over a larger area, reduce the maximum fallout concentrations, and move the position of maximum fallout downwind. See A. Broido and A.W. McMasters, "The Influence of a Fire-Induced Convection Column on Radiological Fallout Patterns," Technical Paper No. 32, California Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, Calif., March 1959.



Source: FCDA Manual TM-8-1, July 1953

FIGURE 5.2 Fire Seasons Map of the United States fire weather, the humidity exceeds 70 percent, the wind velocity is less than 13 mph and there has been more than 1/4 in. precipitation in the past 5 days (Ref. 14). Clearly, even these rules are very rough. Much more accurate predictions can be made on the basis of laborious, detailed, field measurements. However, completely reliable predictions on whether an isolated ignition will develop into a fire in a given area are still unobtainable.

5.2 Urban-Fire Characteristics and Factors Influencing Urban-Fire Spread

5.2.1 Urban-Fire Characteristics

Much effort has been spent on determining the characteristics (burning rates, flame temperatures, heat transfer rates, combustion product composition, etc.) of fires in buildings. Basic research related to fires is currently summarized in Ref. 15, a continuing journal. Studies of models can provide certain relevant information (e.g., Ref. 16), but modeling of all pertinent fire parameters can easily be shown to be impossible. A few full-scale experimental test fires in buildings have been instrumented and analyzed (Refs. 7, 17 to 20). Finally, there is a wealth of qualitative observations by experienced fire fighters. The following paragraphs include some of the rough, but more quantitative, data derived from these studies that may be of use in fire protection studies:

At a reasonable degree of ventilation, temperatures in a burning room reach a steady state value not greater than 1100°C (Ref. 21).

Steady-state radiant intensities emitted by well-ventilated fires are about 4 cal/cm^2-sec (at the surface of the fire) at the representative fire load of 10 lb/ft^2 (weight of combustible material per unit plan area). The intensity increases somewhat with increasing fire load (Ref. 21).

Representative burning times for buildings in various urban areas are listed in Table 5.1. Here, "violent burning" means the most active burning, during which the radiation intensity exceeds 50

TABLE 5.1

Burning Times of Buildings in Urban Areas

Construction Type	Violent Burning		Residual Burning		Total Burning Time
	Time (Minutes)	Percent of Total Energy Release	Time (Minutes)	Percent of Total Energy Release	
Light Residential	10	80	12	20	36 hours
Heavy Residential	13	70	20	30	72 hours
Commercial	25	60	60	40	7 days
City Center and Massive Manufacturing	55	30	120	70	2 months

Source: Ref. 13.

percent of its maximum value; "residual burning" means predominantly glowing combustion, but with some flaming still occurring, during which the radiation intensity lies between 50 and 10 percent of its maximum value; the "total burning time" is the time during which an unattended fire remains hot enough to flare up again if prodded by a favorable change in weather. Violent burning of a building seldom exceeds an hour, but total burning times are very long (of the order of months) in cites. The differences between construction types can probably be correlated fairly well with differences between fuel load.

Once any building, or section of a building, reaches the "violent-burning" stage, practically no fire-fighting efforts can prevent substantial damage to the building. The only effective efforts then are those spent in attempting to prevent the fire spreading to other buildings or to other parts of the burning building. We consider next the factors influencing urban fire spread.

5.2.2 Urban-Fire Spread

Convective and radiative heat transfer constitute the principal mechanisms of fire spread between buildings. In addition to these, heat conduction may be of some importance in fire spread within a building. The parameters influencing fire spread are therefore principally those affecting the convective and radiative transfer processes.

Fire protection engineers have gained much experience concerning conditions under which fires will spread. This has led to highly detailed specifications of rational building codes (e.g., Ref. 22). These specifications are based principally upon empirical observations. Recently, attempts have been made to provide analytical bases for building code specifications. Curves enabling one to compute the safe building separation as a function of building widths, building heights and percent "openings" have been computed in Refs. 21 and 23. The data for these curves come (1) from the observation that a steady radiant intensity of 0.8 cal/cm^2-sec is required to ignite typical building materials, (2) from the observation that more than 0.3 cal/cm^2-sec is required to ignite kindling materials commonly found in rooms, (3) from the observed radiant intensity produced by fires (stated in Sec. 5.2.1), and (4) from geometrical considerations. The percent "openings" is the fraction of building face areas occupied by doors, windows, and combustible wall materials. This analysis necessarily emphasizes radiant heat transfer; convection effects, often producing ignition by flying brands, are not treated properly. Other significant parameters (fuel loading, etc.) are also neglected here. Therefore, most fire protection engineers prefer to rely upon the established empirical methods (Ref. 24). It does appear, however, that analytical studies which are more comprehensive (and therefore more complex) than those in Ref. 21 can be of value in obtaining improved, more precise, and perhaps less complicated criteria for "no fire spread." Considerations similar to those in Ref. 21 are currently in use for predicting fire spread from nuclear explosions (Ref. 7).

Some factors influencing fire spread in urban areas are:

Building separation distances

Building density, the ratio of the projected roof area to the total area

Building heights

Building fuel-loading

Wind

Other weather factors (but only to a slight extent)

Building construction (a multitude of factors enter here; e.g., external wall material, paint, window-opening area, window shutters, firewalls, parapeted (extending above the roof) firewalls, automatic sprinkler systems)

Building contents

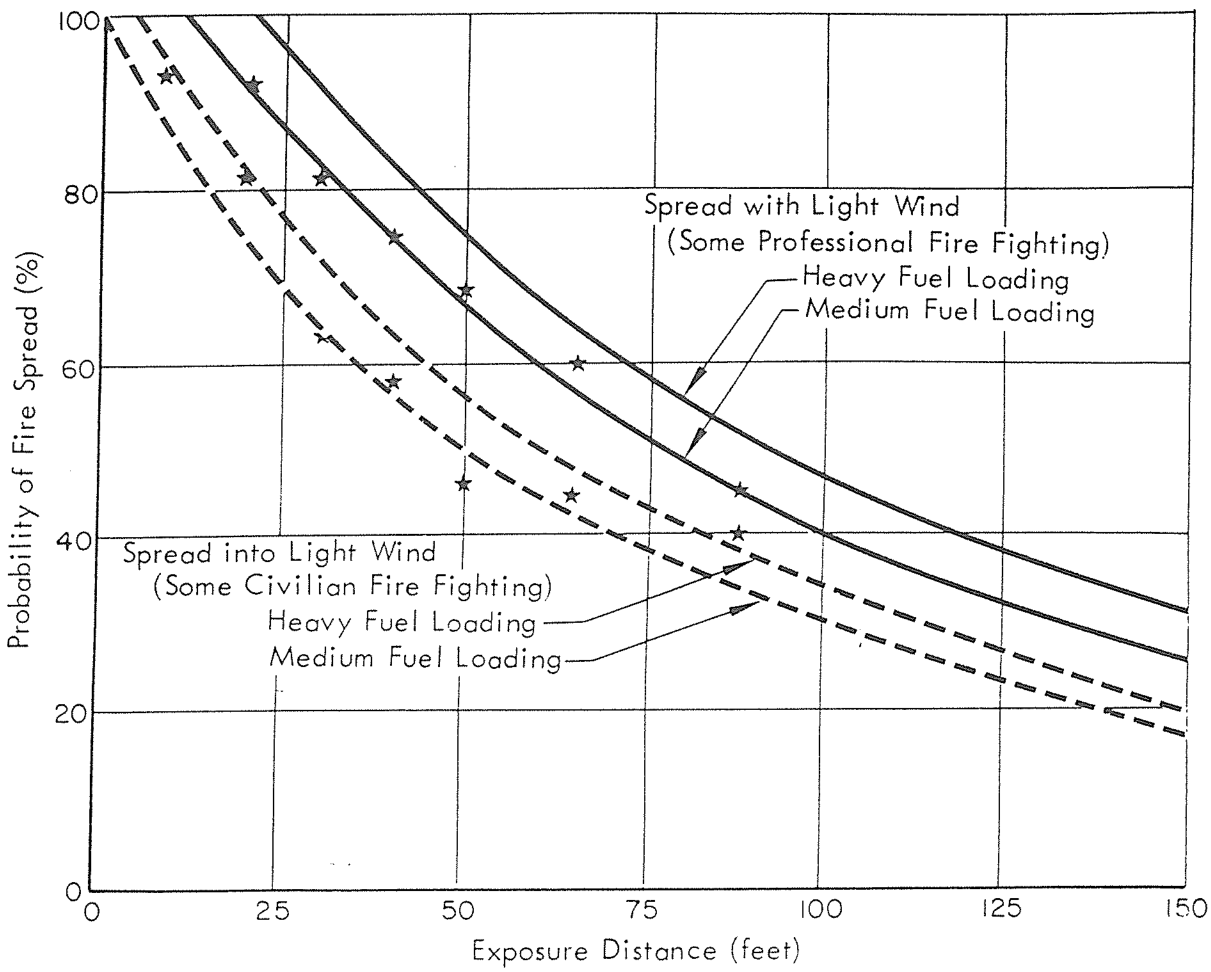
The reader is referred to suggested building codes (e.g., Ref. 22) for the effects of these factors on fires which start in only one building or compartment. Here we shall merely point out some data specifically applicable to fires from multiple ignition sources.

A detailed analysis of the fire spread following an incendiary attack on Hachiji, Japan, has been made in Ref. 25. The points shown in Fig. 5.3 give the effect of building separation on probability of fire spread, as computed in that study. The effect of fuel loading indicated in Fig. 5.3 was suggested in Ref. 13. Clearly, the exposure distance has a dominant influence on the probability of fire spread. A light wind also has a substantial effect; fire spread to leeward is enhanced by increased radiant heat transfer from tilted flames and by increased susceptibility to flying firebrand spotting due to tilted convection columns.

A rough consideration of the effect of building height indicates that building separation should exceed building height to prevent fire spread (Ref. 26).

The effect of building density on fire spread is not entirely independent of the effect of building separation distances. Clearly, there is a geometrical relationship between the two in typical urban areas. A proper assessment of the effect of building density should be carried out at different constant values of building separation. This has not been done. Instead, only the following rough rules have been given (Ref. 27): For building densities from 0 to 5 percent, fire spread does not occur. For building densities for 5 to 20 percent, fire spread may occur, but mass fire development is unlikely. For building densities above 20 percent, over an area ≧ 1 sq. mi., mass fires, urban conflagrations and fire storms are possible.

Fire-resistant wall materials and parapeted fire walls can be extremely effective in preventing fire spread in cities, provided these walls divide the city blocks into many completely enclosed compartments. The failure of repeated attempts by means of incendiary attacks to produce fire storms and large-scale conflagrations in Berlin during World War II, has been attributed directly to the extraordinarily high degree of compartmentization of the city (Ref. 28). Fire walls that do not isolate compartments are, however, relatively ineffective.



Source: Ref. 13

FIGURE 5.3 Probability of Urban Fire Spread Across Various Exposure Distances, by Type and Wind Direction

Automatic sprinkler systems are usually ineffective in multiple fire areas (Ref. 29). The capacities of such systems are usually designed to service only one or two rooms and, when a whole building is aflame, the output of each sprinkler is so small that it has no effect on the fire. Sprinkler systems can seriously deplete the water supply in multiple fire areas, thus reducing pressure in the water mains and thereby hampering other forms of fire suppression.

A statistical study of fire-spread rates in urban areas has shown that the average spread rate is 0.12 mph, for fires burning from 1 to 18 hours. (See Refs. 13, 30.) This is somewhat lower than most quoted values. Wide variations (almost an order of magnitude) about the average value are observed. The meaning and usefulness of average spread rates in urban areas are not clear.

5.2.3 Recent Studies of Fire Spread from Nuclear Detonations

A number of recent studies have been designed to determine the extent of fire spread following nuclear detonation. These studies attempt to develop computer programs (Refs. 7, 31) and modeling methods (Ref. 32).

Reference 7 attempted to include, as quantitatively as possible, all of the effects discussed above. The objective was to determine from the probability of ignition the expected damage as a function of ground distance, weapon yield, etc. When all pertinent factors are taken into account, the computer program becomes very large. Consequently, results thus far have been obtained only for single city blocks and for tract areas with relatively uniform building properties.* Even in these cases, certain oversimplifications are introduced (e.g., the effects of flying brands are not included properly). Nevertheless, the results are by far the most realistic ones available.

A study that attempts to gloss over the details discussed above breaks cities down into unit cells about one block in size and develops (1) a probabalistic model and (2) a deterministic

*The computer program has been written in such a way that results for individual blocks and tracts can be put together to obtain fire spread results for a whole city.

model for predicting the rate of fire spread from cell to cell (Ref. 31). Unfortunately, so many essential factors are overlooked in this kind of approach that the results have little or no relationship to reality.

Since complete modeling of fires in structures is not possible one would expect that complete modeling of the process of fire spread in mass fires is not feasible. This is indeed the result obtained in Ref. 32. Modeling of certain aspects of mass fires, however, may be possible.

5.3 Conditions for the Development of Wild-Land Conflagrations

5.3.1 Characteristics of Wild-Land Fires

There has been much basic and applied research on the characteristics of wild-land fires. The reader may consult Ref. 13 for bibliography on this work. Burning rates, flame temperatures, heat transfer rates, etc., have been studied. In Table 5.2, we reproduce data analogous to that given in Table 5.1 for urban fires. The terms have the same meaning as in Table 5.1. The numbers given were obtained principally from expert field observers.

5.3.2 Wild-Land Fire Spread

Wild-land conflagrations can develop only when conditions favor wild-land fire spread. Therefore, fire-spread criteria govern when wild-land conflagrations occur.

In small wild-land fires, radiative heat transfer is usually the principal fire spread mechanism. The flame height and flame angle then strongly influence rate of spread. In large fires with more active convective currents above them, convective effects, especially the convection of flying firebrands, provide the principal spread mechanism.

Factors influencing wild-land fire spread include:

Fuel type

Fuel-loading

4.2.4 The Need for Basic Research

To obtain a basic understanding of the ignition process is not an impossible task. Many problems as yet undefined would arise. However, many relatively well-defined problems are also involved. These include:

a. Locating where (solid, gas, interface) ignition first occurs

b. Identifying the chemical constituents that act as fuel and oxidizer in the ignition reaction

c. Discovering the products of the radiant pyrolysis of the solid

d. Assaying the influence on ignition of solid and gas-phase diffusion processes

e. Analyzing the mass-average motion of the gas

f. Investigating the influence of the moisture content of the solid upon the ignition process

g. Attempting to determine the reaction kinetic path

h. Developing simplified models of the elementary steps of the ignition process

i. Determining the influence of the rate of delivery of radiant energy upon the diffusion, fluid motion, heat transfer and chemical kinetic processes involved in ignition

The preceding list is not complete. To obtain a fundamental understanding of the ignition process entails a long series of studies that are best classified as basic research. A few studies of this kind have been reported (e.g., Ref. 11, which attacks problem a. above). However, very little effort is being expended along these lines. A satisfactory answer to the scientific ignition problem (Sec. 4.2.1) requires a significantly expanded effort in this direction.

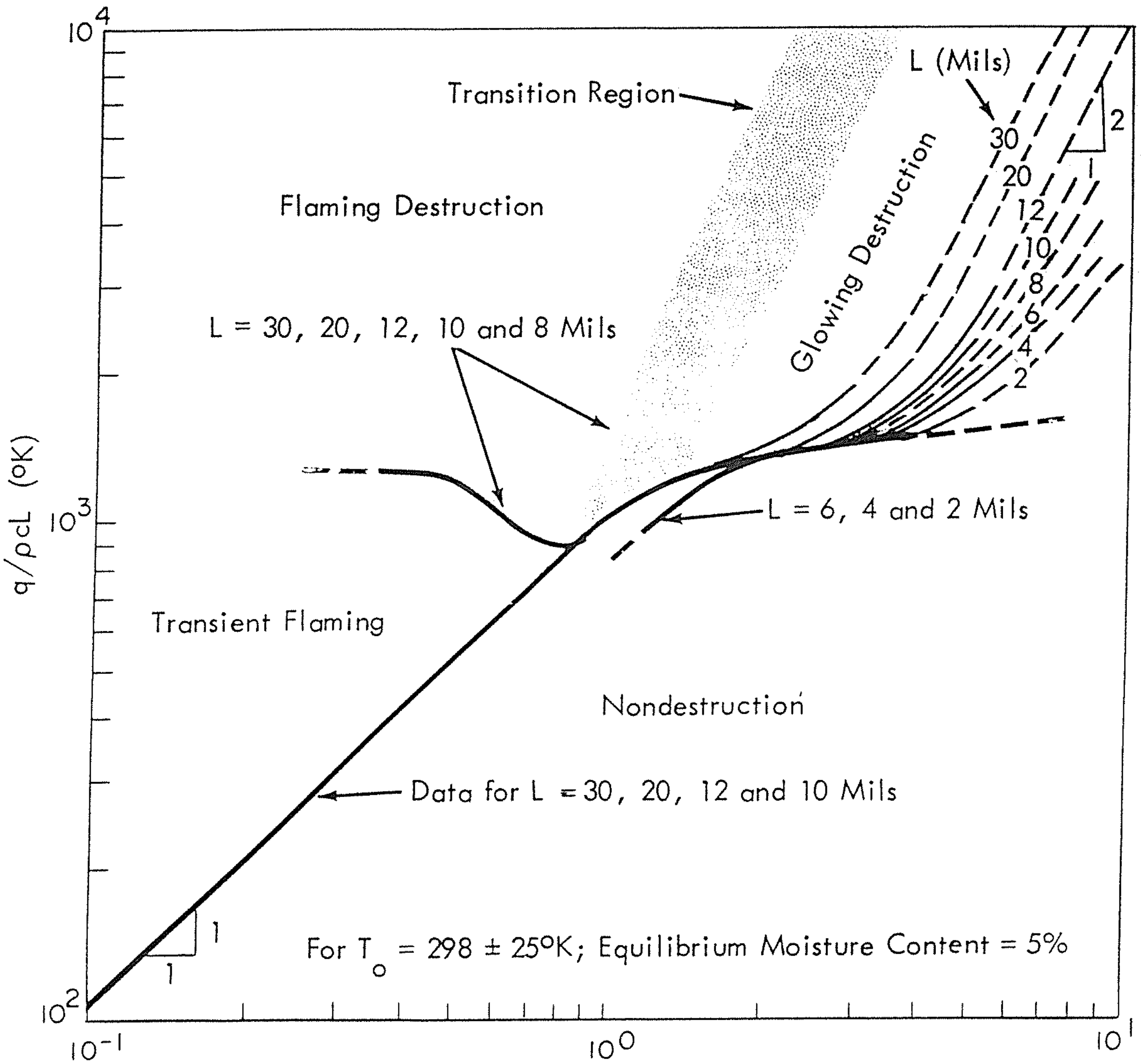
4.2.5 Existing Results on Ignition Conditions

Let us return now to questions of the precise nature, utility, and validity of existing data. Martin's experimental results on blackened α - cellulose for rectangular pulses are summarized in the convenient dimensionless plot shown in Fig. 2. For α - cellulose, approximately, $\rho = 0.6$ gm/cm^3, c = 0.35 cal/gm ^{o}K (dry), and k = 0.0002 cal/cm-sec ^{o}K. Hence, $\alpha = k/(\rho c) = 0.0009$ cm^2/sec. These numbers enable one to obtain dimensional values from Fig. 4.2.

