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# FUNDAMENTAL PROCESSES OF IGNITION AND COMBUSTION RELATING TO FIRES CAUSED BY NUCLEAR DETONATIONS

by

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Commanding Officer and Director

# FUNDAMENTAL PROCESSES OF IGNITION AND COMBUSTION RELATING TO FIRES CAUSED BY NUCLEAR DETONATIONS

USNRDL-TR-67-63, dated 25 March 1967, by S. B. Martin, R. H. Renner and R. E. Jones

## SPECIAL SUMMARY

### The Problem

A sound development of methods for evaluating, predicting, and protecting against the fire effects of nuclear attack on urban areas depends upon a knowledge of the importance of the various parameters involved in all phases, and at many levels of detail in each phase, of the overall incendiary process. Of fundamental importance to the subject of fire behavior, are the processes of ignition and combustion of the materials which make up the fuel that sustain the fire. To properly understand the nature of fires that could result from nuclear attack on urban areas, so that the extent and magnitude of their threat might be evaluated and possible countermeasures devised, a basic understanding of ignition and combustion processes and the sensitivity and interrelation of the parameters affecting these processes is required.

### The Findings

A state-of-the-art review of the fundamental processes of ignition and combustion pertinent to the prediction and assessment of urban fire vulnerability has been performed. The types of ignition and combustion are defined, and the parameters governing the processes of ignition and combustion are described; in addition, a brief discussion of the role of these processes on the mechanisms of fire propagation is given. The effects of various physical parameters on ignition and combustion phenomena are discussed and cursorily evaluated. These parameters include heat-transfer properties, fuel geometry, atmospheric environment, moisture content, optical absorptivity, trace inorganic substances, and the size of fuel area exposed. Several approaches for correlating ignition data are presented; a review of the information concerning exposure to pulses from high-altitude explosions is included. An estimate of the reliability of the various approaches for correlating ignition data and an approximate ranking of parameters are given.

The material presented will be useful for determining the importance of each ignition and combustion parameter, the synergistic effects of interacting parameters, and additional information needed on the governing parameters and their interrelations.

## ABSTRACT

The fundamental processes of ignition and combustion are reviewed to date as part of the OCD program for assessing urban vulnerability to fire from nuclear bursts. Sufficient background information is provided for use in future fire-damage assessments and fire-protection procedures. Included are definitions of the types of ignition and combustion, the factors governing ignition and combustion, and the mechanisms by which fire propagates. The technical material presented serves as background information for determining the importance of each of the parameters governing ignition and combustion, the synergistic effects of interacting parameters, and what additional information is needed on the governing parameters and their interrelations.

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## SECTION 1

### INTRODUCTION

#### 1.1 STATEMENT OF THE TASK

The study reported here is a part of an overall NRDL study sponsored by the Office of Civil Defense (OCD) to provide necessary background information for future fire-damage-assessment procedures and to provide guidance in the choice of research areas that can produce the maximum improvement in such procedures. The description of the overall study in the OCD Research Task Order follows:

"Perform a comprehensive identification of the parameters pertinent to an assessment of the vulnerability to fire of urban areas from nuclear weapon attacks and other causes in the trans- and post-attack periods and an evaluation of their relative importance. The investigation should include, but not be restricted to, parameters associated with: level of ignition energy; atmospheric transmission; weather and climate; kindling fuel characteristics and distribution; fire development from thermal-radiation-set ignition points and other causes, such as blast and accidents; building geometry and arrangement; city plan and topography."

This report presents a state-of-the-art review of the fundamental processes of ignition and combustion reported on by us previously in the overall comprehensive study of urban fire-vulnerability parameters.<sup>1</sup> OCD suggested the separate publication of this review in order to make the information that it contains more widely available to an audience with interests in the area of ignition and combustion processes.

#### 1.2 OBJECTIVES OF STUDY

The objectives of the study reported here have been to (1) identify and define the parameters that govern ignition and combustion processes pertinent to assessing urban fire vulnerability to nuclear bursts, and (2) provide sufficient background information so that a sensitivity analysis of the various parameters can be performed for the purpose of determining (a) the relative importance of each parameter to a full understanding of urban fire vulnerability, (b) the possible synergistic effects of interacting parameters, and (c) what additional information is needed on the sensitive parameters and their interrelations.

### 1.3 SCOPE AND APPROACH

The fundamental processes of ignition and combustion were studied and reviewed to provide background information for future urban-fire-vulnerability assessment procedures. The technical material presented here should be a useful state-of-the-art review for those with interests in assessing the fire effects of nuclear-weapon bursts. Information pertinent to urban fire is presented, along with definitions of the types of ignition and combustion, the factors governing ignition and combustion behavior, and the mechanisms by which fire propagates. Included is information on the range of nuclear-attack conditions considered to be likely at the present time and within about a decade.

An attempt is made to present the most up-to-date information; particularly with respect to the thermal threat from high-yield, high-altitude, nuclear-weapon bursts.

Ignition and combustion phenomena are known to contribute to each of the behavioral phases of urban fire from nuclear weapons; namely, ignition, fire buildup, intraunit spread, interunit spread, large-scale interaction, and mass-fire development. A framework is presented on which to develop fire-vulnerability assessment procedures. To accomplish the foregoing in the area of ignition and combustion processes, the subject matter was categorized so that the pertinent parameters could be enumerated.

## SECTION 2

### TYPES OF IGNITION AND COMBUSTION

Most organic solids burn in air through a stepwise process of pyrolysis consisting of volatilization, mixing of the volatiles with oxygen in the air, and the vigorous vapor-phase oxidation of the flammable constituents accompanied by the release of heat, part of which must return to the solid to maintain pyrolysis. Exceptions to these solids include materials that contain their own oxidants, such as solid propellants (which are of very limited interest--if at all--to the subject of urban fire vulnerability), and materials that do not generate significant volatile products even at high temperatures, such as charcoal. The common case of pyrolysis followed by rapid oxidation in the vapor phase is usually accompanied by a buoyant plume of luminous gas that represents the region of diffusive mixing of fuel with oxygen and the zone of intense chemical activity called a flame. It is appropriate, therefore, to refer to this type of burning as flaming combustion.

The burning of volatile-poor fuels, such as charcoal, occurs when the surface of the solid reaches a temperature (about 600°C for charcoal) at which the solid itself begins to oxidize rapidly. In the case of charcoal, carbon is first oxidized to carbon monoxide by oxygen, which has diffused to it from the air surrounding it. The CO can then be oxidized to CO<sub>2</sub> as it diffuses out into the air. This type of burning is termed glowing or smoldering combustion. Since at least a large part of the heat of the first reaction (about 26 kcal/mol) is available at the surface to maintain the high temperature needed to sustain the reaction, the controlling factor in glowing combustion is the availability of atmospheric oxygen at the fuel surface.

The foregoing discussion implies that combustion is a steady (or at least quasi-steady) process that sustains itself as long as fuel and oxygen are available to one another and the heat release of the reaction exceeds the combined conduction, convection, and radiation heat losses from the reaction zone (pyrolysis plus oxidation). The transient process that initiates the steady process is called ignition. Ignition may be termed either flaming or glowing, depending on which form of combustion it initiates, but it may be further classified as (1) spontaneous or piloted, depending on whether or not it occurs as the result of heating

alone or in the presence of flame or spark from an already-burning fuel, or (2) as sustained or transient, depending on whether or not burning continues after the external source of heat has been removed. This dependence on external sources of heat and other external igneous agents, in addition to its unsteady, initiating character, makes ignition distinct from combustion.

THEORY OF IGNITION AND COMBUSTION

Most organic solids burn in air... pyrolysis consisting of volatile... oxygen in the air, and the volatile... initial constituents accompanied by the... solid to maintain pyrolysis... solid includes water... (which are of very limited... subject of which the... significant volatile products... the common case of pyrolysis... phase is usually accompanied... represents the region of... sorts of intense chemical... phenomena, to refer to this...

The burning of volatile... the surface of the solid... at which the solid itself... charcoal, carbon... has diffused to it from the air... oxidized to CO<sub>2</sub> as it diffuses... is formed glowing or smoldering... of the heat of the first reaction... the surface to maintain the high... reaction, the controlling factor... ability of atmospheric oxygen...

The foregoing discussion implies that... least quasi-steady) process that... oxygen are available to one another... exceeds the combined conduction... from the reaction zone... that initiated the steady process... toward either flaming or glowing... it initiated, but it may be further... ignited, depending on whether or not it occurs as the result of heating...

## SECTION 3

### FACTORS THAT GOVERN COMBUSTION BEHAVIOR

#### 3.1 FUEL COMPOSITION

One of the main factors governing combustion behavior is the composition of the fuel. When heated sufficiently, most organic solids are readily converted to vapors through sublimation, melting and boiling, or decomposition, or a combination of these. Simple changes in state are not commonly experienced by the organic materials that are used in construction and furnishings and otherwise make up the bulk of the fuel loading in urban areas. These materials are typically natural or synthetic polymers. They may soften or even melt when heated, but volatilization occurs entirely through thermal decomposition. As a result, the composition of the vapors may bear little resemblance to the solid from which they originate, particularly when there is a carbon-rich residue (char) produced by the selective elimination of certain portions of the molecules that made up the original solid.