Some of the theories mentioned in Sec. 4.2.3 can be made to fit, through the adjustment of values of one or more unknown parameters, certain boundary lines of regions shown in Fig. 4.2. For example, the theory of Ref. 9 fits the boundary of the flaming destruction region when the square root of the Fourier modulus is greater than 0.4. At smaller values of the Fourier modulus, Ref. 9 predicts that this boundary line will continue to increase to much higher values of the integrated energy flux, a behavior which is in disagreement with the experimental results. In this region, the theoretical results are incorrect; the theory becomes inapplicable because it predicts unreasonably high surface temperatures that would lead to gasification of the surface, a process that is neglected in the theory. (Ref. 12) At our present stage of understanding, we have little choice but to use existing correlations of experimental observations such as those shown in Fig. 4.2 while being careful to restrict application to problems within the limited zones of validity of the correlations. When used with such discretion, results should be as accurate as the experimental data used for establishing parameter values (probably 20 to 30 percent).

4.2.6 The Ignition Problem for Bomb Pulses

For the experimental data to be useful, they must be applicable to the energy pulses delivered by nuclear explosions. Since experiments with square radiant energy pulses do not simulate the flux-time curves of nuclear weapons, in place of our original problem one should ask "what integrated flux is required for ignition



Source: Ref. 5

$\sqrt{\text{Fourier Modulus}^{*}} = \sqrt{\alpha t}/L$

* dimensionless

L = thickness of sample, α = thermal diffusivity,
ρ = density of the solid, c = specific heat,
q = integrated energy flux, t = radiation time

FIGURE 4.2 Regions of Ignition for Blackened Alpha-Cellulose Sheets when the flux-time relationship correspond to that of a nuclear explosion?" Unfortunately, this question establishes a large family of problems because, as indicated in Sec. 2 the flux-time curves of bombs vary considerably with weapon yield and with burst height. One may expect a corresponding variation in the integrated energy required for ignition.

In Ref. 6 Martin has investigated the way in which his curves are modified for flux-time curves corresponding to representative sea-level bursts. He summarizes his results by stating that "No simple square-wave weapon pulse equivalence is found for ignition, but it can be stated that equivalent effects* are observed for weapon pulses having peak irradiance** of about 3 times the irradiance level of the square-wave input; [when these "equivalent" pulses are compared, it is found that] sustained flaming ignition at the higher irradiances*** [requires] up to 40 percent less energy and sustained glowing† [requires] up to 1/3 more energy when delivered in the form of the simulated weapon pulse." These results may be useful in making relatively accurate adaptions of the laboratory results to weapon thermal effects. Martin has remarked that low yield weapons require roughly 1/3 less energy for ignition than do rectangular pulses and that high yield weapons require roughly twice as much energy for ignition than do rectangular pulses.

4.2.7 Ignition Energy Conditions Expressed as Functions of Weapon Yield

For sea-level bursts, characteristic pulse lengths are roughly proportional to the square root of the yield (see Sec. 2.2.1).

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*By this Martin means that the minimum in the "flaming destruction" curve in Fig. 4.2 occurs at the same value of q for each of these pulses and that certain other qualitative characteristics of the curves are the same.

**The irradiance is energy flux (cal/cm^2-sec).

***Here Martin means "at small values of the Fourier modulus" or "for short pulses."

†This occurs at large values of the Fourier modules (i.e., for long pulses).

This observation enables one to replace the pulse length by the yield as the abscissa in Fig. 4.2. It has become standard practice to make this replacement (e.g., Fig. 4.3 or Ref. 8) in presenting data on the critical ignition impulse. Although the practice has some obvious advantages from the viewpoint of applications, it adds all of the uncertainties in the thermal pulse length and shape to the uncertainties in the ignition data. It also tends to imply that the pulse length depends <u>only</u> upon the yield, thereby obscuring the sensitive dependence upon height of burst and any variation with weapon design.

For burst heights up to about 20 miles, curves such as Fig. 4.3 can be rendered applicable, in a rough approximation, by multiplying the yield by the ratio of the atmospheric density at the burst height to the sea-level density (see Sec. 2.3.3). For high altitude bursts, however, the curve is entirely inapplicable.

4.2.8 Relative Ignitability of Various Kindling Materials

It is obviously of interest to relate the detailed results on α-cellulose to ignition conditions for materials commonly found in urban and wild-land environments. Such relations are necessarily imprecise because of the variations in composition of environmental materials. Nevertheless, approximate relationships have been developed. (E.g., Ref. 7). It is found, for example, that the curves for dark newspaper correspond approximately to the curves for 0.5 mil blackened α-cellulose. As reported in Refs. 13 and 14, a variety of common materials, in order of decreasing ignitability, may be listed as follows:

Dust mop, gray cotton
Wool pile chair upholstery, dark color
Newspaper, dark areas
Rotting wood
Heavy cotton draperies, dark color
Beech leaves
Corrugated kraft board; newspaper, medium print;
heavy canvas, olive green

TABLE 5.2

Burning Times of Fuels in Wild-Land Areas

Fuel Type	Violent Burning		Residual Burning		Total Burning Time
	Time (Minutes)	Percent of Total Energy Release	Time (Minutes)	Percent of Total Energy Release	
Grass	1-1/2	>90	1/2	<10	30 minutes
Light Brush (12 tons/acre)	2	60	6	40	16 hours
Medium Brush (25 tons/acre)	6	50	24	50	36 hours
Heavy Brush (40 tons/acre)	10	40	70	60	72 hours
Timber	24	17	157	83	7 days

Source: Ref. 13.

Moisture content of fuel
Humidity
Precipitation
Surface winds
Upper atmospheric winds
Lapse rate of the atmosphere
Other weather factors
Topography
Firebreaks

The fuel type has a strong influence on the rate of spread of small fires. Fuel-loading (the total amount of combustible per unit area) is more important for large fires.

As indicated earlier in Sec. 5.1.4, weather parameters exert a critical influence on the spread of small fires. For large fires, moisture content of fuels, humidity, and precipitation are somewhat less important, and surface winds and upper atmospheric conditions become more highly influential. Strong surface winds increase "flame contact" of unburned materials on the leeward side of the fire, which substantially increase the spread rate. Depending on upper atmospheric conditions, large fires can develop tall convection columns (Ref. 13), sometimes more than 25 kft high. Under these conditions, upper atmospheric winds can transport burning flying brands over large distances (perhaps 5 miles), thereby increasing the average rate of spread.

Topography is of considerable importance in fire spread. All fires burn upward much more rapidly than they burn downward. Fire spread rates roughly double for each 15° increase in upward slope. The decrease in spread rate with increasing downward slope is not so great. More quantitative data on the effect of topography are available in Ref. 13.

A rough composite assessment of the effects of surface wind, humidity, and topography upon fire spread in wild-lands is given in Tables 5.3, 5.4, and 5.5. These tables are self-explanatory.

TABLE 5.3

Burning Potential and Fire Effects

Burning Potential	Type and Rate of Spread	Civil Defense Requirements
Low	Slow-burning fires, no spotting.	No direct danger; fire can be controlled at will; control action can be made on an individual structure basis.
Moderate	Fires burn rapidly, individual building fires combine to form an area fire.	Organized action needed to corral fire and confine to area originally ignited.
Dangerous	Fast-moving fires which spread readily over large areas and throw spot fires ahead 1/4 to 1/2 mile.	Probability of mass damage high. Aggressive, organized action of all available personnel and equipment is essential to limit mass damage.
Critical	Conflagration-type, fast-moving fire fronts and fire storm highly probable.	Personnel and equipment should be evacuated from in front and from near the flanks of such fires. Organized action only on rear and flanks with plans to attack head when changes in fuel or burning conditions permit.

Source: Ref. 27.

Man-made firebreaks (areas in which all combustible material is removed) of reasonable widths are highly effective in preventing spread of small wild-land fires. For large fires with well-developed convection columns, only large natural firebreaks are very effective. A currently popular "barrier theory" of forest fire spread places emphasis on the sizes and locations of firebreaks in predicting the extent of fire spread. This theory has met with some success.

For wild-land fires burning from 6 to 24 hours, the average of the measured spread rates of past fires is 0.16 mph (Refs. 13, 30). Wild-land fires have been known to spread as fast as 1 mph. These numbers are obtained by dividing measured total run distances by observed total run times.

Simplified "no-fire-spread" criteria for various types of urban and wild-land fires have been reported in Ref. 13. These criteria are based upon empirical observations and represent the opinions of professional fire-fighters.

6. MASS FIRES AND THEIR EFFECTS

6.1 The Occurrence of Fire Storms and of Urban and Wild-Land Conflagrations

6.1.1 Definitions

While the term "mass fire" refers to any large fire, the terms "conflagration" and "fire storm" are usually restricted to rather specific types of fires. A conflagration is a large propagating fire; substantial fire spread is the key attribute of a conflagration. Thus, conflagrations are capable of damaging areas much larger than the area of initial ignition. A fire storm, on the other hand, is a large, intense, localized fire, usually with a single well-defined convection column extending high above it. The key element in the definition of a fire storm is the presence of high velocity fire-induced winds; wind velocities greater than 75 mph are required in a representative specific definition. Fire storms do not spread to regions outside the initial area of ignition, but destruction is often complete within the area of ignition.

6.1.2 History

Many mass urban fires have occurred in the past through natural causes. Among the more well-known examples are: the London fire (1666); the Moscow fire (1812), which burned 5 days; the Hamburg fire (1842), which burned 4 days; the Chicago fire (1871); the San Francisco fire (1906), which burned 3 days; and the Tokyo fire (1923). Most of these are probably best classified as conflagrations; for example, the Tokyo fire spread over 12,000 acres (600 acres ≈ 1 sq. mi.) of the central part of the city (Ref. 1). However, some of these fires exhibited occasional high local wind velocities, which are commonly associated with fire storms. For example, in Ref. 2

the description of the Chicago fire cites observations of burning planks lifted by fire whirlwinds (localized vortices with intense circulation) and dropped up to 3/8 mile beyond the fire.

All of these urban conflagrations, however, are small compared with typical wild-land conflagrations. The largest U.S. forest fire was the Pashtigo fire in Wisconsin and Michigan, which burned 5900 sq. mi. in October 1871 (Ref. 3). This fire occurred at the same time as the Chicago fire and claimed more lives than the 250 recorded in Chicago. In August 1910, 5000 sq. mi. burned in a mass conflagration in Idaho and Montana (Ref. 4). As recently as 1950, 3000 sq. mi. burned in Alaska (Ref. 5). Smaller wild-land fires that burn much larger areas than any of the natural urban conflagrations are quite common (e.g., the Stewart Fire, San Juan Capistrano, California, December 1958, about 100 sq. mi.). Although practically all large wild-land fires are best classified as conflagrations, nevertheless, large fire whirlwinds with high circulatory velocities and tall, well-defined convection columns often occur in wild-land fires. (See Refs. 6, 7.) Thus, mass wild-land fires often exhibit many of the characteristics of fire storms.

Mass fires were first created deliberately by man during World War II, principally in the incendiary raids on Germany and Japan (Ref. 8). These fires burned more intensely but for shorter times than the previous natural urban conflagrations. Probably due to the predominant use of combustible building construction materials in Japan, the attacks on Japanese cities often gave rise to large-scale urban conflagrations. Tokyo, Osaka, and Kobe are examples of Japanese cities experiencing large conflagrations. The severest conflagration was in Tokyo (March 1945), where 16 sq. mi. burned and 85,000 lives were lost. These fires were often accompanied by violent atmospheric convection. Fire spread was not so common in German cities, but there were at least four well-documented cases of intense fire storms, viz., in Hamburg (1943), Kassel (1943), Darmstadt (1944), and Dresden (1945). In a number of other cities (e.g., Stuttgart), high-speed fire-induced winds were reported. The most publicized fire storm is that which occurred in Hamburg, where 40,000 lives were lost,* 70,000 of the city's 100,000 trees were blown down, and instances of automobiles and trucks being lifted into the air were reported. However, the most lethal fire ever recorded is probably the Dresden fire storm in which casualty estimates ranged from 100,000 to 300,000, the presently accepted number being about 150,000. A vivid, if somewhat controversial, account of the Dresden fire storm may be found in Ref. 9. It is worth pointing out, however, that even in the center of the fire-storm area in Hamburg, more than 85 percent of the people survived, and in Dresden, using the most pessimistic figures, 80 percent of the population of the inner city survived.** Thus, the worst known mass fires have not produced devastation approaching total annihilation.

By comparison with the mass fires discussed above, the fire effects of the 20-kt atomic explosions at Hiroshima and Nagasaki are not great. In Nagasaki, mainly because of the hilly terrain (reducing the number of ignitions) and the large number of firebreaks (reducing fire spread), less than 2 sq. mi. burned. In Hiroshima, where the flat valley and short separations between buildings favored both ignition and fire spread, only 5 sq. mi. were burned. (These results cannot be related to our thermal ignition criteria because it is not known for certain whether the fires resulted from primary thermal ignitions or secondary blast ignitions.) A mild fire-induced wind of 30 to 40 mph was observed in Hiroshima, and very little fire spread occurred beyond the initially ignited area.

Today's nuclear weapons are capable of igniting much larger areas than those burned in Hiroshima and Nagasaki. Some past natural wild-land conflagrations have burned over areas of the same order of magnitude of 5,000 to 10,000 sq. mi. as those which, according to the most liberal estimates, could be exposed to simultaneous multiple ignitions by an explosion of a 50- to 100-Mt bomb under

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*This is the largest known number of casualties ever caused by a fire before 1945.

**People are known to have died between burning buildings (from radiant heat), in basement "shelters" (from carbon monoxide poisoning and heat), and within the burning buildings themselves. People survived by taking refuge in well-designed shelters or by evacuating the areas of intense fire.

optimum conditions. Therefore, the area of ignition threatened by a nuclear weapon is not large compared to previously observed burned areas. Hence, the principal difference between fires induced by large nuclear bombs and previous large conflagrations is that the ignitions are simultaneous in the former case. This difference will lead to much shorter total burning times for the bomb-induced fires. However, because of wide natural variations in fuel type, thickness, density, etc., the bomb-induced fires will not all develop simultaneously; their behavior should rather resemble that of previous large-scale conflagrations, but with a time scale compressed by as much as an order of magnitude. The degree of destruction within the initial area of ignition, and the extent to which additional large regions will be burned over as a result of propagation will depend upon the factors affecting fire development and spread, discussed in Sec. 5. Thus, no qualitatively new fire phenomena are expected to be produced by large nuclear explosions.

6.1.3 Fire Storms

Since all mass fires are highly nonhomogeneous, it is difficult to decide precisely what constitutes a "fire storm." Originally, the term was intended to denote a fire-induced storm exhibiting all characteristics of a meteorological storm, viz., wind, clouds, and rain. Wind is induced by free convection resulting from the buoyancy force on the hot gases produced in the fire. Gaseous H_2O, a principal product of combustion, often condenses into clouds resembling ordinary cumulus clouds (Ref. 7) as a consequence of being transported upward into cooler air, the temperature of which is below the condensation point of the water. There is no a priori reason why these clouds cannot become sufficiently saturated to produce precipitation, and there have been scattered reports of rain falling in intense forest fires. More recent definitions (Sec. 6.1.1) do not include clouds and precipitation (which are clearly secondary) as requirements.

Many qualitative mechanisms have been proposed as being essential aspects of fire-storm development. A feedback mechanism has been suggested whereby an increased burning rate produces stronger convection columns which give rise to an increased air inflow velocity. This velocity, in turn, tends further to increase the burning rate (Ref. 10). A series of experimental studies on the effect of forced ventilation on laboratory fires has been undertaken in an effort to ascertain the validity of this hypothesis. (See Ref. 10, 11.) Forced air flow into the fuel bed increases the burning rate, but forced air flow into the flame or convection regions has little effect (Ref. 10).

Another hypothesis is that, in order for a fire storm to occur (specifically, in order for very high wind velocities to occur), wind shear (a horizontal velocity gradient perpendicular to the direction of the wind) must be present in the ambient atmosphere (Ref. 12). The velocity gradient necessitates a high speed circulatory motion when the air is drawn into the fire by a convection column. In this view, a fire storm resembles a large fire whirl (Ref. 6). Simple small-scale laboratory demonstrations have shown that, when a fire is enclosed so that air entrainment must occur tangentially instead of radially, the character of the flame is changed dramatically; the flame height has been made to increase from less than 1 ft to as much as 11 ft, the burning rate increases by a factor of 3, and inflow velocities have been observed to increase to 20 mph (Ref. 13). Fire whirls as large as 600 ft in diameter and with velocities up to 125 mph have been observed in forest fires (Ref. 14). It is plausible, therefore, that circulatory winds are responsible for many of the reported instances of high air velocities in urban fire storms. According to Ref. 12, laboratory experiments with fires on rotating tables are being undertaken in an attempt to gain a basic understanding of the influence of wind shear.

From a fluid dynamical viewpoint, it is clear that convection columns play an important role in the entrainment of air into fire storms. Consequently, an understanding of the character of a convection column is essential for an understanding of fire storms;

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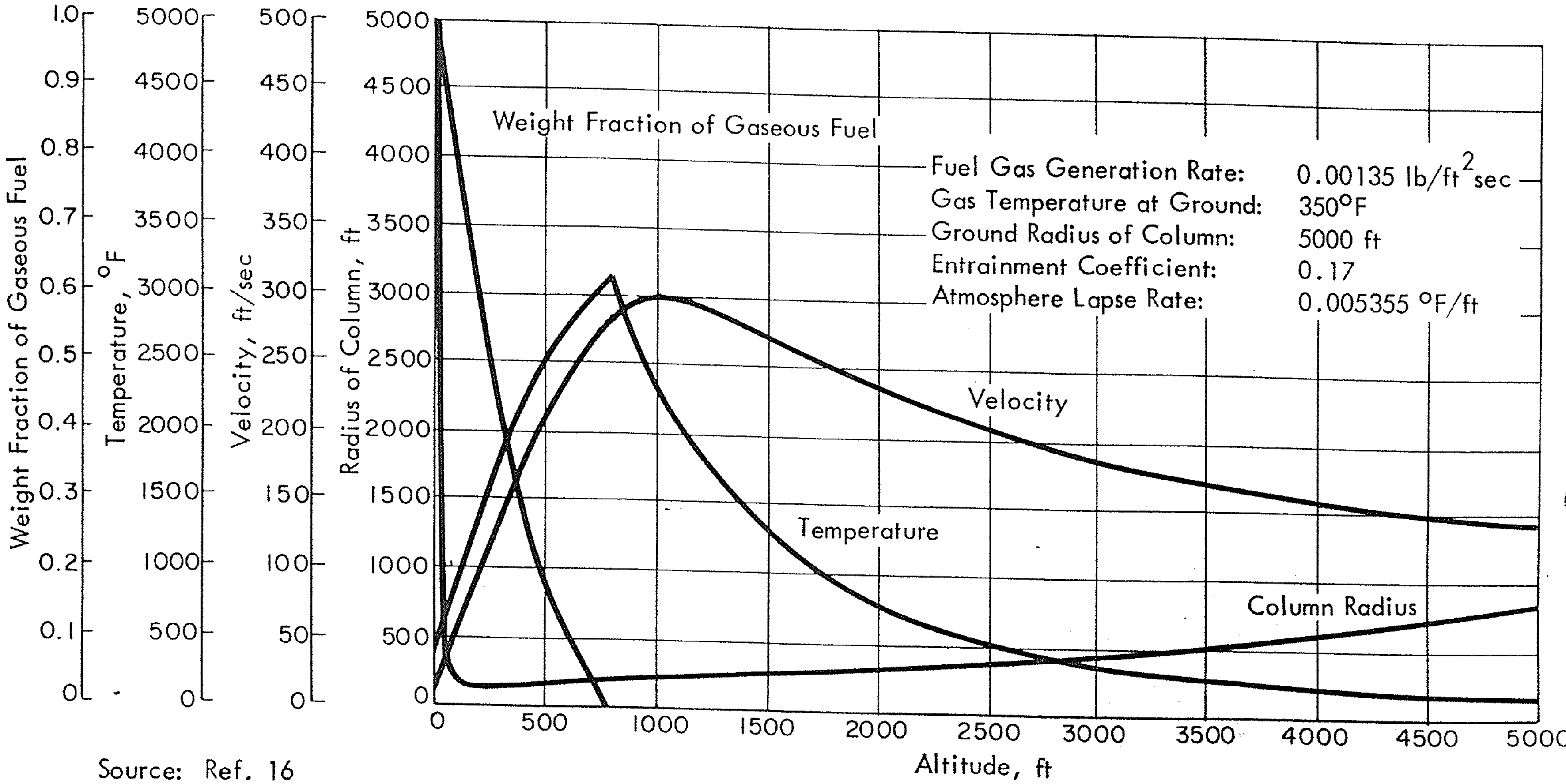

Source: Ref. 16

FIGURE 6.1 Predicted Variation of Conditions Within Convection Column with Altitude (note, for example, that the convection columns are essential elements in each of the mechanisms described above). Thermal convection plumes have been analyzed under various sets of conditions in the past.* Reference 16 deals specifically with the large convection columns above fire storms, including the effects of combustion and composition variations within the column, radiation losses from the hot gases, the lapse rate of the atmosphere, varying fuel supply rates and various base-burning areas. Through a numerical integration, the integral boundary layer method yielded solutions for properties as functions of altitude within the column, such as those shown in Fig. 6.1. Some of the parameters entering the analysis, particularly the entrainment coefficient α for the plume, are known very imprecisely for fire storms and, therefore, the numerical results may not be very accurate. Furthermore, concentration and temperature profiles are known to be given very imprecisely by analyses of this type, and hence the possible implications that flame heights are very large and that oxygen concentrations are reduced to dangerously low levels in the center of a fire storm should not be taken very seriously (Ref. 16). The parameter of greatest interest, the induced horizontal wind velocity near the ground, is not given by this theory because the boundary layer approximation breaks down near the ground. Thus, it is not yet known whether rotational motion is essential for achieving ground winds of hurricane force. An application of the boundary layer approximation in a different manner may provide an answer to this question (Ref. 16).

A uniform fuel source is postulated in fire storm convection column analyses (Ref. 16). However, urban and wild-land areas always burn nonuniformly. The merging of convection columns above individual clumps of fire in order to form a single large convection column above the fire storm, therefore, may be an integral part of fire-storm structure. This merging process has been rather successfully modeled in the laboratory by using many small gas jets. (See

*See Ref. 15 and references quoted in Ref. 16.

Refs. 17, 18.) Certain aspects of fire-storm development and structure are therefore amenable to laboratory modeling analysis. To simultaneously model all essential characteristics of a fire storm, however, would be very difficult or impossible.

The following question is often raised: "Might not a fire storm resulting from simultaneous ignitions over a very large area be much more intense than the fire storms encountered in the past?" The guess of most experts is "no." Most fire experts estimate that, when an area of radius greater than roughly 1/2 mile is aflame, a physical phenomenon occurring within that area will differ negligibly from the same phenomenon occurring within an infinite fire environment. Since fires larger than 1/2 mile in radius have been observed, fire storms resulting from large areas of ignition are expected to be comparable in intensity to previous fire storms. Reasons given for the limitation to roughly 1/2 mile are of the following types:

a. High-speed fire-induced winds have not been observed to extend beyond 1/2 mile outside of the fire, even in the largest known fire storms.*

b. The wind velocity is not observed to increase or decrease uniformly inside a large burning area; instead, conditions are highly nonuniform and, therefore, the maximum distance of influence of collective phenomena within a large fire should probably be comparable with the more accurately observed distance of influence outside the fire (Ref. 14).

c. Some highly simplified theoretical models of fire storms have failed to produce correlation distances greater than 1/2 mile.** (Ref. 19)

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*It might be noted, however, that measurable fire-induced winds (i.e., winds of a few mph) have been recorded as far as 2 mi. from intense fire storms (Ref. 14).

**For example, oxygen depletion does not appear at first glance to be able to produce large interaction distances because all the air needed to burn a typical house is contained in a volume with base area equal to the plan area of the house and with a height of only about 200 ft.

d. Although it is obviously possible to identify characteristic lengths substantially greater than 1/2 mile (e.g., the scale height of the atmosphere), such lengths have not been related rationally to ground-correlation distances for flaming areas.

These preceding arguments are frought with uncertainties but appear to be the best that are currently available.

It should be clear from our discussion that fire-storm phenomena are not well understood. Possibly none of the mechanisms discussed above can explain all characteristics of fire storms. Alternatively, perhaps each of the above mechanisms can account for the principal observed properties of fire storms; for example, in some cases, the high velocity winds that have been experienced may be due to rotation and, in other cases, to strong radially symmetrical convection. There are a host of basic research problems related to fire storms, and a clear conception of what constitutes a fire storm will not emerge until many of these problems are solved. (See Sec. 1.11.)

6.2 Damage Caused by Large-Scale Urban and Wild-Land Fires

6.2.1 Urban Fires

In urban areas, fire damage can be classified as property damage and human casualties. The extent of severe property damage in mass urban fires has been discussed in Sec. 6.1.2. In relation to property damage, it may be worth mentioning that many factories destroyed by fire in World War II were back to nearly full production within a month of the attack (Ref. 8); fire damage to property alone does not necessarily produce long-term incapacitation.

Casualties from mass urban fires in the past have been given in Sec. 6.1.2. Fire alone is not extremely effective in claiming human lives; the majority of the people survive. In this connection, it is of interest to point out the strong evidence that people can survive any mass fire if they take refuge in a shelter beneath 2 or 3 ft of earth, located where no rubble or fire debris will fall on top of the shelter or the air vent. (See Refs. 20, 21.) Reports of shelter casualties have always referred to basement shelters under burning buildings, where the occupants were exposed to high temperatures for > 2 to 3 hours, or shelters with ventilation adjacent to burning or smoldering materials, where the carbon monoxide concentration usually reaches lethal levels. To provide adequate sheltering from mass fires is not difficult.

6.2.2 Wild-Land Fires

Long term effects of fires on wild-land regions have been studied intensively by the U.S. Forest Fire Service, U.S. Department of Agriculture. Often, certain types of fires are highly beneficial to forests; this observation has led to "prescribed burn" procedures in U.S. forest management. Other fires are highly detrimental to wild-lands. It is often difficult to decide whether a given fire has been beneficial in an overall sense, because fires have favorable effects on some properties and unfavorable effects on others. Also, whether or not the effect of a particular type of fire on a given property is favorable depends upon many parameters (e.g., a beneficial fire in flat land may be undesirable in hilly terrain). The intricacies of this problem are much too complex to be discussed here. The voluminous literature will not be cited. Representative of the difficulties encountered in ecological studies, Ref. 22 states: "...it is universally agreed that the replacement of pine and spruce forests in the northern Lake States by aspen is entirely the result of past fires. Whether this is good or bad depends upon whether you want conifers or aspen."

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APPENDIX A

CALCULATION OF HIGH-CONFIDENCE LIMITS ON IGNITION RADII

The results of Sec. 1.7 through 1.9 enable us to calculate the ground radius R inside of which ignitions will occur. In terms of the integrated energy flux q required for ignition, the transmissivity T of the atmosphere and the total energy Q emitted in the thermal pulse of the weapon, the formula determining R is

$$q = TQ/4\pi S^2 , \qquad (1)$$

where

$$S^2 = R^2 + h^2 \qquad (2)$$

is the square of the slant path length from the burst point to the ground, and it is assumed that the thermal radiation from the burst can be considered to emanate from a point. In view of Eq. (1), of Sec. 1, Eq. (1) above can be written as

$$R = (7.95\ T\eta W/q - h^2)^{\frac{1}{2}} , \qquad (3)$$

where the weapon yield W is in kilotons, q is in cal/cm^2 and h and R are in km. When the thermal efficiency η, the atmospheric transmissivity T and the ignition energy q are known, Eq. (3) may be used to compute the ignition radius as a function of the weapon yield and the burst height.*

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*Equation (3) is not really an explicit formula for R because the factor T depends upon R.

We have substituted high-confidence limits for η, T and q into Eq. (3) in order to obtain high-confidence upper and lower bounds for R at specified values of W and h.* Our aim was to specify the parameters η, T and q as accurately as they can be specified in a representative operational situation. Thus, a reasonable number of unsaturated newspapers (or their equivalent) were assumed to be present, so that the limits on q can be taken as 2 and 20 cal/cm^2 for all values of W and h. (See Sec. 1.9.) The limits employed for η were the boundaries of the shaded region in Fig. 1.3. Typical meteorological data (visibilities and type of cloud cover, if any) were assumed to be available for estimating T.

Calculations were performed for only two sets of weather conditions, the average clear day (visibility quoted as 10 miles, no clouds) and medium cloud cover (ground visibility about the same as for the average clear day, sky completely overcast with medium clouds, but no rain). We believe that these two cases characterize representative conditions favorable to ignition and representative conditions unfavorable to ignition, respectively. Clearly, ignition radii will exceed our average clear day values if the visibility is unusually high, and ignition radii may be much less than our medium cloud cover values if the ground visibility is very low and there are dense clouds. Since our principal objective is to ascertain representative orders of magnitude of uncertainty, we have not prepared ignition radii catalogues for the whole realm of possible weather conditions.

For bursts above the atmosphere (specifically, for values of h $\geq$ 10 km), values of T on the average clear day were taken from Fig. 3.2; limits were defined by drawing lines that bound all curves and points shown in the figure. For sea-level bursts on the average clear day, Eq. (2) of Sec. 1 was used for T, with bounds on T_A taken as 0.65 and 0.90 and with representative high-confidence limits on V assumed to be 10 km and 40 km.**

*The validity of this procedure is considered in Appendix B.
**In Eq. (2) of Sec. 1, D = R for sea-level bursts.

associated with cloud cover, cloud transmissivities for medium cloud cover were assumed to be bounded, with high confidence, by the limiting values of 0.4 and 0.2. (See Sec. 1.8.) In the calculations for medium cloud cover, these cloud transmissivity factors* were included in T and the rest of the computation was completed in the same way as for the average clear day, for all R curves except the upper bound, sea-level-burst curve. The upper bound on R for sea-level bursts was taken to be somewhat higher** for medium cloud cover than for the average clear day in order to account for the possibility of reflection of radiant energy from the clouds.

The results of the calculations appear in Figs. 1.1 and 1.2 and are discussed in Sec. 1.4.

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*The increase in the path length through the cloud with decreasing elevation angle leads to a corresponding decrease in the cloud transmissivity which was included.

**The enhancement factor employed in T lay between 2 and 4. The correct factor is strongly dependent upon the geometry, the earth's albedo, etc., and therefore a precise computation was not attempted.

APPENDIX B

THE MEANING OF HIGH-CONFIDENCE LIMITS

We calculated high-confidence limits on the ignition radius R simply by substituting high-confidence limits for the thermal efficiency η, the atmospheric transmissivity T and the minimum integrated energy flux for ignition q into the formula for R. It might be suggested that this gives limits on R that are much wider than reasonable and that one perhaps should use the square root of the sum of the squares of the deviations of η, T and q from their mean values in order to obtain high-confidence limits on R. This last suggestion is <u>not</u> acceptable because the high-confidence limits on the parameters are so wide that appreciable changes in the functions occur between these limits and conventional error analysis is inapplicable. The only acceptable approach for refining our definition of high-confidence limits on R is to express the probability distribution of R in terms of the probability distributions of η, T and q and to calculate, from this expression, the x% confidence limits on R in terms of the given x% confidence limits on η, T and q.

This correct approach encounters two major difficulties. First, it is not clear precisely what numbers constitute x% confidence limits on η, T and q. The numbers employed in our calculation are believed to lie between 90% and 100% confidence limits, but perhaps they are as low as 80% confidence limits; there is no sound basis for establishing exactly what percentage confidence limits we have chosen. Second, and most important, there is no information at all about the functional forms of the probability distributions for η, T and q. For some probability distributions, our method will yield accurate x% limits on R from x% limits on η, T and q (with the same value of x for all parameters). For other distributions, our method can be inaccurate. It is worth emphasizing, however, that if our numbers correspond to the narrowest 100% confidence limits on η, T and q, then our method yields precisely the narrowest 100% confidence limits on R. It was on the basis of this observation that our method was adopted.

In view of the difficulties mentioned above, it is unprofitable to attempt to compute accurate x% confidence limits on R. The formula for computing the probability distribution of R from the probability distributions of η, T and q is given below, for use in case information concerning these last three distributions becomes available. A simpler related problem is also considered in an effort to obtain some conception of the magnitude of the change in the percentage confidence limits that our method of calculation might produce.

If $x_1, \ldots, x_n$ are real random variables and

$$z = f(x_1, \ldots, x_n) \tag{1}$$

is a known function of these variables, then the probability distribution of z is given by

$$P(z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \delta \left[z - f(x_1, \ldots, x_n)\right] P(x_1, \ldots, x_n) \, dx_1 \, dx_2 \ldots dx_n \quad , \qquad (2)$$

where δ is the Dirac delta function and $P(x_1, \ldots, x_n)$ is the joint probability distribution of $x_1, \ldots, x_n$. In our present terminology, "probability distribution" means what statisticians often term "frequency function" or "density function"; i.e., the probability of finding the random variable z in the range dz about z is P(z)dz, and the probability of finding x_1 in the range dx_1 about x_1, x_2 in the range dx_2 about x_2, ..., <u>and</u> x_n in the range dx_n about x_n is $P(x_1, \ldots, x_n) \, dx_1 \, dx_2 \ldots dx_n$. If $x_1, \ldots, x_n$ are statistically independent, then

$$P(x_1, \ldots, x_n) = P_1(x_1) \, P_2(x_2) \ldots P_n(x_n) \quad , \qquad (3)$$

where $P_i(x_i)$ is the probability distribution of x_i $\left[\text{i.e., } P_i(x_i)dx_i \text{ is the probability of finding } x_i \text{ in the range } dx_i \text{ about } x_i\right]$.

Applying Eqs. (1) and (2) to the function R^2+h^2, we find

$$P(R^2+h^2) = \int_0^{\infty}\int_0^{\infty}\int_0^{\infty} \delta(R^2+h^2-7.95T\eta W/q)P(\eta,T,q)\,d\eta\,dT\,dq \quad . \qquad (4)$$

See Appendix A for notation and for the appropriate function $f(x_1, \ldots, x_n)$. If η, T and q are statistically independent, then

$$P(R^2+h^2) = \int_0^{\infty}\int_0^{\infty}\int_0^{\infty} \delta(R^2+h^2-7.95T\eta W/q)P_1(\eta)P_2(T)P_3(q)\,d\eta\,dT\,dq \quad , (5)$$

where P_1, P_2 and P_3 are the distribution function for η, T and q, respectively. The quantities W and h are fixed constants in the above equations; η, T, q and R are the random variables. One integration can readily be performed in Eq. (4) or Eq. (5); we find, for example, from Eq. (5) that

$$P(R^2+h^2) = \int_0^\infty \int_0^\infty (q/7.95TW)P_1\left[(R^2+h^2)q/7.95TW\right] P_2(T)P_3(q)dTdq \ . \quad (6)$$

To proceed any further entails assigning functional forms to P_1, P_2 and P_3. Since no basis for choosing these functions yet exists, we terminate the present development at this point.*

Consider next the related problem in which there are two independent random variables x and y, and

$$z = xy \quad . \tag{7}$$

Here,

$$P(z) = \int_0^\infty \int_0^\infty \delta(z-xy)P_1(x)P_2(y)dxdy = \int_0^\infty (1/y)P_1(z/y)P_2(y)dy \quad , \tag{8}$$

where it is assumed that x and y are non-negative $\left[\text{i.e., } P_1(x) = 0 \text{ for } x < 0 \text{ and } P_2(y) = 0 \text{ for } y < 0\right]$.