The commonest chemical constituent of the fuels making up the bulk of the fuel loading of urban areas is cellulose. As it burns, cellulose is pyrolyzed to char (as much as a third to a half of the original weight) and a complex mixture of volatiles that, on the average, are correspondingly poorer in carbon (and to some extent hydrogen) content than the original solid was.<sup>2,3</sup> This mixture of vapors and gases which is highly oxygenated contains a considerable fraction of nonflammable constituents (water and carbon dioxide). The main flammable constituents are the so-called tars, which are relatively high-molecular-weight compounds, including carbohydrates, furan derivatives, aldehydes, and (if lignins are present as in wood) aromatic compounds. The flammability of the volatile products depends on the char-tar ratio produced by pyrolysis.<sup>4,5,6,7,8</sup> It has been known for some time that the presence of certain catalytic agents in cellulosic fuels will enhance the production of char at the expense of tar, which renders the fuel either less flammable or non-flammable.<sup>4,5,9,10</sup> This catalytic action is the principle on which fire-retardant agents are supposed to work.<sup>4,11</sup>

Once the flow of volatiles stops or slows to the point where air can get in to the charred surface, flaming combustion gives way to glowing

combustion. Glowing combustion may continue, develop into flaming combustion again, or go out. The reestablishment of flaming ignition can occur whenever a fresh supply of volatiles appears. This recurrence will typically happen when uncharred material remains buried under a layer of char that is glowing with sufficient intensity (because of either the wind or the radiant heat from adjacent fuels) to supply heat by conduction and pyrolyze the buried fuel. Glowing combustion will not normally go out until the fuel is used up unless it suffers a severe oxygen deficiency or extreme heat loss, such as that frequently encountered in isolated fuel elements.

It may be inferred from the foregoing that, in addition to composition of the fuel, some of the factors affecting the combustion behavior of solid fuels include (1) the heat of combustion, (2) the heat-conduction properties of the fuel, (3) the geometry of the fuel and the proximity of other burning fuels, and (4) the atmospheric environment in which the fuel is burning. Let us consider these one at a time.

### 3.2 HEAT OF COMBUSTION

Heats of combustion of the commoner fuels in urban areas range from 4 to 5 kcal  $g^{-1}$  or 7000 to 9000 Btu  $lb^{-1}$  as listed in Ref. 12. Wood with a modest moisture content, say, 12% or 13% by weight, has typically a heat of combustion ranging from 4.0 to 4.5 kcal  $g^{-1}$ , depending on the kind of wood and its resinous content. Cotton and paper-pulp products are about the same. Plastics (and other synthetic polymers) generally have higher heats of combustion ranging up to 10.3 kcal  $g^{-1}$  ( $\sim 18,500$  Btu  $lb^{-1}$ ). The heat of combustion of coal varies greatly, but typically lies in the range 6 to 8 kcal  $g^{-1}$  (11,000 to  $\sim 14,000$  Btu  $lb^{-1}$ ). Considering the preponderance of cellulosic materials in most urban areas, a reasonable average value for the heat of combustion of urban fuels appears to be 4.5 kcal  $g^{-1}$  ( $\sim 8000$  Btu  $lb^{-1}$ ).

The rate at which the heat of combustion is released depends on factors remaining to be discussed. It should be mentioned at this point, however, that the heat released during the combustion of wood charcoal is 7.1 kcal  $g^{-1}$  ( $\sim 12,900$  Btu  $lb^{-1}$ ),<sup>13</sup> or about  $\frac{1}{2}$  to  $\frac{1}{3}$  of the total heat release of the original fuel. Since glowing combustion of wood generally follows the flaming process and lasts over a considerably longer time, this information is of some value in estimating the heat-release history of a single fuel element. Similar data are not available for paper products, cotton fabrics, and other thin fuels, but it is probably safe to say that a much larger fraction of their heats of combustion is released in a short period (during flaming) unless they have been treated with a flame retardant.

The moisture content of a fuel has some influence on the heat released during combustion, although it seems to be less a factor in the amount of heat released than it is in the rate of burning (and, hence, rate of heat release). It can, of course, determine whether or not a fuel will burn at all. The heat of combustion (per unit mass of dry wood) of wood containing an equal weight of water is about 85% of that of the bone-dry material (oven-dried).<sup>2</sup> It is very difficult to burn wood that has an equal weight of water in it; and even under the most extreme heating conditions, it is virtually impossible to burn wood containing twice its weight in water.

### 3.3 HEAT-CONDUCTION PROPERTIES

The heat-conduction properties of a fuel, as expected, have a marked effect on burning rate. If the rate of heat conduction into a thick material away from the surface is very high, the temperature of the surface and the material just under the surface, which is the source of volatile products, will be less than it would be for a material that does not conduct the heat away as fast. As a consequence, the rate of production of volatiles will be less, the flames will be feebler, and their contribution of heat to the surface will be less, which in turn will reduce the flow of volatiles. In the extreme, the burning rate will fall to zero. This behavior is normal for large pieces of wood when they lack external sources of heat.

The other extreme in heat conduction--materials with very low thermal conductivity--is not conducive to rapid burning either. Under such conditions, surface temperatures may be very high, but the amount of subsurface material that is hot enough to generate volatiles is severely limited by the inability of the material to conduct heat to it. In this case, an initially flaming fuel will cease to flame actively; but it may continue to burn by glowing combustion. The tendency of low-density materials, such as balsa-wood, cotton linters, and punky wood, to smolder or glow rather than flame is probably due in part to their low thermal conductivity, although it may in some cases be an effect of extraneous contents, such as mineral impurities.

### 3.4 FUEL PROPERTIES AND CONFIGURATION AND THE INFLUENCE OF OTHER PROXIMATE BURNING FUELS

Little of quantitative nature can be said concerning the dependence of combustion behavior on the properties and dimensions of a fuel element or on the spatial arrangement of fuel elements with respect to one another. Some qualitative ideas can be gained from observation of, and experience with, burning wood; these may be summarized as follows:<sup>2</sup>

1. Although a single burning piece of wood will normally require heat from an outside source in order to continue burning, it may at the same time furnish heat to other pieces, mainly by its volatile combustibles burning at a distance from its own burning surface.

2. A local failure in air supply with continued application of heat results in charring without combustion, so that the volatiles do not burn until they reach a more adequate supply of air.

3. Wood at a distance from the main combustion area may be heated by radiant heat to the charring temperature without combustion. In this case, the volatiles must reach ignition temperatures before they can be burned.

4. A spatial arrangement in which the combustion is explosive is the distribution of very fine, dry wood particles near enough to each other that the combustion of one will ignite others and yet far enough apart that each is surrounded by sufficient air for its complete combustion.

5. In a fuel mixture of large and small pieces, the smaller ones may be entirely consumed with only superficial combustion of the large ones.

6. A very large piece of wood may be subjected to high temperatures for some time with only superficial combustion or charring. For this reason, a wooden beam may retain its strength properties under fire conditions that would cause the failure of a steel member.

7. When small pieces of wood burn in a plentiful supply of air, both charcoal and volatile combustibles burn about as fast as they are produced. Under other conditions (large pieces or limited air supply), the charcoal burns more slowly, and much is left to glow and/or smolder by itself after flaming stops.

8. Since a good deal of shrinking occurs as wood is converted to charcoal, the surface of the charcoal is usually distorted and cracked. Glowing combustion will continue in these crevices long after combustion has stopped elsewhere because of the heat-conserving property of this configuration.

Although the foregoing list does not help much in analyzing fire behavior, it does give some feeling for the important parameters. For example, it seems clear that the surface-to-volume ratio is important, as are the compactness and distribution of large and small elements of a fuel bed. These are factors anyone who has successfully built a campfire knows intuitively, but the relationships are so complex that they have defied analytical description for a century or more.

### 3.5 AMBIENT ATMOSPHERIC ENVIRONMENT

A reduction in the  $O_2$  content of ambient air has a pronounced effect on combustion behavior. Solid fuels, such as wood, burn more and more slowly as the partial pressure of  $O_2$  is reduced until at about 120 mm of mercury ( $\sim 16\%$   $O_2$  by weight, threshold concentration) combustion stops even under the best of the other conditions. The presence of  $CO_2$ , or certain other gases (such as halogenated compounds), increases somewhat the threshold  $O_2$  concentration. One or more of these conditions may exist in an urban fire. The  $O_2$  concentration may be reduced in an enclosure, whereas  $CO_2$  and, in some cases, halogen compounds are products of fires in furnishings, finishes, and building materials.

The water-vapor content of the atmosphere has a significant influence on the burning rate of materials that absorb moisture. An example of the amount of moisture absorbed at equilibrium by wood is shown in Fig. 1 from Ref. 14. Moisture contents do not generally exceed 20% even under conditions of very high relative humidities. Hawley<sup>2</sup> comments that wood with 10% moisture burns noticeably faster than wood with 20% moisture, but quantitative data are unavailable. Much the same situation exists regarding the effect of air motion on burning rate. It is widely recognized that burning rate increases with increased air motion over the material (at least to a point, since high winds can "blow a fire out"), but again only the grossest sort of qualitative information can be found.

For more detailed information on combustion behavior and the properties of fuels and ambient atmospheric environment that govern it, the reader should consult Refs. 2,4,6,11,15,16,17, and 18.