First, suppose that x and y have rectangular distributions;

$$P_1(x) = \begin{cases} 0 & , x < \bar{x} - \Delta_1 \\ 1/(2\Delta_1) & , \bar{x} - \Delta_1 < x < \bar{x} + \Delta_1 \\ 0 & , x > \bar{x} + \Delta_1 \end{cases} \tag{9}$$

*It might be remarked that, for example, the x% upper confidence limit on R^2, denoted by R_x^2, is determined from $P(R^2+h^2)$ by the formula

$$\int_0^{R_x^2+h^2} P(R^2+h^2)d(R^2+h^2) = \tfrac{1}{2} + \frac{x}{200}$$

$$P_2(y) = \begin{cases} 0 & , y < \overline{y} - \Delta_2 \\ 1/(2\Delta_2) & , \overline{y} - \Delta_2 < y < \overline{y} + \Delta_2 \\ 0 & , y > \overline{y} + \Delta_2 \end{cases} \tag{10}$$

For brevity of notation, assume further that

$$(\overline{x} + \Delta_1)(\overline{y} - \Delta_2) \le (\overline{x} - \Delta_1)(\overline{y} + \Delta_2) \quad ; \tag{11}$$

[if Eq. (11) is not satisfied, one need only interchange the definitions of x and y and it will be]. Substitution into Eq. (8) and integration yields

$$P(z) = \begin{cases} 0 & , z<(\overline{x}-\Delta_1)(\overline{y}-\Delta_2) \\ \dfrac{1}{4\Delta_1\Delta_2} \ln\left[\dfrac{z}{(\overline{x}-\Delta_1)(\overline{y}-\Delta_2)}\right] & , (\overline{x}-\Delta_1)(\overline{y}-\Delta_2)<z<(\overline{x}+\Delta_1)(\overline{y}-\Delta_2) \\ \dfrac{1}{4\Delta_1\Delta_2} \ln\left(\dfrac{\overline{x}+\Delta_1}{\overline{x}-\Delta_1}\right) & , (\overline{x}+\Delta_1)(\overline{y}-\Delta_2)<z<(\overline{x}-\Delta_1)(\overline{y}+\Delta_2) \\ \dfrac{1}{4\Delta_1\Delta_2} \ln\left[\dfrac{(\overline{x}+\Delta_1)(\overline{y}+\Delta_2)}{z}\right] & , (\overline{x}-\Delta_1)(\overline{y}+\Delta_2)<z<(\overline{x}+\Delta_1)(\overline{y}+\Delta_2) \\ 0 & , z>(\overline{x}+\Delta_1)(\overline{y}+\Delta_2) \end{cases} \quad , \tag{12}$$

whence,

$$\int_0^z P(z)dz = \begin{cases} 0 , & z<(\overline{x}-\Delta_1)(\overline{y}-\Delta_2) \\ \frac{z}{4\Delta_1\Delta_2}\left\{\ln\left[\frac{z}{(\overline{x}-\Delta_1)(\overline{y}-\Delta_2)}\right]-1\right\} + \frac{(\overline{x}-\Delta_1)(\overline{y}-\Delta_2)}{4\Delta_1\Delta_2} , & (\overline{x}-\Delta_1)(\overline{y}-\Delta_2)<z<(\overline{x}+\Delta_1)(\overline{y}-\Delta_2) \\ \frac{1}{4\Delta_1\Delta_2}\left[z\ \ln\left(\frac{\overline{x}+\Delta_1}{\overline{x}-\Delta_1}\right) - 2\Delta_1(\overline{y}-\Delta_2)\right] , & (\overline{x}+\Delta_1)(\overline{y}-\Delta_2)<z<(\overline{x}-\Delta_1)(\overline{y}+\Delta_2) \\ \frac{z}{4\Delta_1\Delta_2}\left\{\ln\left[\frac{(\overline{x}+\Delta_1)(\overline{y}+\Delta_2)}{z}\right]+1\right\} + \frac{4\Delta_1\Delta_2-(\overline{x}+\Delta_1)(\overline{y}+\Delta_2)}{4\Delta_1\Delta_2} , & (\overline{x}-\Delta_1)(\overline{y}+\Delta_2)<z<(\overline{x}+\Delta_1)(\overline{y}+\Delta_2) \\ 1 , & z>(\overline{x}+\Delta_1)(\overline{y}+\Delta_2) \end{cases} \quad . \quad (13)$$

The lower and upper x% confidence limits on z are obtained from Eq. (13) by solving the equations $\int_0^z P(z)dz = \frac{1}{2}-x/200$ and $\int_0^z P(z)dz = \frac{1}{2}+x/200$, respectively, for z. Since in general this involves solving a transcendental equation for z, we shall proceed directly to a numerical example.

Let $\overline{x} = \overline{y} = 1$ and $\Delta_1 = \Delta_2 = 0.8$. Then, from Eq. (13), the x% confidence limits on z are given by

$$\frac{1}{2} \pm \frac{x}{200} = \begin{cases} 0 , & z<.04 \\ \frac{z}{2.56}\left\{\ln\left[\frac{z}{.04}\right]-1\right\} + \frac{.04}{2.56} , & .04<z<.36 \\ \frac{z}{2.56}\left\{\ln\left[\frac{3.24}{z}\right]+1\right\} - \frac{.68}{2.56} , & .36<z<3.24 \\ 1 , & z>3.24 \end{cases} \quad . \quad (14)$$

TABLE B-1

COMPARISON OF EXACT AND APPROXIMATE CONFIDENCE LIMITS ON z = xy, WHEN x AND y HAVE RECTANGULAR PROBABILITY DISTRIBUTIONS WITH LOWER AND UPPER LIMITS OF 0.2 and 1.8

Confidence Percentage x	Exact Lower z	Exact Upper z	Lower x & y	Upper x & y	Approximate Lower z	Approximate Upper z
100	.040	3.24	.20	1.80	.040	3.24
95	.130	2.65	.24	1.76	.058	3.10
90	.175	2.36	.28	1.72	.078	2.96
80	.225	2.01	.36	1.64	.130	2.69
50	.390	1.445	.60	1.40	.360	1.960
20	.650	1.055	.84	1.16	.707	1.346

The lower and upper values of z, corresponding to various chosen values of x, as obtained from Eq. (14), are shown in the second and third columns of Table B-1. Also shown in Table B-1 are the corresponding upper and lower values of x and y, computed from $\frac{1}{2}\pm x/200 = (x-\overline{x}+\Delta_1)/2\Delta_1 = (y-\overline{y}+\Delta_2)/2\Delta_2$ which reduces to $1\pm0.8x/100 = x = y$ in the present example, and the upper and lower values of z computed by substituting these limiting values of x and y directly into Eq. (7). These last values of z, labeled "approximate" in Table B-1. are evidently the values obtained by a procedure analogous to that used in computing high-confidence limits on R. It will be noted from Table B-1 that, although we have chosen an extreme case in which high-confidence limits on both x and y differ by a factor lying between 5 and 10, nevertheless the exact high-confidence upper limits on z differ from the approximate ones by no more than 35%, and the exact high-confidence lower limits on z differ from the approximate ones by no more than a factor of 2.25. It may be remarked that the approximate limits on z obtained with 80% confidence limits on x and y are about the same as the exact 95% confidence limits on z. However, the observation that the exact 95% upper and lower high-confidence limits differ by a factor of 20.4, while the approximate 95% upper and lower high-confidence limits differ by a factor of 53.5, indicates that the factor of ~ 2.6 by which these ratios differ is small compared with the factor of ~ 20 by which the upper and lower high-confidence limits differ. One may thus infer that, for rectangular probability distributions of the original variables, the approximate method for computing high-confidence limits on z does not lead to gross errors in these limits.

Next, suppose that x and y are normally distributed about their mean values $\overline{x}$ and $\overline{y}$ with standard deviations σ_1 and σ_2. Then

$$P_1(x) = \frac{1}{\sqrt{2\pi\sigma_1{}^2}} e^{-\frac{(x - \overline{x})^2}{2\sigma_1{}^2}} \qquad (15)$$

and

$$P_2(y) = \frac{1}{\sqrt{2\pi\sigma_2{}^2}} e^{-\frac{(y - \overline{y})^2}{2\sigma_2{}^2}} \qquad (16)$$

Substitution into Eq. (8) yields

$$P(z) = \frac{1}{2\pi\sigma_1\sigma_2} \int_{-\infty}^{\infty} \frac{1}{y} \exp\left[- \frac{(y - \overline{y})^2}{2\sigma_2{}^2} - \frac{(z/y - \overline{x})^2}{2\sigma_1{}^2}\right] dy \qquad (17)$$

The value of P(z) given by Eq. (17) can be expressed in terms of tabulated functions only for special values of the parameters; [e.g., if $\overline{x} = \overline{y} = 0$ then $P(z) = \frac{1}{\pi\sigma_1\sigma_2} K_o\left(\frac{z}{\sigma_1\sigma_2}\right)$, where K_o denotes the modified Bessel function of the second kind of order zero]. However, the asymptotic expansion of P(z), valid for large values of z, can be obtained in terms of previously tabulated functions from Eq. (17).

This expansion is useful for computing upper high-confidence limits on z. Since we intend to compare the present results with those obtained above with rectangular distributions, we shall write down the asymptotic expansion only for the special case $\bar{x} = \bar{y} \equiv \alpha$ and $\sigma_1 = \sigma_2 \equiv \sigma$, which is analogous to the case $\bar{x} = \bar{y}$ (= 1) and $\Delta_1 = \Delta_2$ (= 0.8) treated above. We obtain

$$P(z) = \frac{1}{2\sigma\sqrt{2\pi z}} e^{-\frac{(z+\alpha^2)}{\sigma^2}} \left\{ e^{-\frac{2\alpha\sqrt{z}}{\sigma^2}} \left[1 - \frac{\alpha}{4\sqrt{z}} + 0\left(\frac{1}{z}\right)\right] + e^{+\frac{2\alpha\sqrt{z}}{\sigma^2}} \left[1 + \frac{\alpha}{4\sqrt{z}} + 0\left(\frac{1}{z}\right)\right] \right\}, \tag{18}$$

where $0(\frac{1}{z})$ denotes terms of order 1/z. When $\alpha > 0$, Eq. (18) becomes

$$P(z) = \frac{1}{2\sigma\sqrt{2\pi z}} \exp\left[-\frac{(\sqrt{z}-\alpha)^2}{\sigma^2}\right]\left[1 + 0\left(\frac{1}{\sqrt{z}}\right)\right], \tag{19}$$

the integral of which is

$$\int_z^\infty P(z)dz = \frac{\sigma}{2\sqrt{2\pi z}} \exp\left[-\frac{(\sqrt{z}-\alpha)^2}{\sigma^2}\right]\left[1 + 0\left(\frac{1}{\sqrt{z}}\right)\right] \tag{20}$$

To obtain the upper X% confidence limit on z [determined by $\int_z^\infty P(z)dz = 1/2 - X/200$] from Eq. (20) requires solving a transcendental equation for z.

Suppose $\alpha = 1$ and $\sigma = 0.3$. A standard deviation of $\sigma = 0.3$ is rather large for a quantity of unit mean that is known to be positive; the value of σ was chosen to provide rough correspondence with the rectangular distribution considered above and with the problem that engendered this study. The resulting upper X% confidence limit on z, calculated from Eq. (20), is shown in the second column of Table B-2. Values of X below 90 are not included in this table because the asymptotic expansion is invalid below $X \approx 83$; it is not very accurate at $X = 90$, where it underestimates the upper confidence limit on z somewhat. Also shown in Table B-2 are the corresponding upper confidence limits on x and y, and the approximate upper confidence limit on z, computed by substituting these values of x and y directly into Eq. (7).

TABLE B-2

COMPARISON OF EXACT AND APPROXIMATE UPPER HIGH-CONFIDENCE LIMITS ON $z = xy$, WHEN x AND y HAVE NORMAL PROBABILITY DISTRIBUTIONS ABOUT MEANS OF UNITY WITH STANDARD DEVIATIONS OF 0.3

Confidence Percentage X	Asymptotic Upper z	Upper x and y	Approximate Upper z
99.9	2.66	1.99	3.95
99	2.06	1.77	3.15
98	1.88	1.70	2.89
95	1.57	1.59	2.52
90	1.15	1.49	2.23

It will be noted that the approximate upper confidence limit differs from the asymptotic upper confidence limit by 50 to 90% in Table B-2.* This discrepancy is more than twice as great as that obtained with the rectangular distribution. Thus, the approximate method of calculating high-confidence limits is not as accurate for a normal distribution as for a rectangular distribution. This is to be expected from the shapes of the two distribution functions. Intuition also dictates that the approximate procedure would be more accurate for a bimodal distribution than for a rectangular distribution.

Thus, in the absence of any information on the probability distributions of η, T and q, it is pointless to attempt to calculate how accurately our approximate method for computing high-confidence limits on R reproduces the same percentage confidence limits on R that were used for η, T and q. On the basis of the preceding analysis, one might guess that the calculated limits on $(R^2 + h^2)$ are too wide typically by a factor of 2, perhaps by a factor of 5 in some cases, but often by a negligible amount. Discrepancies of this order are small compared with the range of uncertainty obtained in Appendix A.

*The approximate upper limit on z obtained with the 90% upper confidence limits on x and y is approximately equal to the asymptotic 99.5% upper confidence limit on z.

APPENDIX C

RECOMMENDED RESEARCH

A selection of pertinent research investigations is given below. They are divided according to the general areas upon which they principally bear, although some of the investigations are relevant to more than one general area. As indicated in the text, it is not possible at the present early stage to state precisely how the results of these studies would combine to improve our ability to predict fire damage from nuclear thermal pulses.

1. Thermal Pulse

1.1 The thermal yield of high-altitude (50 to 400 km) high-yield (above 2 Mt) nuclear weapons should be studied carefully, both theoretically and, if permissible, experimentally. The theoretical study should be carried out by a highly competent team of physicists, who will account as accurately as possible for all pertinent physical phenomena and will use electronic computers when necessary.

The nature of the problem is such that a very careful study by the best theoretical physicists probably can yield results sufficiently reliable to eliminate thermal efficiency as a substantial contributor to our uncertainty in ignition radii. The study would last about three years. Preliminary steps in this direction already may have been taken.

2. Ignition

2.1 Accurate ignition energy data should be obtained for shorter pulse times and for larger irradiated areas than those of the current data. Such measurements are now in progress.

2.2 Measurements of temperatures and of radiant emission should be made to find whether exothermic reactions first begin in the solid, in the gas, or at the solid-gas interface during the radiant ignition process of cellulosic materials. One related study has been reported, but much more work is needed.

2.3 Gas-sampling measurements should be performed to discover what gaseous products are produced in the radiant pyrolysis of cellulose. A number of studies of this type have been reported, but apparent contradictions exist so that the state of affairs is not yet clear. The uncertainties might be cleared up by obtaining time-dependent profiles of the gas composition through analysis of gas samples taken at various positions above and within the cellulose. The results are needed for an understanding of the radiant ignition mechanism.

2.4 Attempts should be made to identify, through theoretical and experimental studies, what chemical constituents act as fuel and oxidizer in the ignition reaction of cellulose ignited by radiation. The results are necessary for an understanding of the ignition process.

2.5 Theoretical analyses of the radiant ignition process should be performed. The analyses should account for the fact that the system is basically non-premixed. Studies along the lines currently being employed in investigations of solid propellant ignition might be applied very fruitfully to radiant cellulose ignition.

2.6 The relative importance of molecular diffusion and of convective motion in radiant ignition processes should be studied theoretically (by estimating the magnitudes of terms in the governing equations) and experimentally (by sampling techniques).

2.7 Further attempts should be made by physical chemists to unravel the reaction kinetic path and to determine the rates of the elementary reaction steps of the ignition of cellulose. Accompanying this study, attemps should be made by combustion theorists to develop useful simplified models of the elementary steps in the ignition process. Such studies might lead to relatively accurate specifications of radiant ignition conditions.

2.8 Gas sampling and temperature measurements (2.2 and 2.3) should be performed at varying moisture contents of the material in an effort to determine the mechanism (physical or chemical) by which moisture contained in the solid affects the radiant ignition process of cellulose.

2.9 An experimental study should be initiated to determine the sorption characteristics of cellulose for various gases (e.g., CO, CO_2, and O_2). The purpose of the investigation would be to (a) ascertain under what conditions and to what extent physical adsorption occurs, and (b) to ascertain under what conditions and by what mechanism chemisorption occurs. This is basic input data needed in developing an understanding of the ignition and combustion mechanisms of cellulose, e.g., to interpret rationally the results of study 2.3.

2.10 Basic research should be conducted to determine such properties as explosion limits and flammability limits for mixtures of air and cellulose decomposition products. The results would have direct bearing on ignition conditions for cellulose. A modification of this experiment, employing various simulation techniques, could be used to provide information on the problem listed in study 3.8.

2.11 A definitive survey should be made of the distribution of potential ignition materials in the real environment and of the extent to which they are exposed to potential muclear detonations. Only very small statistical samples of needed data of this type are available.

3. Fire Spread

3.1 A group of official forest-fire observers, should be appointed who would be responsible for seeing that forest fire records are obtained in a complete, logical, impersonal, and scientifically intelligible form. Educational requirements for a responsible position in the group would be a Bachelor's degree in science or engineering. The group would be charged with compiling records of fuel type, fuel-loading, terrain, natural and man-made fire-break locations, detailed weather conditions (pre-fire, during fire and post-fire), linear fire propagation rates, fire-control activities and their effects, qualitative characteristics of the fire, extent of damage, long-term consequences of the fire, etc. In some cases, records currently compiled by the Forest Fire

Service would be sufficient. But in most cases, these records would have to be modified or supplemented for scientific clarity.

At least for the large fires, this task would require an observer to be on the scene at the fire-control headquarters. The observer would not be permitted to take part in or interfere with any fire-fighting activities. He would listen to or read the usual fire-fighting progress reports and, after the fire, inquire about any logical inconsistencies or omissions from the persons involved. He would supplement the field data on fire spread rates for large fires by employing infrared photographic records of fire spread taken from airborne vehicles above the fire by supporting personnel. If necessary, he would carry out some post-fire field measurements himself. The principal aim of his report should be scientific comprehensibility; if certain relevant or essential data are unobtainable, this should be noted as in typical scientific reports.

The observer's reports should be filed in a central office and should be indexed according to size of fire, weather conditions, fuel type, terrain, etc. The existence of the file should be made known to the scientific community by all possible means. The reports would be of special interest to the research establishments of the Forest Fire Service, U. S. Department of Agriculture. The reports would be of great value in establishing the multi-dimensioned functional dependences of fire-spread rates, no-fire-spread conditions, and the extent of fire damage upon the many parameters influencing fire behavior.

3.2 Make a detailed review of existing raw data on wildland fire spread with the following objective: to discover the effect of each individual parameter upon the rate of spread, when all other parameters are fixed. Thus, values of all of the parameters listed in Sec. 5.3.2 should be tabulated, and cases in which all values except one are practically the same should be selected. The variation of the spread rate with variations in the single remaining parameter should then be noted. This should be done for as many different fixed combinations of the other parameters as possible. The process should then be repeated for each of the other parameters. In this manner, the spread rate can be expressed as a multidimensional function of the governing parameters, and the relative importance of the various parameters can be assessed. This may enable one to identify a few key parameters governing wild-land fire spread and to develop analytical methods for predicting spread rates. Studies similar to this have been made previously, but they are not quite as systematic as the suggested investigation.

3.3 The method described in 3.2 should be used to investigate the effects of the parameters listed in Sec. 5.2.2 upon no-spread criteria for urban fires. From the scatter in the results, an attempt should be made to discover what parameters not listed in Sec. 5.2.2 can significantly influence urban fire spread. Very few careful studies of this type have been made for urban fire spread.

3.4 Analytical studies should be undertaken to determine the influence of convective heat transfer and of convection of sparks, firebrands, etc. upon urban fire spread. Fire spread by radiation in urban areas is relatively well understood today; a comparable theoretical understanding of convective heat transfer may enable one to calculate analytically with confidence the conditions under which fire spread will occur in urban areas.

3.5 The results of studies (3.3) and (3.4) should be compared to see how accurately theoretical calculations can be made to agree with real-world observations.

3.6 The effect of a flow of air on the rate of glow-burning of small wooden fuel elements should be measured. The experimental measurements would consist of determining the glow-burning rate as a function of airflow rate and of determining whether a critical velocity exists above which glow-burning will cease. The results would bear on conditions under which glowing ignition may give rise to small fires.

3.7 A program should be conducted to obtain the effect of a flow of air on the flame-burning rate of single, small wooden cylinders.

The program could be carried out very conveniently in the test section of a low-speed wind tunnel. In such a facility the air speed could be controlled easily. The end-burning rate should be measured for various air speeds and for various orientations of the cylinder with respect to the airstream. The results would have many implications regarding fire spread.

3.8 Experimental measurements should be made of the critical speed of an airstream necessary to blow out an end-burning flame in a small wooden cylinder. The experiments could be conducted in a suitable low-speed wind-tunnel facility. The cylinder would be ignited at one end, and the air speed increased until a speed is reached at which the flame is blown out. In this way, the "blowout speed" could be obtained for various orientations of the cylinder with respect to the air and for various cylinder diameters. Data of this type appear to be lacking and would have a number of implications regarding fire spread by flying brands, combustion in fire-storm areas, etc.

3.9 A program should be conducted to ascertain the conditions under which a small flaming sphere of wood, suddenly placed on a large horizontal flat wooden sheet of finite thickness, will create a propagating flame in the large sheet. A series of experiments could be conducted by varying the sphere size and by varying the thickness of the large wooden sheet. Another series of experiments could be conducted by using glow-burning spheres instead of flaming spheres. The implications of the study regarding fire spread by convection of burning materials are obvious.

3.10 Wind-tunnel measurements should be made of the drag force on burning wooden cylinders and spheres, and the results should be compared to the drag force on non-burning cylinders and spheres. This would provide one first step toward understanding the mechanism of convective transport of burning materials.

3.11 A theoretical and experimental study should be undertaken to determine the stable equilibrium position taken by an asymmetrically burning (i.e., burning on one end) wooden cylindrical body in a steady low-speed flow of air. The experimental study may be conducted in a wind tunnel by measuring the torque on the body for various orientations of the body with respect to the flow of air. This bears on the problem mentioned in (3.9).

3.12 An experiment should be conducted to measure the critical spacing necessary for the spread of fire from one vertical wooden cylinder to an identical vertical wooden cylinder. One of the cylinders would be ignited at its base, and the critical separation distance above which the fire will not spread could be determined for various lengths and for various diameters of the cylinders. This fire-spread experiment could be analyzed to ascertain whether radiative or convective heat transfer is dominant, and by making measurements on cylinders of different sizes, scaling laws might be inferred. Thermocouple temperature measurements and Schlieren photographs should be made in an effort to facilitate the theoretical interpretation.

3.13 An experiment should be conducted to measure how the critical spacing (necessary for the spread of fire from one vertical wooden cylinder to an identical vertical wooden cylinder) depends on a horizontal flow of air over the vertical cylinders. Keeping the cylinders in a vertical position, experiments could be conducted for various orientations of the two cylinders with respect to the direction of airflow. Fire-spread implications are again obvious.

3.14 A program should be conducted to obtain the flame spread <u>rate</u> in a linear array of identical vertical wooden cylinders as a function of size and spacing of the cylinders in the array. The dependence of the flame spread rate upon the speed and direction of a horizontal flow of air should also be measured in a suitable wind tunnel.

3.15 Studies 3.7, 3.8, 3.10, 3.11, 3.12, 3.13, and 3.14 should be carried out for fuel elements of different shapes (e.g., sheets) and for fuel elements oriented in different directions with respect to gravity (e.g., horizontal cylinders).

3.16 The effect of atmospheric humidity on the results of studies 3.6, 3.12, and 3.13 should be ascertained.

4. Fire Storms

4.1 The possibility of partial modeling of fire storms should be investigated theoretically. Complete scaling is known to be impossible, but it may be possible to keep the most important dimensionless groups invariant and thereby obtain a reasonably accurate model. The ability to construct a reasonably valid experimental model of a fire storm would be invaluable in enabling us to investigate its controlling mechanisms.

4.2 A theoretical and experimental study should be made (e.g., with hot-wire measurements) of the statistical structure of turbulence in buoyant plumes, measuring eddy sizes, correlation functions in various directions, the energy spectrum, etc. This data is essential if the structure of the convection column above a fire storm is to be understood. Reliable data of this type require a great deal of time and patience to acquire.

4.3 A theoretical analysis should be made of the influences of varying the atmospheric-lapse rate and of introducing small amounts of circulation into the atmosphere upon the structure of buoyant turbulent plumes. Such an investigation might uncover critical atmospheric conditions required for the development of fire storms.

4.4 The observed behavior of laboratory fire whirls should be explained by means of a theoretical analysis.

APPENDIX D

MEETING PROGRAM
NUCLEAR WEAPONS AND LARGE-SCALE FIRES
INSTITUTE FOR DEFENSE ANALYSES

October 31 - November 1, 1963

THE THERMAL PULSE

Porzel, Mr. F.B.
IDA/RESD

"The Thermal Pulse as a Function of Nuclear Weapon Yield and Altitude"

Rand, Dr. S.
IDA/RESD

"Reradiation from Air Heated by a High-Altitude Burst (> 40 <180 km)"

Tucker, Dr. Ben L.
IDA/RESD

"Further Comments on the Thermal Pulse"

Gauvin, Mr. Hervey and Cahill, Mr. John
Air Force Cambridge Research Laboratory

"Thermal Pulses at High Altitude" (above 100 kft)

Passell, Dr. Thomas O.
Stanford Research Institute

"Radiative Energy Transfer from Nuclear Detonations above 50 km Altitude"

ATMOSPHERIC TRANSMISSION

Gibbons, Dr. M.G.
Naval Radiological Defense Laboratory

"Atmospheric Transmission of Thermal Radiation from Nuclear Weapons"

Gauvin, Mr. Hervey and Cahill, Mr. John
Air Force Cambridge Research Laboratory

"Pulse Transmission Under Various Atmospheric Conditions"

Dutton, Lt. John
Climatic Center, USAF

"Probability of Occurence of Ground Patterns of Thermal Radiation from High-Altitude Nuclear Weapon Detonations"

Rogers, Mr. Jack C.
Stanford Research Institute

"Ignition of Material by Large-Yield Nuclear Weapons for Various Burst Heights and Atmospheric Conditions"

Altman, Dr. Harry
U.S. Weather Bureau

"Weather Forecasts and Large-Scale Fires"

Willoughby, Dr. A.B.
United Research Services

"Ignition Countermeasures" (Smoke screens)

IGNITION

Scorgie, Mr. G.C., Head
Mathematics/Physics Group
Atomic Weapons Research Establishment
Aldermaston, Berkshire, England

"Phenomonology of High-Altitude Bursts"

"Target Response, i.e., Ignition and Fire Spread"

Martin, Dr. S.B.
Naval Radiological Defense Laboratory

"Time Dependence of Ignition of Materials (720 ms)"

Hochstim, Dr. A.
IDA/RESD

"Ignition Conditions Required for Very Short Time Scales (10 to 100 ms)"

FIRE PROPAGATION

Lansberg, Dr. Helmut
U.S. Weather Bureau

"Climatological Factors Conducive to Conflagrations"

Hill, Dr. J.
Rand Corporation

"History and Observations on Large-Scale Rural and Urban Fires"

Broido, Dr. A.
U.S. Department of Agriculture, Forest Service

"Qualitative Observations on Fire Storms" (Definitions, conditions under which they occur, minimum size, etc.)

Willoughby, Dr. A.B.
United Research Services

"Fire Models as They Pertain to Prevention of Fire Spread"

Nielsen, Dr. Hugo J.
Illinois Institute of Technology

"A Computer Model for the Analysis of the Convective Column of Fire Storms"

Salzberg, Dr. Fred and Waterman, Dr. Tom
Illinois Institute of Technology

"Computer Model for Fire Spread in Urban Areas"

"Prevention of Mass Fires"

Chandler, Dr. Craig
U.S. Forest Service

"Large Scale Forest Fires" (Effects of geography, material composition, weather, etc., on fire-fighting methods)

Lotz, Chief Eric A.
Director of the Bureau of Personnel, Training, and Civil Defense
Los Angeles 12, California

"Some Experiences with Large-Scale Urban and Suburban Fires"

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RESEARCH PAPER P-47

Nuclear TP

EFFECTS OF FIRES FROM THE NUCLEAR THERMAL WEAPON (U)

F. A. Albini

S. Rand

March 1964

INSTITUTE FOR DEFENSE ANALYSES
RESEARCH AND ENGINEERING SUPPORT DIVISION

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INSTITUTE FOR DEFENSE ANALYSES
RESEARCH AND ENGINEERING SUPPORT DIVISION

Contract SD-50
Task 28

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Acknowledgment

The authors acknowledge with appreciation the generous consultations of Dr. F. A. Williams and District Fire Chief Henry C. Galotta. The book "Fire and the Air War," edited by Horatio Bond, Chief Engineer of National Fire Protection Association, provided valuable background information and statistics quoted herein. Constructive criticism by and suggestions from Dr. B. L. Tucker, Dr. D. B. Olfe, and Mr. L. M. Biberman contributed substantially to the final form of the manuscript.

CONTENTS

FIGURES

TABLES

I. Introduction

Recently a considerable interest has developed in the effects of very large yield nuclear weapons detonated at high altitudes, that is, above typical interception altitudes for currently conceived anti-missile systems. Under these conditions, the blast effects are negligible compared to the more serious effects of thermal reradiation from the bomb-heated air. Basic to future defense planning is the question of whether the thermal weapon, detonated beyond the range of projected interceptors, can be made significantly more destructive than the blast from a weapon of the same yield, exploded near sea level, but also beyond the range of interceptors which are designed to protect a given area.

The thermal weapon produces a heat pulse, which is expected to ignite combustible materials, and thereby eventually cause wide-spread fires over a given area. In estimating the damage caused by the weapon, many factors must be considered. These include:

1. The efficiency of the weapon, that is, the fraction of the total bomb yield which is reradiated by heated air.

2. The transmission factor through the atmosphere, that is, the fraction of the reradiated energy which can penetrate the atmosphere and reach the ground.

3. The pulse required to ignite typical combustible materials.

4. The probability of many small fires developing into a conflagration or fire storm, and the overall destructiveness to life and property which would result.

The uncertainties associated with the first three factors have been considered previously. It has been found that, for a 100 MT bomb detonated at an altitude of 50 km, current estimates place limits on the efficiency of 15% and 60%. This energy is radiated primarily in the visible part of the spectrum. The atmospheric transmission factor is probably best known, although it depends critically on weather conditions. For a clear day, estimates range between 50% and 90% transmission. Average cloudiness causes a reduction in the transmission by about a factor of 4, although thick storm clouds may reduce the transmission by up to a factor of 50. The pulse required for ignition is quite uncertain. In accordance with current knowledge, it may be asserted that a pulse of 20 cal/cm^2, delivered in a reasonably short time, like less than a few seconds, will cause virtually all paper and dry leaves or sticks to burn. We further expect that typical cloth products, such as curtains and clothing, will also burn when irradiated by a pulse of this magnitude. A lower limit on the pulse required for the burning of paper and leaves has been set at 2 cal/cm^2. Thus we observe that the critical ignition pulse is uncertain by up to a factor of 10.

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The fact that fires will occur throughout a large city may be ascertained from geometrical considerations. A bomb at 50 km, which delivers a pulse of 100 cal/cm^2 at ground zero, will produce about 60 cal/cm^2 at the edge of a city which is 30 km in radius. There is little doubt that a pulse in excess of 20 cal/cm^2 will result in a serious fire hazard.

Extensive damage may arise both from fires caused by irradiation from the initial pulse, and by the spread of fire from one locale to another. A pulse ranging from 60 to 100 cal/cm^2 will cause the burning of paper, leaves, clothing, upholstery, and window curtains, as well as some wooden furniture. We therefore expect that many suburban houses, as well as residences in the outlying areas of the city, will be set aflame by the initial pulse. This is because these buildings are likely to be made of combustible materials, or have ignitable roofs. Furthermore, residential windows are often decorated with curtains or wooden venetian blinds, and, if the bomb is detonated over the center of the city, the pulse will be transmitted through windows in the outlying parts of the city with very little attenuation. Because of the large number of fires, professional fire fighting activity will probably be ineffectual. We expect therefore that if a single house on a residential block can be caused to burn intensely, then the entire block will probably burn. Although the relatively wide streets associated with one and two story houses provide effective fire breaks, it would appear that

CONTENTS

FIGURES

TABLES

Light (i.e., radiant heat) scattered by the atmosphere, particularly if there is haze, can penetrate windows vitually unattenuated and can approach the same intensity as the direct illumination. On a clear day, with visibility of 10 miles, we estimate that 2% of the direct radiation will be scattered into a vertical window by the atmosphere, while industrial haze (visibility 2 miles) could yield 10% scattered radiation. Overcast sky or light fog introduces attenuation as well as scattering and vastly complicates the problem.

Reflected light from rooftops, streets, foliage, etc., may contribute significantly to the heat pulse passing through a window, or may be entirely negligible, depending upon the detailed geometry of the city and the window in question. Although the "diffuse" light (heat) thus entering a vertical window is much less effective than the direct radiation, there can be no question that it will start a number of fires in the illuminated rooms. Sky-lighted rooms are, of course, expected instantly to be aflame. Subsequent analysis of the firespread will reveal that until the number of fires initiated instantaneously exceeds 10% of the buildings, the final damage level is relatively insensitive to this quantity.

If the bomb is detonated "off-center," with respect to the downtown area, the damage should usually be more extensive. We will, for the present, assume that the burst is directly over the center of the city.

3. The pulse required to ignite typical combustible materials.

4. The probability of many small fires developing into a conflagration or fire storm, and the overall destructiveness to life and property which would result.

The uncertainties associated with the first three factors have been considered previously. It has been found that, for a 100 MT bomb detonated at an altitude of 50 km, current estimates place limits on the efficiency of 15% and 60%. This energy is radiated primarily in the visible part of the spectrum. The atmospheric transmission factor is probably best known, although it depends critically on weather conditions. For a clear day, estimates range between 50% and 90% transmission. Average cloudiness causes a reduction in the transmission by about a factor of 4, although thick storm clouds may reduce the transmission by up to a factor of 50. The pulse required for ignition is quite uncertain. In accordance with current knowledge, it may be asserted that a pulse of 20 cal/cm^2, delivered in a reasonably short time, like less than a few seconds, will cause virtually all paper and dry leaves or sticks to burn. We further expect that typical cloth products, such as curtains and clothing, will also burn when irradiated by a pulse of this magnitude. A lower limit on the pulse required for the burning of paper and leaves has been set at 2 cal/cm^2. Thus we observe that the critical ignition pulse is uncertain by up to a factor of 10.

When a beam of light is incident on glass at a grazing angle, the fraction of the power transmitted across a single surface is given, as a power expansion, by

$$t = \frac{2(n^2+1)}{(n^2-1)^{\frac{1}{2}}}\,\epsilon - \frac{4(n^4+1)}{n^2-1}\,\epsilon^2, \qquad (1)$$

where ϵ is the grazing angle, assumed to be much less than unity, and n is the index of refraction for glass in the visible part of the spectrum. For commercial glass ($1.5<n<1.9$), Eq. (1) may be written, to within a few percent,

$$t = 5.7\epsilon - 20\epsilon^2 \qquad (2)$$

Taking account of multiple reflections within a pane of glass, the total transmission of an incoherent beam is given by

$$T = \frac{t}{2}\left[1-(1-t)^{2N}\right], \qquad (3)$$

where t is given by Eq. (1), and N is the number of internal reflections. The value of N can be shown to be

$$N = (n^2-1)^{\frac{1}{2}}\,\frac{y}{2d}, \qquad (4)$$

where y is the vertical distance traversed by the ray in the glass of thickness d, and again, n is the index of refraction. By combining Eqs. (1), (3), and (4), we have the limiting values

$$\begin{aligned} T &= \frac{2(n^2+1)^2}{(n^2-1)^{\frac{1}{2}}}\,\frac{y}{d}\,\epsilon^2, && 2(n^2+1)\,\frac{y}{d}\,\epsilon \ll 1 \\ &= \frac{n^2+1}{(n^2-1)^{\frac{1}{2}}}\,\epsilon, && 2(n^2+1)\,\frac{y}{d}\,\epsilon \gg 1 \end{aligned} \qquad (5)$$

Eq.(5) gives the fraction of the incident pulse which will be transmitted through closed windows, in order to produce internal ignitions.

The fact that fires will occur throughout a large city may be ascertained from geometrical considerations. A bomb at 50 km, which delivers a pulse of 100 cal/cm^2 at ground zero, will produce about 60 cal/cm^2 at the edge of a city which is 30 km in radius. There is little doubt that a pulse in excess of 20 cal/cm^2 will result in a serious fire hazard.

Extensive damage may arise both from fires caused by irradiation from the initial pulse, and by the spread of fire from one locale to another. A pulse ranging from 60 to 100 cal/cm^2 will cause the burning of paper, leaves, clothing, upholstery, and window curtains, as well as some wooden furniture. We therefore expect that many suburban houses, as well as residences in the outlying areas of the city, will be set aflame by the initial pulse. This is because these buildings are likely to be made of combustible materials, or have ignitable roofs. Furthermore, residential windows are often decorated with curtains or wooden venetian blinds, and, if the bomb is detonated over the center of the city, the pulse will be transmitted through windows in the outlying parts of the city with very little attenuation. Because of the large number of fires, professional fire fighting activity will probably be ineffectual. We expect therefore that if a single house on a residential block can be caused to burn intensely, then the entire block will probably burn. Although the relatively wide streets associated with one and two story houses provide effective fire breaks, it would appear that

A "locale" might be either a building or a city block considered as a unit. In the following treatment we shall consider the spread of fire from one locale to another in a statistical way and relate the results to specific locales by inserting appropriate values for the parameters which characterize the process.

First let us choose a unit of time, and consider the process to be proceeding stepwise. For example, a large, modern structure should burn vigorously, if unchecked, for an average of 1-2 hours, while it might take 5-6 hours for a block to burn out. Considering the locales categorically, though, it is only necessary here to pick a symbolic, average time, say t_o, during which one locale is considered to burn. During this time, there is a certain a priori probability that the fire would be spread from one locale to another, presuming that the latter had not previously been burnt, and that the two locales in question are isolated from all others. Call this probability q. As the locales are not in fact isolated, it is useful to introduce another parameter, N, defined as the average number of locales to which fire might be spread from any given locale.