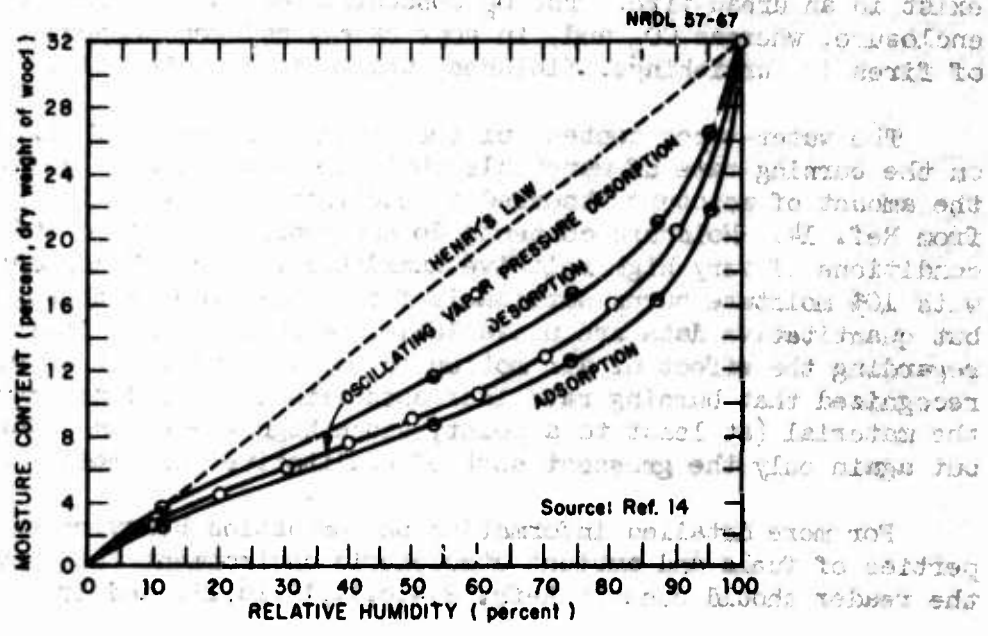


Figure 1 Moisture Content Vs Relative Humidity (Vapor Pressure) for Sitka Spruce Under Normal Desorption-Absorption Conditions and Under Oscillating-Vapor-Pressure Description Conditions at 25°C

## SECTION 4

### FACTORS THAT GOVERN IGNITION BEHAVIOR

#### 4.1 GENERAL

The ignition behavior of cellulosic fuels exposed to intense radiant energy has been studied extensively because of its relationship to nuclear-weapon effects. Much of this work, therefore, has been done under conditions of greatest pertinence to the thermal-radiation aspects of nuclear explosions (high radiant-flux levels and short thermal pulses); but to a large extent, the information gained is relevant to the broader subject of ignition of organic solids by a variety of heat sources. Accordingly, we develop the subject here by first reviewing the state of knowledge generated by research in the field of ignition of cellulosic solids by thermal radiation and then discuss any unique or neglected aspects of the broader subject.

#### 4.2 IGNITION OF CELLULOSIC SOLIDS BY THERMAL RADIATION

##### 4.2.1 Basic Process

The ignition behavior of cellulosic solids exposed to thermal radiation is governed by (1) the characteristics of the radiation; (2) the dimensions, extraneous contents, and optical and heat-transfer properties of the solid; and (3) the composition of the atmosphere surrounding the solid. In some cases, ignition behavior is also influenced by the geometry of the solid and the motion of the air around the solid.

When a cellulosic solid is heated at one surface by a remote radiant source, the response can be described in one of three ways: sustained flaming ignition, transient flaming ignition, or glowing ignition. These terms are chosen to indicate both the form of combustion initiated and whether or not combustion is self-sustained after the heat source is removed.

Spontaneous flaming ignition (initiation of either sustained or transient flames by a remote heat source alone) of a cellulosic solid occurs in the gas phase in front of the heated surface where the volatile products generated by the local application of heat to the surface of the solid mix with air under conditions amenable to the development of an

accelerating rate of reaction between the fuel constituents and the oxygen of the air. Accordingly, a complete description of the process would include heat transfer, fluid mechanics, and chemical kinetics. In detail, consideration would have to be given to such factors as the deposition of heat in the solid and how the decomposition of the material is influenced by the transient temperature distribution, the diffusion of the volatile pyrolysis products, the mixing of the issuing volatiles with the surrounding air, the kinetics and thermochemistry of the oxidation reactions, and the combined heat losses of the system during the course of the ignition process.

Very often, however, in complex processes like this, much can be learned using an analytical model that does not attempt to consolidate all of the factors involved. The heat-transfer, fluid-mechanics and chemical-kinetics parts of the process can frequently be decoupled and individually scrutinized to discover which (if any) exerts the greatest control on the system under experimental study. A model based on the controlling mechanism (if one exists) will often correlate experimental data and reveal, in the nonideality of the incomplete model, the importance of missing factors. A large body of ignition data for cellulosic solids has been successfully correlated with parameter groupings derived from equations that describe the diffusion of heat into an inert solid. Two basically different approaches have been taken to achieve data correlation; both are briefly reviewed next.

#### 4.2.2 Two Approaches to Correlating Ignition Data

Workers at the Joint Fire Research Organization (JFRO) in England have treated the ignition of wood using a mathematical model of an inert solid with Newtonian heat losses and taking as a criterion for ignition the attainment of an "ignition temperature." For thermally thick materials, the ignition criterion suggested by theory is a fixed surface temperature. The early work of Lawson and Simms<sup>19</sup> at JFRO indicated that transient flaming (spontaneous) ignition occurred when the temperature of the exposed surface of wood reached 350 to 600°C, depending on the variety of wood. Subsequent work<sup>20</sup> in dimensional analysis of the thermal balance of irradiated solids has provided results for both spontaneous transient ignition and spontaneous sustained ignition. For thermally thin solids, empirically determined criteria are a fixed surface temperature of about 500°C for spontaneous ignition and a similar mean-temperature value for sustained ignition. The sustained-ignition correlation, however, breaks down completely for very low and high rates of heating.

The important parameters in the JFRO correlations are the thickness of the fuel, the properties of the fuel that control the diffusion of heat in the solid (conductivity, density, and specific heat capacity), the Newtonian cooling constant (a function of temperature), and the time-irradiance characteristics of the radiant pulse. Other parameters that must be allowed for are moisture content of the fuel, size of the area irradiated, external drafts, the absorptivity and diathermancy of the exposed surface (as determined by the spectral distribution of the source of radiation), and preheating. This latter group of parameters has been studied more exhaustively at JFRO than probably anywhere else in the world.

A similar approach to a generalized solution of the ignition problem began in this country about 1955 when Sauer<sup>21</sup> successfully correlated some preliminary ignition data for black alpha-cellulose (2% carbon content) exposed to constant irradiance (square-wave) pulses from a carbon-arc source (approximating a 5500° to 6000°K black body). In effecting the correlation, he chose to avoid specifying (or even introducing the concept of) an ignition temperature. The resulting correlation was quite simple in nature and yet remarkably successful except for low rates of heating. It treated only diffusion of heat into the solid and ignored chemical effects and heat losses. The success of the technique indicated that neither chemical effects nor heat losses are important over a very wide range of exposure conditions. During the years since, the group at NRDL that cooperated with Sauer (and the California Forest and Range Experiment Station) in the initial correlation program has adopted Sauer's basic tenets and has developed the correlation to a high level of precision and utility.

The final ignition-behavior pattern (taken from Ref. 22 for square-wave exposure of black  $\alpha$ -cellulose is shown in Fig. 2, where  $Q$  is ignition threshold radiant exposure,  $\rho$  is density,  $c$  is specific heat,  $L$  is fuel thickness,  $\alpha$  is thermal diffusivity ( $\alpha = k/\rho c$ , where  $k$  is thermal conductivity), and  $t$  is exposure duration. Note that, at small values of the Fourier modulus (short times or thick materials), transient ignition occurs at the smaller values of radiant exposure and is followed at higher radiant exposures by sustained ignition. The threshold of spontaneous flaming ignition in this region is found to be independent of sample thickness. The threshold line is given by the expression

$$\frac{H\sqrt{t}}{\sqrt{k\rho c}} = \left[ \frac{H\sqrt{t}}{\sqrt{k\rho c}} \cdot \frac{\sqrt{t}/\rho c L}{\sqrt{t}/\rho c L} = \frac{Q/\rho c L}{\sqrt{kt/\rho c/L}} = \frac{Q/\rho c L}{\sqrt{\alpha/L}} \right] = \text{constant} \quad (1)$$

where  $H$  is irradiance. This expression suggests that the criterion for ignition is the attainment of a constant high temperature at the exposed surface (estimated to be at least 600°C). Recent radiometric measurements



by Alvares<sup>23</sup> indicate that the temperature of the exposed surface at the instant of ignition is between 600 and 650°C and is independent of the irradiance level and also independent of sample thickness as long as it is sufficiently great that no appreciable rise in back-surface temperature occurs before ignition.

At larger values of the modulus, flames persist after exposures that terminate at the earliest appearance of flame. At still larger Fourier moduli, flaming ignitions are frequently preceded by or entirely replaced by glowing ignitions. At this point, there occurs a transition from ignitions controlled primarily by diffusion of heat into the solid to ignitions governed by fluid mechanics; that is, convective heat losses and/or convective mixing of fuel and air become increasingly important in the process. For this reason, the correlation technique based only on heat conduction fails to correlate the data, and there occurs a separation into a family of curves for different thicknesses. These curves approach an asymptotic value of roughly  $0.5 \text{ cal cm}^{-2} \text{ sec}^{-1}$  which is called the critical irradiance.\* This asymptote may well represent the combined heat losses from both surfaces of a cellulosic sheet at a temperature that, for very slow heating, corresponds to ignition. Accordingly, this temperature would be about 300°C (for a  $\frac{3}{4}$ -inch-diameter circular sample with surfaces vertical and having an emissivity of 0.9), which is in good agreement with measurements of ignition temperatures for furnace heating and the like.<sup>25,26</sup>

This value of "mean temperature for ignition" is significantly lower than the JFRO "fixed mean temperature" for sustained ignition of thermally thin solids.<sup>20</sup> The NRDL-measured "surface-ignition temperature" for thick solids<sup>23</sup> is noticeably higher than the JFRO empirically derived value.<sup>20</sup> The JFRO "mean temperature" successfully correlates ignition data for a time-irradiance regime that is rather far removed from the critical-irradiance regime. As mentioned earlier, the JFRO correlation breaks down for low rates of heating, but its critical-irradiance values agree quite well with the NRDL estimates both in magnitude and insensitivity to differences between materials. This agreement suggests that the "mean temperature" for ignition of thermally thin materials is not really constant, but rather a function of the duration (and hence rate) of heating.

The differences between values of "surface temperature" for ignition of thermally thick solids (500°C as empirically derived by JFRO, and 600° to 650°C as measured radiometrically by NRDL) may be the result, as Simms<sup>20</sup> suggests, of the smallness of the exposed area used in the NRDL experiment; but for the irradiance levels used, this explanation is not entirely convincing. Perhaps, these differences indicate that it is not altogether wise to attach much physical significance to empirically derived numbers.

\* Since this material was reviewed more up-to-date information on critical irradiances and their dependence on various parameters has been reported.<sup>24</sup>

### 4.2.3 Ignition Behavior and Temperature Profiles

It is of some interest to attempt to interpret the ignition-behavior curves of Fig. 2 in terms of temperature profiles attained during exposure. First, let us consider very short exposure durations ( $t < 0.1 L^2/\alpha$ ). If the material is reasonably opaque, the energy is deposited in a very thin layer of material at the surface, which causes very high temperatures. The result is violent ablation, and ignition occurs almost instantly; but it persists only after the solid has suffered extensive ablation.

At the other extreme, for long, low-irradiance exposures ( $t > 4L^2\alpha$ ), the material is (dimensionally) too thin to maintain a temperature gradient. The result is a uniform, low temperature that is slowly attained. The material is smoothly converted to char and will often glow instead of flame because it runs out of gaseous fuel (which is relatively poorly combustible anyway because of its high  $\text{CO}_2$  and  $\text{H}_2\text{O}$  concentration) before temperatures rise high enough to induce ignition. As indicated earlier, ignition at long times depends on heat losses and certain, as yet ill-defined, geometric factors.

For intermediate exposure durations, the nature of the response is governed by thermal diffusion in the exposed solid. Persistence of flames (or glowing combustion) at the end of the exposure depends on the thickness and volumetric heat capacity of the material. It is convenient to examine two cases. In the first case ( $0.1 < \alpha t/L^2 < 0.6$ ), energy is distributed throughout the sample by conduction, which causes the unexposed surface to exhibit a small but finite temperature rise; but the exposed surface reaches the ignition temperature, say  $600^\circ\text{C}$ , before the average overall temperature is high enough (in excess of  $300^\circ\text{C}$  at least) to sustain the flow of volatile fuel. Clearly, if the temperature profile existing at the end of the exposure relaxes to a value of only  $150^\circ\text{C}$ , for example, the flow of volatiles will, for all practical purposes, cease and flaming will abruptly stop. Therefore, transient flaming is the threshold effect, and only after a somewhat greater radiant exposure will ignition be sustained.

In the second case ( $0.6 < \alpha t/L^2 < 4$ ), the average temperature of the material exceeds a value that is sufficient to maintain the flow of volatiles by the time the exposed surface reaches the ignition temperature and flames always persist. The major characteristics of ignition behavior can be explained, at least qualitatively, on the basis of the foregoing discussion.

#### 4.2.4 Effect of Moisture Content and Optical Absorptivity

Experimental work with  $\alpha$ -cellulose containing varying amounts of carbon black in atmospheres of controlled relative humidity<sup>27</sup> clarified the influence of moisture content and optical properties on the ignition behavior. It was found that, for most kindling fuels (typical absorptivities of about 0.4 or 0.5 and higher), the ignition behavior is described by the correlation pattern of Fig. 2 after allowance is made for the heat capacity of the moisture content and by multiplying the radiant-exposure values by the radiant-energy absorptivity of the material that corresponds to the spectral distribution for the appropriate source temperature. Therefore, to estimate ignition radiant exposures for a variety of cellulosic kindling fuels under a wide range of conditions, corrections can be readily applied to values computed for dry, black  $\alpha$ -cellulose using the expression.

$$Q_{2,m} = (1/a)(1 + 3.2m) Q_{1,0} \quad (2)$$

where  $Q_{2,m}$  is the radiant exposure required to ignite a cellulosic material<sup>28</sup> having radiant-energy absorptivity  $a$  (lying between about 0.4 or 0.5 and 1.0) and moisture content  $m$  (expressed as a fraction of the dry weight of the material), and  $Q_{1,0}$  is the radiant exposure required to ignite cellulose having unit absorptivity and zero moisture content. For more detailed information, the original reference<sup>27</sup> should be consulted.

#### 4.2.5 Effect of Traces of Certain Inorganic Substances

It has been observed that traces of certain inorganic substances have a profound influence on both the ignition behavior and the thermal decomposition (pyrolysis) of cellulose.<sup>8,9,10</sup> Such substances appear to catalyze reactions whose main final products are char, water, and the oxides of carbon. These reactions in turn promote the glowing combustion of a radiantly heated cellulosic fuel often to the exclusion of flaming ignition. The process is not, as yet, well understood, but it is receiving considerable attention by Broide<sup>8</sup> and co-workers at the Pacific Southwest Forest and Range Experiment Station in Berkeley and by Parker and Lipka<sup>28,29</sup> at NRDL. This work may find application in ignition-countermeasures development.

#### 4.2.6 Reliability of Radiant Exposure Values for Ignition

Uncertainties in the values of integrated radiant exposure required to ignite black  $\alpha$ -cellulose exposed to a constant irradiance are very small. To a high level of confidence, the values lie well within  $\pm 10\%$  of the central-tendency curves derived experimentally. Ignition values can be reproduced years apart, usually to within a percent or two using the same material, even if an entirely different source (such as an incandescent-tungsten source rather than a carbon-arc source) is used.<sup>24</sup> Moreover, the values are accurate in that all radiometric measurements are based on calibrations against the absolute, water-flow calorimeter.<sup>30</sup> Virtually as much can be claimed for less idealized kindling fuels, depending primarily on how well the required characteristics are known or can be estimated. For materials (except plain white materials) containing significant mineral impurities and noncellulosic substances, such as wool and nylon, ignition values derived from the  $\alpha$ -cellulosic ignition correlation curves are probably good to better than 20%.

#### 4.2.7 Factors Affecting Incendiary Threat of Nuclear Attack

In the practical problem of evaluating the incendiary threat of nuclear-weapon explosions, numerous complicating factors must be considered before attempting to apply the results noted in 4.2.6. In addition to such factors as thermal-radiation attenuation by the intervening atmosphere, and the field of view, distribution, and location (relative to other combustibles) of the kindling fuels in a target complex, there are complicating factors involving thermal-pulse characteristics of nuclear explosions, area and uniformity of exposure, and the geometrical complexity of real kindling fuels in "real-world" situations. The latter group of factors is the subject of the next discussion.

4.2.7.1 Exposure to Thermal Pulse of Low-Altitude Explosions. Experimental work in this area<sup>31</sup> was basically a repetition (though less extensive in scope) of the earlier NRDL measurements, but a thermal pulse designed to simulate the effective part of the thermal pulse of low-altitude nuclear air bursts<sup>32</sup> was used instead of the square-wave pulse. The correlation necessarily had to be modified in one important respect. Since the duration of thermal pulses from nuclear bursts cannot be rigorously defined, it was necessary to use the time to peak irradiance in the Fourier modulus. By the same token, the total radiant exposure is somewhat indefinite. Experimentally, with the laboratory-simulated pulse, the peak radiant power  $H_{\max}$ , the time to peak power  $t_{\max}$ , and the radiant exposure  $Q$  can be measured and are found to be related by

$$Q = \int_0^{10t_{\max}} H(t)dt = 2.07 H_{\max} t_{\max} \quad (3)$$

However, the laboratory pulse does not include the long, low tail of the thermal pulse, which includes some 20% of the thermal energy. From field measurements, we estimate the total radiant exposure to be

$$Q = \int_0^{\infty} H(t)dt = (2.6 \pm 0.5) H_{\max} t_{\max} \quad (4)$$

Consequently, this difference should be borne in mind whenever attempting to apply laboratory data to weapon-effects problems. Because of the still unsettled state of scaling relationships, the only really reliable and generally useful thermal-pulse ignition data are those reported in terms of both  $H_{\max}$  and  $t_{\max}$ .