We assume that throughout the city there is initially a spatially-uniform random distribution of fires (this restriction will be relaxed later). Let the a priori probability that a locale, selected at random from the city, is on fire during the time t (where $nt_o<t<(n+1)t$) be denoted by P_n. Generally P_n must be a function also of the position of the locale with respect to ground zero; this spatial dependence will be considered at the end of this section.

With that assumption therefore we expect that residential areas will be completely destroyed, and the central area of the city may or may not be largely destroyed, depending upon the degree of fire spread. The final degree of destruction to which the downtown area is subjected, after all fires have burned themselves out or been extinguished by firemen, is expected to depend upon three effects: the initial extent of small fires directly after the burst, the mechanism and probability of fire spread from one locale to another, and the extent of fire fighting activity. It will be shown presently that, under the conditions envisaged, fire fighting activity will rarely have any significant effect on the final extent of the damage. The final result is also, within rather broad limits, nearly independent of the initial number of fires. For example, let us assume that within a few hours after the attack, some fraction P_o of the city blocks in the downtown area are burning intensely. In view of the discussion concerning the invulnerability of downtown buildings, we expect P_o to be small, probably less than 0.1, and yet greater than a number like 0.001. It will be shown that for P_o within these rough limits, the fraction of downtown blocks, which are eventually burnt out, is fairly independent of P_o, and depends almost entirely on the probability of fire spread.

The initial density of fires is expected to be relatively low out to some radius R from the center of the city, and sufficiently high to render nearly complete destruction beyond the radius R, and well into the suburbs. We now estimate the "cut-off" radius R.

Furthermore, it follows from the definition of q and $\gamma(m)$, that

$$\gamma(m) = 1 - (1-q)^m \tag{12}$$

By substituting Eqs. (11) and (12) into (10), and performing the summation, we find

$$B_n(Nq,N) = 1 - (1-qP_n)^N, \tag{13}$$

where we have written B_n as a function of the two parameters Nq and N. The parameters are chosen in this manner because, as will be shown, the solution depends rather weakly on the parameter N, so long as the product Nq is held fixed. For example, we have from Eq. (13),

$$\begin{aligned} B_n(Nq,1) &= NqP_n \\ B_n(Nq,\infty) &= 1 - e^{-NqP_n}, \end{aligned} \tag{14}$$

so that, for any given situation, we have the limits

$$1 - e^{-NqP_n} < B_n < NqP_n \tag{15}$$

which depend only on the product Nq. In fact, it follows from (15) that

$$B_n \approx NqP_n, \qquad \text{for} \quad NqP_n \ll 1 \tag{16}$$

In general, a combination of Eqs. (9) and (13) with (8) will yield the equation for P_n as a function of n. The solution depends on the parameters Nq and N, as well as on the initial conditions (initial distribution of fires). However, limits can be placed on the solution, by using each of expressions (14) in place of (13). The limits for P_n, obtained by using Eqs. (14), depend only on the single parameter Nq. It will be shown that in almost all cases of interest, the limiting values for P_n are not very different, so that the solutions are virtually independent of N, so long as Nq is fixed.

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It is interesting to note that as $P_o \to 0$, the quantity $1-A_\infty$ approaches a nonvanishing value. To show what the limiting value is, we look for an analytic solution under the condition

$$P_o << 1 \tag{17}$$

Such a solution is possible with the added condition

$$Nq - 1 << 1 \tag{18}$$

These two conditions allow us to make three mathematical approximations. It will be shown, when the solution is obtained, that

1. Conditions (17) and (18) allow us to set $NqP_n << 1$, so that B_n may be approximated by NqP_n, as given by Eq. (16).

2. $\sum_{m=0}^{\infty} P_m << 1$, so that A_n, as given by Eq. (9), may be approximated by

$$A_n \simeq 1 - \sum_{m=0}^{n} P_m .$$

Then Eq. (8) becomes

$$P_{n+1} = \left(1 - \sum_{m=0}^{n} P_m\right) NqP_n \tag{19}$$

3. Finally, it will be shown that conditions (17) and (18) permit us to treat n as a continuous variable, so that Eq. (19) may be written as an integro-differential equation. Setting $P_{n+1} \approx P(n) + \frac{\partial P}{\partial n}$, Eq. (19) may be written

$$P + \frac{\partial P}{\partial n} = \left(1 - \int_o^n P(m)dm\right) NqP \tag{20}$$

It is clear from the form of Eq. (20), that if $Nq<1$, then $P(n)$ is an exponentially decaying function. We will therefore limit our studies to $Nq>1$.

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Analysis indicates that this quantity is small compared to unity if

$$\alpha^2 \equiv (Nq-1)^2 + 2NqP_o << 1,$$

which again retrieves conditions (17) and (18).

Eq. (23) is the solution we seek. As $P_o \to 0$, we find that

$$1 - A(\infty) \to \frac{2(Nq-1)}{Nq}, \qquad Nq-1<<1. \qquad (26)$$

A few comments are in order. There is an apparent discontinuity in the solution (26), since it is clear that if P_o vanishes identically, then we must have $1-A(\infty) = 0$ (there is no fire), but if P_o is extremely small, we arrive at the nonvanishing result (26). We conclude that as $P_o \to 0$, the time required to attain the solution (26) becomes infinite.

Since the quantity $1-A_\infty$ is relatively insensitive to variations in P_o, as indicated by Fig. 2, the more important parameter is Nq. In Fig. 3, we have plotted $1-A_\infty$ as a function of Nq for various values of the parameter P_o. Again the relative unimportance of P_o is apparent. However, for very small values of P_o, it is necessary to include two effects which have thus far been neglected. Since the initial distribution of fires is in fact not uniform (see Section II), there must be a preferential direction for the spreading of fires. For example, if the probability distribution of fires at the center of the city is very low, the dominant mechanism for burning the downtown area may be the spreading of fires from the suburbs. Also, if P_o is very small, it becomes reasonable to include the effects of professional fire fighting activity. We will first consider modification resulting from a non-uniform spacial distribution of fires.

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the Taylor expansions (28), we find

$$B_n = 1 - (1-qP_n)^4 + q(1-qP_n)\frac{\partial^2 P_n}{\partial x^2} + q^2(1-qP_n)^2\left(\frac{\partial P_n}{\partial x}\right)^2 \qquad (29)$$

This is the value of B_n, for $N = 4$, which replaces expression (13) when a one-dimensional spacial dependence is included. A combination of Eq. (29) with (9) and (8) yields the equation for fire spread. A comparison of the relative magnitudes of the various terms of Eq. (29) indicates that the terms which involve spacial derivatives are small compared to the quantity $1-(1-qP_n)^4$ as long as the variation in the initial probability distribution, P_o, over one spacial unit (separation between locales) is small compared to P_o itself. In accordance with the considerations of Section II, this is generally expected to be the case; therefore, spacial dependences will be included henceforth only insofar as the initial distribution is non-uniform.

The effect of fire fighting activity may also be considered. Another parameter, which relates to the effectiveness of fire fighting, would then be needed. We define the quantity M as the ratio of the number of fires which all firemen in a city can extinguish during time t_o (time for a locale to burn) to the total number of locales in the city. If we think in terms of a large city, then M may be interpreted as a density.

We outline the derivation of an equation which is to replace (8), (9), and (13). The quantity M is the fraction of fires which could be extinguished during a given time step, if all locales were burning. Let R_n be the fraction of fires which occur during the time interval $nt_o<t<(n+1)t_o$, assuming that there is no fire fighting activity during that time. If fires are chosen at random the Taylor expansions (28), we find

$$B_n = 1 - (1-qP_n)^4 + q(1-qP_n)\frac{\partial^2 P_n}{\partial x^2} + q^2(1-qP_n)^2\left(\frac{\partial P_n}{\partial x}\right)^2 \qquad (29)$$

This is the value of B_n, for $N = 4$, which replaces expression (13) when a one-dimensional spacial dependence is included. A combination of Eq. (29) with (9) and (8) yields the equation for fire spread. A comparison of the relative magnitudes of the various terms of Eq. (29) indicates that the terms which involve spacial derivatives are small compared to the quantity $1-(1-qP_n)^4$ as long as the variation in the initial probability distribution, P_o, over one spacial unit (separation between locales) is small compared to P_o itself. In accordance with the considerations of Section II, this is generally expected to be the case; therefore, spacial dependences will be included henceforth only insofar as the initial distribution is non-uniform.

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$$P_n \equiv R_n - M, \tag{34}$$

so that Eq. (30) becomes

$$P_{n+1} = A_n B_n - M, \tag{35}$$

where A_n and B_n are given by Eqs. (9) and (13) respectively. Since R_n is the probability that a given locale is on fire during the time interval $nt_o<t<(n+1)t_o$, assuming that firemen make no effort to extinguish the fire, it follows from Eq. (34) that P_n is the same quantity, with fire fighting activity included. By comparing Eq. (35) with (8), it is evident that the effects of firemen can be included by subtracting the quantity M from the right hand side of the equation at each time step. When $A_n B_n \leq M$, then all fires have been extinguished.

The effectiveness of fire fighting is measured by the magnitude of M. The more fire houses, per capita, in a city, the greater will be M. We defined M to be the fraction of the total possible number of fires, if all locales were simultaneously burning, which could be extinguished by firemen during the time t_o. Now if the locales we speak of are city blocks, then it is clear that some reinterpretation is required. When an entire city block is burning intensely, there is virtually no hope that firemen will be able to have any effect on the fire, even under the most favorable of circumstances. Their strategy must almost certainly include the watering down of neighboring blocks, in order to keep the fire from spreading, without hope of saving the block in question. Now if a block is watered down before a fire can "jump" from a neighboring

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Because of the relative unimportance of fire fighting activity, we may conclude that if a single structure on a city block burns, then the entire block will almost certainly burn. The question remains as to the probability that a fire will jump across a street from one block to the next. Thus we will consider the "locales," as discussed in Section II, as city blocks, with the appropriate value N=4. In this section we will estimate values for q, so that the parameter Nq becomes determined.

The value of q, corresponding to a pair of blocks, may be affected by automobiles in the street which separates them. However, the initial pulse will set virtually all unsheltered motor vehicles on fire, because of access of the beam to automobile seats and floor boards. Typically, about one-half hour is required for an automobile to burn, so that except in the neighborhoods of wooden structures, cars will have burned up before buildings are flaming intensely. Therefore, automobiles in the streets are not expected to provide an effective access to fire, and need not be considered in the determination of q. (On rare occasions, an automobile gasoline tank may explode, and thereby spread burning debris. However, it is known that such a phenomenon is so highly unlikely that it need not concern us.)

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roughly 4.8 cal/cm -sec. The flux required to ignite combustible material is determined predominantly by the kindling temperature of the material. If the radiant flux is I, and the temperatures of two opposite faces of a piece of wood, for example, are T_1 and T_2 respectively, then after a steady state is achieved,

$$I = \sigma T_1^4 + \sigma T_2^4, \quad (36)$$

where σ is the Stephan-Boltzmann constant. The two temperatures are related by

$$\sigma T_2^4 = \frac{k(T_1 - T_2)}{L}, \quad (37)$$

where L is the thickness of the wood, and k is its heat conductivity. It can be shown that for L greater than few centimeters, we have $T_1 \gg T_2$, and

$$I \approx \sigma T_1^4. \quad (38)$$

For a typical kindling temperature for wood, of 500 C, we obtain very nearly

$$I \approx 0.5 \text{ cal/cm}^2\text{-sec}. \quad (39)$$

This result agrees well with the result quoted in the literature of $0.3<I<0.8$ cal/cm^2-sec. Thus we estimate that if the flux across the street is reduced by more than a factor of ten compared to the flux at the open window of a burning room, then the fire will not "jump."

Three dominant factors contribute to the reduction in flux. These include the fraction of the walls of the burning building which is window, a transmission factor for the radiation through intervening media, and a geometrical reduction factor. Typically, we expect that 40% of the walls of downtown buildings are composed roughly 4.8 cal/cm -sec. The flux required to ignite combustible material is determined predominantly by the kindling temperature of the material. If the radiant flux is I, and the temperatures of two opposite faces of a piece of wood, for example, are T_1 and T_2 respectively, then after a steady state is achieved,

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Equating expression (41) to the reciprocal of 1.9, we obtain the minimum ratio of height of building to building separation, such that the fire will spread to another block. The result is

$$\left(\frac{h}{D}\right)_{MIN} = 1.24 \qquad (42)$$

We conclude that the best value of q, for a given city, is the fraction of the total number of buildings whose height exceeds the separation from the building across the street by more than a factor of 1.24. In most American cities this fraction is less than 0.25. For example, observations in Washington, D. C. indicate that about 7% of the buildings are sufficiently high to satisfy the requirement (42). In Fig. 6, we have plotted the cumulative probability density of the height to separation ratio for Washington. We conclude that, for Washington, $Nq \approx 0.3$, and by inspection of Fig. 3, the center of the city will probably not burn. In fact Nq would not be equal to unity for Washington, (and, therefore, by Fig. 3, a significant fraction of the downtown area would not burn) unless $\left(\frac{h}{D}\right)_{MIN}$ were as low as 0.85.

We expect that the value given by Eq. (42) is probably low for the quantity $\left(\frac{h}{D}\right)_{MIN}$. For example, we used the value 4.8 cal/cm^2-sec for the radiation flux at an open window of a burning room. A value as low as 4.0 cal/cm^2-sec has been quoted in the literature. Furthermore, it has been assumed that all rooms on one side of a burning building, as well as all buildings on that side of the block, are on fire simultaneously, and that the block is extremely long. All of

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The next question is: Of those who survive the initial pulse in the suburbs and outlying areas, what fraction will succumb to widespread fires which eventually consume the area. An attempt to estimate this number from first principles would probably be fruitless. However, we note that the fire conditions are not greatly different from the conditions which resulted from incendiary air attacks on German and Japanese cities during World War II. We feel it reasonable to use the data obtained from these attacks as a guide.

As an example, the incendiary air attack carried out on the German city of Hamburg by the RAF during the night of July 27/28, 1943, demonstrated the effectiveness of fire as a weapon of war. That attack, as well as two somewhat less extensive bombings, accounted for the destruction of 55%-60% of the city, of which 75-80% was due to fire. Of the 1,760,000 inhabitants of the city, it is ber of people on the streets, in parks, playgrounds, motor vehicles, etc., who are not given sufficient warning, of the order of a few minutes. Without any warning system whatsoever, we estimate that the fraction of fatalities in this category can be as high as 15%, between 8:30 and 9:00 AM, when as many as 1/4 of the working force is driving to work, and possibly 1/3 of the school children are on the street or in buses. Offhand estimates at other times of the day are: about 6% between 7:00 and 8:30 AM, 2% between 9:00 AM and 3:00 PM, 9% between 3:00 and 3:30 PM, 6% between 4:30 and 6:30 PM, 1% between 3:30 and 4:30 PM, as well as 6:30 PM and midnight, and very few between midnight and 7:00 AM. With even a rudimentary warning system, all of these numbers can be reduced to negligible proportions.

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Finally, it should be noted that the greatest threat from fire, to people in the streets, relates to the radiant intensity of heat to which they are exposed. The World War II attacks were carried out primarily on industrial areas, where the buildings are generally taller than in residential areas. It is not difficult to show that where the buildings are taller, the radiant flux is generally greater.

Despite these differences, the suburban fires which we envisage are sufficiently similar to those in the bombed out cities of World War II, that we feel justified in using the statistics from these raids. Furthermore, any other approach appears to be virtually hopeless. In Table II, we have listed some cities which were attacked by incendiary bombings during the war along with population estimates at the time of the attacks. In the third column, we have included the fractions of the cities destroyed, and by assuming a uniform population distribution, we have listed the number of people affected in the fourth column. The fifth column includes the numbers of fatalities, and in the final column, we have the percentage of fatalities among those who were affected by the attacks. These last numbers range from 2.8% to 12.8%, without any discernible relationship between the percentage of fatalities and the nature of the city or the attack. (A typical attack on a German city involved roughly 1000 tons of high explosives, 500 tons of 30 lb oil incendiaries, and 600 tons of 4 lb magnesium incendiaries. In the Japanese attacks later in the war, considerably will be possible in the raid we envisage, where the fire will engulf many hundreds of square miles.

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VI. Conclusions

We may conclude that the thermal weapon will result in almost complete destruction throughout the suburbs and outlying areas of cities. Furthermore, in regions of most American cities where the initial distributions of fires are low, fire spread from block to block is highly unlikely. This contention is supported by the data obtained from World War II incendiary raids, where fire spread was in fact found to be unlikely, and where almost every city block had to be individually bombed.

We may further conclude that a certain degree of preparation will immeasurably increase the chances for survival of the centers of cities during and after an attack by the thermal weapons. If each of the downtown buildings had windows covered by metallic venetian blinds, or non-combustible window shades, virtually all of the buildings can be made invulnerable to the initial heat pulse as well as the ensuing fires. This suggestion is strengthened by the fact that such a defensive measure would not only be inexpensive, but useful also in control of peacetime fires.

The value of a warning in general is self-evident, but the value is even greater as a defensive measure against an attack envisaged here. It should be iterated that exposure to the initial pulse is almost certainly fatal, but practically any opaque covering will serve as a shelter. It is anticipated that with as little as a few minutes warning, a person will be able to find such shelter.