As anticipated, the ignition behavior for thermal pulses was found to be remarkably similar to that for square-wave pulses. Contrary to the case for charring of wood, however, no simple square-wave thermal-pulse equivalence was to be found. Qualitatively similar responses were observed when the thermal-pulse peak irradiance is roughly 3 times the square-wave peak irradiance; thus

$$H_{\max}/H = 2.7 \pm 0.2 \quad (5)$$

However, the thermal pulse is significantly more efficient (20% to 40% less radiant exposure required) than the square-wave pulse for short exposures and significantly less so for long exposures.

High-reliability estimates of ignition-threshold radiant exposure  $Q$  (cal cm<sup>-2</sup>) of cellulosic fuels of thickness  $L$ , density  $\rho$ , specific heat (constant pressure)  $c$ , optical absorptivity  $a$ , and thermal diffusivity  $\alpha$  can be obtained as a function,  $f$ , of the conventional nuclear-weapon thermal pulse of characteristic time  $t_{\max}$  for the range of  $\alpha t_{\max}/L^2$  as shown in Fig. 3 through the use of the following normalizing relationship:

$$\frac{a Q_0}{\rho c L} = f \left( \frac{\alpha t_{\max}}{L^2} \right) \quad (6)$$

For larger values of  $\alpha t_{\max}/L^2$  than shown in Fig. 3 the relationship is:

$$\frac{a Q_0}{\rho c L} = 1500 \left( \frac{\alpha t_{\max}}{L^2} \right)^{0.2} + \frac{q t_{\max}}{\rho c L} \quad (7)$$

$Q_0$  is the threshold radiant exposure for moisture-free fuel. The value  $Q_0$  can be converted to the value for any desired relative humidity by multiplying by an appropriate factor determined from a relationship between moisture content and relative humidity such as the one shown in Fig. 1. (See Eq. (2), p. 17.). The quantity  $q$  in Eq. (7) is an empirically derived quantity that depends primarily on the optical absorptivity

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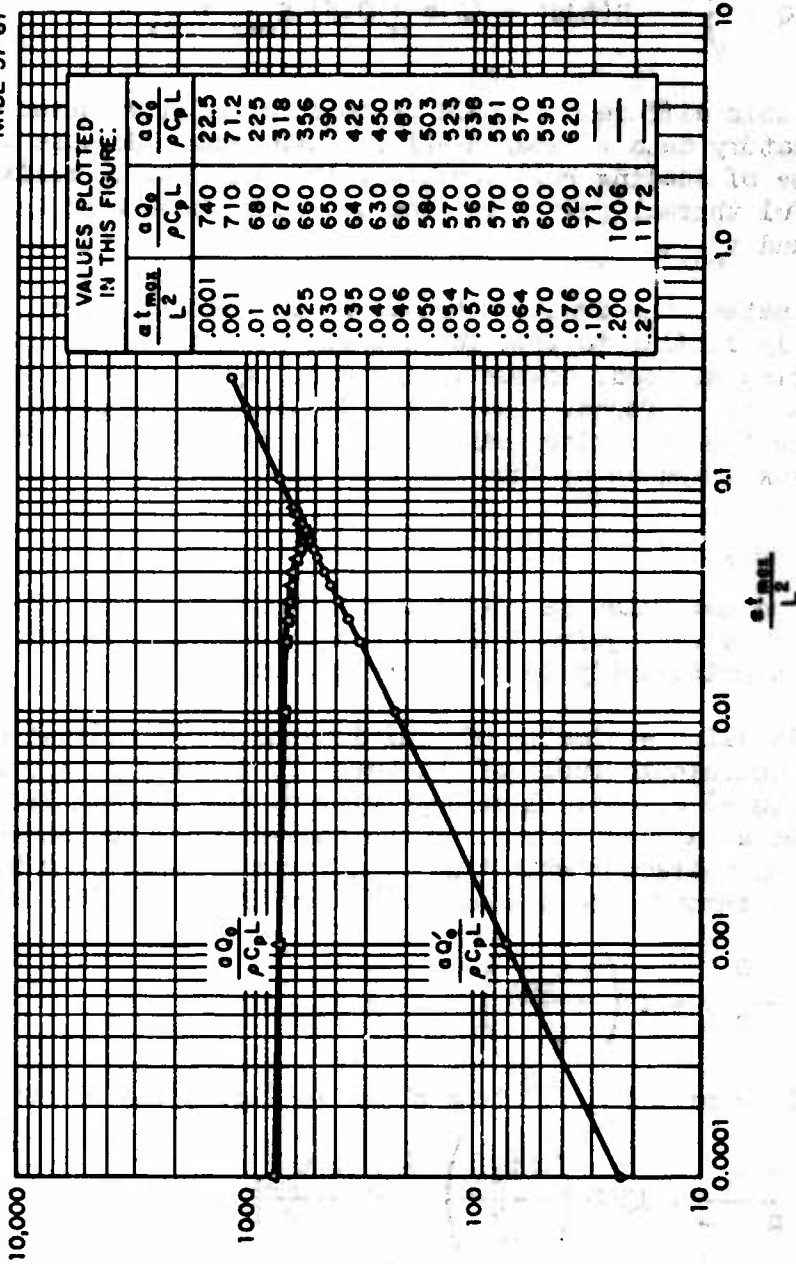


Figure 3 Ignition Correlation Diagram for Cellulosic Fuels (Low-Altitude Weapon Pulse)

and geometry of the fuel.\* It has values ranging from about 1 or less for dark-colored geometrically complex fuels to 2 or more for light-colored, plane-sheet-configuration fuels (and could be considerably higher for optically-thin materials or cases of considerable air motion).  $Q_0'$  is the value for transient (unsustained) cases (see Fig. 3).

From the resulting correlation, it is possible to predict the radiant exposures required to ignite a variety of kindling fuels under a wide range of conditions and over a wide range of weapon yields and burst altitudes knowing only the properties of the fuel and the appropriate altitude-weapon yield  $t_{\max}$  scaling. The job of measuring the necessary physical properties of every material of interest is not as formidable as it might at first seem, since the more difficultly measured properties, such as diffusivity, heat capacity, and moisture content, exhibit a regular dependence on such readily determined properties as thickness, weight per unit area, and the relative humidity of the environment.

A scaling equation, such as

$$t_{\max} = 0.032 (W\rho/\rho_0)^{\frac{1}{2}} \quad (8)$$

where  $W$  is in kilotons,  $\rho$  is air density at burst altitude, and  $\rho_0$  is air density at sea level, can be used to extend ignition estimates to burst altitudes up to about 20 miles, but the higher-altitude estimates are not as reliable because of uncertainties in the air density- $t_{\max}$  scaling and because the thermal pulse may not be accurately duplicated by the laboratory pulse on which the estimates are based.

Aside from uncertainties introduced by possible simulation deficiencies, basically the same reliability can be attached to the experimentally derived curves for sea-level thermal pulses as those for square-wave pulses. Actual experimental measurements<sup>3</sup> made at the Naval Applied Science Laboratory (NASL) on black cotton sateen, newspaper (printed area), and pine needles using pulses simulating air bursts of yields somewhat greater than nominal yield (20 KT to 10 MT) fall largely within about 20% of values computed from the  $\alpha$ -cellulose correlation, although there are several values that differ by about 30%. It is noteworthy that the NASL values for black  $\alpha$ -cellulose show variations from the NRDL values that are generally as great as those for real kindling fuels and that the values themselves are in all cases larger. The larger values may be due to the small spot size of the NASL source. The effect of exposure area is discussed later in 4.2.7.3.

\* The quantity  $q$  is proportional to the critical irradiance of the exposed material. For a complete discussion of the dependence of critical irradiance on the optical properties of fuels and their geometries see Ref. 24.

4.2.7.2 Exposure to Thermal Pulse of High-Altitude Explosions. Recent interest in the incendiary capability of high-altitude nuclear explosions has sparked a flurry of theoretical and experimental work directed toward the assessment of ignition behavior for very short pulses of very high radiant power. The previous lack of experimental data for these short exposures is due, in large measure, to the radiant-power limitations of simulation facilities. Megaton-yield weapons detonated at altitudes from about 30 to 60 kilometers are expected to radiate the effective part of their thermal energy in times on the order of tens to hundreds of milliseconds. Anticipating radiant-exposure values for the sustained ignition of typical kindling fuels to be on the order of  $10^2$  cal cm<sup>-2</sup>, we expect to need irradiance levels on the order of  $10^2$  to  $10^3$  cal cm<sup>-2</sup> sec<sup>-1</sup> to properly simulate high-altitude bursts of high-yield weapons. Carbon-arc sources, at best, provide irradiances extending only into the lower part of this range. Xenon flashtubes have the capability of very high radiant-power levels, but their pulse durations are generally less than 1 msec with a consequent inadequate radiant-exposure level.