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TABLE I. STATISTICS FOR VARIOUS U.S. CITIES

City	Average $\left(\frac{h}{D}\right)$	Standard Deviation For $\frac{h}{D}$	Fraction of Locales For Which $\frac{h}{D} > 1.0$	$\frac{h}{D} > 1.4$	$\frac{h}{D} > 1.24$	Fraction of Central City Which Burns
Philadelphia	1.42	1.62	0.58	0.29	0.38	0.6
Baltimore	0.96	0.67	0.42	0.15	0.21	0.05
Washington	0.72	0.44	0.16	0.02	0.06	0
Cleveland	1.37	1.12	0.57	0.38	0.43	0.45
San Francisco	1.20	1.40	0.62	0.33	0.48	0.75

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San Francisco	1.20	1.40	0.62	0.33	0.48	0.75

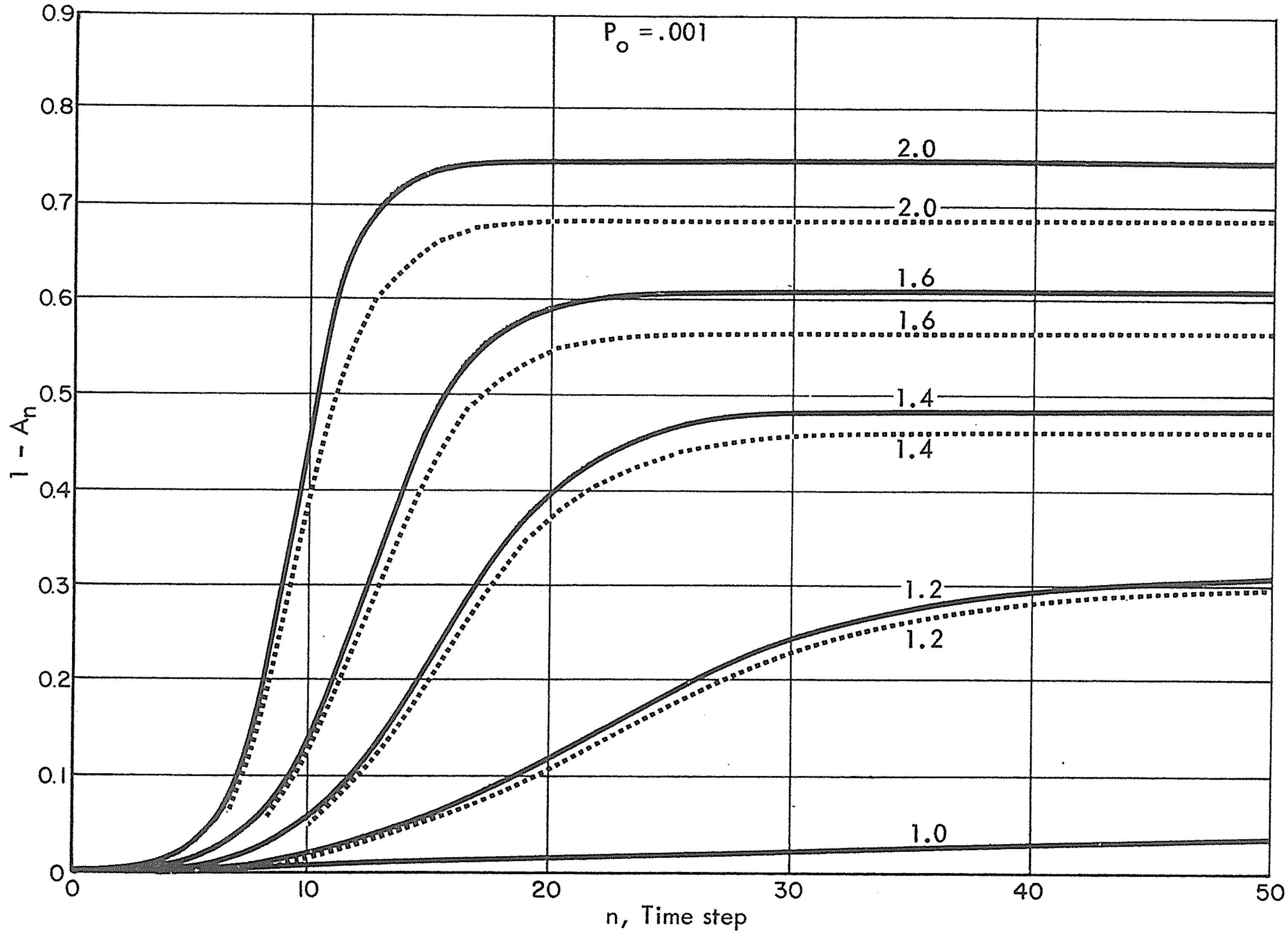

FIGURE 1a Probability of Fire as a Function of Time Step

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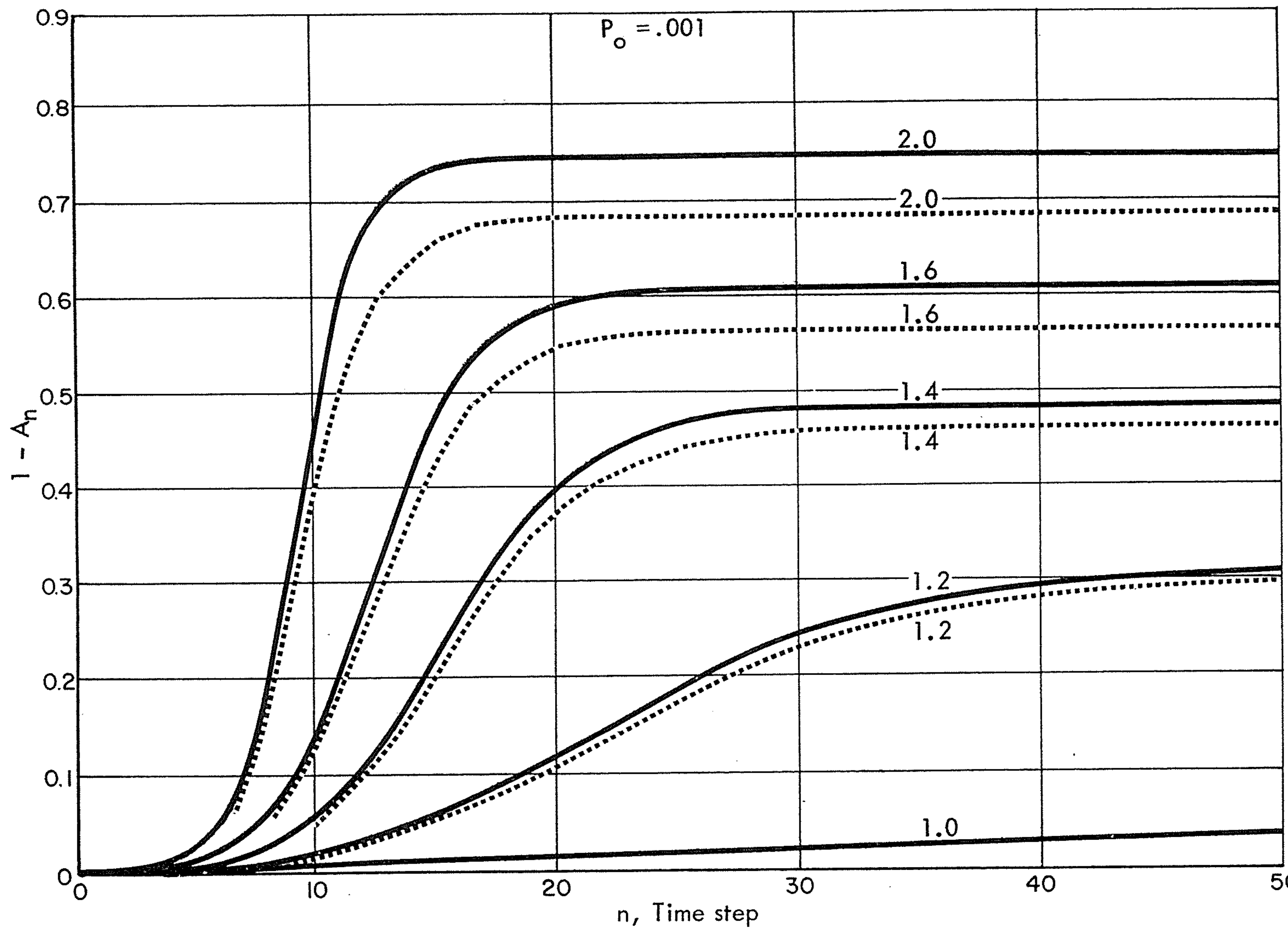

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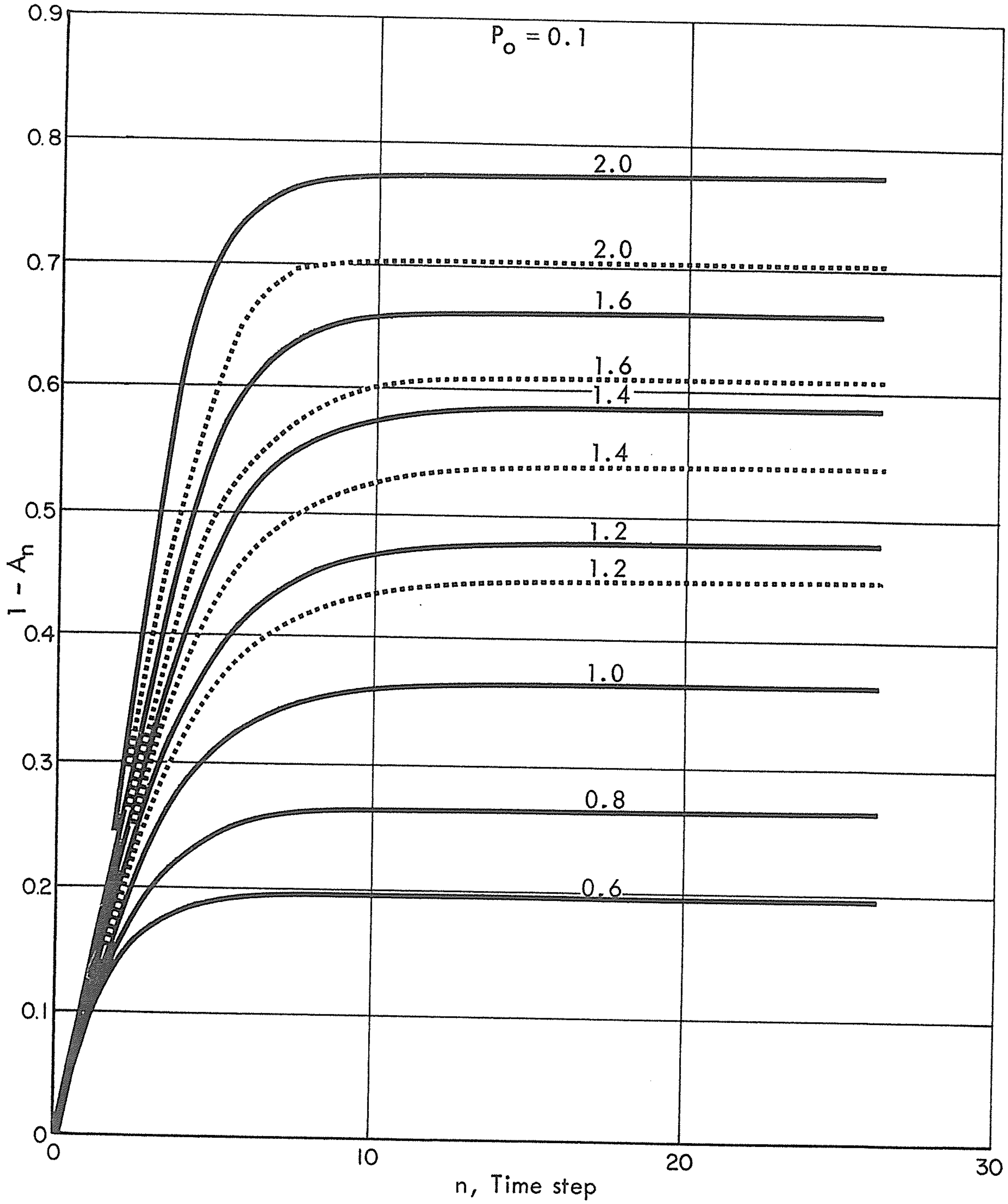

FIGURE 1c Probability of Fire as a Function of Time Step

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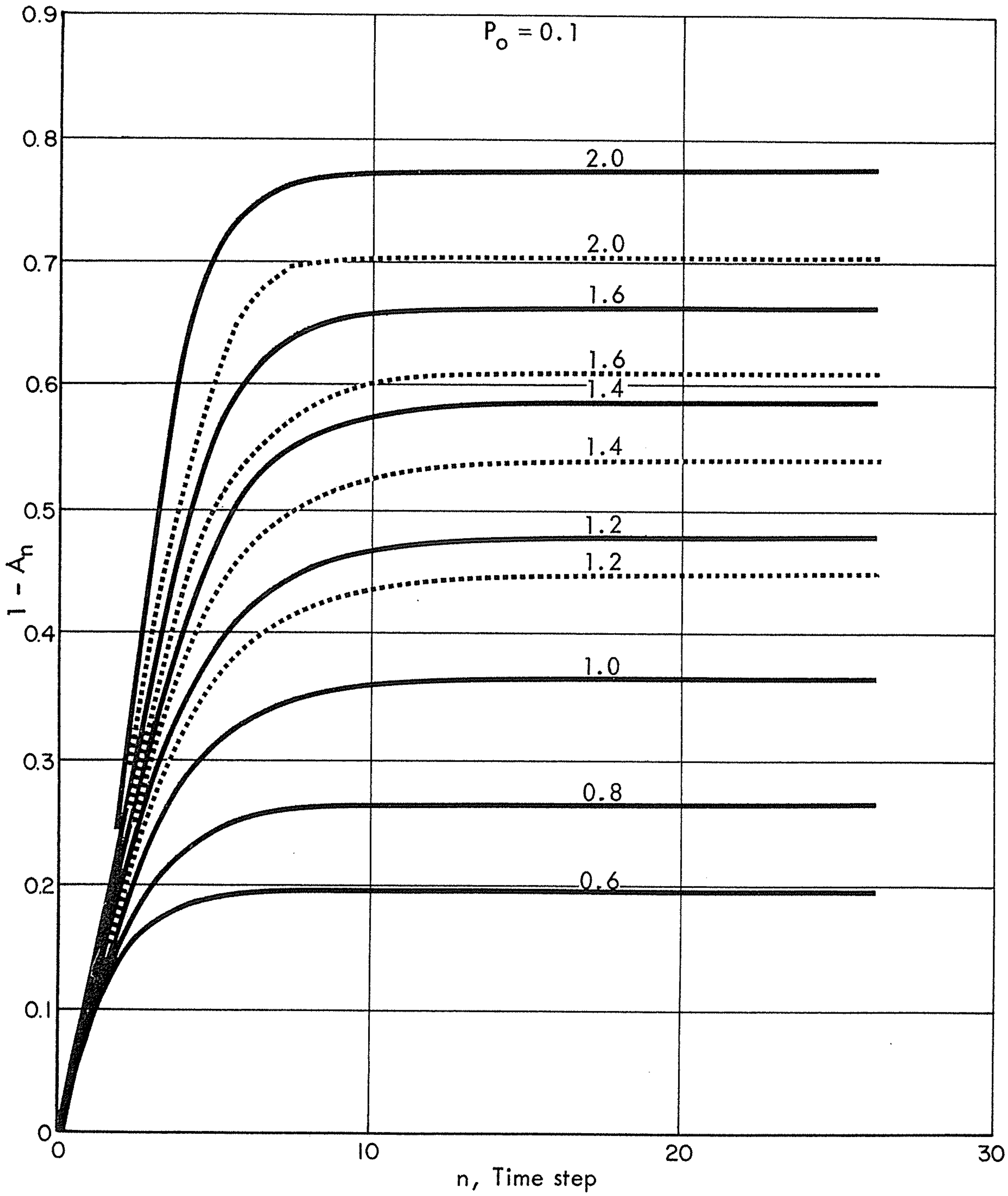

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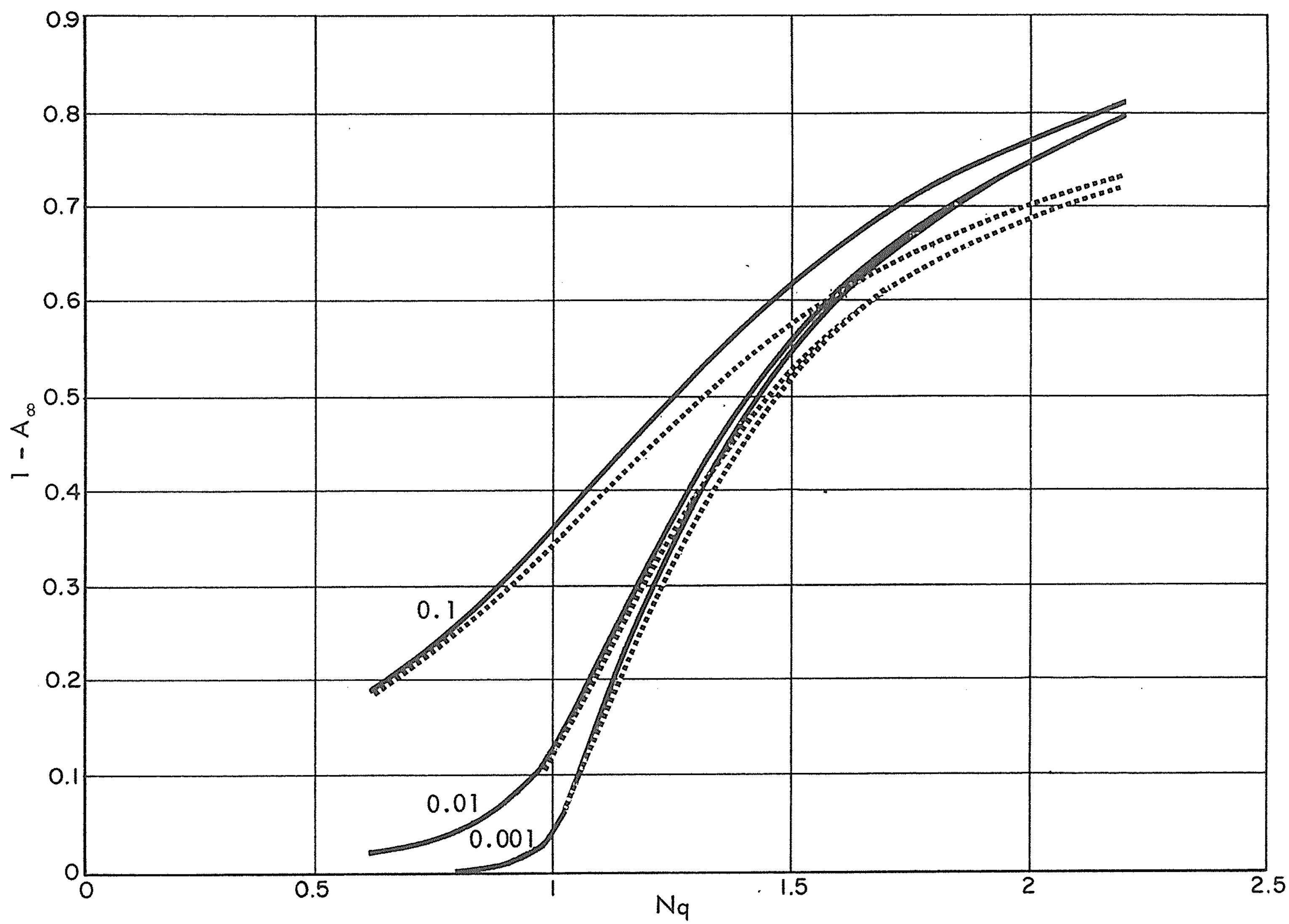