Certain theoretical analyses indicated that, for exposures of high radiant power, sustained-ignition thresholds would exhibit a very strong time dependence and would rise precipitously to very high radiant-exposure levels as pulse durations are made increasingly shorter. For example, Siddons<sup>34</sup> used as a computational model a kinetically simple, first-order, chemically reacting system whose temperature history is given by the solution of the heat-conduction equation for an inert, opaque slab irradiated on one face and cooled convectively and radiatively at both faces. The sustained-ignition threshold was taken as that point where the volatile content of the material falls to some arbitrary low level. Despite the relative elegance of this model, it does not take into account surface ablation, and it calculates unreasonably high surface temperatures that lead to overestimates of radiative cooling.

On the experimental side, xenon-flashtube measurements made at the Naval Applied Science Laboratory<sup>35</sup> showed no evidence of a sharp upturn in the ignition threshold for pulses intended to simulate high-altitude MT-range explosions at about 75 kilometers. The flashtube pulse, which peaked at about 1 msec with an irradiance of at least  $1500$  cal cm<sup>-2</sup> sec<sup>-1</sup> and was virtually out by 10 msec, ignited closely printed classified pages of newsprint with a radiant exposure of  $4.6$  cal cm<sup>-2</sup>.

Meanwhile, Martin<sup>36</sup> at NRDL extended the square-wave correlation for cellulose to smaller values of the Fourier modulus (included in Fig. 2) using a more intense carbon-arc source than was previously used, which provided useful exposures down to 20- or 30-msec duration. Ignition radiant exposures were found to retain their proportionality to the product of density, specific heat and thickness ( $\rho cL$ ) while increasing less than a factor of 2 for an order-of-magnitude reduction in exposure duration.

Hochstim and McLain\* at the Institute for Defense Analysis (IDA) obtained short-pulse ignition data from an ingenious Fresnel lens system, which utilizes solar radiation. Their data generally support the NRDL results.

At present, there is insufficient yield-altitude scaling information to permit detailed simulation of thermal pulses from high-altitude bursts (above 30 km). In fact, the information is so scanty that we can only guess at the applicability of currently available laboratory ignition data to high-altitude bursts. Our experience\*\* is limited to the two high-altitude shots of Operation Hardtack, shots Teak (megaton range, 77 km) and Orange (megaton range, 43 km), and two of the high-altitude, submegaton yield shots of the 1962 Pacific series, Kingfish and Bluegill, whose burst altitudes were "tens of kilometers" above sea level. All of these bursts exhibited a single, brief pulse of thermal radiation, which indicates that the usual shock-formed air-opacity phenomena of low-altitude bursts are absent in high-altitude bursts. The most reliable evidence, however, indicates little change in thermal efficiency with altitude up to perhaps 80 km.

Shot Teak exhibited a very brief thermal pulse whose radiant power was greater and whose duration was shorter by some 3 orders of magnitude than those for the same-yield weapon detonated at sea level. One of the 1962 shots showed somewhat the same pulse characteristics; but because of the difference in altitude of the two shots, little can be said about the yield dependence of pulse duration. Some theoreticians propose a very weak dependence of duration on yield in this altitude regime. In spite of their limitations, xenon flashtubes appear to be at this time the best sources for simulating pulses from weapons at these altitudes.

Shot Orange exhibited a thermal pulse that was more nearly a square-wave pulse than a low-altitude-burst thermal pulse, whereas the pulse of a somewhat higher explosion of the Pacific 1962 series was similar but decayed somewhat more rapidly. In view of the current state of uncertainty about pulse shapes from high-yield explosions in this altitude region, we can conclude only that the ignition radiant-exposure values determined with 30- to 100-msec duration square-wave pulses roughly approximate the ignition thresholds for megaton-weapon bursts at altitudes say, between 30 and 80 km. Experimentally determined values for ignition of printed and unprinted newspaper by 28- to 110-msec, square-wave pulses<sup>36</sup> and for three irradiance values are shown in Table 1. Note that the values do not change drastically with duration in this range. (Also compare Fig. 4.)

\* Private communication.

\*\* Ref. 32, pp. 676 and 677e. Three other 1962 shots (Checkmate, Tight-rope, and Starfish) and the three ARGUS shots of 1958 were not of operational interest in regard to thermal effects on the ground, since they were of low yield and/or were detonated at extremely high altitude.

Table 1

Square-Wave Pulse Ignition Values for Newspaper

Description	Irradiance (cal cm <sup>-2</sup> sec <sup>-1</sup> )	Duration (msec)	Radiant Exposure (cal cm <sup>-2</sup> )
Newspaper, darkest half-tone areas	50	42	2.1
	75	33	2.5
	100	28	2.8
Newspaper, gray half-tone	50	60	3.0
	75	40	3.0
	100	33	3.3
Newspaper, text areas	50	80	4.0
	75	60	4.5
	100	50	5.0
Newspaper, unprinted	50	110	5.5
	75	60	4.5
	100	55	5.5

4.2.7.3 Effects of Fuel Exposure Area and Geometry. Laboratory exposures are necessarily idealized. Because of the limited area of uniform exposure and limited depth of field of the heated spot of most simulation facilities, laboratory studies are necessarily limited to flat samples of small exposure area that are usually exposed with surfaces in a vertical plane normal to the optical axis of the heat source. The use of this type of exposure precludes observation of any possible influences of nonuniform exposure and of sample orientation, geometry, and area of nonuniform exposure. Hottel<sup>37</sup> has pointed out that, in the regime where ignition governed by diffusion heat loss gives way to ignition governed primarily by convective heat loss (that is, for long exposures), the radiant exposures required to ignite materials like newsprint should depend on the exposure or heated area of the specimen. Measurements in a muffle furnace indicated to him that the temperature required for ignition rises as the heated area is decreased, which suggests a diluting effect on resultant combustible volatiles in addition to an increased convective heat loss for small specimens. Moreover, at a given temperature, small specimens glowed, whereas larger specimens flamed. Taken together, these results indicate that the previous carbon-arc-exposure results used for long thermal-pulse exposures tend to overestimate the radiant exposures for ignition of large exposed areas and to predict glowing ignitions where flaming ignitions would occur.

Experience at this laboratory (NRDL)<sup>24</sup> definitely supports the latter indication, but it is not clear yet whether it is the result of increased area or of nonuniform irradiation. Simply removing the aperture from a given type of specimen (increasing the exposure area) frequently results in flaming ignition for an exposure that otherwise could have caused glowing ignition. Bending part of the sample back away from the heated spot or casting the penumbra of an opaque object on part of the exposure area causes the same result.

Recent studies by both NASL<sup>38</sup> and NRDL<sup>24</sup> using large-area heat sources (banks of incandescent-tungsten, tubular-quartz-envelope lamps) show the same significant lowering of flaming thresholds (frequently down to the previous glowing thresholds), but the lowest irradiances required for ignition fail to drop significantly below previously reported values; that is, critical irradiances for black  $\alpha$ -cellulose remain at about  $0.5 \text{ cal cm}^{-2} \text{ sec}^{-1}$ , and for newspaper, about  $1 \text{ cal cm}^{-2} \text{ sec}^{-1}$ .

On the other hand, geometrically complex specimens (crumpled, wrinkled, folded, multiple sheets, etc.) have significantly lower ignition thresholds at long times of exposure than their plane-sheet counterparts. A loosely folded newspaper, for example, appears to have a critical irradiance of about  $0.5 \text{ cal cm}^{-2} \text{ sec}^{-1}$  compared to  $1 \text{ cal cm}^{-2} \text{ sec}^{-1}$  for a single sheet. This small difference in asymptotic value can have a major effect on estimates of ignition radiant exposures for long

pulse durations. Figure 4 indicates the current estimate of the broad-band relationship between newspaper ignition thresholds and weapon yield (modified by air density). The band represents estimated values for dark-printed single sheets or for loosely folded or crumpled sheets with ordinary text printing. Moisture contents are those for relative humidities in the 40% to 50% range.

4.2.7.4 Effects of Repetitive Exposures by Multiple Bursts. A factor that has not received any amount of attention thus far is the effect of multiple bursts (repetitive exposures) on the ignition behavior of fuels. Clearly, if a fuel is exposed to a series of repetitive exposures, all of which are (1) of insufficient intensity to cause an irreversible change in the properties of the fuel and (2) far enough apart in time to allow reversible changes to the initial state (for all practical purposes), nothing will happen by way of damage to the fuel. But if any one of the exposures fails to satisfy the first condition, or if two or more exposures in combination violate the second condition, then there is a distinct probability that the fuel will be ignited by the series of exposures. It would appear at first sight that, if any one of the series of exposures is capable of igniting the fuel, this probability becomes unity (this is obviously so if the igniting exposure is the first of the series). But if the preceding exposures have failed to ignite the fuel while depleting its pyrolysis-product reserve, it might fail to ignite when exposed to a pulse that would surely have ignited it in its original state. However, this prospect seems quite unlikely and certainly not worthy of serious consideration in the usual situation of mixed fuels.

The cases of increased ignition susceptibility due to reversible or irreversible changes in fuel properties by a previous exposure does seem to demand serious consideration and is somewhat amenable to evaluation. The important reversible changes that occur in fuels as the result of exposure to subignition radiant-energy levels are the generation of a temperature profile and the removal of moisture. The first of these is extremely transient in nature. It can be said categorically that, if the repetitive exposures are more than a few seconds apart, they will not be able to build up the fuel temperature to a level that will cause ignition. Diffusion of moisture occurs more slowly than diffusion of heat, but the most that can happen to the fuel by the second reversible change is to get it "bone dry" and somewhat more ignitable. But elevated temperatures are still a requirement, and unless the pulses are in rapid order, ignition cannot result.