FIGURE 3 Total Fraction of Fires as a Function of Nq

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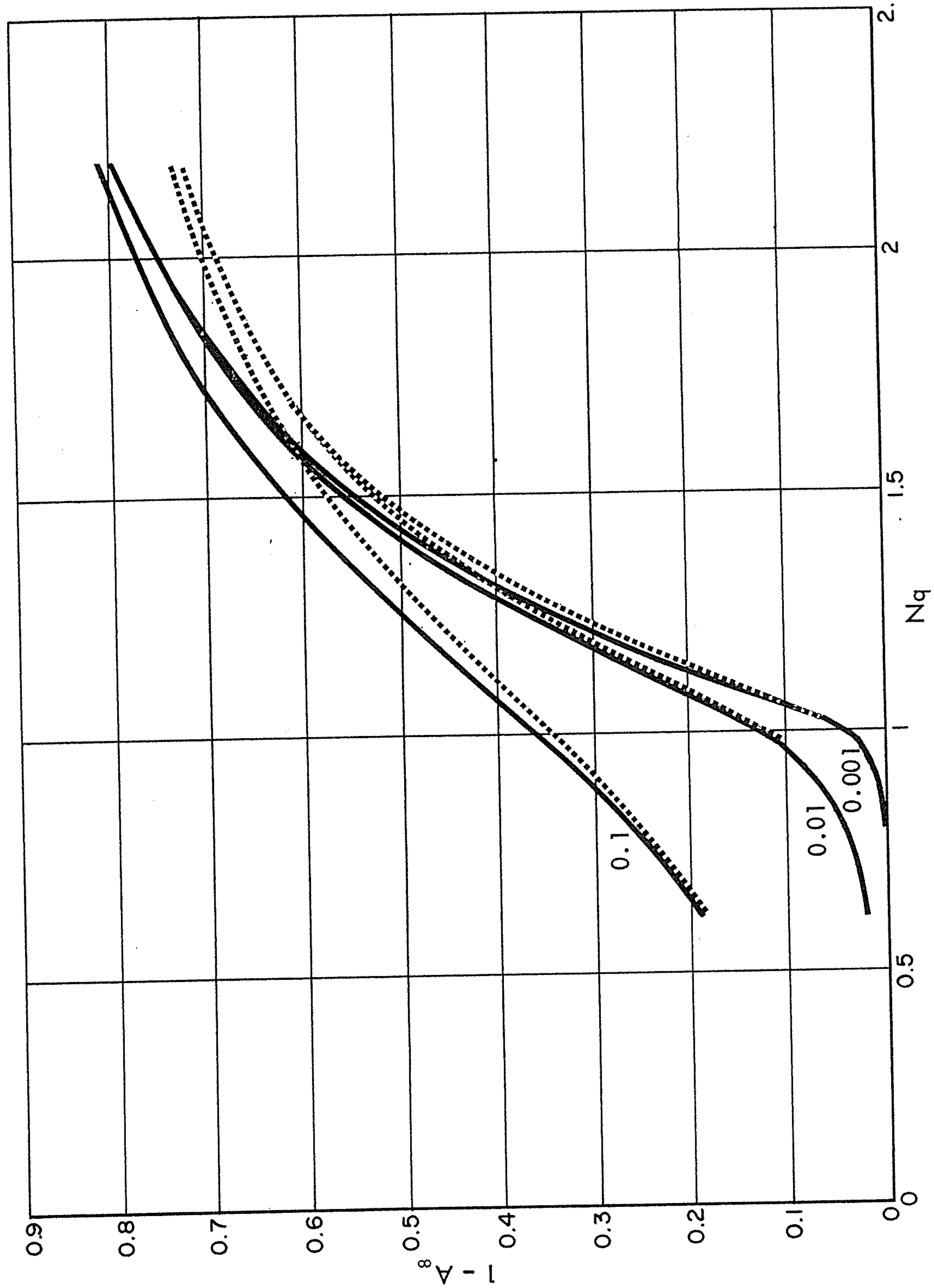

FIGURE 3 Total Fraction of Fires as a Function of Nq

R3-13-64-24

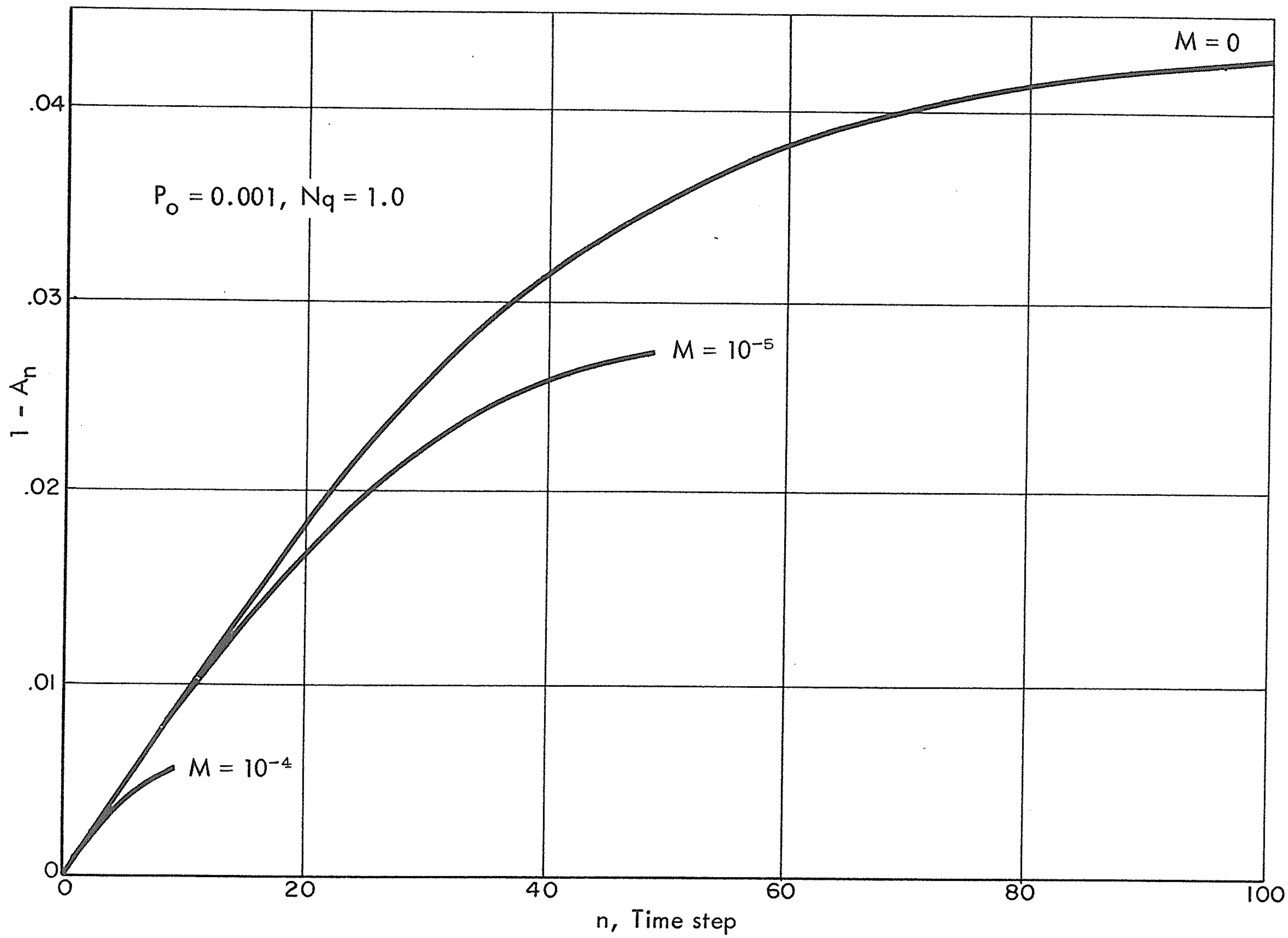

FIGURE 5a Effects of Fire Fighting Activity

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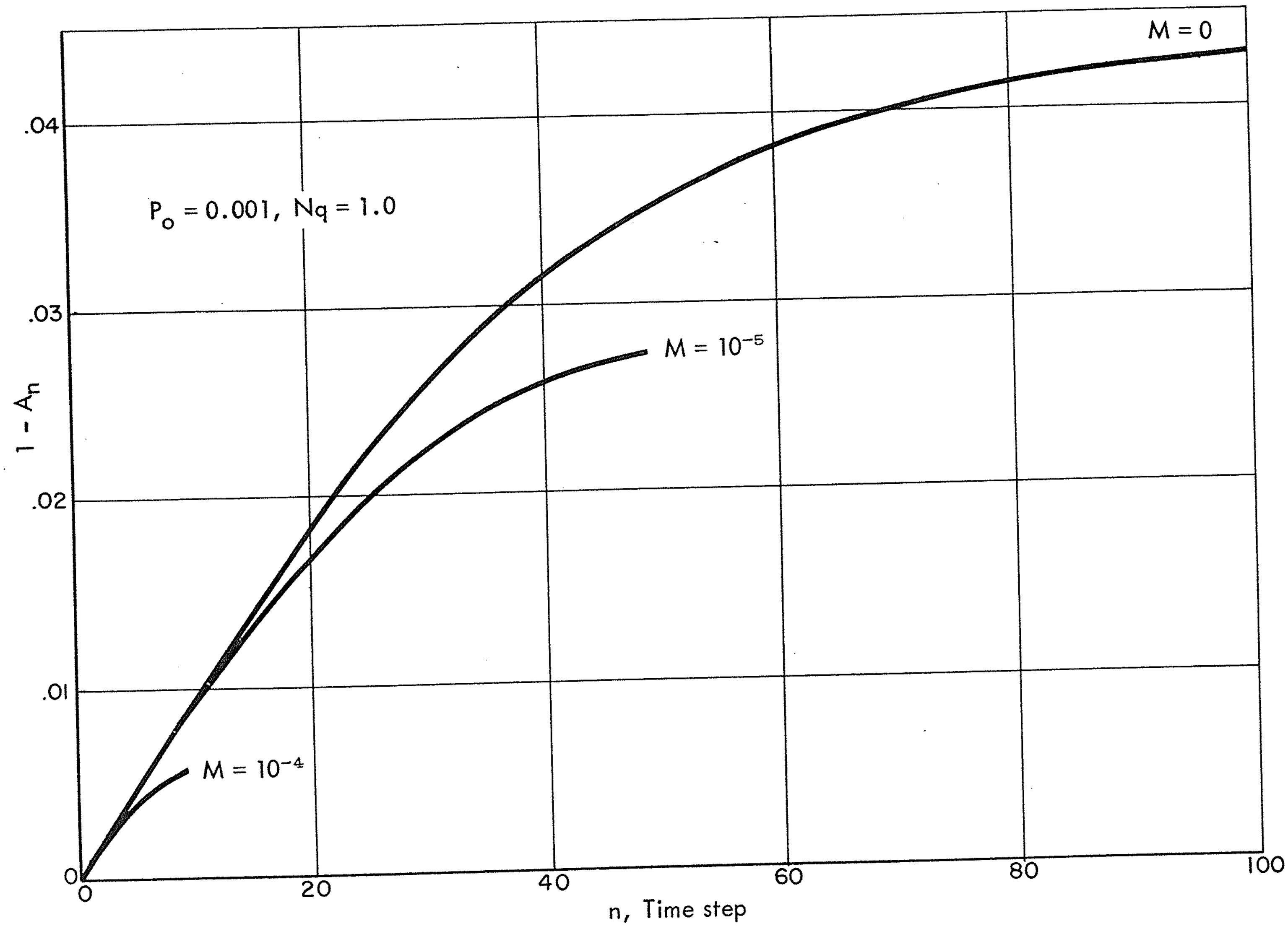

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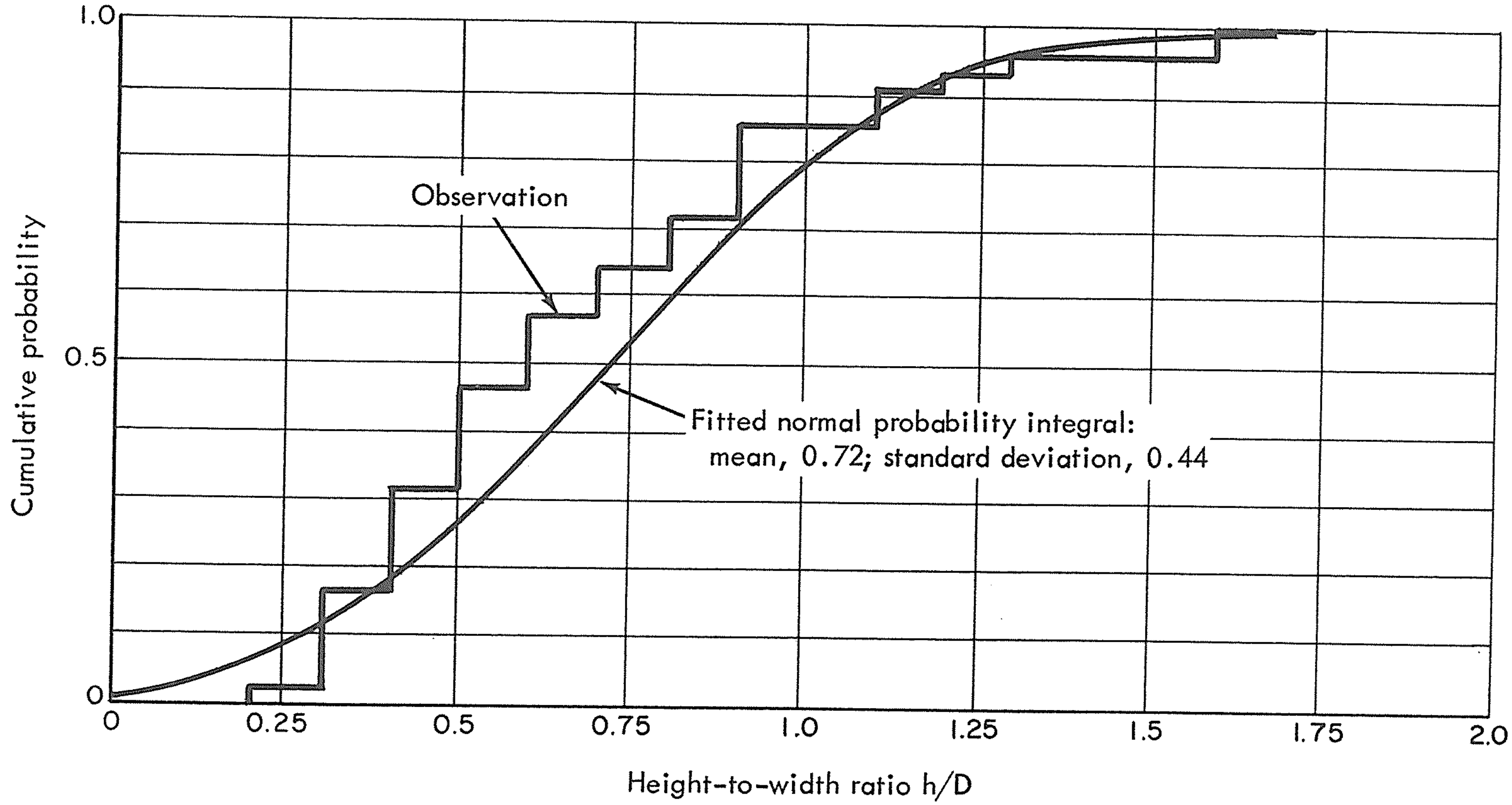

FIGURE 6 Cumulative Distribution of Height-to-Width Ratio for a Section of Northwest Washington, D.C.

R3-13-64-28

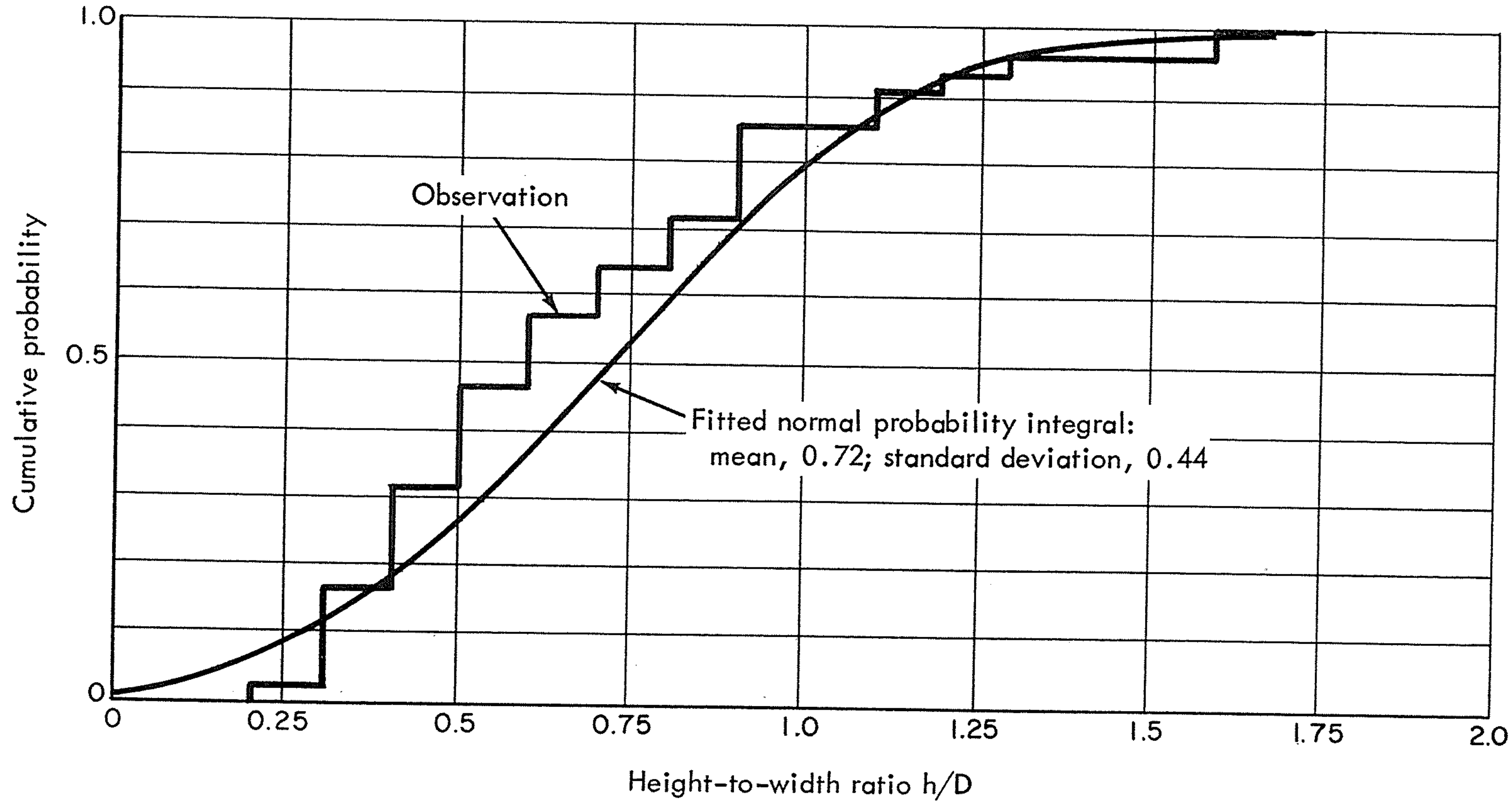

FIGURE 6 Cumulative Distribution of Height-to-Width Ratio for a Section of Northwest Washington, D.C.

R3-13-64-28