However, when the exposures are in rapid order or when they are of flux levels such that individually they generate temperatures in the fuel surface that are several hundred degrees centigrade, then irreversible changes occur, such as pyrolysis of the organic constituents of the fuel. The resulting increase in the optical absorptivity of the fuel (unless it

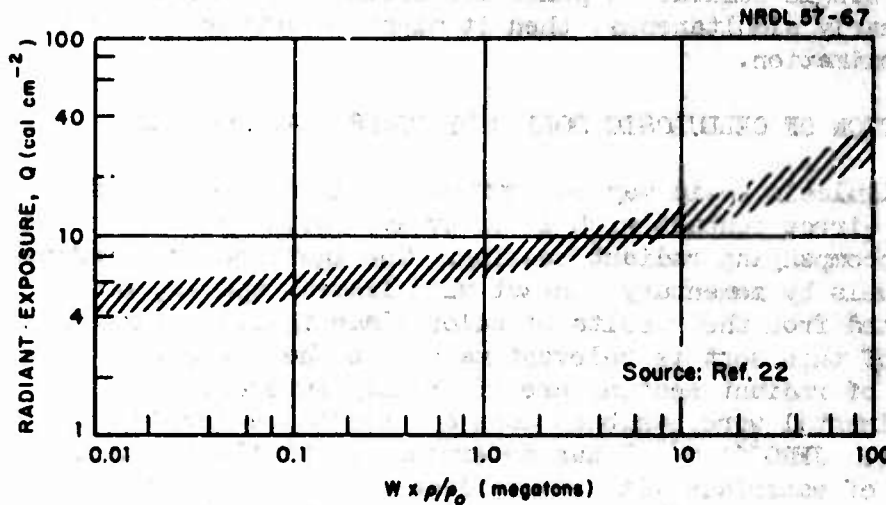


Figure 4 Ignition-Threshold Radiant Exposures for Newspaper Vs Weapon Yield (Modified by Air Density, or Burst Altitude). The fraction  $\rho/\rho_0$  is the air density at burst point divided by air density at MSL.

was already black) plus the evolution of volatile fuel substances make the fuel susceptible to ignition by a subsequent pulse which by itself would otherwise have been incapable of igniting the fuel. Ignition by multiple bursts need only be considered, therefore, for rapid-order bursts where the radiant exposure from no single pulse exceeds the ignition threshold by itself and where together the time averaged irradiance will be at least  $1 \text{ cal cm}^{-2} \text{ sec}^{-1}$  or more. If they are very close together in time, the sum of their individual contributions can be used to provide a single cumulative pulse for estimating ignition radii. If they are not nearly simultaneous, then it might be better to use a square-wave approximation.

#### 4.3 IGNITION OF CELLULOSIC SOLIDS BY OTHER HEAT SOURCES

A cellulosic solid may be ignited by flames, hot gases, or hot solids in direct contact with it or by any combination of these with or without accompanying radiant heating. The ignition of irradiated cellulosic fuels by momentary contact with flames, sparks, or firebrands can be evaluated from the results of pilot-flame ignition experiments. Since ignition of this sort is relevant mainly to the subject of fire propagation, low rates of radiant heating are of primary interest. In fact, most of the experimental work has been done at irradiance levels near the critical irradiance. JFRO<sup>19, 39-42</sup> has determined critical-irradiance values for a variety of materials with pilot flames in the gas-mixing region and on the exposed surface. These results show about a factor-of-2 reduction in the minimum irradiance level required for ignition when a pilot flame is present.

Weatherford and Sheppard<sup>43</sup> theoretically analyzed and experimentally investigated the ignition behavior of cellulosic solids heated by high-temperature airstreams in the virtual absence of radiation. The major contribution of their work is in revealing the unique features of ignition by convective heating, such as might be experienced in fire propagation when heat from flames or hot gases engulf an unignited fuel.

Their major effort has been given to (1) recomputing, by a finite-differences method, the temperature profiles and rates of volatile-fuel production used in a mathematical model<sup>44</sup> of heated slabs of wood originally proposed by Bamford, Crank, and Malan<sup>44</sup> and (2) re-examining criteria for ignition and sustained burning. They discovered that the thickness increments used in the Bamford, Crank, and Malan computations were not thin enough, which gives rise to a situation of (computed) fuel depletion in one increment before significant vapor generation begins in the next. This computational defect, they conclude, caused unrealistic undulations in the curve of computed rates of vapor generation vs time and led to an erroneous supposition that the requirement for sustained ignition was the production of a specified vapor-generation rate of  $2.5 \times 10^{-4} \text{ g cm}^{-2} \text{ sec}^{-1}$ .

The results of Weatherford and Sheppard<sup>43</sup> indicate order-of-magnitude differences in vapor-generation rate for conditions equivalent to the sustained-ignition thresholds of Bamford et al. Their new results also provide graphical correlations of surface temperature and vapor-generation rates with time for convectively heated slabs (both one-sided and symmetrical two-sided heating) in terms of the temperature of the source and the initial properties of the slab (notably thickness, conductivity, diffusivity, and film coefficient). Vapor-generation rates were found to be nearly constant for given surface temperatures and source temperatures.

They noticed that the data of Bamford et al., have an approximately constant Fourier number (ratio of the product of heating duration and thermal diffusivity to the square of the slab thickness) and that this number corresponds approximately to the point at which the surface temperature of the slab departs perceptibly from that of a semi-infinite solid. To provide a definite and rigorously definable criterion, they propose the concept of a thermal feedback wave propagating from the center of symmetry in a slab heated on both surfaces or from the unheated surface of a one-side heated slab, and relate the threshold of sustained ignition to the arrival of the feedback wave to the heated surface. They find support for this proposed criterion in the agreement between the theoretical maximum thickness for sustained ignition of slabs with one-sided heating and that observed experimentally by Bamford et al., (approximately 0.3 cm for their conditions).

On the experimental side, Weatherford and Sheppard<sup>43</sup> measured piloted ignition times for hardboard and alpha-cellulose using a convective heating source with temperature in the range of about 700°K to 800°K. Their data were correlated on a basis derived from their theoretical work. They also correlated published ignition data of other laboratories on the same (or nearly the same) basis in an effort to discover similarities and to resolve differences in choices of ignition criteria. Weatherford and Sheppard combined the data of Bamford et al., with interpolated results of their own data (normalized to 800°K). The combined results<sup>21</sup> show a distinctly similar pattern to the radiant ignition data of Sauer<sup>21</sup> and Martin, Lincoln, and Ramstad.<sup>22,27</sup>

The final correlation (a Biot-Fourier correlation) shows that convective-heating ignition behavior is dependent on a Biot number parameter (ratio of the product of slab thickness and film coefficient to the thermal conductivity of the slab material). For Biot numbers greater than about 1 (source temperature = 800°K), a transient threshold occurs; that is, flames flash from the pilot through the gases over the heated surface and persist as long as external heating is maintained, but die out if the heat source is removed. Bamford et al.<sup>44</sup> worked under conditions corresponding to Biot numbers between about 1 and 10, but were unable to observe this threshold, since they were bathing the slab with

flame. If heating is continued, the threshold of sustained flaming is reached. Beyond this threshold the material continues to flame if both the pilot and heat source are removed. This threshold appears to have a constant Fourier number (about 0.3 for an 800°K source).

All of the data of Weatherford and Sheppard were taken at conditions of heating in the Biot-number range of 0.1 to 1. As a result of normalizing to 800°K, however, their data overlap the lower Biot-number range of the earlier work.<sup>43</sup> Their ignition responses can be described as (1) "sustained piloted flame after heat-source removal," and (2) "sustained piloted flame in presence of heat source." The latter satisfies the conditions of transient flaming if flames persist only in the presence of the heat source. On the lower Biot-number range (less than about 1 for source temperature of 800°K), response (1) is the only form of ignition observed and the only form anticipated, since Fourier numbers of 0.3 or greater correspond to the first ignition threshold.

Weatherford and Sheppard conclude that the first appearance of flames over the convectively heated surface of a cellulosic slab, in the presence of a pilot, coincides with the occurrence of a relatively constant surface temperature and, more importantly, with the attainment of a minimum rate of volatile fuel-production. (They do not quote values, but from their paper, it appears that these values are about 500°K and between 1 and 10 g cm<sup>-2</sup> sec<sup>-1</sup> for an 800°K source). Finally, they conclude that, in addition to the foregoing requirement for flaming ignition, sustained flaming will occur only when the temperature profile in the slab has established itself to a level where it is "self-stabilizing (relative to its behavior upon heat-source removal)."

## SECTION 5

### MECHANISMS OF FIRE PROPAGATION

#### 5.1 GENERAL

Fire propagates through a solid-fuel complex through a series of events that include both ignition and combustion. In a continuous fuel element, the process is a steady, continuous one in which it is frequently difficult to define the line of demarcation between ignited and unignited fuel. The unignited fuel is heated to its "ignition point" by radiation, convection, and conduction of some part of the heat of combustion of the burning fuel. The relative importance of each mode of heat transfer will depend on factors considered below.

In a discontinuous fuel array, conduction plays no part at all. For large separations or generally downward propagation, radiation is the dominant heat-transfer mechanism; but fires can propagate by convection heat transfer or by convectively translated, burning solid-fuel elements, commonly referred to as firebrands. Propagation through discontinuous fuel arrays occurs in a series of discrete events; there is a clear distinction between ignited and unignited fuels, and the instant of ignition is a well-marked point in time.

#### 5.2 HEAT-TRANSFER MECHANISMS

As a solid-fuel element burns, the heat generated by the reactions is transported away from the high-temperature region in several ways. From the flame zone, heat is radiated as governed by the temperature and emissive efficiency of the flames. Flames originating from the gas-phase oxidation of the pyrolysis products of cellulosic solids (and most other solid fuels as well) are highly luminous and radiantly emissive because of the high concentration of solid particles, some of which may be derived directly from the solid fuel, but are mainly due to soot-forming reactions favored by the oxygen-deficient conditions of diffusion flames. In addition, a significant fraction of the energy radiated appears in the near-infrared emission bands of water and carbon dioxide.

Energy radiates from the flame zone in all directions; some of it (a small part in general) radiates back to the solid fuel which supplies the volatile fuel, some radiates to unignited fuel where part of it is absorbed by the fuel (which raises the latter's temperature), and the remainder radiates to the noncombustible surroundings. In considering fire propagation, it is the amount of heat absorbed by the unignited fuel that we are concerned with. This amount is determined primarily by geometric factors. In general, the closer the unignited fuel is to the flame (and hence, the greater the solid angle of the field of view of the unignited fuel subtended by the flame), the greater will be the radiant-energy contribution. Other factors include the emissive power and spectral distribution of the flame and the effective absorptivity of the fuel.

The remainder of the heat of combustion in the flame zone (a large or even dominant fraction) is given up to its immediate surroundings by the direct transfer of kinetic energy of molecular motion. The flame imparts its energy to the air through a complex process of turbulent-eddy and/or laminar-diffusive mixing with air, along with collisional deactivation and redistribution of molecular kinetic energy in translational, vibrational, and rotational forms.

If the buoyant plume of air (burning gases and/or combustion products) encounters a solid object whose temperature, on the average, is less than the local temperature in the plume, heat is transferred to the surface of the solid through a quiescent layer (or film) of gas on the surface and subsequently into the solid by molecular conduction. The rate of diffusion of heat into the solid in this manner is governed by a variety of interacting parameters including the gas-phase velocity profile, the temperature gradient (which in turn is dependent on the motion of the gases, their heat-transfer properties, the heat-transfer properties of the solid, etc.), the surface characteristics of the solid, and the flow of decomposition products (if any) from the solid. The usual approach to problems of this sort is to resort to an empirically determined film coefficient rather than to attempt a detailed analysis in terms of the large number of abstruse factors involved. The work of Weatherford and Sheppard,<sup>43</sup> already alluded to, is a good example of this. The convective transfer of heat from flames to solid objects is, of course, a salient factor in fire propagation.

Once active pyrolysis ceases in the burning fuel (because of either depletion of volatile-fuel components of the solid or insufficient feedback of energy from the flame zone), combustion is limited by the rate of diffusion of oxygen to the air-fuel interface and occurs at or very close to the glowing surface. The temperature of the glowing surface will typically run to 900°C (or even higher with a forced draft). The charred surfaces of organic solids are optically opaque and exhibit high emissivities (though there is a tendency toward diathermancy to, and

reduced emissive efficiency of, the lower-frequency photons of the infrared region). In consequence of the high temperatures and good radiating properties of solids undergoing glowing combustion, a very large share of the energy that escapes the combustion zone is in the form of radiation: as much as  $3 \text{ cal sec}^{-1}$  from every square centimeter of area of the surface, distributed in wavelength as a nearly black- (or gray-) body spectrum, which peaks around  $2.5 \mu$  with approximately 95% of the energy at wavelengths longer than about  $1.6 \mu$ . Thus, the glowing solid fuel is a much more efficient radiator than the flames it fed at an earlier stage in its combustion. Probably 30% to 90% of the heat losses from the glowing solid are by radiation, though convective losses become increasingly more important as the speed of the air motion around the glowing solid is increased.

A significant fraction of the heat released in the combustion zone is conducted into cooler regions of the solid fuel or into other fuel elements in contact with it. The role of conducted heat in fire propagation is probably not important in most instances, since it is a relatively slow process compared to other propagation mechanisms. Conduction unquestionably is important, however, in penetration of fire through barriers, such as the walls of a room. This subject is treated in somewhat more detail in Ref. 1.

### 5.3 MASS-TRANSFER MECHANISMS

Mass-transfer mechanisms that play a part in fire propagation can be classified as follows: (1) Flow of hot or burning gases; (2) translation of burning solids such as firebrands, and (3) flow of burning liquids, e.g., gasoline flowing downhill.

The first class is inextricably connected to convective heat transfer and has been discussed briefly in 5.2. Innumerable factors with complex interactions prevent the making of first-principle generalizations. Empirical estimates can be made with modest reliability for a variety of cases using parameters that grossly describe the system (for example, dimensions of heat source and environment, rate of heat release, ambient fluid motion, and buoyancy properties of the fluid).

Firebrands, glowing embers, sparks, and other burning solids can be translated from the fire to unignited fuels by (1) falling under the influence of gravity, (2) being forcibly ejected by the explosive release of hot gases, and/or (3) being lifted away by the buoyant action of the fire. The probable relative ranges of these modes of mass transfer increase in the order given, under most circumstances. Only rarely will falling burning pieces of a fuel complex tumble or roll to a distance greater than the height of the burning complex. The slope of the surface (ground or floor) is obviously a factor here.

Explosive ejection can be of two forms, differing in scale: (a) moisture and pyrolysis products trapped in cells or voids in the fuel proper or between fuel elements can, on their release, carry relatively tiny solid particles up to a few feet away from the fire (these same particles are frequently the ones carried aloft by buoyant forces); and (b) rupture of containers of compressed gases at high pressure, as well as the detonation of explosives and other extremely rapid-burning fuel that may be contained within a burning structure, can throw relatively massive burning pieces of material for hundreds of feet.

Burning solids carried up from the fire by buoyancy can range from the tiniest of sparks to massive construction members and will travel anywhere from a few feet to a few miles, depending on the intensity of the fire from which they originate and the wind structure above the fire.

The only published and generally disseminated information on transport mechanisms of burning solids up to the time of this writing is that of Tarifa et al.<sup>45</sup> They experimentally determined the changes in aerodynamic drag and the losses in weight, both as functions of time and windspeed, of spherical and cylindrical firebrands of several varieties of wood. They found that firebrand flight paths can be estimated, for all practical cases, by assuming that their flight paths are directly related to their terminal falling velocities. With this simplification and the experimental data, Tarifa et al. were able to calculate flight paths for two different convection models; vertical and inclined convection columns of constant velocity in a constant horizontal wind. These calculations show that even small spherical or cylindrical firebrands can reach very great horizontal distances while still burning if they leave the convection column and are picked up by the horizontal wind before they reach a certain critical height. The distances to which hazardous concentrations of firebrands are carried depend heavily on the inclination of the convection column and therefore on the horizontal wind velocity.

Additionally, the distance depends on firebrand size, density, and shape, convection velocity, and the species of wood of which the firebrand is composed. Neither the moisture content of the wood nor the spinning or tumbling motion of the firebrands exerts much influence on the flight paths. Similar measurements and calculations should be made on firebrands of other shapes. Given sufficient information about convective velocity profiles above the free-burning fires, wind conditions with distance and altitude, and the number, sizes and shapes of firebrands produced with time, a very reasonable estimate of the fire-propagating potential of the firebrands generated by a large fire could probably be obtained. Before this state-of-the-art will be realized, however, considerable work remains to be done.

## SECTION 6

### CONCLUSIONS

In conclusion then, a distinction has been made between processes of ignition and combustion and the role of each in fire propagation has been described. Parameters that characterize the fuel--its composition, heat of combustion, heat conduction-properties, its geometry and proximity to other fuels--and the parameters that characterize its environment--composition of the ambient atmosphere and its local motion--have been presented and discussed in terms of their relative importances in combustion and ignition processes and both processes have been related as much as possible to the subject of fire initiation by thermal radiation from nuclear detonations and fire propagation by the mechanisms of conductive and radiative heat transfer and convective heat and mass transfer including firebrands.

The process of combustion of solid fuels of the type common to urban areas is generally understood, but detailed descriptions for complex situations are still beyond the state of the art. The process appears to be strongly dependent on fuel geometry and arrangement and on the composition and motion of the local atmosphere, but quantitative relationships are largely unavailable. Ignition of these fuels, i.e., the transient processes of initiation of combustion, is not as well understood, but empirical relationships are available for quantitative estimation of ignition criteria and conditions. As with the steady-state process, however, the dependence on complex fuel geometries and arrangements and on the atmospheric environment has not been adequately investigated.

Fire propagation by conductive, radiative and/or convective heat transfer can be treated as a series of ignition events and as such is amenable to analysis. However, the role of firebrands in fire propagation, notably the processes of their generation and transport have not as yet received enough research attention. Consequently this mechanism of fire spread cannot be reliably assessed at the present time.

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